SOME REMARKS ON THE N.A.O. INDEX, RELATED OCEANOGRAPHIC FACTORS, AND ITS POSSIBLE FIT TO THE RECRUITMENT INDEX OF THE NORTH ATLANTIC SWORDFISH (Xiphias gladius)

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SUMMARY

Based on the results and hypotheses presented in previous documents, and taking into account preliminary information on atmospheric and oceanographic phenomena which may be related to the NAO, this paper discusses general aspects that might be of interest in the future studies, debates and definition of possible fits and relationships between global atmospheric indicators, such as the NAO and associated oceanographic phenomena, with the recruitment levels or other variables estimated from fishery data.

RÉSUMÉ

D’après les résultats et hypothèses présentés dans des travaux antérieurs, et tenant compte de l’information préliminaire sur les phénomènes atmosphériques et océanographiques qui peuvent être liés à la NAO, le présent document examine des aspects généraux qui pourraient s’avérer intéressants pour les études ultérieures, les débats et la définition des éventuels ajustements et relations entre les indicateurs atmosphériques globaux, tels que la NAO et les phénomènes océanographiques associés, avec le niveau de recrutement ou autres variables estimées d’après les données sur la pêche.

RESUMEN

Basándose en los resultados e hipótesis presentados en anteriores documentos, y teniendo en cuenta la información preliminar sobre fenómenos atmosféricos y oceanográficos que pueden estar relacionados con la NAO, este documento plantea aspectos generales que pueden resultar de interés para futuros estudios, debates y definiciones de posibles ajustes y relaciones entre indicadores atmosféricos globales, como la NAO, y los fenómenos oceanográficos relacionados con ellos, y los niveles de reclutamiento u otras variables estimadas a partir de los datos de pesquerías.

KEYWORDS

Key words: swordfish, environment, NAO, recruitment.

1. INTRODUCTION

The methodology of population dynamics has traditionally explained recruitment variability (R) as a function of the spawning fraction of the female stock (SSB) as the only, or at least the main factor. This relationship has been studied and discussed in a great number of small pelagic and demersal stocks. The conclusions drawn have been well summarized by several authors (Gulland, 1977; Sparre and Venema,
1997; Cadima, 2000). These SSB/R functions proposed were generalized to most of the fish stocks. However, several authors have carried out reviews and expressed their thoughts regarding the importance of other potential and probably more important factors to explain the inter-annual and inter-decadal variability of the recruitments and stocks (Tromp, 1980; Beamish, 1995; Maravelias et al., 2000). A summarization of this broad debate was included in Larrañeta (1996) and, to some extent, in papers previously cited.

After examining all of these, it is clear that one of the greatest difficulties in biological studies is determining the success or failure of the processes that lead to recruitment. Among the variables reported by Russell (1931) as conditioners of the biomass of a cohort, possibly three (R, M, G; and particularly the first two in the case of the great migrators) depend largely on environmental conditions. The inter-annual variability in oceanographic conditions has been accepted as the cause of the survival of the pre-recruits, to a greater or lesser extent, which contributes to the inter-annual variability of the stock recruitment levels. This variability, however, is rarely considered as an important factor in the reproductive behavior of the adults.

These oceanographic factors were rarely considered, or often assumed to be random with a negligible effect in the "long" run. Therefore, the models which were commonly used to explain R did not take into account the ecological or environmental aspects that could be better able to predict recruitment levels than the SSB. The absolute recruitment levels (R) of some tuna from temperate zones estimated using VPA, such as the albacore and the bluefin tuna, have been associated to some extent with atmospheric processes, such as the North Atlantic Oscillation Index (NAO) (Santiago, 1998). Catches of juvenile albacore in the NE Atlantic have also been associated with the Gulf Stream Index and other oceanographic indices (Ortiz de Zarate et al., 1998; Lavin et al., 2000) probably also linked to NAO. In recent years many studies have been carried out on the impact of environmental factors on the recruitment levels of different species.

Simple fits between the relative annual recruitment estimations of North Atlantic swordfish and the values of the “winter NAO index” have been presented in previous papers (Mejuto, 1999, 2000, 2001) suggesting that these R fluctuations may be primarily the result of a combination of as yet undetermined environmental factors which affect the mortality of the larvae and pre-recruits and/or the reproductive strategy of the adult swordfish. The balance of this combination of environmental factors (positive-negative) could, to a certain extent, be summarized in the NAO index or in other similar indices.

The goal set by any reproductive strategy is to maintain or to reach the greatest possible biomass within the biotic and abiotic conditions as allowed by the environment in which the stock lives. Although it is difficult to establish the relationship between the NAO and R based on the available data, the object of this paper is to discuss some of the general aspects which might help to focus future research, with a view to establish relationships between R and the environmental factors that might prove to be crucial in the interpretation of the dynamics of this species.

A conference of the American Geophysical Union (AGU) was recently held in late 2000 with the title of "The North Atlantic Oscillation". The information provided by experts from all over the world at this meeting proved to be of great interest. Although the NAO is a highly complex general indicator that should probably be teleconnected to variables of other geographic areas, it could also provide an overall summary of a combination of factors affecting environmental variability, and consequently the dynamics of the atmosphere, oceanography and specific biology of each region. The fluctuations in the NAO have been linked to a great number of fluctuations in terrestrial, freshwater and marine populations. It has been specifically related to the fluctuations in the recruitments of some species.

2. METHODS

Previous documents have reported in detail the methods employed to calculate the variables used in the fit between the NAO and the CPUE age 1 (Mejuto, 1999, 2000, 2001). The estimations of the annual
Recruitment indices (CPUE age 1) were calculated from individual trips carried out during the period 1983-1999 by Spanish surface longline vessels targeting the North stock. Catch and size/age data from each trip used were obtained by taking a census of generally 100% of the fish caught in each trip. Trips in which the number of fishes sampled was under 85% of the total fish caught were omitted from the analyses. Nominal CPUEs of the traditional longline gear were standardized for the period 1983-1999 using GLM procedures which take into account factors such as area, quarter and their interaction (Mejuto et al., 2001).

The winter (December-March) index of NAO was based on the difference in normalized sea level pressures (SLP) between Lisbon (Portugal) and Reykjavik (Iceland), normalized relative to a 120-year period 1864-1983. Standardized CPUE data from age 1 (CPUE1) were compared with the winter North Atlantic Oscillation (NAO) Index. The NAO Index from year $y$ was contrasted with the CPUE1 from year $y+1$.

3. RESULTS AND DISCUSSION

The more recent fit between the recruitment indicators (CPUE1) and the winter index of NAO is presented in figure 1. Although it was not able to be updated in relation to previous documents (Mejuto, 2001) the thoughts and discussion included here are based on these previous results.

3.1 The problem with fishery data

Since there is a greater natural mortality rate in the pre-recruit and recruit stage, owing to biotic and abiotic factors, it is evident that $R$ will be strongly conditioned by these factors. Thus, we would expect the possible SSB/R relationships to be, in principle, inaccurate (Cadima, 2000).

When we attempt to establish relationships between environmental indicators and stock indicators (especially when they come from commercial fleets) it is first necessary to make a careful selection of the most appropriate indicators to be used.

The absolute estimates of recruits obtained from models that include, among other data, matrices of catches and standardized catch rates per unit of effort of several fleets, have been used as annual recruitment indicators. Therefore the estimates of the absolute values of $R$ are the result of combining information from many fleets with very different data and behaviors from both a qualitative and quantitative standpoint. Moreover, the $R$ estimates during the last years of the time series (the most recent ones) are usually assumed to be statistically less accurate because problems of convergence.

Another possible approach to establish these fits is to estimate the relative abundance of $R$ based on specific indicators from one or several fleets/ages that are assumed to be relatively reliable. This option was used for the swordfish in previous documents. The use of this option as opposed to the first is recommended because of the type and intensity of sampling carried out on the fleet used as an indicator; the consistency in the fishing activity over the available series and the scientific control of some of the qualitative aspects of the basic data, including the control of potential bias caused by the regulation of minimum size or TACs in force. However, the fact that the second option was considered to be appropriate for a specific fleet/species does not necessarily mean that it is generally ideal or suitable for other fleets/species.

In both options the CPUE data used as indicators appear to be basic, not only for precise stock assessment, but also to be able to establish any kind of relationship between absolute or relative abundances and environmental factors. Up to the present time, we have used CPUE1 data for the swordfish, taking advantage of the relative consistency of this Spanish fleet over time, among other aspects as mentioned. However, this fleet has recently introduced major changes in the longline, so that in a period of a couple of years, the traditional longline gear has been widely replaced by the "Florida
style” gear, so we would expect very few observations related to traditional longlines. The change in fishing gear will be an additional limitation which must be studied carefully to be able to continue producing the reliable CPUE historical series that are currently available.

Therefore, there must be a correct selection of the variables to attempt to establish these relationships, taking into account for each species/stock, the limitation of available data, the type of fisheries, etc. But special consideration must be given to the qualitative confidence we have in the selected data.

3.2 The problem of the definition of the NAO index.

Among many other elements that contribute to the different definitions and the uncertainty of the NAO, (which may be widely debated by the experts), at first glance, we can detect some elements that may make it difficult to define these relationships. Obviously NAOs may be defined from SLP observations obtained at different terrestrial stations (Lisbon, the Azores, Cadiz, the Bermudas, etc.). Several papers have compared the different series and have found, in some cases, differences between them and consistencies among others. It is quite possible, however, that the selection of these stations for the definition of the NAO and its relationship to oceanographic factors should adapt to the biological characteristics of the different species and to other spatial-temporal aspects of the oceanographic parameters that are suspected of affecting recruitment variability.

On the other hand, the time period used for the normalization of the SLP anomalies is not the same for all the authors. In some cases the SLP anomalies at each station were normalized relative to the 120-year period 1864-1983, but Hurrel (1995) normalized them relative to 1864-1994. Similarly, it is possible to use NAO values referring to different monthly periods.

It is clear that the NAO could provide an overall summary of the variability of certain atmospheric-oceanographic parameters in specific areas of the North Atlantic. It is important to point out, however, that a geographic change in the location of the focal points that serve to define the NAO may decrease or increase the expected associated effects. This makes it difficult to predict certain oceanographic and biological parameters in specific areas based only on the simple NAO values, however it could be useful in identifying the type of cycle we are in. It seems that the NAO is not easy to predict on a yearly scale with the current models, as its teleconnection with other atmospheric and oceanographic phenomena is complex, but it is likely that it will soon be possible to obtain a prediction of the type of cycle to expect. In this sense, recent studies done by Rodwell et al. (Rodweel pers. com.) suggest the possible prediction of winter NAO values and sign from the previous spring (May) SST anomalies in the North Atlantic. If the projection is positive /negative, then prediction pattern would predict positive/negative winter NAO with around 66 % of chance.

3.3 Effects related to the NAO

When atmospheric indicators such as the NAO are defined, the first stage creates a certain euphoria or predisposition for trying to explain any type of phenomenon based on these indicators, followed generally by a second opposing period consisting of absolute incredulity. The NAO cycles have been linked to a great deal of atmospheric fluctuations and with changes in terrestrial, marine and freshwater ecosystems, with agricultural production cycles, with the quality of the wines of certain areas and even with the price fluctuations of some heating fuels. Some of these associated oceanographic and atmospheric impacts have been summarized by Dickson (pers. com.); Otterson, 2000²; Greene, 2000²; Straile, 2000²; Enfield, 2000²; Atkingson, 2000².

During the AGU 2000 conference on NAO some associated oceanographic phenomena were noted (see annex 1 for additional information) and recommended for investigation with regard to the biological

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aspects and the recruitment of certain stocks, such as the swordfish. Some of the atmospheric and oceanographic changes are explained using the NAO, but they produce different effects depending on the geographic region. The definition of these types of relationships requires a line of research that would continue over time, which is difficult to tackle on a unilateral basis, since there would be a need for multidisciplinary teams.

From an oceanographic point of view, several authors have postulated that there is a close correlation between the NAO fluctuations and the SST anomalies. For this type of fisheries studies, it would seem fitting to establish these relationships by previously defining the appropriate spatial-temporal windows related to the behavior and distribution of the species for reproduction, as well as defining the estimated areas-periods for larvae and recruitment.

The NAO cycles have been related to the dominant winds systems (the trade winds) and to variations in the oceanic rotations, presumably affecting the drift of the surface layers and the resulting drift of the eggs and larvae. Positive or negative NAO cycles condition the direction and the force thereof.

Perhaps, however, one of the most interesting points is the relationship between the NAO and the indices of water mass transport, thermocline position, the heating or cooling of the subpolar rotation, the availability of zooplankton of some species and the position of the system formed by the Labrador-Gulf Stream currents, among others. Some of these effects have been put forth as being the primary cause of the variability in the recruitment and growth of some species (Drinkwater, 2001; Maravelias et al., 2000) and should be investigated for the North Atlantic stocks of swordfish and albacore.

The NAO has also been related to variations in salinity-temperature, which affects the density of the water masses. If this were true, in the reproduction and recruitment areas there would be changes in the buoyancy of the eggs and larvae, whose effect would be essential in explaining larval viability (Nisshing and Vallin, 1996; Vallin et al., 1999). This change in buoyancy might have a combination of impacts: (a) to favor, to a greater or lesser extent, the transport conditions of the eggs and larvae by means of the currents and winds; (b) to put the eggs and larvae in more or less favorable conditions in terms of oxygen concentrations; (c) to favor, to a greater or lesser extent the availability of food for the larval stages; (d) other effects.

Many of the above factors would contribute to the explanation of the hypothesis of "retention areas" and "appropriate habitat" (Iles & Sinclair, 1982; Sharp, 1980, quoted by Larrañeta, 1996) proposed as one of the plausible hypothesis to explain the cyclic fluctuations of R as a result of the mortality cycles (M) of eggs and pre-recruits of the North Atlantic swordfish (Mejuto, 1999).

In keeping with this, Cardinale and Arrhenius (2000) reported on the importance of certain environmental factors on recruitments. They used the term "reproductive volume (RV)", previously introduced by McKenzie et al., (2000), where RV represents the volume of water capable of leading to the successful development of the larval stages, defined within optimum ranges of oceanographic conditions (Tº, S_sal,O2, etc.). This RV concept appears to run along the same lines as the above hypothesis on the reproductive strategy of the swordfish (Mejuto, 1999), who introduced the concept of the contraction and expansion in space and time of the SATp (potential spawning areas-times) with a possible impact on the size of the SSBe (effective spawning stock biomass) and/or the optimal areas for the viability of the eggs and larvae and the variability of M as a consequence of the retention or escape from these areas.

### 3.4 Other remarks

In previous documents some fits were presented between the NAO and CPUE1 variables, with annual recruitment assumed as index of abundance. These fits were carried out for a short period of time during which appropriate data from fishery activity is available. The availability of new data in the future will probably allow for a more suitable and sophisticated definition of the models.
For this species, the cyclic trend of the recruitment indices observed in the fisheries assumed to be indicators cannot be easily explained by the variability of the SSB. Therefore, if these data for the recruitment indices are assumed to be valid, hypotheses must be put forth that would allow such cyclic phenomena to be explained and suggest lines of research to be followed for their possible validation, based on biological aspects, behavior and their environment.

Disregarding aspects of a predictive nature, the fits proposed in previous documents (Mejuto, 2001) basically suggest two characteristic patterns of recruitment (Figure 1). A pattern of low and relatively constant recruitment, generally coinciding with positive NAO values, and a pattern of generally high recruitment between 1985-1988 and in recent years, coinciding with negative, extremely negative or near zero NAO values.

However, the NAO is considered in these documents to be a “symptom” capable of summarizing, to a certain extent, the result of oceanographic phenomena that would be those that really would affect the recruitment level. Therefore, these oceanographic aspects are the final objective we seek to be able to explain these cyclic variations. The identification and evaluation of such oceanographic variable/s will probably be more useful for the prediction of R than the use of a global indicator such as NAO. Moreover, their identification would allow for a more accurate definition of alternative global indices, similar to the NAO, easily obtainable, but more appropriate for explaining the oceanographic phenomena that occur in areas conducive to the spawning and successful development of the eggs, larval stages and pre-recruits.

The importance of identifying these relationships was clearly demonstrated by using the simple exercise of assuming as true a relationship between NAO and R over recent history (or with some of the oceanographic factors associated with the NAO). This relationship could explain, to a great extent, the wide ranging natural cyclic fluctuation of the recruitment and biomass of these stock (Mejuto, 2000); it could explain the trends observed in the biomass of the stock in very specific periods of time; it could help to predict future trends of the stock, etc. It is clear that the combination of biotic and abiotic factors is one of the most important mechanisms in the study of the dynamics of tunas and similar species, as the interactions between these factors are essential to be able to explain the variability of R, and consequently, the fluctuations in stock abundance.

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LITERATURE CITED


General description and scientific statement

The purpose of this proposed Chapman Conference is to bring together atmospheric scientists, oceanographers and paleoclimatologists with interests in interannual to multidecadal climate variability and its predictability as well as scientists who study the socio-economic impacts of climate variability. The conference will focus on the North Atlantic Oscillation (NAO), which is a poorly understood yet dominant pattern of atmospheric circulation variability. In order to advance understanding of this topic, it is critical to foster better communication amongst these groups of scientists.

What is the NAO and why is it important?

The climate of the Atlantic sector and surrounding continents exhibits considerable variability on a wide range of time scales. Improved understanding of this variability is essential to assess the likely range of future climate fluctuations and the extent to which these fluctuations are predictable, and to assess the potential impact of climate change due to anthropogenic forcing.

A remarkable feature of the NAO that has motivated much recent study is its trend toward a more positive phase over the past 30 years. In fact, the magnitude of this recent trend appears to be unprecedented in the observational record (Hurrell 1995a), and based on reconstructions using paleoclimate data, perhaps over the past several centuries as well (Stockton and Glueck 1999). The most pronounced anomalies have occurred since the winter of 1989 (Hurrell 1995a; Walsh et al. 1996; Thompson and Wallace 1998; Watanabe and Nitta 1999) when record positive values of an index of the NAO have been recorded. Moreover, the trend in the NAO accounts for several remarkable changes recently in the climate and weather over the middle and high latitudes of the Northern Hemisphere, as well as in marine and terrestrial ecosystems. Among these changes are:

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- Strengthened subpolar westerlies from the surface to the lower stratosphere (Thompson et al. 1999).

- Pronounced regional changes in precipitation patterns (Hurrell 1995a; Hurrell and van Loon 1997; Dai et al. 1997) resulting in the advance of some northern European glaciers (Hagen 1995; Sigurdsson and Jonsson 1995) and the retreat of Alpine glaciers (Frank 1997).

- Changes in sea-ice cover in both the Labrador and Greenland Seas as well as over the Arctic (Chapman and Walsh 1993; Maslanik et al. 1996; Cavalieri et al. 1997; Parkinson et al. 1998; McPhee et al. 1998; Deser et al. 1999).

- Pronounced decreases in mean sea level pressure (SLP) over the Arctic (Walsh et al. 1996).

- Changes in the physical properties of Arctic sea water (Sy et al. 1997; Morison et al. 1998; McPhee et al. 1998; Dickson 1999; Dickson et al. 1999a,b).

- Changes in the intensity of convection in the Labrador and the Greenland-Iceland Seas (Dickson et al. 1996; Houghton 1996) which in turn influence the strength and character of the Atlantic meridional overturning circulation.

- Stratospheric cooling over the polar cap (Randel and Wu 1999), and total column ozone losses poleward of 40°N (Randel and Wu 1999; Thompson et al. 1999).

- Changes in storm activity and the shifts in the Atlantic storm track (Hurrell 1995b), changes in within season variability such as blocking (Nakamura 1996).

- Trend in North Atlantic surface wave heights (Kushnir et al. 1997).

- Changes in the production of zooplankton and the distribution of fish (e.g., Fromentin and Planque 1996).

- Changes in the length of the growing season over Europe (Post and Stenseth 1999), and changes in the population dynamical processes of several terrestrial species (Post et al. 1999; Stenseth et al. 1999).

All these appear to be strongly related to the recent trend in the NAO.

This unprecedented behavior of the NAO in recent decades and, more generally, its pronounced low-frequency behavior over the longer record have added to the debate over our ability to detect and distinguish between natural and anthropogenic climate change. Hurrell (1996) has shown, for example, that the recent upward trend in the NAO accounts for much of the observed regional surface warming over Europe and Asia, as well as the cooling over the northwest Atlantic over the past several decades. The NAO accounts for about one-third of the hemispheric inter-annual surface temperature variance over the past 60 winters. Since global average temperatures are dominated by temperature variability over the northern landmasses, a significant fraction of the recent warming trend in global surface temperatures can thus be explained as a response to observed changes in atmospheric circulation. In particular, changes over the North Atlantic are associated with the NAO (see also Graf et al. 1995; Thompson et al. 1999). Since the NAO is a natural mode of atmospheric variability, one could argue that much of the recent warming is not related to the build-up of greenhouse gases in the atmosphere over the past century. This viewpoint, however, ignores the possibility that anthropogenic climate change might influence modes of natural variability, perhaps making it more likely that one phase or another of the NAO be preferred over the other phase (Palmer 1999; Corti et al. 1999). Understanding the physical mechanisms that govern the NAO and its intraseasonal-to-interdecadal variability, and how modes of natural variability such as the NAO may be influenced by anthropogenic climate change remain, therefore, central research questions.

What are the mechanisms which govern NAO variability?
Although the NAO is a natural mode of variability of the atmosphere, surface, stratospheric or even anthropogenic processes may influence its phase and amplitude. At present there is no consensus on the process or processes that are responsible for observed low frequency variations in the NAO, including its unprecedented upward trend over past 30 years.

There is ample evidence which shows that much of the atmospheric circulation variability in the form of the NAO arises from internal atmospheric processes. Atmospheric general circulation models (AGCMs) forced with climatological annual cycles of solar insolation and sea surface temperature (SST), and fixed atmospheric trace-gas composition, display NAO-like fluctuations (e.g., Kitoh et al. 1996; Saravanan 1998; Osborn et al. 1999; Shindell et al. 1999). The governing dynamical mechanisms are eddy mean flow interaction at the exit region of the Atlantic storm track and eddy-eddy interaction between baroclinic transients and low-frequency variability (Wallace and Lau 1985; Lau and Nath, 1991; Ting and Lau, 1993; Hurrell, 1995a). Such intrinsic atmospheric variability exhibits little temporal coherence so that the low-frequency variations evident in the ~150-year observational record of the NAO could be interpreted as sampling variability. Wunsch (1999), for instance, has argued that the observed NAO record cannot be easily distinguished from a random stationary process. Indeed, the spectral density of the NAO is nearly white with only slight broad band features near biennial and decadal time scales (Hurrell and van Loon 1997; Jones et al. 1997). However, paleoclimate evidence suggests that NAO variability is highly intermittent and does not exhibit a preferred time scale (Appenzeller et al. 1998a). Nonetheless, the climate system is not stationary, so alternative hypotheses to stationarity also need to be posed (Trenberth and Hurrell 1999). The trend evident in the NAO index over the past 30 years, for instance, exhibits a high degree of statistical significance relative to the background interannual variability (Thompson et al. 1999), and it exceeds the interdecadal variability during the first 100 plus years of the instrumental record. While paleoclimate evidence suggests that prolonged positive and negative NAO phases have occurred in the past (Appenzeller et al. 1998a; Cook et al. 1998; Mann 1999), the extreme positive values of the index evident since the late 1980s may be unprecedented over the past 5 centuries (Stockton and Glueck 1999). Either the recent trend is a reflection of natural variability occurring on multi-decadal or longer time scales, or it is a component of the global response to external forcing (Corti et al. 1999).

Recently, Thompson and Wallace (1998; 1999) suggested that the NAO might be more appropriately thought of as an annular (zonally symmetric) hemispheric mode of variability characterized by a seesaw of atmospheric mass between the polar cap and the middle latitudes in both the Atlantic and Pacific Ocean basins. A very similar structure is also evident in the Southern Hemisphere. They name this mode the Arctic Oscillation (AO) and showed that, during winter, its vertical structure extends deep into the stratosphere. Similar findings have previously been recognized in the context of tropospheric-stratospheric coupling (Baldwin et al. 1994; Perlwitz and Graf 1995; Cheng and Dunkerton 1995; Kitoh et al. 1996; Kodera et al. 1996). During winters when the stratospheric vortex is strong, the AO (and NAO) tends to be in a positive phase. Baldwin and Dunkerton (1999) suggest that the signal propagates from the stratosphere downward to the surface, so that the recent trends in the tropospheric circulation over the North Atlantic could be related to processes which affect the strength of the stratospheric polar vortex. For instance, tropical volcanic eruptions (Robock and Mao 1992; Kodera 1994; Kelly et al. 1996), ozone depletion (Volodin and Galin 1999), and changes in greenhouse gas concentrations resulting from anthropogenic forcing (Graf et al. 1995; Shindell et al. 1999) all may act to cool the polar stratosphere and strengthen the polar vortex.

On the other hand, it has long been recognized that fluctuations in SST and the strength of the NAO are related (Bjerknes 1964), and there are clear indications that the North Atlantic Ocean varies significantly with the over lying atmosphere. The leading mode of SST variability over the North Atlantic during winter consists of a tri-polar pattern with a cold anomaly in the subpolar region, a warm anomaly in the middle latitudes centered off of Cape Hatteras, and a cold subtropical anomaly between the equator and 30N (e.g., Deser and Blackmon 1993, Kushnir 1994). The emergence of this pattern is consistent with the spatial form of the anomalous surface fluxes associated with the NAO pattern (Cayan 1992). The strength of the correlation increases when the NAO index leads the SST, which indicates that SST is
responding to atmospheric forcing on monthly time scales (Battisti et al. 1995; Delworth 1996; Deser and Timlin 1997). But SST observations also display a myriad of long-term (interannual and decadal) responses (Kushnir 1994; Hansen and Bezek 1996; Sutton and Allen 1997; Visbeck et al., 1998), which allows for the possibility that decadal and longer-term variations in the state of the ocean surface imprint themselves back on the atmosphere.

While intrinsic atmospheric variability may exhibit temporal incoherence, the ocean can respond to it with marked persistence or even oscillatory behavior. The time scales imposed by the heat capacity of the upper ocean, for example, can lead to low frequency variability of both SST and lower tropospheric air temperature (Frankignoul and Hasselmann, 1977; Barsugli and Battisti 1998). Basin-wide, spatially-coherent atmospheric modes such as the NAO may also interact with the mean oceanic advection in the North Atlantic to preferentially select quasi-oscillatory SST anomalies with long time scales (Saravanan and McWilliams 1998). Stochastic atmospheric forcing may also excite selected dynamical modes of oceanic variability that act to redden the SST spectrum (Griffies and Tziperman 1995; Frankignoul et al. 1997; Capotondi and Holland 1997; Saravanan and McWilliams 1997; 1998; Saravanan et al. 1999). These theoretical studies are supported by observations of winter SST anomalies born in the western subtropical gyre that spread eastward along the path of the Gulf Stream and North Atlantic Current with a transit time of roughly a decade (Sutton and Allen 1997). Moreover, the SST anomalies reflect anomalies in the heat content of the deep winter mixed layers which, when exposed to the atmosphere in winter (Alexander and Deser 1995), could provide the forcing to drive the NAO on the advective time scale of the gyre (McCarty et al. 1996).

A key question is the sensitivity of the middle latitude atmosphere to changes in surface boundary conditions, including SSTs, sea-ice, and/or land. Robertson et al. (1999a) report that changing the SST distribution in the North Atlantic affects the frequency of occurrence of different regional low-frequency modes and substantially increases the interannual variability of the NAO simulated by their AGCM. The experiment by Rodwell et al. (1999) also points to SST in the North Atlantic as having a marked effect on NAO variability. By forcing their AGCM with observed SST patterns and sea ice distributions, they successfully captured much of the multi-annual to multi-decadal variability in the observed NAO index since 1947, including about 50% of the observed strong upward trend over the past 30 years. However, many other AGCM experiments have led to rather confusing and inconsistent conclusions (Kushnir and Held, 1996). Additionally, several recent studies conclude that NAO variability is closely tied to SSTs over the tropical South Atlantic (Xie and Tanimoto 1998; Rajagopalan et al. 1998; Robertson et al. 1999b). Variations in the tropical Atlantic are substantial and involve strong interannual and decadal variations of meridional SST gradients. Such variations, which most likely affect the Hadley circulation, potentially modulate North Atlantic middle latitude atmospheric variability through an atmospheric bridge mechanism akin to that acting over the Pacific (e.g., Lau and Nath 1996; Trenberth et al. 1998). The response of the atmosphere to changes in tropical, middle and high latitude SST distributions within the Atlantic Basin remains a problem that needs to be addressed.

The role of sea ice in producing atmospheric variability is also not well understood. Changes in sea-ice cover in both the Labrador and Greenland Seas as well as over the Arctic appear to be well correlated with the NAO (Deser et al. 1999). The relationship between the sea level pressure (SLP) and ice anomaly fields is consistent with the notion that atmospheric circulation anomalies force the sea ice variations (Prisenberg et al. 1997). Feedbacks or other influences of winter ice anomalies on the atmosphere have been more difficult to detect, although Deser et al. (1999) suggest that a local response of the atmospheric circulation to the reduced sea ice cover east of Greenland in recent years is also apparent.

Watanabe and Nitta (1999) have suggested that land processes are responsible for decadal changes in the NAO. They find that the change toward a more positive wintertime NAO index in 1989 was accompanied by large changes in snow cover over Eurasia and North America. Moreover, the relationship between snow cover and the NAO was even more coherent when the preceding fall snow cover was analyzed, suggesting that the atmosphere may have been forced by surface conditions over the upstream land mass. Watanabe and Nitta (1998) reproduce a considerable part of the atmospheric circulation
Several recent studies suggest that both the oceanic wind forced gyre circulation and the thermohaline circulation can actively interact with atmospheric flow to produce coupled decadal and interdecadal climate variability. Latif and Barnett (1996) and Gritzner et al (1998) argued that when positive SST and sub-surface heat content anomalies in the central North Atlantic, are created by an enhanced subtropical ocean gyre circulation. The response in the atmosphere is an anticyclonic circulation pattern and a weakened storm track, which locally enhances the SST anomalies. The atmospheric response, however, also consists of a wind stress curl anomaly that spins down the subtropical gyre, thereby reducing the northward transport of heat and eventually creating negative SST and sub-surface heat content anomalies. This lag between positive and negative feedback between the ocean and the atmosphere leads to oscillatory behavior on decadal time scales. Other studies have suggested a coupled mode of variability involving the thermohaline circulation. The modeling results of Timmermann et al. (1998), for instance, suggested that an anonymously strong thermohaline circulation produces positive SST anomalies over the North Atlantic. The atmospheric response is a strengthened NAO, which, in turn, produces anomalous fresh water fluxes, and Ekman transport off New foundland and the Greenland Sea. The resulting reduction in sea surface salinity is advected by the subpolar gyre and eventually reduces the convective activity south of Greenland, thereby weakening the strength of the thermohaline circulation. The outcome is reduced poleward oceanic heat transport and the formation of negative SST anomalies, which completes the phase reversal and results in multi-decadal variability. It must be recognized, however, that the presence of periodicity or correlated behavior between the atmosphere and ocean in both observations and models does not necessarily imply the existence of a coupled mode. Either damped modes of the uncoupled ocean that are stochastically excited by atmospheric variability (e.g., Saravanan and McWilliams 1998) or unstable modes of the uncoupled ocean that express themselves spontaneously (e.g., Jin 1997; Goodman and Marshall 1999; Weng and Neelin 1998) can also produce such behavior.
Figure 1. Expected values of the annual standardized index of CPUE age 1 (solid line) of the North Atlantic swordfish related to N.A.O. index one year before, using a smoothing local regression (loess) for fitting the observed values (dots). (from SCRS/00/156.)