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The Bohuslän herring periods: are they controlled by climate variations or local phenomena?

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Abstract:

Records of the herring fishery off the Swedish coast of Bohuslän, in the Skagerrak, date back to the 10th century. Nine periods each one lasting several decades are known during which large quantities of herring were caught very close to the shore boosting up local economy. So, in the 1895-96 season, more than 200 000 tons have been landed. During the 'interim' periods, which stretched over 50 or more years, the herring fishery played no role in this region. Neither is it known what caused the herring, very likely originating from the North Sea, to amass such large concentrations in inshore waters nor was there any certainty whether local/regional or global environmental forcing influenced appearance and disappearance of the fish. Several other herring fisheries in European waters overlap with the last Bohuslän periods whereas the Norwegian spring spawning herring and some sardine fisheries exhibit alternating periods. A study of the climatological-hydrographic scenario of all Bohuslän periods showed that, on a decadal scale, they coincide with times when there were a strong ice cover off Iceland, severe winters in western Europe with extremely cold air and water temperatures, an intensification of westerlies as indicated by negative anomalies in the NAO Index and a minimum of southwesterly winds over England in response to meridional migrations of the atmospheric polar front zone. The conclusion is that climate variation governs the alternating herring and sardine periods.

Key words: herring and sardine stock fluctuations, climate variation, NAO Index, polar front zone

1. INTRODUCTION

In view of the recent interest in long-term time series of marine populations the Bohuslän fishing periods dating back to the 10th century instigated our curiosity with respect to climate impact. When investigating these periods, very soon we came across a number of other time series of fishing periods for herring and sardine in European waters the reports on which covered several centuries. Obviously, it seemed worthwhile to study these different historical fisheries in a comparative manner to find out whether they were forced by the same climatic regime. Whereas there are quite a number of reports on these fisheries, this is the first attempt to analyze the dynamics of all these fisheries comparatively in the context of climate variation and climate forcing.

This study is a contribution to the GLOBEC-SPACC (Small Pelagic Fishes and Climate Change) Programme. The Second Backward-facing Workshop of the Cod and Climate Change Programme of GLOBEC in Bergen, March 1996, initiated this study.

2. DESCRIPTION OF THE FISHERIES

2.1 Bohuslän Herring Fishery

The Bohuslän region is a coastal stretch between the North Sea and the Baltic Sea, at the eastern side of the Skagerrak (Fig.1). The Bohuslän coast is characterized by deep fjords and numerous small rocky islands, also called skerries. As the Skagerrak connects the Baltic with the North Sea, the hydrographic conditions of the Bohuslän coast are extremely variable. Off Bohuslän, under normal conditions, high salinity water from the North Sea flows at the bottom into the Skagerrak whereas the Baltic Sea water of lower salinity moves above into the opposite direction. However, depending on wind direction and stress and on sea water level of the Baltic Sea which is very much influenced by precipitation the outcome of the interplay of in- and outflowing waters can fluctuate very much.

Periodically, large amounts of spent herring (Clupea harengus) migrate during autumn to this coast and overwinter in the skerries and fjords. They are then caught over a period of several decades (Cushing 1982, Devold 1963, Höglund 1978, Lindquist 1983, Sahrhage and Lundbeck 1992). These Bohuslän herring periods have been reported since about 1 000 years and nine such periods are known (Höglund 1978, Lindquist 1983, Sahrhage and Lundbeck 1992)(Fig.2):

1. *end of 10th century - early 11th century*
2. *end of 11th century - early 12th century*
3. *end of 12th century - mid-13th century*
4. *end of 13th century - mid-14th century*
5. *mid-15th century*
6. *1556 - 1590*
7. *1660 - 1680*
8. *1747 - 1809*
9. *1877 - 1906*

Naturally, as further one goes back, as less precise are the data on this fishery. Only the periods since the 16th century are really certain.

Up to about 1900, the Bohuslän fishermen used beach seines and set nets to catch the herring (Höglund 1978). Consequently, only when the herring was very close to the shore it could be fished. When the fish stayed in the open sea, they were not accessible to the fishery (Höglund 1978). This situation changed drastically once purse seines (about 1900) were introduced. Bohuslän periods are defined as those times when masses of herring came close to the shore to be caught by beach seines. The times when large shoals stayed in the open sea are not considered as Bohuslän periods. From 1907 to 1920, considerable amounts of herring have been caught with purse seines in the open sea off Bohuslän. It is not known whether such "open sea periods" have occurred previously.

The question what kind of herring was responsible for the periods has been the subject of hot discussions (Devold 1963, Höglund 1978). However, Höglund (1972, 1978) studying old reports on the number of herring in measuring barrels and investigating remnants of the activities of former fish oil factories from the 18th century such as vertebrae and other bones concluded very convincingly that it was North Sea herring invading the Bohuslän coast during the periods (Lindquist 1983) and Cushing (1982) assumes that it was Buchan and, maybe, Dogger herring.

The Bohuslän herring fishery yielded in some years astonishingly high amounts of fish although only beach seines were used: e.g. 270 000 t in one season in the 18th century (Höglund 1978) and 216 000 t in 1895/96 (Lindquist 1983). Not surprisingly, the herring periods were of extraordinary socio-economic importance and the well-being of the whole region depended on the herring periods (Lindquist 1983). That explains why there are reports dating back to the 10th century.

2.2 Norwegian Spring Herring Fishery

Norwegian spring, Icelandic spring and Icelandic summer spawners are the three stocks of the Atlanto-Scandian herring (Dragesund et al. 1980, Jacobsson 1980). The Norwegian spring herring is the largest stock of the three. Its total biomass may have ranged between 15 to 20 million t in a virgin state (Dragesund et al. 1980). Its main habitat is the Norwegian Sea (Fig. 1) and it spawns on several grounds along the Norwegian coast.

Historical records indicate that it has undergone large fluctuations during the last 500 years (Devold 1963, Beverton and Lee 1965, Skjoldal et al. 1993). Periods with large catches have alternated with periods of extreme scarcity (Fig. 2). However, Beverton and Lee (1965) and Rottingen (1992) point out that it is not clear how much of this periodicity is due to real changes in abundance or to changes in migration routes preventing the fish from coming within the limited range of the coastal fishing fleets. Boeck and Petterson suggested already as early as 1871 and 1926 that the migration patterns of herring were profoundly changed through secular periods. Cushing (1982) did not disagree but believed that the greatest changes on decadal scales were due to changes in recruitment or year class strength.

So, the migration routes of the Norwegian spring spawning herring have changed considerably during the last decades (Dragesund et al. 1980, Rottingen 1992). However, this seems to be linked to changes in stock size (Dragesund et al. 1980). Also, size of area and locations of spawning change with stock size (Dragesund et al. 1980). The same applies to changes in the size of the feeding area (Holst and Iversen 1992). In addition, the well-known anticlockwise pattern of migration between spawning, feeding and overwintering areas has changed into a clockwise one (Rottingen 1992).

The high catches of the Norwegian spring spawning herring ceased in 1970 (Dragesund et al. 1980). According to Cushing (1982), their end was probably premature as the fishery was extinguished by recruitment overfishing on adults in the East Icelandic Current and on juveniles in Norwegian fjords (Ulltang 1978). However, as the spawning and the fishing area moved further and further to the north as during the end of the previous period at the 60s and 70s of the 19th century, Cushing (1982) suggests in analogy that the period was in its final phase, anyway. He also points to the reversal of the Russell Cycle between 1965 and 1979 which may indicate years when the Norwegian spring spawning herring period might have ended naturally.

The periods of the Norwegian spring spawners and the Bohuslän herring seem to alternate with each other (Ljungman 1883, Devold 1963, Beverton and Lee 1965, Cushing 1982, Skjoldal et al. 1993) (Fig. 2).

2.3 Herring and Sardine Fishery off Southwestern England

The Channel is roughly the geographical boundary between the areas of distribution of the rather cold water preferring herring and the more warm water adapted sardine (Sardina pilchardus) (Fig. 1). Fishing for both species off the southwestern tip of England, off Cornwall and Devon, has been reported since at least the 16th century (Southward et al. 1988). Whereas the numbers of sardine (also called pilchard) increased in the catches westwards during the period 1895-1911, the numbers of herring predominated towards the East (Southward et al. 1988) . The geographical boundary between the two species seems to shift to and fro on a decadal scale. Consequently, periods of the herring fishery have alternated with those of the sardine fishery (Fig. 2) (Cunningham 1906, Southward et al. 1988). There is hardly any information on the herring fishery off Cornwall and Devon from the second half of the 18th century published in scientific journals. However, not all respective relevant historical sources have been processed (pers. comm., A. Southward). Although the herring catches were relatively small when compared to the yields of the Norwegian spring spawning herring or the Bohuslän herring, it was a major loss for the city of Plymouth when the herring fishery collapsed in 1930 (Southward et al. 1988).

The periods of herring and sardine fisheries off southeastern England seem to be linked to the Russell Cycle (Southward et al. 1988) which is a periodic and synchronous alternation of appearance and disappearance of a large number of pelagic species, zooplankton and fish, including eggs and larvae, in the western Channel which has been recorded since 1924 (Russel 1915, Cushing and Dickson 1976, Cushing 1982, Southward 1980). Changes in species composition in the Russell Cycle are accompanied by changes in ambient temperature (Cushing 1982). When the Russell Cycle changed again from a warm water to a cold water system between 1965 and 1979 the herring failed to re-appear in abundance off the south coast of Devon. Southward et al. (1988) assume that the strength of the warming after 1920 coupled with intensive fishing in the 1920s wiped out the herring stock which formed the basis for the big commercial fishery off Plymouth.

2.4 French Herring Fishery in the Channel

There are data on herring and sardine fisheries of French fishermen in the Channel since the 18th century. The fishing areas of the northern French herring fleet have been changing considerably in the 18th and 19th centuries according to local abundances and accessibility of the herring (Binet 1988). The main areas were the northern North Sea, the East Anglian coast and the Channel (Fig. 1). Although the landings in the French fishing harbours of the Normandy and the Picardy were a mix from different areas, the herring yields from the Channel can be identified as they were landed fresh in contrast to the salted herring originating from the more distant North Sea fishery (Binet 1988). The herring periods of the French Channel fishery seem to have been from 1750 to 1810 and from 1880 to 1910 (Fig. 2). Dieppe was the main fishing harbour for the Channel herring in the 18th century, whereas this position was taken over in the 19th century by Boulogne. Peak catches reached about 50 000 t in 1905 (Binet 1988). The distant North Sea fishery required larger vessels which, in addition to smaller ones, were also used in the Channel fishery (Binet 1988).

2.5 Bay of Biscay Herring Fishery

A small herring population dwells in the Bay of Biscay off southern Brittany (Fig. 1) which has been mentioned first in 1728 (Binet 1988). The centre of the distribution is off the estuaries of the rivers Vilaine and Loire, occasionally the fish have been caught as far south as Arcachon. Due to the relative unimportance of this fishery, reports are rather sporadic, but indicate nevertheless periods of presence and absence (Fig.2). Fishing between the estuaries of Loire and Vilaine has been recorded for 1741, 1756 (exceptional catches), 1757, 1773, 1788 (followed by several poor years) 1804, 1827 and 1838 (Binet 1988). Henceforth, no record has been made until the late 19th century. Then, high catches were reported in 1880, 1883,1894 and 1913. Afterwards catches decreased again (Binet 1988).

2.6 French Sardine Fishery in Channel

Most sardines were caught off southern Brittany and the Vendée region. Occasionally, a fishery developed north of Brest, in northern Brittany, in the Channel (Fig. 1), which is reported on in 1726, 1728, 1752, 1761, 1762, 1764. The sardines disappeared in the first years of the 19th century, but the fishery started again in 1860s and 1870s (Fig. 2) (Binet 1988). Small open fishing boats and drift nets were used in the French sardine fishery which was very close to the coast. During some of the years of sardine crisis, the sardines were sometimes reported as abundant some tens of miles offshore, just out of reach of the small fishing boats (Binet 1988).

3. COMMON FEATURES OF THE FISHERIES

Small pelagic schooling fish can respond dramatically and quickly to climate variations or changes (Hunter and Alheit 1995). Most of them are highly mobile, have short, plankton-based food chains, are highly fecund and have a great plasticity in growth, survival and other life-history traits. These biological characteristics make them very sensitive to environmental forcing and highly variable in their abundance.

Interestingly, all areas of fishing under investigation in this study, to some degree also the Norwegian coast, are bordering the North Sea, are based in transition areas and are under the influence of inflow and outflow regimes between the North Sea and neighbouring regions (MacCall 1990). The Skagerrak and the Channel are extreme habitats for North Sea herring as both areas are at the fringes of its area of distribution. The sardine faces the same situation in the Channel. Herring and sardines in these areas react faster and more drastically to small perturbations in the environment such as for example subtle climate variations or changes (Hunter and Alheit 1995) as they might already be under environmental stress. When environmental conditions are favourable, they can colonize these transition zones rapidly in an opportunistic manner. As soon as the environment deteriorates they withdraw to the centres of their distribution.

The "fisheries periods" are reported historically as presence or absence of fish and fisheries at certain locations. Only the drastic changes between fish-rich and fish-less periods ensured the historical records as the regional economies and the well-being of the population were heavily impacted. The fluctuations of these fisheries could be the result of real fluctuations of biomass or of decadal changes in migration routes moving the fish to areas not accessible to the limited range of fisheries in previous centuries. However, very likely, fluctuations in biomass and migration routes are concomitant phenomena.

The fisheries described here fall into two groups with alternating periods of occurrence. Group 1 comprises the Bohuslän herring, the herring off southwestern England, the herring caught by the French fleet in the Channel off northern Brittany and the Bay of Biscay herring. Group 2 the periods of which do alternate with those of Group 1 consists of the Norwegian spring spawning herring, the sardines off southwestern England and the sardines caught by the French fleet in the Channel (Fig. 2).

4. METEOROLOGICAL-OCEANOGRAPHIC BACKGROUND OF FISHING PERIODS

One characteristic difference between herring and sardine is their temperature adaptation (Southward et al. 1988). The herring is an Arctic-boreal species the distribution of which extends to the North of the Channel whereas the sardine dwells in warmer waters and is usually found to the south of the Channel. In the Channel where both species overlap, cooling should favour a southward extension of the area of distribution and increasing biomass of herring, warming should have the opposite effect. The same mechanism should apply for the sardine, however, under opposite temperature conditions. This strong correlation between temperature and occurrence and abundance of the two species has been found over most of the past 400 years along the south coast off Devon and Cornwall (Southward et al. 1988). The herring fishery was favoured during cold periods and extended further west whereas the sardine fishery was then restricted to western Cornwall. So, during the extremely cool period of the "little ice age", in the second half of the 17th century, sardines were very scarce while herrings were abundant. The sardine fishery is doing better in warm periods. Binet (1988) reports that the southward displacement of the French herring fishery into the Channel coincided with the climatic deterioration at the end of the 18th century. Also, extension and decline of the French herring fishery in the Channel coincide with herring catch records off the south coast of Cornwall and Devon (Fig. 2). Obviously, both fisheries are influenced by the same temperature regime.

Another antagonistic pair of fisheries with respect to opposite temperature regimes are those for the Bohuslän herring and for the Norwegian spring spawning herring. The last period of the Bohuslän fishery (1878 - 1906) was during a cool period whereas the Norwegian herring period from 1920 - 1950 (when the last strong year class appeared) occurred during a period of elevated temperatures. This is confirmed by a plot showing the 5-year running means of the mean January air temperature (in England), the thermal winter index(*)1 composed by Lamb (1977) and the last three Bohuslän periods (Fig. 3). The temperature data are from Manley (1974). Both "temperature" plots sufficiently coincide for the period between 1670-1950. Lamb (1977) has constructed the winter index time series for about 900 years. A comparison to the last seven Bohuslän periods shows that they occurred during severe

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(*) The number of unmistakably mild months (Dec.,Jan.,Feb.) minus the numer of severe months (Dec.,Jan.,Feb.) per decade.

(For the decadal scale at mid-latitudes, it is a commonly accepted notion that changes in the air temperature well reflect associated variations in the water temperature and that significant changes drastically occur during the winter season.)

winters at the latitude of about 50°N in England (0°E) and Germany (12°E) (Fig. 4). This is firm evidence that the Bohuslän periods took place during cold periods (Cushing 1982).

The variability of the regional air temperature on time scales of several decades is mainly controlled not only by anomalies in the atmospheric circulation, but also by very low frequency variations of the Atlantic sea surface temperature (SST) (Werner and Storch 1993). The latter are mainly based on basin-scale changes in air-sea interaction processes which are strictly governed by changes of the heat content within the oceanic top layer due to variations in the meridional heat transport (Gulf Stream, Labrador Current, North Atlantic Current,...). There are basic differences in the dynamics of western and eastern boundary current regimes which again affect the air-sea interaction processes. The associated spatial and temporal variability of meteorological fields is highly different between the northwest and the northeast Atlantic (Bjerknes 1962, 1964, Isemer and Hasse 1987). Already Helland-Hansen and Nansen (1917) found that the greatest temperature anomalies are produced by anomalies in wind patterns and appear or disappear over large sections of the North Atlantic Ocean almost simultaneously. Coolings caused by prevailing northerly winds and warmings are caused by prevailing southerly winds. Changes in wind directions frequently coincide with variations in wind velocity which are mainly responsible for the depth of the wind mixed layer and the heat content involved. Both, wind direction and velocity, affect the sea surface temperature (SST) regionally and influence the air temperature due to regional changes in the net heat flux between ocean and atmosphere on different time and space scales (Wear 1982).

Very low-frequency changes in winds at mid-latitudes can be described by variations in the sea-level air pressure field between low values at subpolar latitudes (Icelandic Low) and high values at subtropical latitudes (Azores High). Fluctuations in the resulting meridional pressure gradient cause corresponding variations in the belt of westerlies, which is embedded in the polar front zone (PFZ). The PFZ separates the cold air masses in the North from warm air masses in the South. Its meridional migration causes a large-scale alternation of atmospheric mass between subpolar and subtropical zones above the North Atlantic Ocean. This relatively regular oscillation was discovered in the 1920s by Walker (1924) and named North Atlantic Oscillation (NAO). The air pressure difference between the Azores and Iceland forms the NAO Index described by Rogers (1984). A negative NAO Index describes anomalously low sea level pressure in Iceland, strong meridional pressure gradients over the North Atlantic and intensified westerlies in the belt of the PFZ. Such a situation is climatically accompanied by a meridional displacement of the PFZ. Using monthly mean values from Baur (1953,1970) and Rogers (pers. comm.), the averaged winter NAO Index

(Jan, Feb, Mar) is significantly correlated (99.9% confidence level) with negative anomalies in the west European air temperature for the period 1874- 1956 (Fig. 5). A similar tendency is shown in Fig.6. Here, January data of the air temperature in England (Manley 1974) and the corresponding NAO values of Rogers are plotted by 5-year running means for 1874-1973.

The relatively cold Bohuslän periods seem to coincide with a climatically significant southward displacement of the PFZ. Also, the Baltic Sea froze more frequently during the Bohuslän periods (Cushing 1982). Unfortunately, no long data series are available on the meridional position of the PFZ, but an indication of its location is given in the records of the seasonal duration of coastal ice at Iceland for many centuries past compiled by Koch (1945). The PFZ is situated more southerly when the coastal ice off Iceland endures for a long time and vice versa. Beverton and Lee (1965) found that the Norwegian herring periods started as the Icelandic ice decreased and ceased when it increased (Fig. 7). The only exception is the period in the 18th century. However, this period is not well defined (Storrow 1947, Höglund 1978) and might also fit into the general scheme (Beverton and Lee 1965, Cushing 1982). Whereas the Norwegian periods are associated with reduced ice cover, there does not seem to be an association between the degree of ice cover and the Bohuslän periods, however, they seem to occur during long periods of ice cover (Fig. 7)(Cushing 1982).

Clearly, the periods of herring and sardine fisheries occur and disappear in relation to temperature regimes. The substantial fluctuations in the regional herring fisheries are well documented on the decadal scale. Consequently, when searching for the agents forcing the herring and sardine populations, we have to take into account climatic changes in response to changes in the oceanic current system on the basin-scale of the North Atlantic Ocean. Such variations influence the atmospheric circulation of the entire hemisphere.

There is a significant link between SST anomalies (SSTA) in the northwestern Atlantic Ocean, the source region of Atlantic cyclones, and the annual position of the PFZ (Moene 1986). Such cyclones travel eastward within the belt of westerlies. According to Schinke (1994), they show significant peak values in their frequency on the decadal scale in the region between 60°W-60°E and 30°N-90°N for the period 1900-1990. The main path of embedded cyclones also migrates with the meridional displacement of the PFZ. A southward (northward) migration of the PFZ is correlated with positive (negative) anomalies of SST in the northwestern Atlantic Ocean. Opposite conditions are prevailing in the northeast Atlantic. There, the wind shifts periodically between westerly and northerly directions, on climatic scales (Cushing and Dickson 1976). However, westerly and southwesterly/southerly winds dominate at lower latitudes, e.g. in the English Channel. Such different wind forcing also causes different wind-driven currents and, consequently, different hydrographic regimes in the oceanic mixed layer.

The herring and sardine periods seem to correspond to different periods of prevailing wind directions. When westerly wind prevailed, the fisheries of Group 1 species were thriving whereas the fisheries of Group 2 were doing well during periods of prevailing southerly wind (Fig. 8). The fishery periods of Group 1 and Group 2 can be described by the following two scenarios:

Group 1 periods: PFZ is in the South, cold temperature at mid- and higher latitudes of the eastern North Atlantic, SSTA<0, ice off Iceland and in the northern Baltic Sea, NAO Index negative, minimum in frequency of SW winds over England, cold water in North Sea, Channel and Skagerrak. This applies for e.g. the Bohuslän periods.

Group 2 periods: PFZ is in the North, warm temperature at mid-and higher latitudes of the eastern North Atlantic, SSTA >0, no strong ice cover off Iceland, NAO Index positive, increasing frequency of SW winds in England, relatively warm water in North Sea, Channel and Skagerrak. This applies for e.g. the sardine periods.

5. DISCUSSION

The different herring and sardine periods are related to meteorological and hydrographic parameters such as sea surface and air temperature, duration of ice cover off Iceland, position of the PFZ, prevailing wind directions and the NAO Index. So, the Bohuslän periods, on a decadal scale, coincide with times when there were a strong ice cover off Iceland, severe winters in western Europe with extremely cold air and water temperatures, an intensification of westerlies as indicated by negative anomalies in the NAO Index and a minimum of southwesterly winds over England in response to meridional migrations of the atmospheric polar front zone. All these parameters change drastically with climate changes. Prevailing wind directions strictly depend on the climatic location of the atmospheric PFZ which determines the main wind direction over the North Atlantic Ocean, the North Sea, and the Skagerrak as well as the mean path of eastward travelling cyclones. Such meridional migrations of the PFZ indicate changes in the atmospheric circulation patterns on the global scale due to changed interaction processes (net heat flux) between ocean and atmosphere. Within the coupled system of the ocean and the atmosphere, the ocean determines the atmospheric response on the decadal scale. Any changes in its meridional heat transport

(Gulf Stream, North Atlantic Current, Labrador Current,...) regionally affect the heat content of the oceanic top layer and, consequently, sea surface temperatures and associated net heat fluxes with a feedback-effect to the winds.

Hence, it is concluded that climate variation governs the alternating herring and sardine periods, especially in hydrographic transition areas. The populations of this study are widely separated from each other. Inspite of the distances of several thousand kilometres between the herring and sardine populations they seem to react to the same forcing which is basin-wide. The answer to the question posed in the title of this contribution is: clearly, the Bohuslän periods are controlled by climate variation.

Acknowledgements

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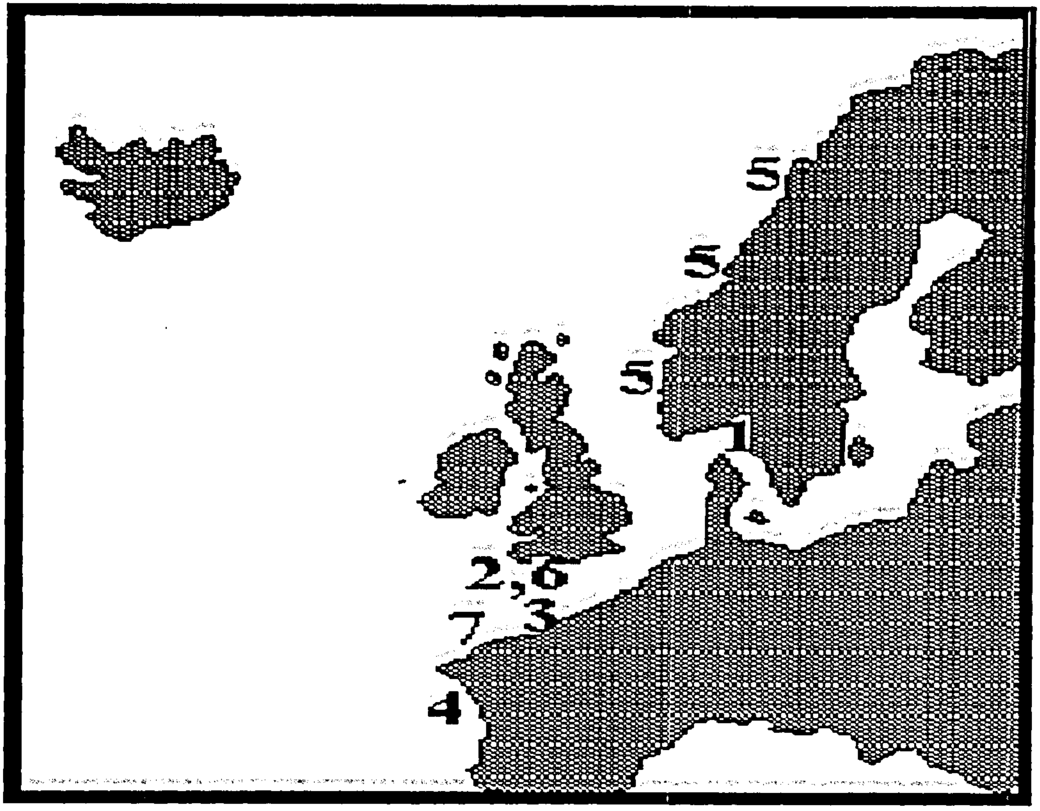

Fig. 1: Geographic locations of fisheries.

1 - *Bohuslän Herring*
2 - *Devon & Cornwall Herring*
3 - *French Chahnel Herring*
4 - *Bay of Biscay Herring*
5 - *Norwegian Spring Spawning Herring*
6 - *Devon & Cornwall Sardine*
7 - *Northern Brittany Sardine*

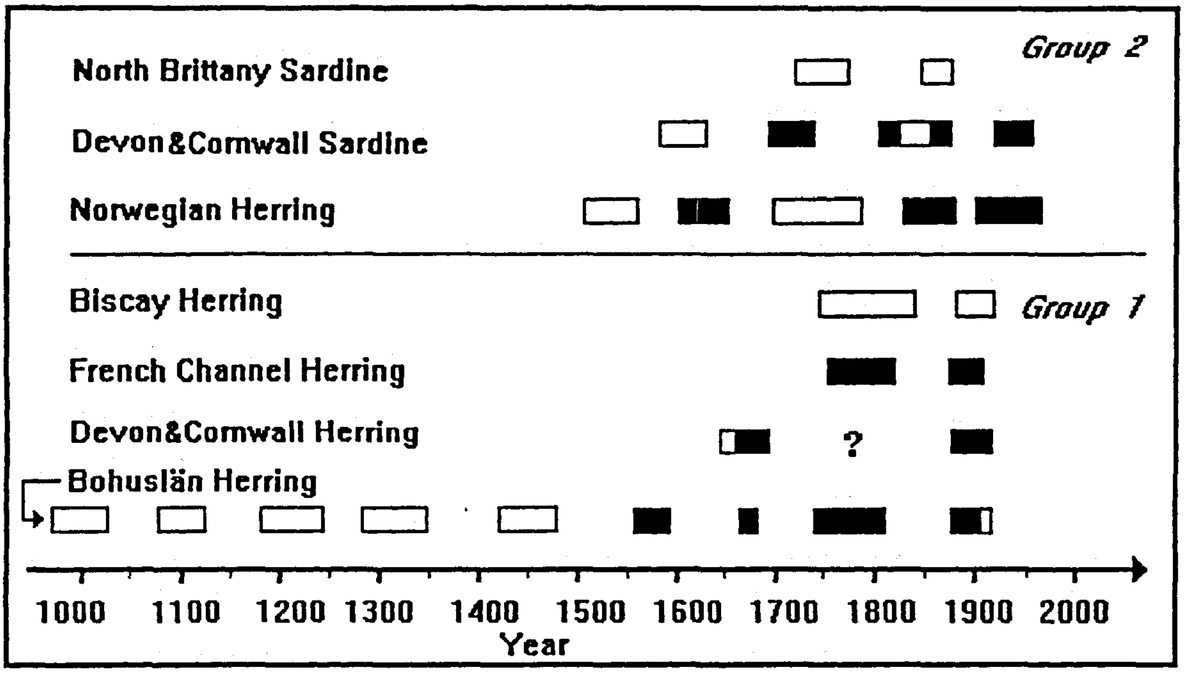

Fig. 2: Historical periods of several European herring and sardine fisheries. Sources:

1 - *Bohuslän Herring* (Höglund 1978, Lindquist 1983, Sahrhage and Lundbeck 1992)
2 - *Devon & Cornwall Herring* (Southward et al. 1988)
3 - *French Channel Herring* (Binet 1988)
4 - *Bay of Biscay Herring* (Binet 1988)
5 - *Norwegian Spring Spawning Herring* (Beverton and Lee 1965, Cushing 1982)
6 - *Devon & Cornwall Sardine* (Southward et al. 1988)
7 - *Northern Brittany Sardine* (Binet 1988)

(The open rectangles depict periods the extension of which is not exactly known!)

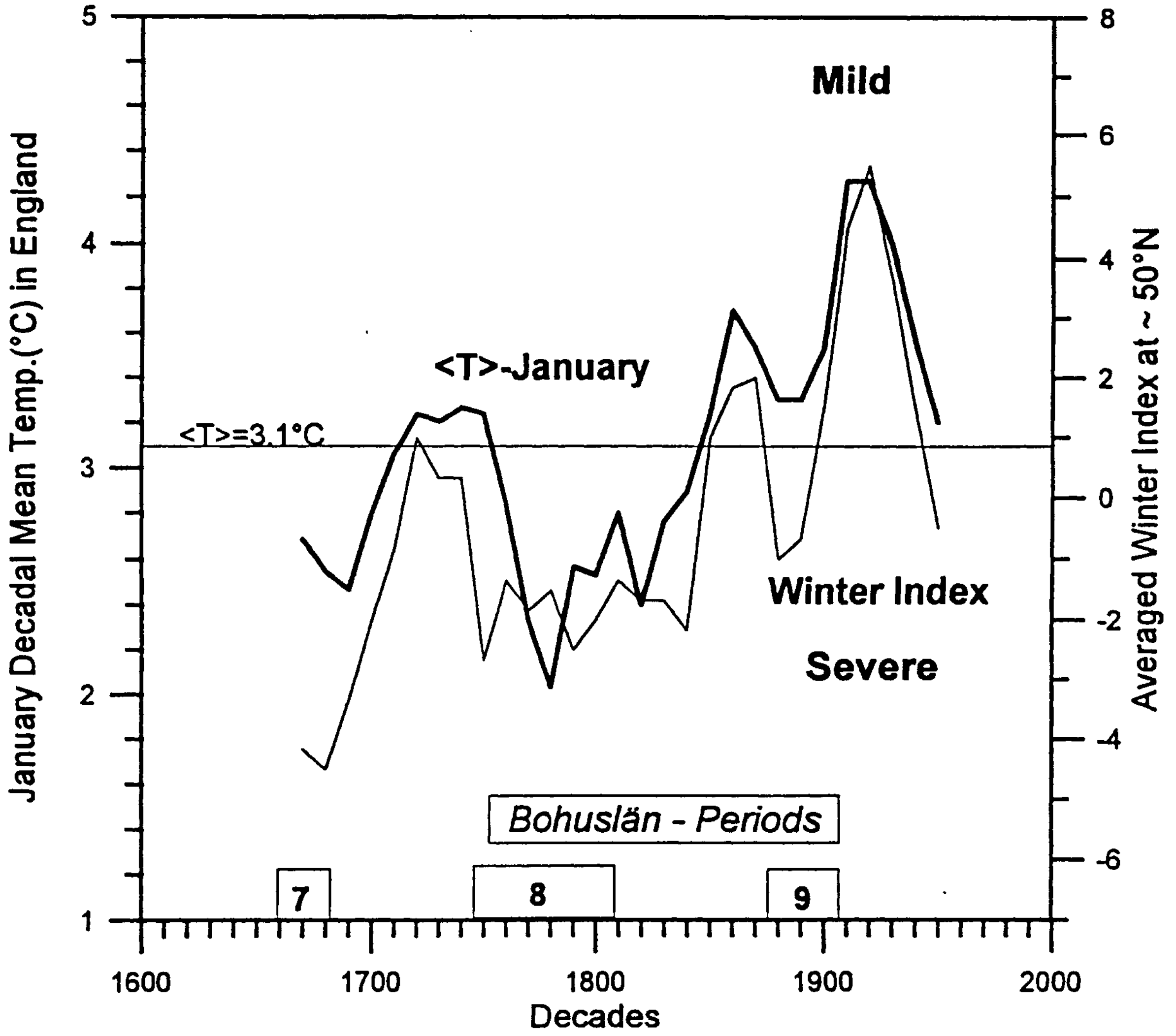

Fig. 3: Averaged "Winter Mildness/Severity Index" from data at ([0°E+12°E]/2) and about 50°N (Lamb 1977) compared to decadal January mean temperature in England (bold line) (Manley 1974). The total mean is <T>=3.1°C. Rectangles with numbers denote the last three Bohuslän periods which occurred during relatively cold winters.
(Negative index values correspond to severe winters.)

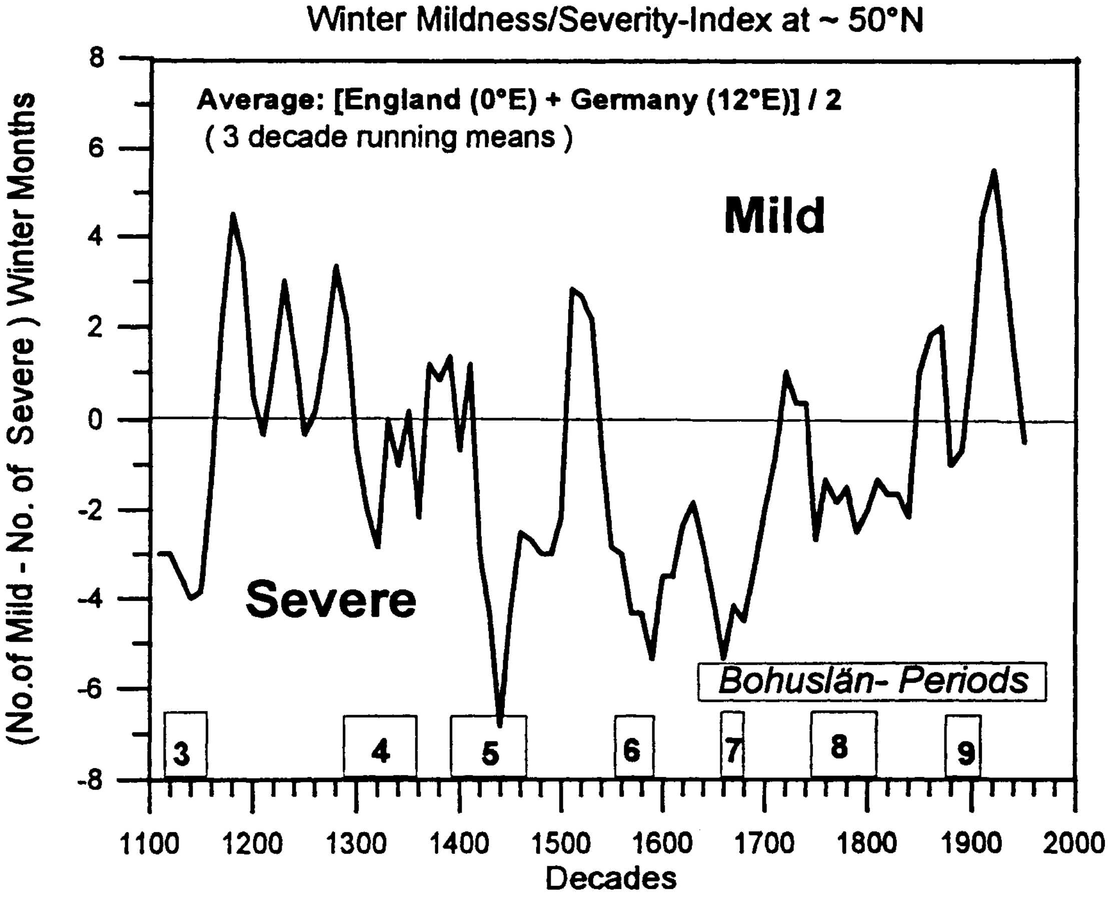

Fig. 4: "Winter Mildness/Severity Index" as in Fig. 3 and Bohuslän periods which correspond to negative peak index values.

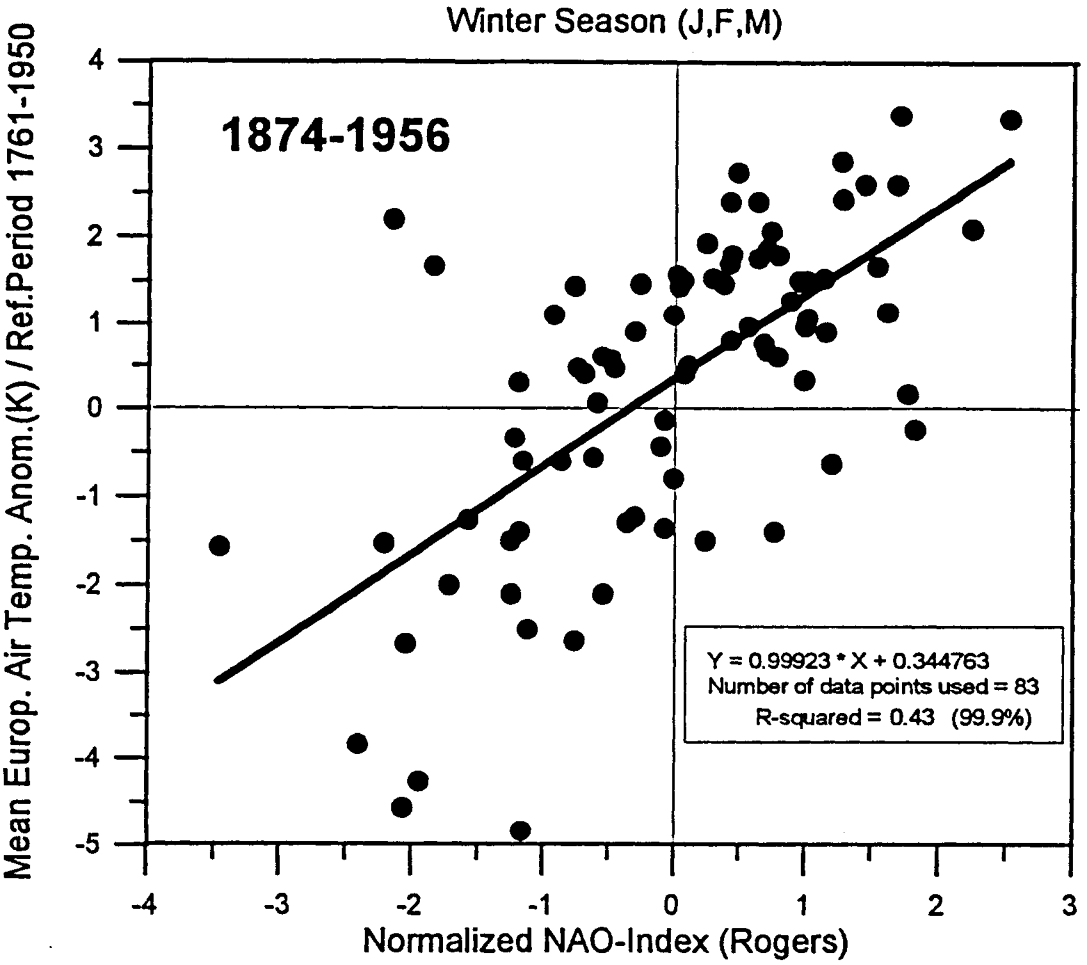

Fig. 5: Regression between the normalized winter NAO-Index (Rogers, pers. comm.) and anomalies of west European air temperatures (Baur 1953, 1970) with the reference period from 1761-1950.

(Negative NAO values correspond to intensified westerlies and/ or a southward displacement of the atmospheric polar frontal zone indicating a clear tendency for severe winters in western Europe.)

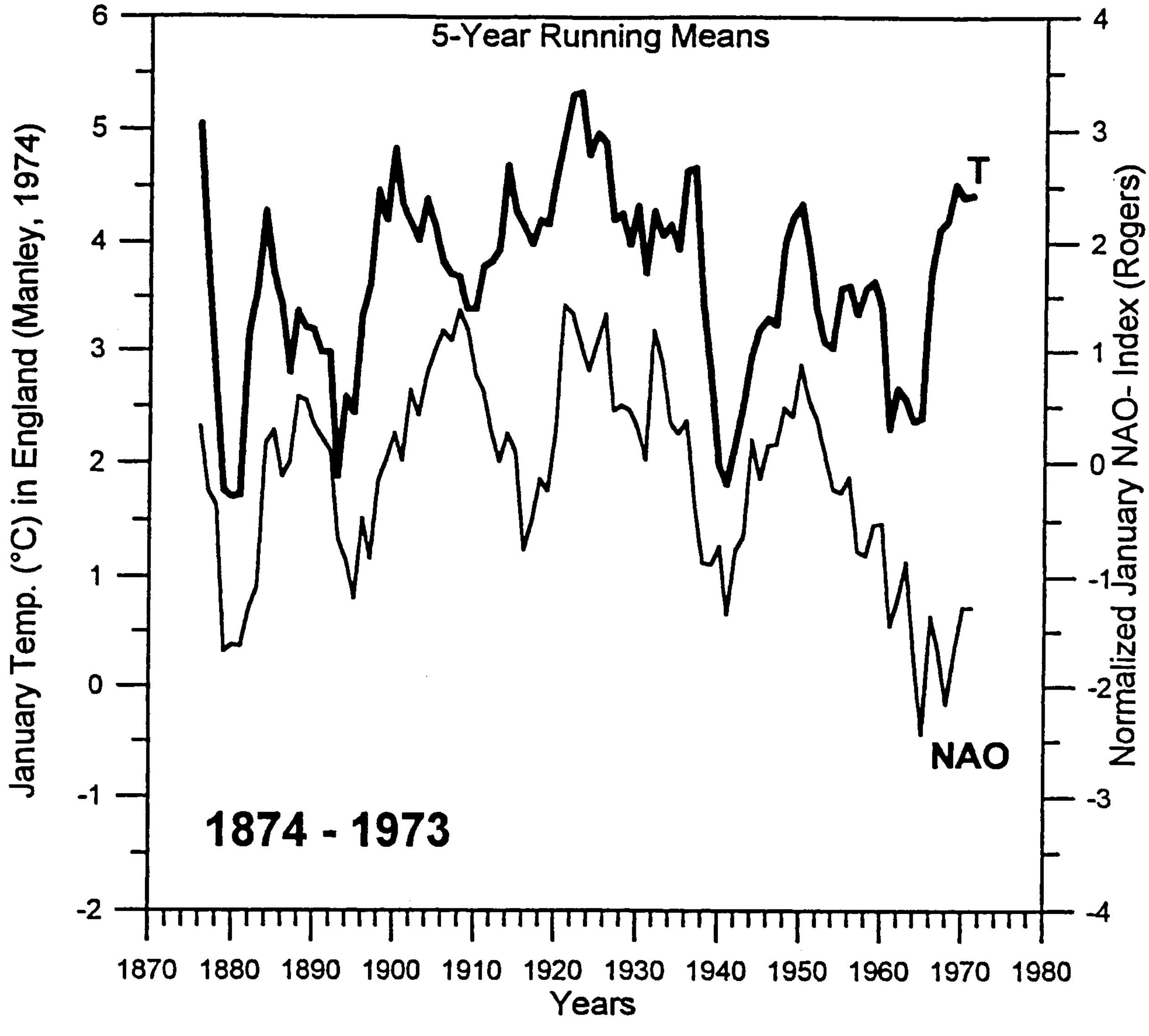

Fig.6 Five-year running means of the January air temperature (T°C) in England (Manley 1974) and normalized January NAO- Index (Rogers pers. comm.)

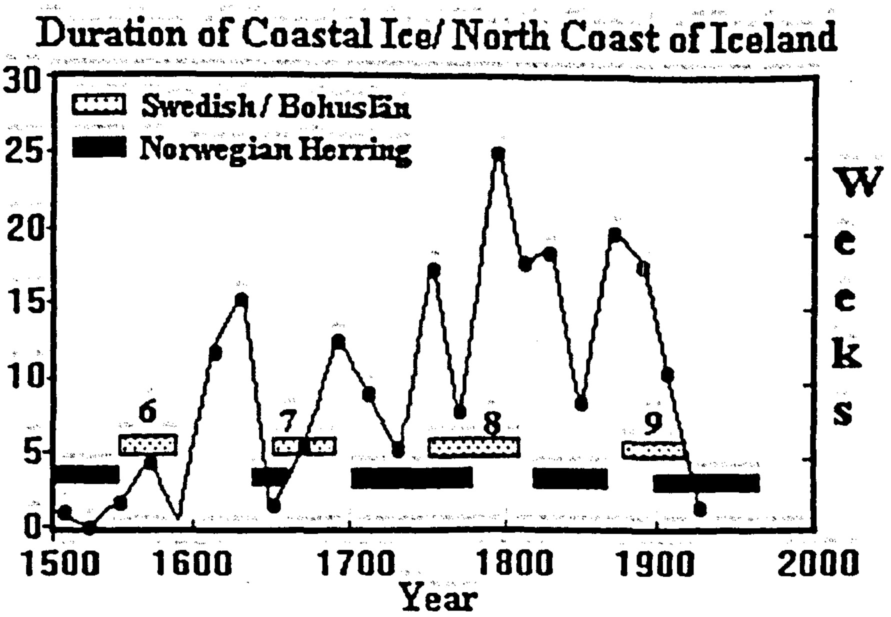

Fig. 7: Norwegian and Bohuslän herring periods and duration of coastal ice at the north coast of Iceland (modified after Beverton and Lee 1965).

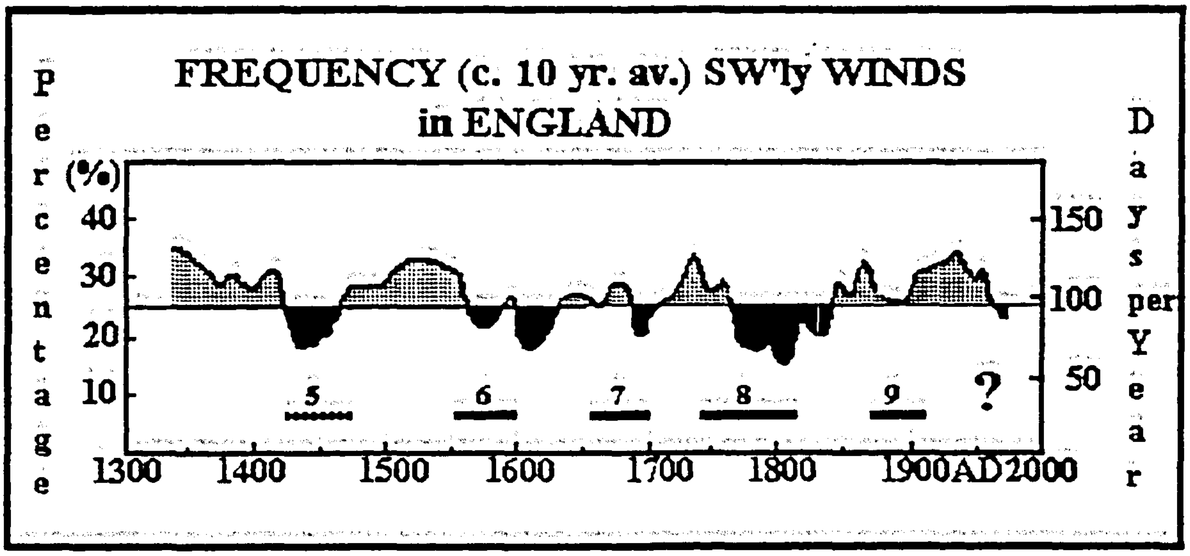

Fig. 8: Frequency of southwesterly surface winds in England, 1340-1978 and Bohuslän periods. The wind curve (modified after Lamb 1972) is from daily observations in the London area from 1669 to 1978 (ten-year averages). The earlier part of the curve is sketched from indirect indications, including various weather diaries, e.g. in eastern England (Lincolnshire) 1340 - 44 and Denmark 1582 - 97.

(The minima of of southwesterly wind correspond to the Bohuslän periods.)

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