THE NORTH ATLANTIC OSCILLATION (NAO)

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1. INTRODUCTION:

1.1 Characteristics of the NAO

The NAO is a large scale alternation of atmospheric mass with centres of action near the Icelandic Low and the Azores High. It is the dominant mode of atmospheric behaviour in the North Atlantic sector throughout the year, although it is most pronounced during winter and accounts for more than one-third of the total variance in sea-level pressure [Figure 1 top panel; Cayan, 1992a]. Simplifying the more complicated index of Walker and Bliss (1932), Rogers (1984) defined an index of the NAO using sea level pressure anomalies from Ponta Delgada, Azores and Akureyri, Iceland, while Hurrell (1995a; 1996) extended the index further back in time by using data from Lisbon, Portugal and Stykkisholmur, Iceland.

A "high-index" pattern, indicating strong midlatitude westerlies, is characterised by an intense Iceland Low with a strong Azores Ridge to its south, while in the "low-index" case, the signs of these anomaly-cells are reversed. Note however that the associated sea level pressure (slp) patterns are not merely reversed between these NAO extrema; their actual configuration, which may critically affect the Ocean's response, is illustrated in the middle panels of Figure 1 [from Rogers, 1990]. It is worth noting also that year-to-year departures from high- or low-NAO index sea level pressure composites are large, so that simple two station indices such as those defined by Rogers (1984) or Hurrell (1995a) have signal-to-noise ratios near 2.5 for winter anomalies (Hurrell and van Loon 1997). The noise, in this case, is a measure of all fluctuations where the two centers of action in the NAO are operating in phase and therefore are not part of the oscillation.

Among its rich blend of frequencies, the NAO index has exhibited considerable long-term variability [Figure 1, lower panel, from Hurrell, 1995; see also Rogers, 1984 and Cook et al 1998]. Cook et al. [1998; see also Hurrell and van Loon 1997] describe concentrations of spectral power around periods of 24, 8 and 2.1 years, but also identify a multi-decadal oscillation with a period of 70 years. Though of interest in itself as the dominant mode of atmospheric behaviour in the Atlantic sector, the present interest of major international programs such as WCRP-CLIVAR in the NAO is centred on the extent to which these multi-annual to inter-decadal changes in the NAO index are predictable.

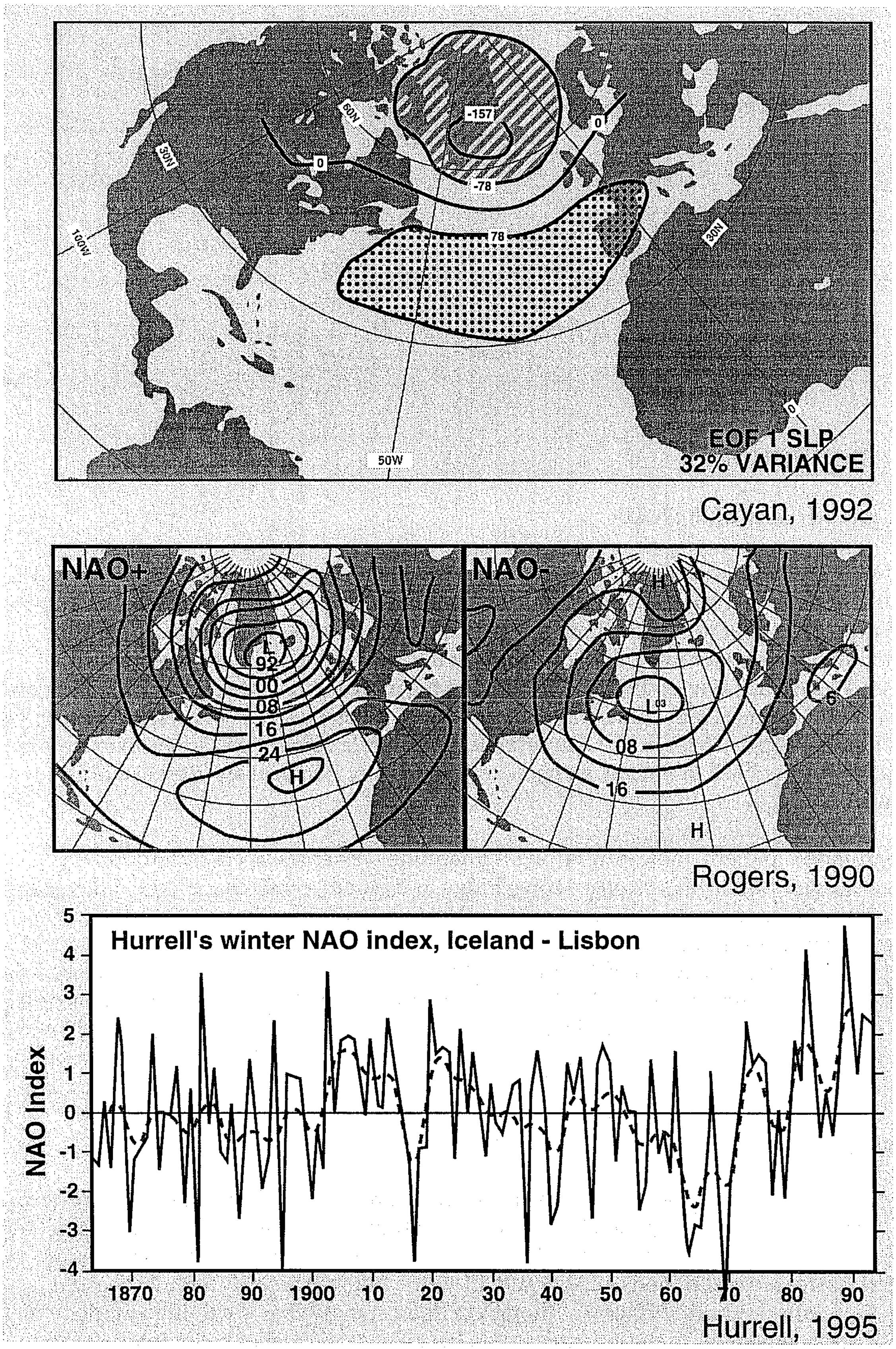

Figure 1. NAO pattern and variability

Of recurrent modes of atmospheric behaviour, the NAO is among the most robust. From the 13 atmospheric circulation modes worldwide considered by Barnston and Livezey [1987], the NAO was the least seasonally-ephemeral [i.e. was the only recurrent mode that is robustly present in every month of the year; Figure 2].

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North Atlantic Oscillation	NAO	■	■	■	■	■	■	■	■	■	■	■	■
Pacific/North American	PNA	■	■	■	■					■	■		■
West Pacific Ostellation	WPO	■	■	■	■	■						■	■
Tropical/N. Hemisphere	TNH	■	■									■	■
Northern Asian	NA	■	■	■							■	■	■
Eurasian Mode 1	EU1	■	■	■	■	■				■	■	■	■
Eurasian Mode 2	EU2	■	■	■						■	■	■	■
East Atlantic	EA	■	■	■	■							■	■
East Pacific	EP	■	■	■									
Subtropical Zonal Mode	SZ			■	■		■	■	■	■	■		
Asian Summer	AS						■	■	■				
North Pacific	NP				■	■	■			■	■		■
Pacific Transition	PT				■	■	■	■					

Figure 2. Robustness of recurrent atmospheric circulation patterns. Shaded squares indicate high average correlations between the patterns of individual years and the full-sample pattern. [Data from Barneston and Livezey, 1987].

Rogers [1990] shows that the NAO accounts for the largest amount of interannual variability in monthly North Atlantic sea level pressure in all but four months of the year. The NAO was also the only circulation mode tested that was coherent with the periodic behaviour of the 700 year stable isotope record from the GISP-2 ice core from central Greenland [White et al, in press; see also Barlow et al, 1993].

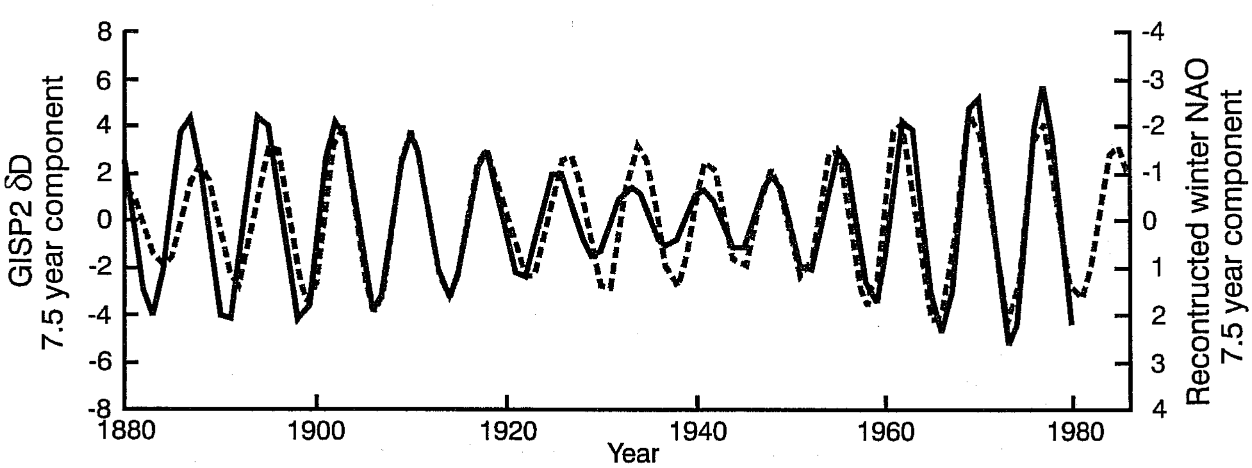

Figure 3. Coherence of the GISP-2 deuterium record and NAO Index (from White et al. 1995)

On shorter time scales, Cayan [1992, a,b,c] has analysed composites of positive and negative NAO months in winter [October to April] to show that the NAO is responsible for generating systematic large amplitude patterns in the anomalies of windspeed [Figure 4], latent and sensible heat fluxes, and hence sea surface temperature over much of the extratropical North Atlantic [Figure 6; around 10-40% of the monthly change in SST anomaly is estimated to be due to these flux anomalies over the winter months and over much of the ocean; Cayan, 1992c, p 875].

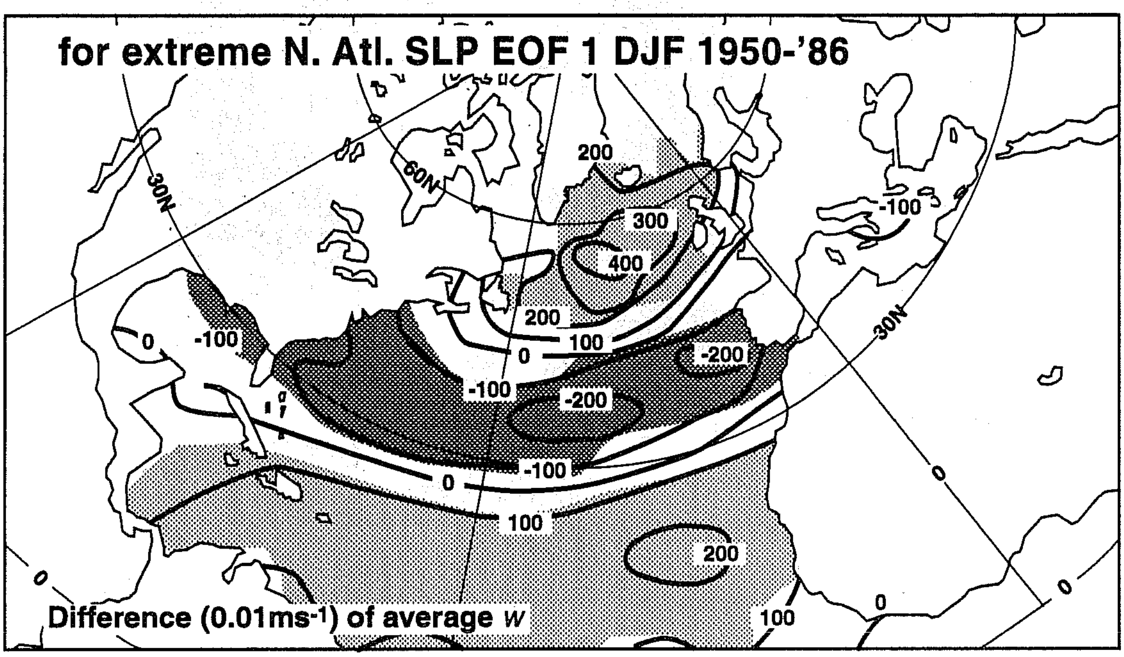

Figure 4. Difference of average winter windspeed [0.01 ms^{-1}] associated with positive vs. negative extremes of the NAO. [From Cayan, 1992c].

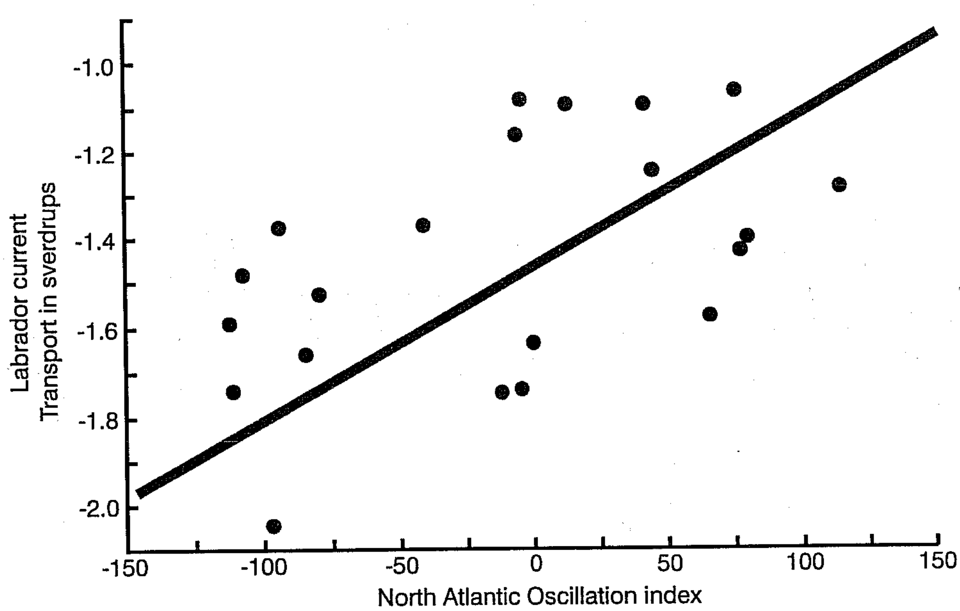

Figure 5. Correlation between Labrador Current transport and the NAO Index. [From Myers, Helbig and Holland, 1989]

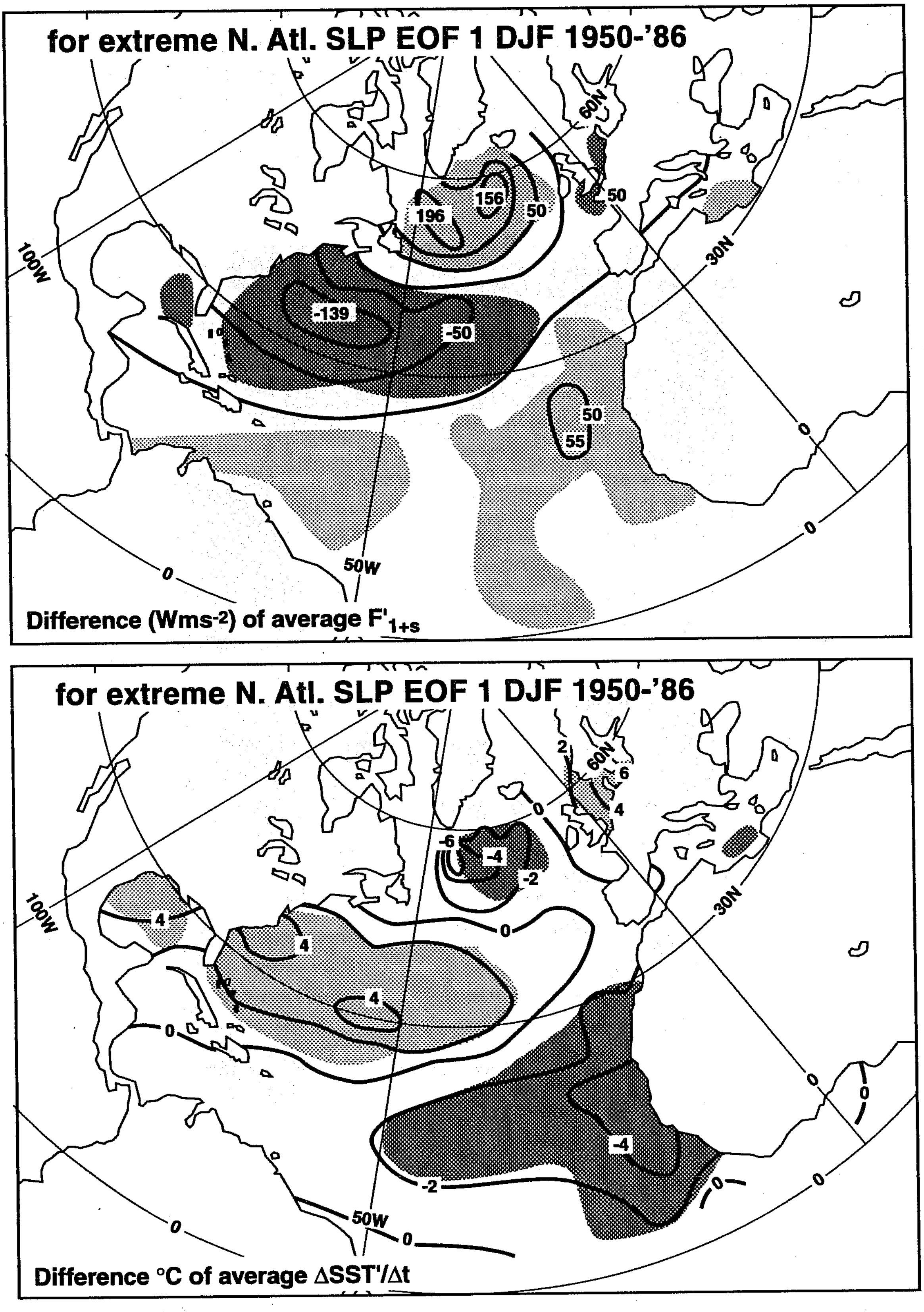

Figure 6. Difference of the average monthly heat flux anomaly [W ms^{-1}, upper panel] and of the average month-to-month change in SST [°C, lower panel] associated with positive vs. negative extremes of the NAO during winter. [From Cayan, 1992c].

In a range of other studies, the interannual and longer-term changes in the winter NAO from one extreme state to the other has also been suggested to determine or modulate deep temperature (T) and salinity (S) on the West Greenland Banks, [Buch, 1995], temperature and salinity fluctuations in the currents of Greenland-Labrador, [Reverdin et al 1997] temperature anomalies of the western subtropical gyre [Molinari et al. 1997], and the baroclinic transport of the subtropical- subpolar gyre system [McCartney, Curry and Bezdek, 1997].

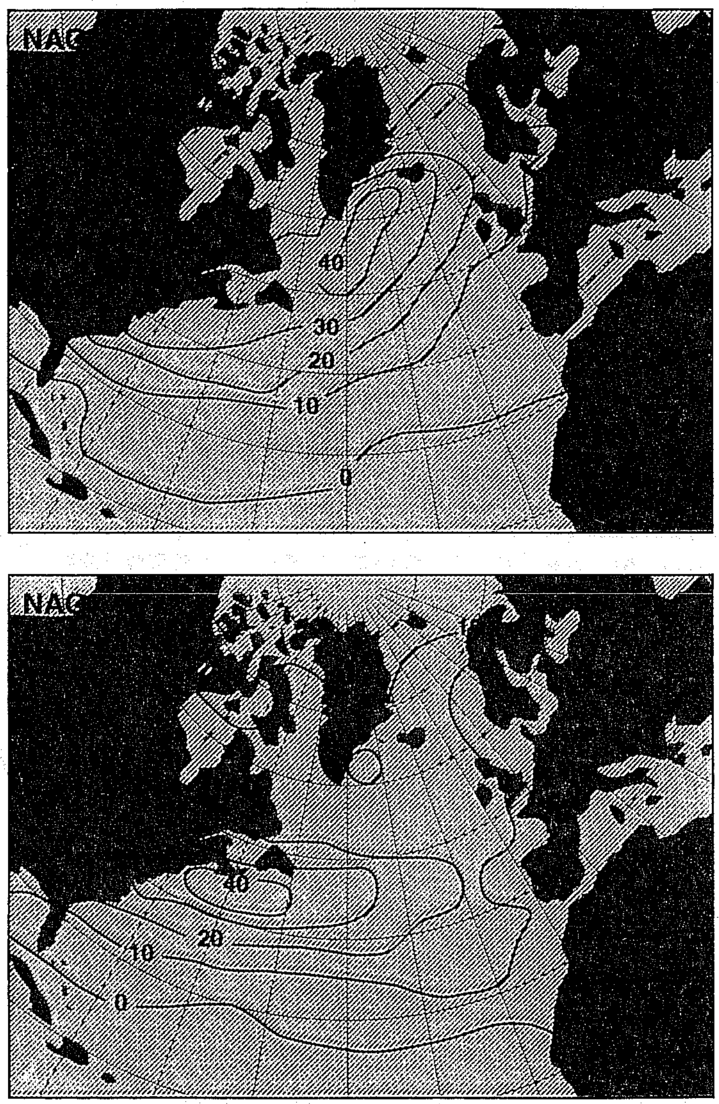

Figure 7. Winter frequency of wave cyclones during high-index [upper panel] and low index [lower panel] extrema of the North Atlantic Oscillation. From Rogers 1990.

It determines the distribution of Atlantic storms [Figure 7 from Rogers, 1990; see also Hurrell, 1995b], the midlatitude westerly wind strength and hence the significant wave height of the North-East Atlantic. [Figure 8; see Bacon and Carter, 1993; Kushnir et al 1997]

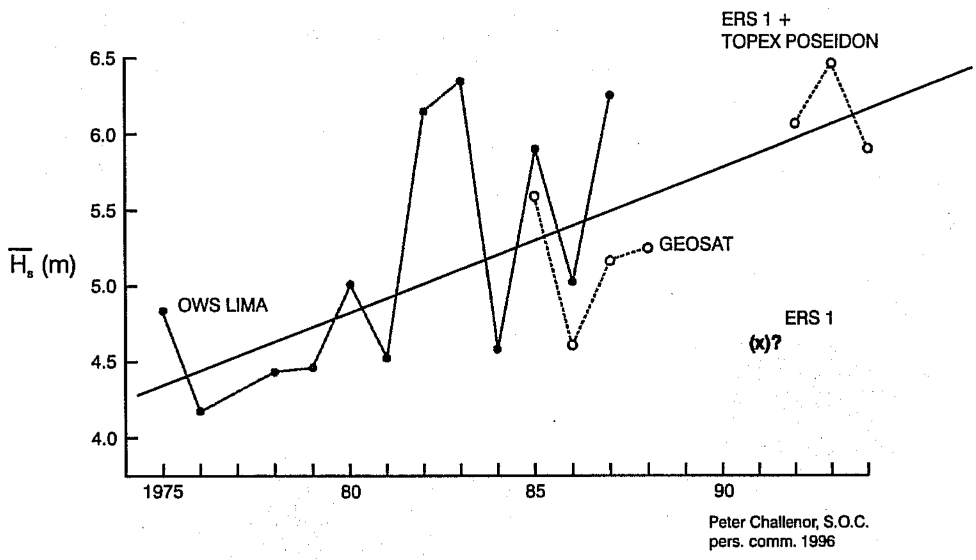

Figure 8. Change in the mean December-January significant wave height (Hs) at OWS LIMA, NE Atlantic, associated with a long-term increase in the North Atlantic Oscillation Index between the 1960s and 1990s.

together with the Atlantic distribution of evaporation and precipitation [Cayan and Reverdin, 1994; Hurrell, 1995a], the meridional heat flux by the atmosphere [Carleton, 1988], the transport of the Labrador Current [Figure 5, from Myers, Helbig and Holland, 1989; Marsh, 1997], Arctic sea-ice [Fang and Wallace, 1994; Mysak et al , 1996], Davis Strait ice volume [Deser and Blackmon, 1993], the iceberg flux past Newfoundland [Drinkwater, in Rhines, 1994], and dust transport from Africa across the Mediterranean and the subtropical Atlantic [Figure 9 from Moulin et al. 1997].

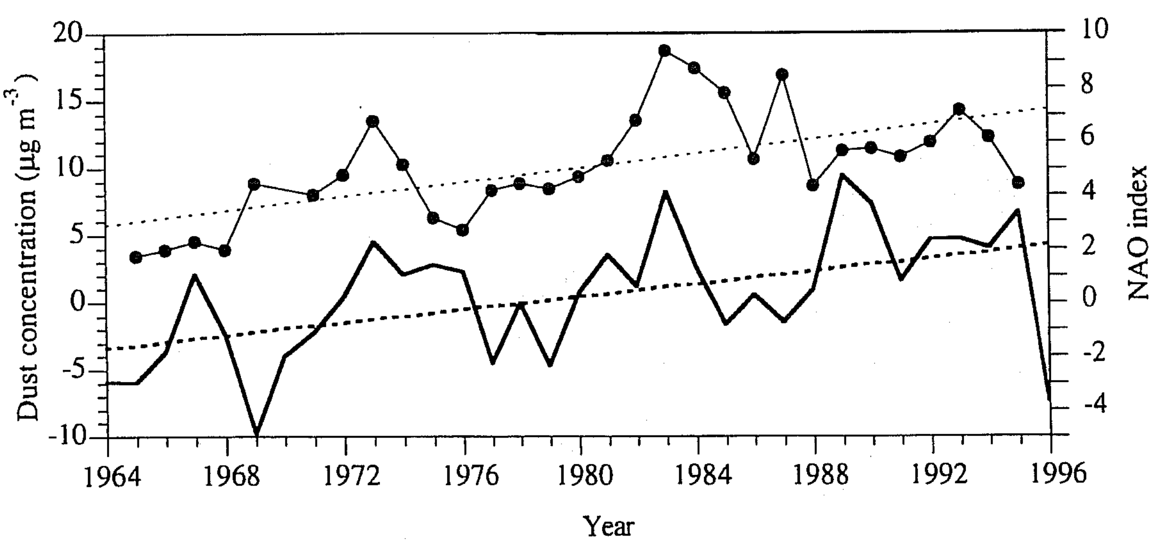

Figure 9. Comparison of the NAO Index (bold continuous line) between 1964 and 1996 with the annual mean surface concentration of desert dust at Barbados, West Indies, between 1965 and 1995 (filled circles: J. M. Prospero, pers. comm.). Dotted lines show the regression line for each variable. From Moulin et al, 1997.

Decadal changes in the NAO have recently been held responsible for determining Eighteen Degree Water characteristics, including convection strength [Talley, 1996; Joyce and Robbins, 1996; Houghton 1996], Labrador Sea Water characteristics, including convection strength [Lazier, 1995; Houghton, 1996], as well as for controlling and coordinating the intensity of deep convection between the three main Atlantic sites [Greenland Sea, Labrador Sea and Sargasso; Dickson et al 1996], thus driving decadal change to considerable depths in the ocean [Figure 10].

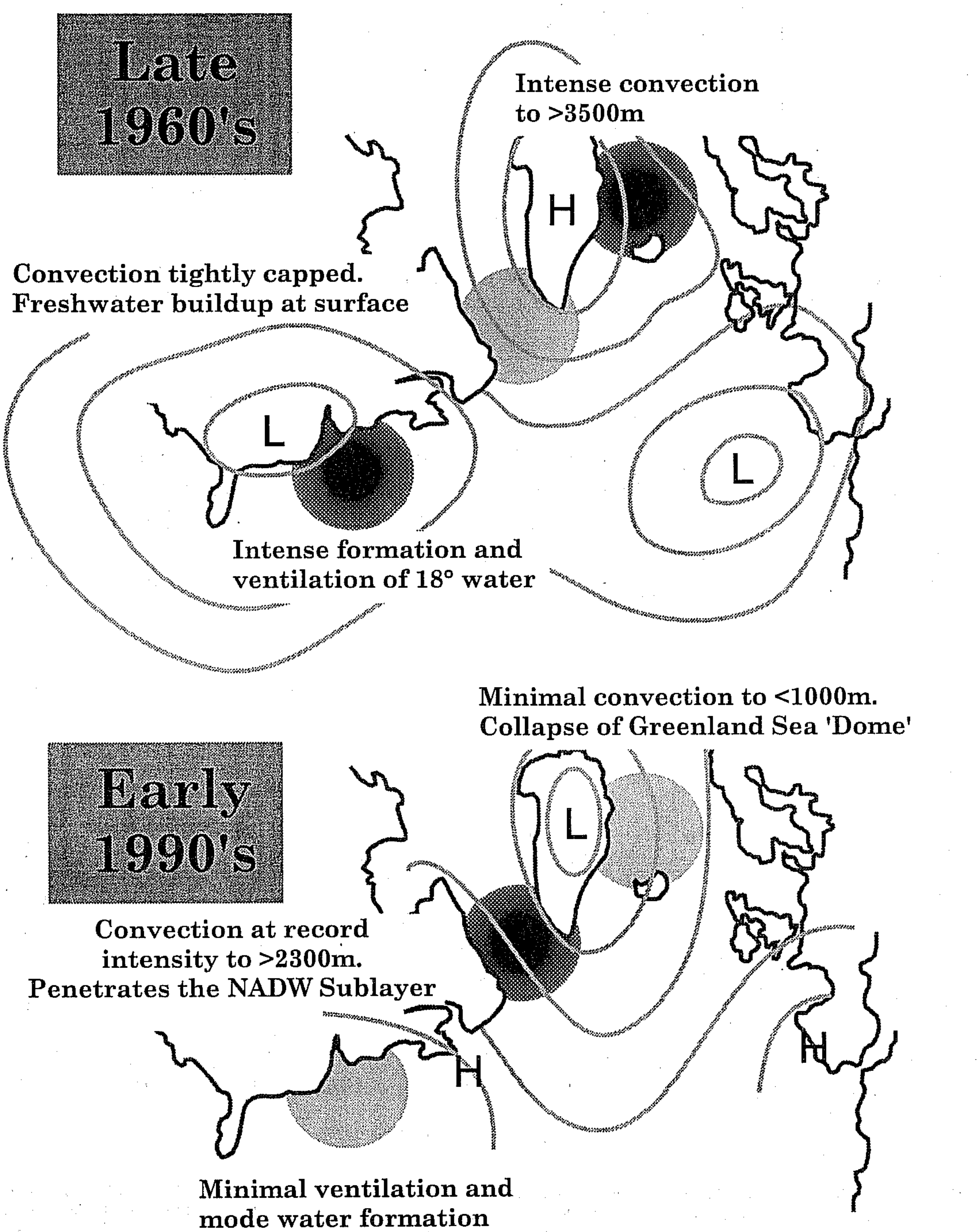

Figure 10. Schematic description of changes in the distribution of winter convective activity in the North Atlantic during contrasting extreme states of the NAO. [Low index 1960s, high index 1990s; from Dickson, 1997]

Further, the amplification of the northern cell of the NAO dipole to record levels in the 1960's was the key factor in generating the largest known dislocation of the freshwater balance of the Northern Gyre, the so-called Great Salinity Anomaly [Dickson et al, 1988], which circled the subpolar domain of the North Atlantic over a 14 year period from the late '60s [possibly with some recirculation thereafter; see Belkin, Levitus and Antonov, 1997].

As might be expected, these radical changes in the climate and marine environment of the North Atlantic sector are held responsible for a wide range of effects on the marine ecosystem, including changes in the production of zooplankton and the distribution of fish. [e.g. Figure 11 from Fromentin and Planque, 1996; see also Friedland, Reddin and Kocik, 1993]

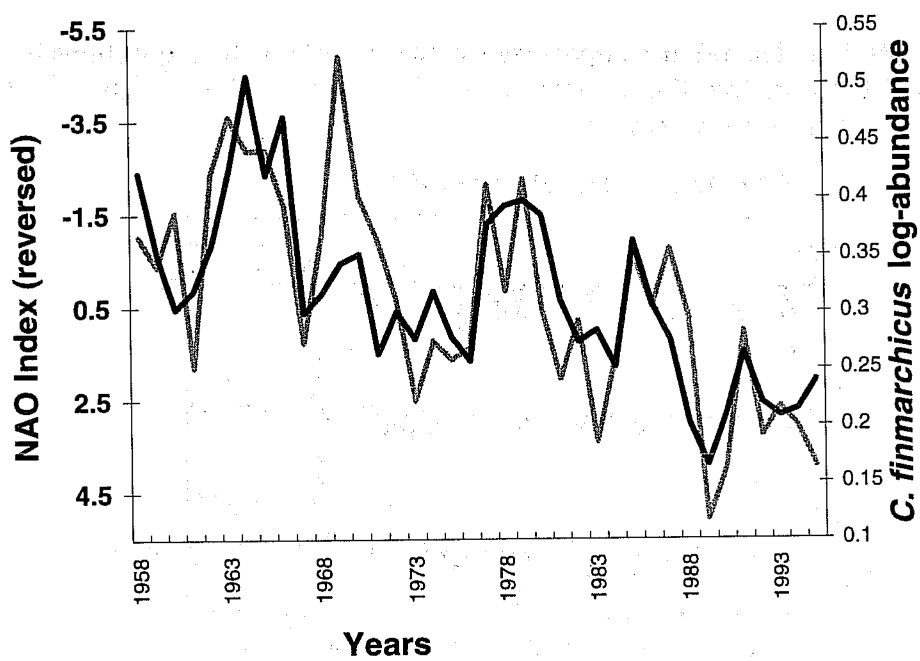

Figure 11. NAO variability and Calanus abundance, NE Atlantic (Fromentin and Planque, 1996)

1.2 The NAO and Global Change.

As the Second Assessment Report of IPCC points out, [see Nicholls et al, in IPCC, 1996], the current global change debate remains centred around six questions related to the detection of climate change and sensitivity of the climate to anthropogenic activity. They are:

Has the climate warmed?
Has the climate become wetter?
Has the atmospheric/oceanic circulation changed?
Has the climate become more variable or extreme?
Is the 20th Century warming unusual?
Are the observed trends internally consistent?

Karl et al [1995] conclude that for many of the climate variables important in documenting, detecting and attributing climate change, the data are not presently good enough for rigorous conclusions to be drawn. Nevertheless, in the first of its series of authoritative reports, IPCC [1990] concluded that global average surface air and sea temperatures had risen by 0.3° C to 0.6° C since the mid 19th Century.

Supplementary analysis [IPCC, 1992, 1996] subsequently confirmed this, using an updated, improved and expanded data-set. The warming has not been uniform in either time or space. Approximately 0.2 to 0.3C of the global increase took place over the last 40 years or so, [the period with the most credible data; see Jones, 1994a,b], and the greatest warming has been located over the continents between 40°N and 70°N, with weak cooling over the intervening oceans [the Cold Ocean Warm Land or COWL pattern; Wallace et al. 1996].

The NAO and its time-dependence appear central to three of the main questions in the global change debate: has the climate warmed, and if so why and how? Figure 12, from Hurrell [1996], explains the connection.

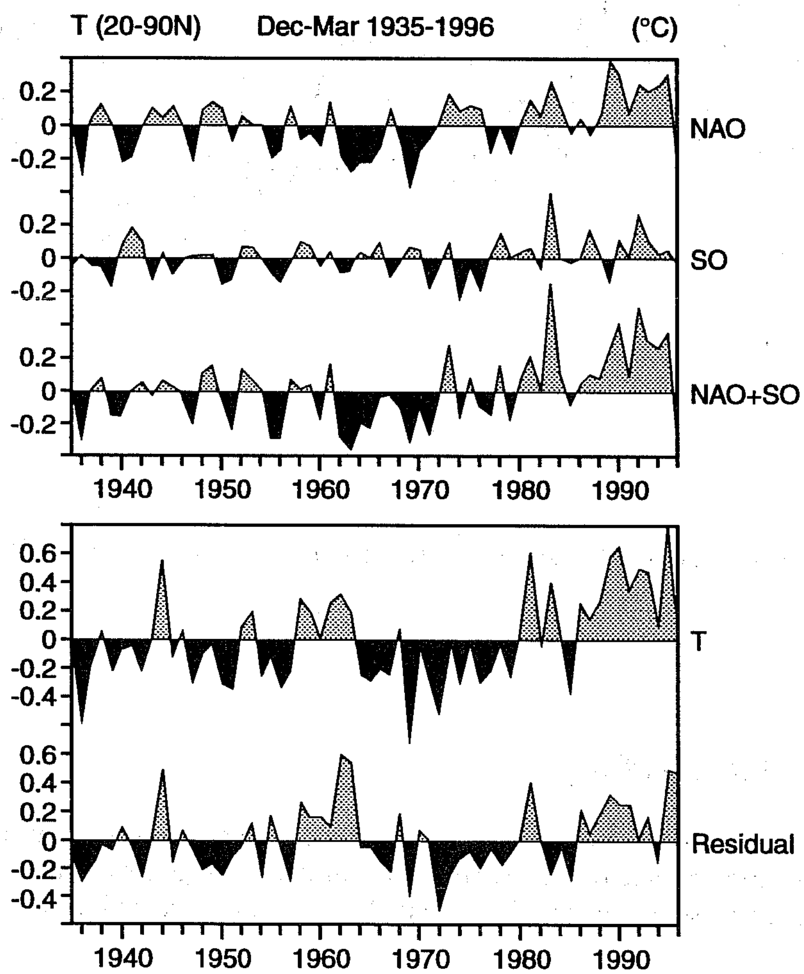

Figure 12. Surface temperature changes of the Northern Hemisphere (20°N-90°N) for December to March associated with the North Atlantic Oscillation (NAO) - top series, upper panel; the Southern Oscillation (SO) - middle series; upper panel; and combined - bottom series, upper panel, relative to the total change - top series, lower panel. The residual temperature record (bottom series, lower panel) is that remaining after the NAO plus SO effects are removed. Note the predominance of positive contributions in the NAO and SO after about the late 1970s (After Hurrell, J. W., 1996)

Using multivariate linear regression, Hurrell has quantified the effect of observed changes in the North Atlantic Oscillation and Southern Oscillation [SO] on Northern Hemisphere extratropical [20N - 90N] temperatures during winters since 1935. The individual and combined response to these circulation changes is shown in the upper three graphs of Figure 12. Together, these two circulation modes explain 49% of the observed interannual variance in hemispheric extratropical temperatures, with the NAO individually accounting for 34% and the SO for 16% [Hurrell, 1996, updated]. Moreover, when the linear effects of the NAO and SO are removed, the residual time-series [lower panel, Figure 12] is found to exhibit no significant trend.
Such results don't tell us if the observed warming is natural or anthropogenic, but we can justifiably conclude that the mechanism of hemispheric warming ----whatever its cause----is acting through an amplification of the NAO in the Atlantic sector and the ENSO (or PNA) signal in the Pacific. Either way the NAO is revealed as a major source of interannual variability in global weather and climate.

1.3 Decadal changes in the NAO index.

Apart from its role in driving large amplitude interannual fluctuations in the climate of the Atlantic sector, the NAO Index has shown signs of variability at decadal time scales also. It appears, however, that this decadal modulation is itself time-dependent.

In the indices of Rogers [1990] and Hurrell (1995a) there is evidence of a long-period, decadal alternation in amplitude since the late 19th century, with low-index extrema during the 1960s [Figure 1 lower panel], and with high-index extrema from 1900-1930 and in the 1990s. From both proxy and observational evidence, however, there is evidence that the multi-decadal signal in the NAO Index has been amplifying with time.

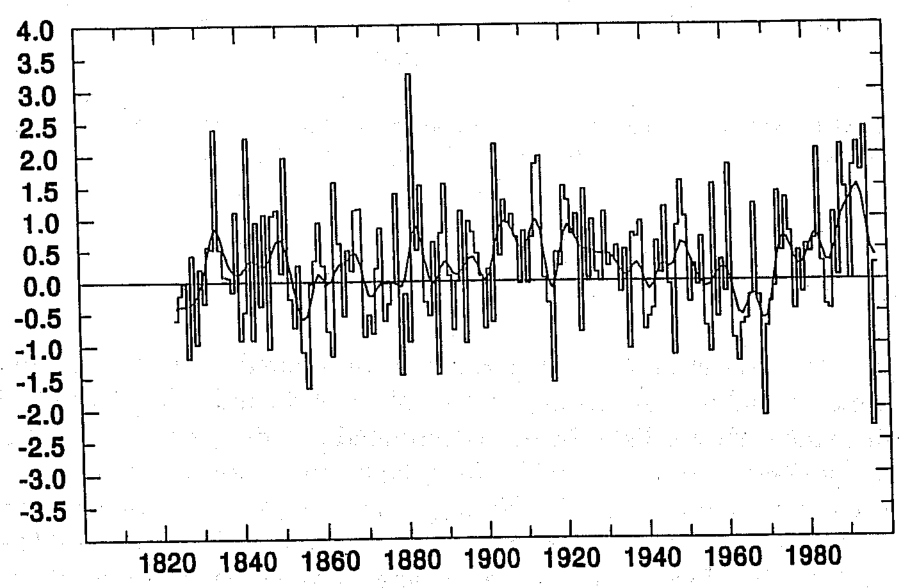

Figure 13. The longest available instrumental record of the behaviour of the NAO Index, constructed for each winter (November to Marcch), 1823-1996, by Jones, Jonsson and Wheeler, (1997). Note that in successive winters, 1995 and 1996, the NAO Index changed from its second-highest to its lowest value in the entire 173-year record

Jones et al [1997] have used early pressure records to costruct a November to March version of the Index for Iceland-Gibraltar, thus extending the instrumental series back to 1821 [Figure13]. Cook et al. [1998] use a 10 tree-ring model [trees from both North America and Europe] to develop the first reconstruction of the winter NAO index back to 1701 [Figure 14]. From spectral analysis of this proxy, they show little sign of decadal variation in the index before 1850, but an amplifying 70-year oscillation after that.

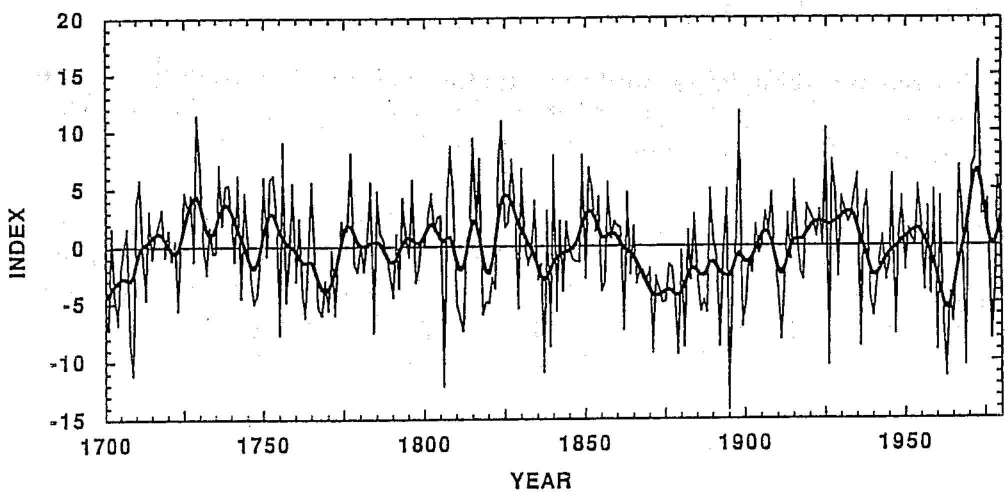

Figure 14. The winter NAO Index since 1700, reconstructed from tree-rings (10 Tree-ring model). The series explains 41% of the variance. From Cook, D'Arrigo and Briffa, 1998.

A high-amplitude interannual variability becomes modulated with an amplifying decadal signal with time, so that ---as shown in other versions of the index [e.g.Hurrell, 1995a], ---- the period since the early 1970's is the most prolonged positive phase of the Oscillation, the late 1980s/ early 1990s is the period with the highest values, and the change from the low-index 1960's to the high index 1990's is the largest low-frequency change of record. Interestingly, the change from the 1994-5 winter value [2nd highest] to the 1995-6 winter value [lowest] is also the largest year-to-year change in the 173 year series. Power spectra computed from running 60-year intervals for the Iceland-Lisbon series since 1865 also clearly demonstrate the tendency for the NAO spectrum to become redder with time [Figure 15, from Hurrell and van Loon 1997].

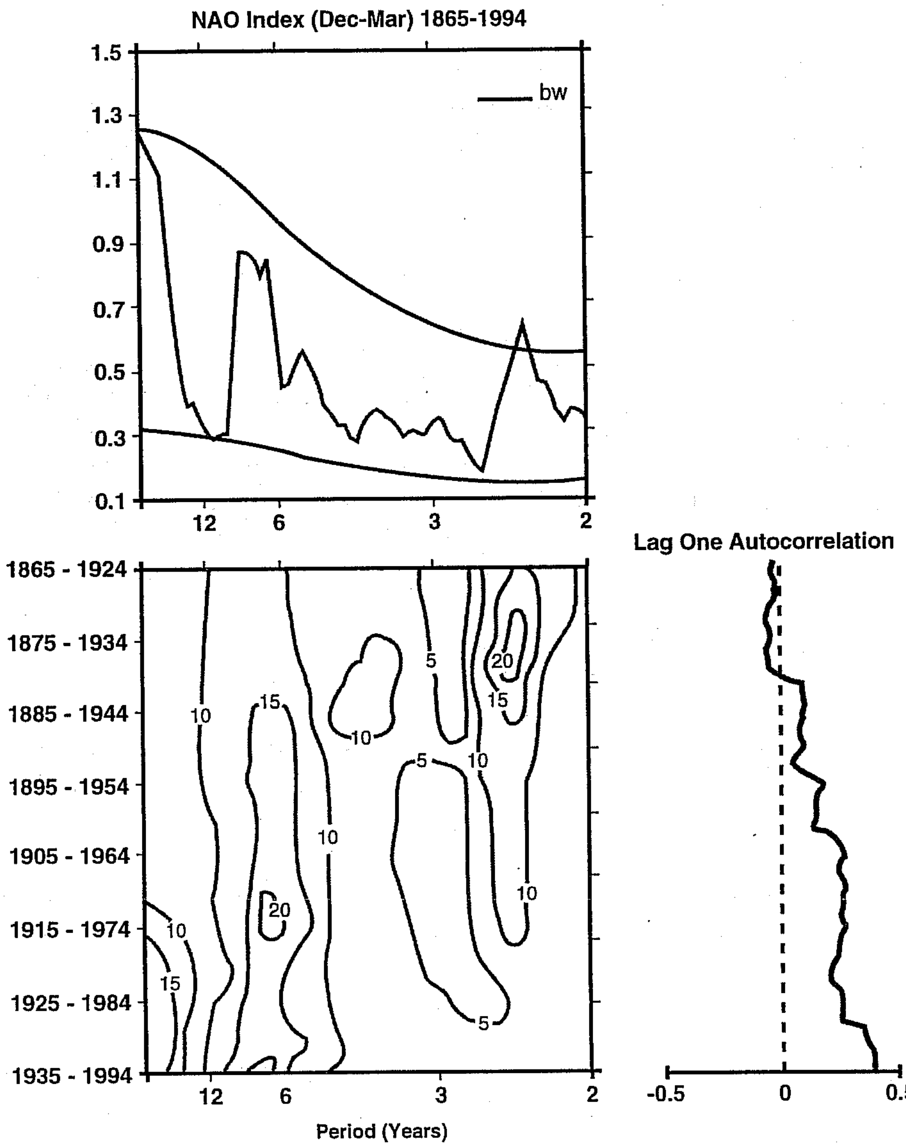

Figure 15. Power spectra of winter (DJFM) NAO Index, 1865-94 (top) and running 60-year intervals. (From Hurrell and van Loon, 1996)

Thus in summary, there is a 3-fold justification for studying the NAO. (1) It controls the factors which effect change in the ocean (i.e. heat flux, windspeed and direction, and P-E). (2) It seems to have made the largest individual contribution to the observed hemispheric warming trend, though we cannot yet tell whether this change owes anything to human activity. (3) The amplitude of its decadal variability component appears to be increasing with time.

The fact that the year-to-year changes in the NAO index are also exceeding the range of past experience suggests that mere "persistence" is likely to be a poor guide to the future behaviour of the NAO. Instead, prediction of the NAO will require an adequate understanding of the factors which provide its long-period memory, protracting, repeating or in some way structuring its short term behaviour into the multi-annual trends that our records seem to show us [Figure 1, lower panel].

investigations will be central to an identification of which components of the climate system, acting either together or independently, produce climate variability over this region of the globe. With respect to the NAO, a key unresolved question is whether observed anomalies in oceanic conditions represent a passive response to decadal changes in the atmospheric circulation, or whether they feedback to force decadal and longer period oscillations in the NAO.

Recent modeling work by Griffies and Bryan (1997) suggests that the North Atlantic ocean may have climate predictability on the order of a decade or longer. Since the oceanic variations are manifest at the surface as decadal to multi-decadal SST anomalies, a key question relevant to predictability is the response of the atmosphere to middle and high latitude SST anomalies. This question has been addressed by many previous theoretical and modeling studies, yet no clear consensus has emerged. In the wintertime extratropics, transient phenomena with time scales of several days consist mainly of migratory baroclinic cyclone waves. The transport of heat and vorticity by transient atmospheric eddies along storm tracks results in strong dynamical interactions between the time-varying and stationary components of the atmospheric circulation, which dictates that a full understanding of the steady-state response to middle latitude SST anomalies must take into account the total effects of the transient waves, including their influence on surface fluxes and further changes to the SST anomalies. Studies have shown that storm track variations accompanying interdecadal changes in the background flow exert a positive feedback on the low-frequency component of the circulation (e.g., Trenberth and Hurrell 1994; Hurrell and van Loon 1997). A design study to further elucidate such relationships is suggested in the next section.

3. DIAGNOSTICS, AND EMPIRICAL STUDIES

3.1 Optimising the NAO index.

Section 1 established that the North Atlantic Oscillation is of global climatic importance and has shown a growing decadal variability since the 1820's. Though we cannot yet tell whether any part of this change is attributable to a growth in human activity, any tendency for the NAO to undergo structured long-period change over years to decades must have predictive value, whatever the cause, if it can be rigorously established. The first diagnostic need is therefore to lengthen and strengthen the NAO Index.

Using different station-pairs, the instrument-based index of NAO behaviour has been successively pushed back to 1873 (Iceland-Azores, Rogers 1990), 1865 (Iceland-Lisbon; Hurrell, 1995a) and 1821 (Figure 13, Iceland-Gibraltar; Jones et al 1997). Early weather records from Reykjavik and Cadiz may permit one further extension back to about 1780 (P.D. Jones, personal communication). Beyond that we are forced to use proxies of NAO variability such as the tree-ring model used by Cook et al. [1998] in reconstructing the NAO winter Index back to 1701. [Figure 14]. Though the winter season is of most interest, as it is the period of strongest pressure gradients and interannual variability [Moses et al, 1987], tree-ring chronologies from mid- to high-latitudes will tend to respond largely to summer temperature variations, as Cook et al. point out.

They base their first long [280 year] reconstruction empirically on the 10 [out of 102] circum-Atlantic chronologies which are best related to the winter NAO Index, and succeed in capturing the spectral characteristics of the instrumental data very well.

One thousand year tree-ring chronologies also exist for cedars from the Atlas mountains of Morocco, [Till, 1985; Chbouki, 1992; Chbouki, Stockton and Myers, 1995] where tree growth is a function of winter rainfall. The link to precipitation there [Lamb and Peppler, 1987] is also stronger than for the alternate long proxy of the NAO: the stable isotope relation from the GISP-2 ice-core in Central Greenland. Moroccan tree-ring data might therefore provide a stronger, more-direct and extended [perhaps 1000-year] proxy for the long-term behaviour of the winter NAO, and should be analysed for this purpose. Ultimately, if a 1000-year paleotemperature curve can be developed for the West Atlantic shelf as is currently planned [O-18 analysis of the bivalve *Arctica* ; Glenn Goodfriend, CIW and Chris Weidman, WHOI, pers. comm.], the optimum NAO proxy might be developed from the combination of all three of these widely-scattered and independent millennial proxies.

And if, by this means, we can demonstrate whether the current amplification of the NAO had occurred *previously* in a thousand-year record, it may be useful guidance as to whether the present change is natural or anthropogenic.

3.2 Detailed study of storm-surface interactions.

In McCartney's analyses [McCartney, Curry and Bezdek, 1997; Curry, McCartney and Joyce 1997], there is clear evidence of a systematic space-time evolution in the temperature anomaly distribution of the upper ocean over much of the extratropical Atlantic and over many decades. These warm and cold epochs in SST reflect anomalies of the heat content of the deep winter mixed layers tracking around around a "warm water transformation pathway" from the Sargasso to the Labrador Sea, and are coincident with the trends in NAO behaviour.

The key unresolved question for CLIVAR is whether they represent the passive response of the ocean to a decadally-evolving atmosphere, or whether they feed back to force decadal changes in the pattern of NAO activity. [McCartney's so-called "missing link"].

Monthly aggregates of SLP and SST remain notoriously difficult to interpret in terms of cause and effect, forcing and feedback. The problem may be more tractable when we disaggregate the apparently-robust changes in the mean Atlantic pressure field or storm climate associated with the NAO into their component cells. Then, robust pressure anomaly patterns may prove to be quite delicate features -----the result of a few more storms, or the usual number of storms exhibiting a slightly faster deepening-rate or a slightly slower eastward progression than usual, for example. We are likely to gain insight into the "sense" of the feedback when the short-term [3-hourly?] changes in the characteristics of storms are identified cell by cell and compared with the slower-evolving temperature anomaly gradients of the underlying surface. [Namias 1951 gives us an analagous example of such a disaggregation study].

There is therefore merit in examining the storm characteristics of two contrasting winter pentades---winters of 1965/66-69/70 [coinciding with extreme low index NAO conditions] and 1988/89-92/93 [high index]---- in relation to the underlying temperature anomaly gradients. These periods had the lowest and highest postwar incidence of Atlantic storms deeper than 950 mb [Figure 16].

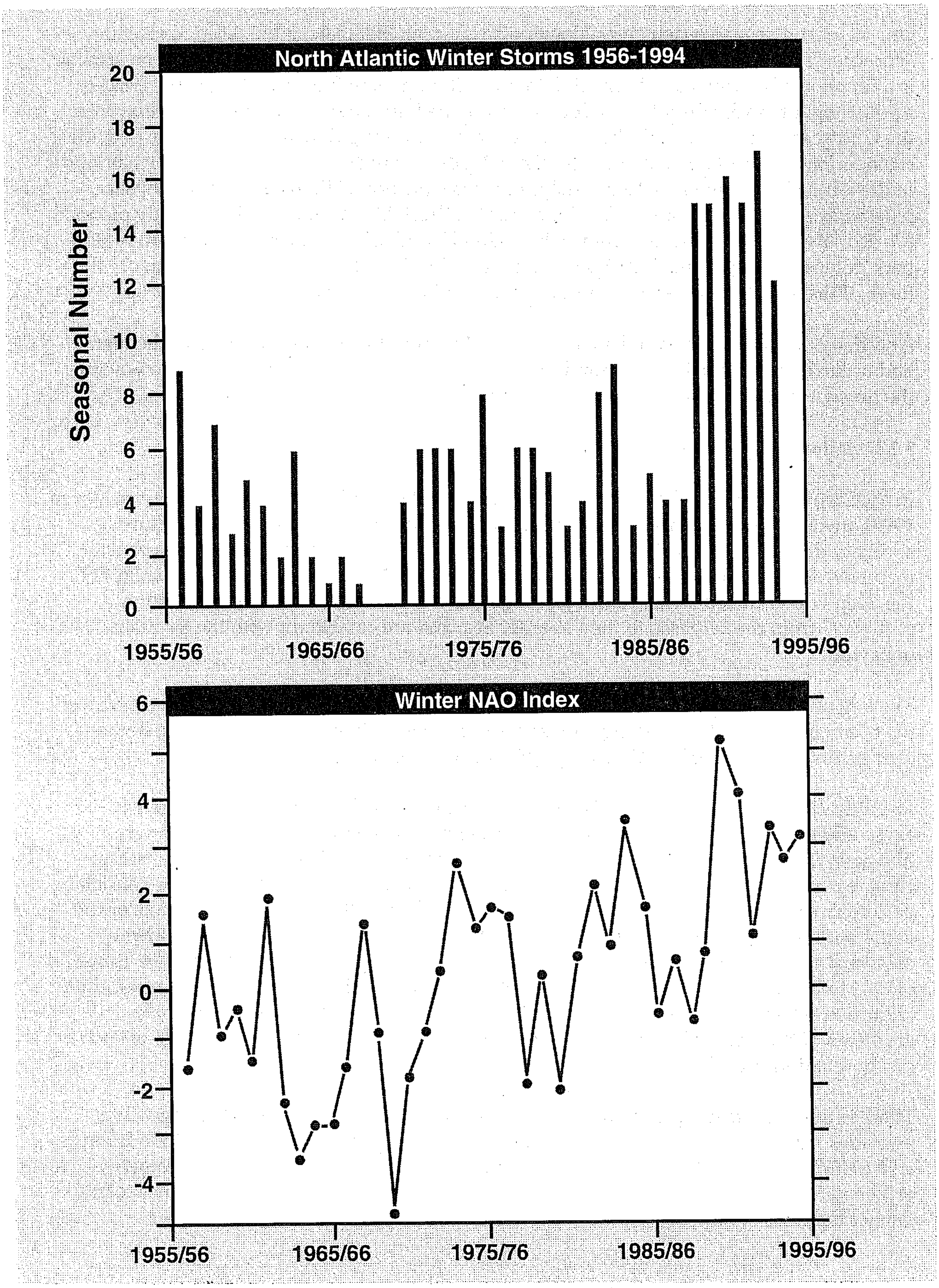

Figure 16. Number of Atlantic storms deeper than 950 hPa (Franke, 1996) compared with changes in the NAO Index (Hurrell, 1995)

4. SPECIAL OBSERVING NEEDS.

4.1 Rationale

The central motivating question of the NAO in CLIVAR (see the CLIVAR Initial Implementation Plan) is whether the observed changes in SST and mode water formation are merely the response of a passive ocean to a decadally-evolving atmosphere, or whether (and how) the ocean might feed back to encourage recurrent behaviour in the NAO (schematic: Figure 17).

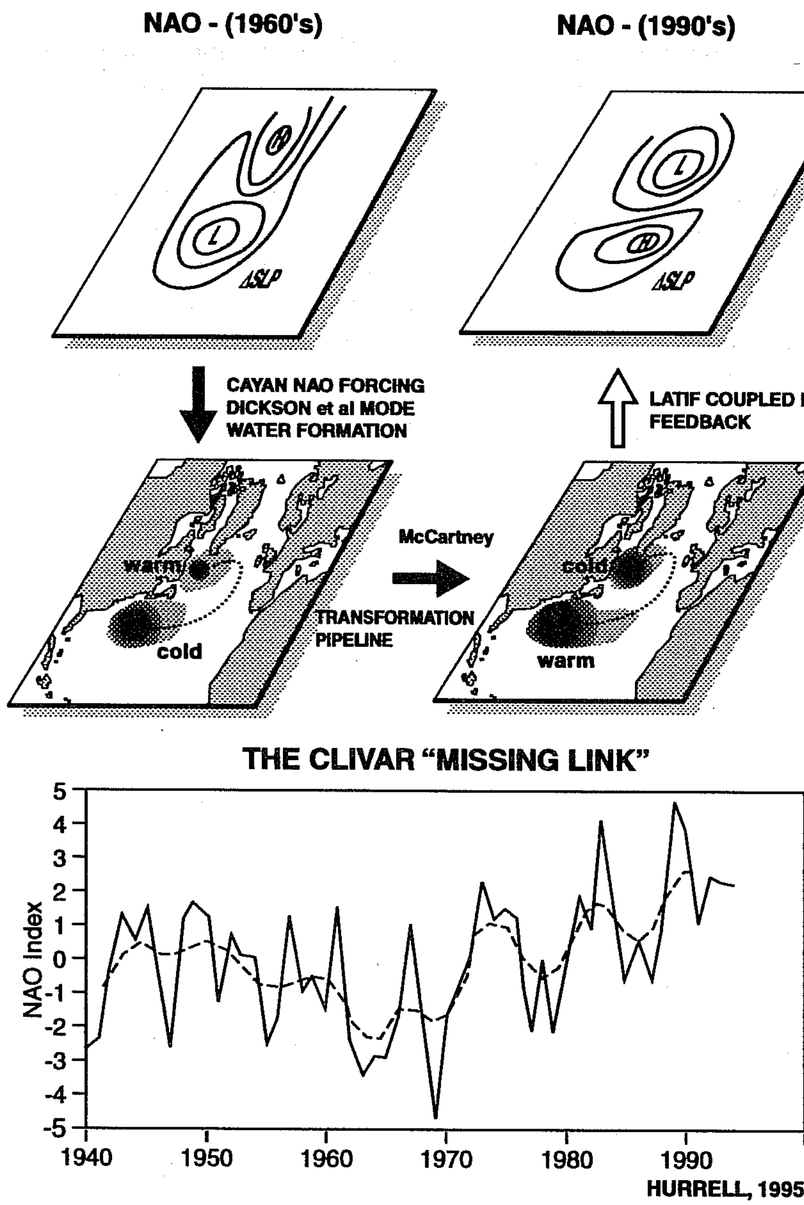

Figure 17. Schematic illustration of the CLIVAR "Missing Link"---can mode water formation, advection and feedback force protracted changes in the NAO?

The non-white character of its spectrum suggests that the link is not merely one of stochastic atmospheric forcing (Hasselmann, 1976), but implies that the system may be coupled (Grotzner et al 1997 ; Timmermann et al 1997), and an amplifying decadal periodicity in the NAO would seem to suggest an increasing involvement of the ocean. However we lack both the evidence and a physical mechanism for the ocean "driving the atmosphere"----- McCartney's so-called "Missing Link".

The field program for NAO in CLIVAR is thus largely set by the need to confirm and quantify the factors which redistribute, protract, or amplify the SST anomaly field of the North Atlantic, and our ideas as to what these factors might be form a necessary introduction to the field plan.

4.2 A DEC-CEN "NAO Array"

Cayan, [1992 b,c] showed that the pattern and amplitude of Atlantic winter heat flux is to a large extent driven by the NAO. Kushnir (1994) then demonstrated that winter SST's in the subtropical and subpolar gyres were warmer during an 15 year period of relatively low atmospheric NAO index (1950 - 1964) than during a subsequent 15 year period of relatively high NAO index (1970-84). Hansen and Bezdek (1996) and Sutton and Allen [1997] later showed that Kushnir's warm and cold periods involved propagating warm and cold SST anomaly patches that move from year to year downstream along the gyres' circulation pathways. McCartney, Curry and Bezdek (1997) explained the recurrence of these propagating SST anomalies by describing them as the surface expression of deep-seated anomalies formed by winter convection and mode water formation, and these processes, in turn, are controlled and orchestrated by the NAO [Dickson et al, 1996]. The current wisdom is therefore that warm and cold SST anomalies track McCartney's "warm water transformation pathway" from the western subtropical gyre around the subpolar gyre to the Labrador Sea, reflecting anomalies of the heat content of deep winter mixed layers.

The process appears to begin with the advection of anomalously warm or cold western subtropical waters into the subpolar transformation pipeline. These advected heat anomalies are sequestered in the mode water, exposed to the atmosphere in winter, isolated by the seasonal thermocline during the warmer seasons, but reappear in subsequent winters, advected downstream [Alexander and Deser, 1995]. Kushnir's warm and cold periods are thus revealed as periods of relatively warm and cold temperatures in the mode water along the transformation pipeline. When the warm water transformation pathway runs warm or cold, the end product of the transformation -----Labrador Sea Water---runs warm or cold also, resulting in an anomalously thin (warm) or thick (cold) LSW layer.These variations in LSW thickness have been found to impact the density structure of the western subtropical gyre with a time lag of 5-10 years (Curry, McCartney and Joyce, 1997).

There are potential feedbacks in this system. (1) by one theory, an increased southward transport of LSW in the DWBC may cause a southward shift of the Gulf Stream which "leaves behind" a large body of warm water in the subpolar gyre, ----- an alternative origin for the warm water which sets the pipeline running warm in the first place. As the LSW becomes depleted, [taking, say 5-10 years to bleed out in the DWBC] the Gulf Stream returns to a more northerly path and the process reverses. (2) Interaction between thermohaline and wind-driven flows may have other effects. For example, the southward propagation of LSW thickness changes and their degree of entrainment into the deep Gulf Stream are thought to have an impact on the stability characteristics of the western boundary current with effects on its downstream intensity. [Spall, 1996] (3) The baroclinic expression of the ingestion of SST and heat anomalies by the subpolar gyre is a potential energy anomaly difference between the subtropical and subpolar gyres which should also effect a change in the eastward upper-ocean transport along the gyre:gyre boundary. For this reason, McCartney refers to the upper ocean potential energy anomaly difference between Bermuda and BRAVO as an "Oceanic NAO Index" [updated in Figure 181 and notes that it appears to lag the atmospheric NAO signal by a few years

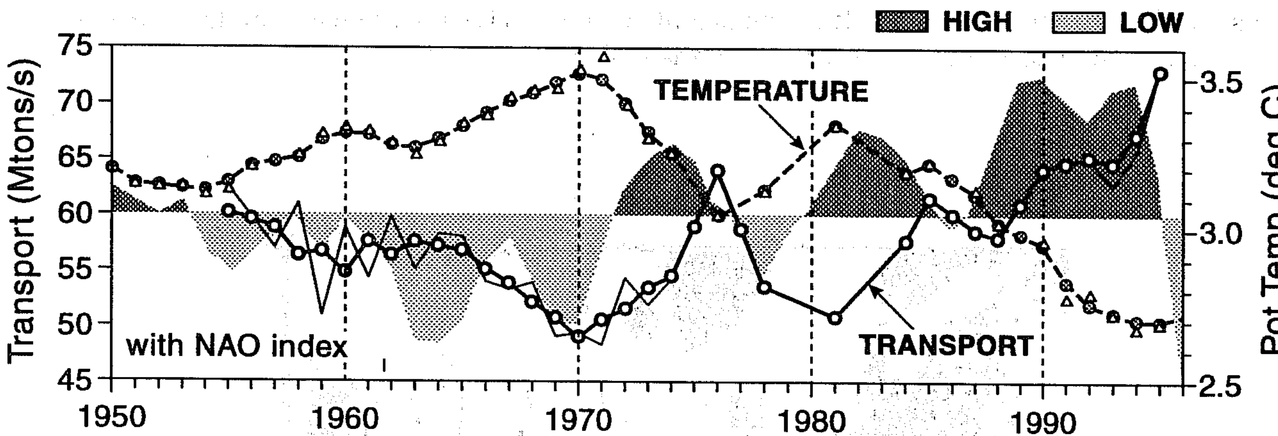

Figure 18. Ocean temperatures and transports related to the NAO:
A low-passed winter NAO Index (Hurrell, 1995, dark grey = high, light grey = low) is plotted with the variation in the temperature of deeply convected water in the Labrador Sea (right scale). Also plotted is the variation in eastward baroclinic transport of the Gulf Stream/North Atlantic Current, as indexed (left scale) by potential energy anomaly differences between the Labrador Sea and Bermuda (an oceanic analogue of the atmospheric NAO Index). The warming temperatures before 1970 (low NAO Index) and cooling thereafter (high NAO Index) are also reflected in subpolar SST. These changes are the underlying cause of the Cold Ocean part of the "Cold Ocean – Warm Land" (COWL, Wallace et al., 1996) pattern in the Atlantic sector in the past 25 years. Oceanic transports appear to lag the NAO by 4-5 years, and decline with the warming Labrador Sea (and general subpolar SST) and declining NAO Index of the 1950s and '60s. The oceanic transports rise again with the cooling Labrador Sea (and general subpolar SST) and strengthening NAO Index of the 1970s, '80s and '90s (until the abrupt shift of winter 1996). The 0.8°C temperature range of this large pool of subpolar water, and the fluctuating range of more than 30% in circulation intensity are some of the indications of a powerful participation of the ocean in this North Atlantic Atmosphere-Ocean Oscillation. (Adapted from McCartney, 1997)

Other variants and theories certainly exist — e.g. the westward and southward propagation of SST anomalies by topographic and/or planetary waves (Greatbach and Peterson, 1996). However the "oceanic NAO index" and the evidence connecting SST history to warm water transformation through winter mode-water convection encompasses much of our present evidence/ideas, and indicates a monitoring strategy.

Temperature alone would be insufficient, but this could be done by high time-resolution hydrography at a few key locations, analagous to the old OWS's [or the continuing Bermuda and OWS M time-series] to supplement the sparser time resolution of XBT's, profiling floats and intermittant hydrographic sections. Given the slow covariant evolution of ocean signals, described above, we suggest that a sparse inter-gyre network of moored deep-parked profiling CTD's, [WHOI Moored Profilers or WMPs in the text which follows], prototypes of which have been tested off Bermuda and now in the Labrador Basin, can assess the evolution of temperature and salinity content in the mode water and thermocline, as well as describe the seasonal capping of the system.

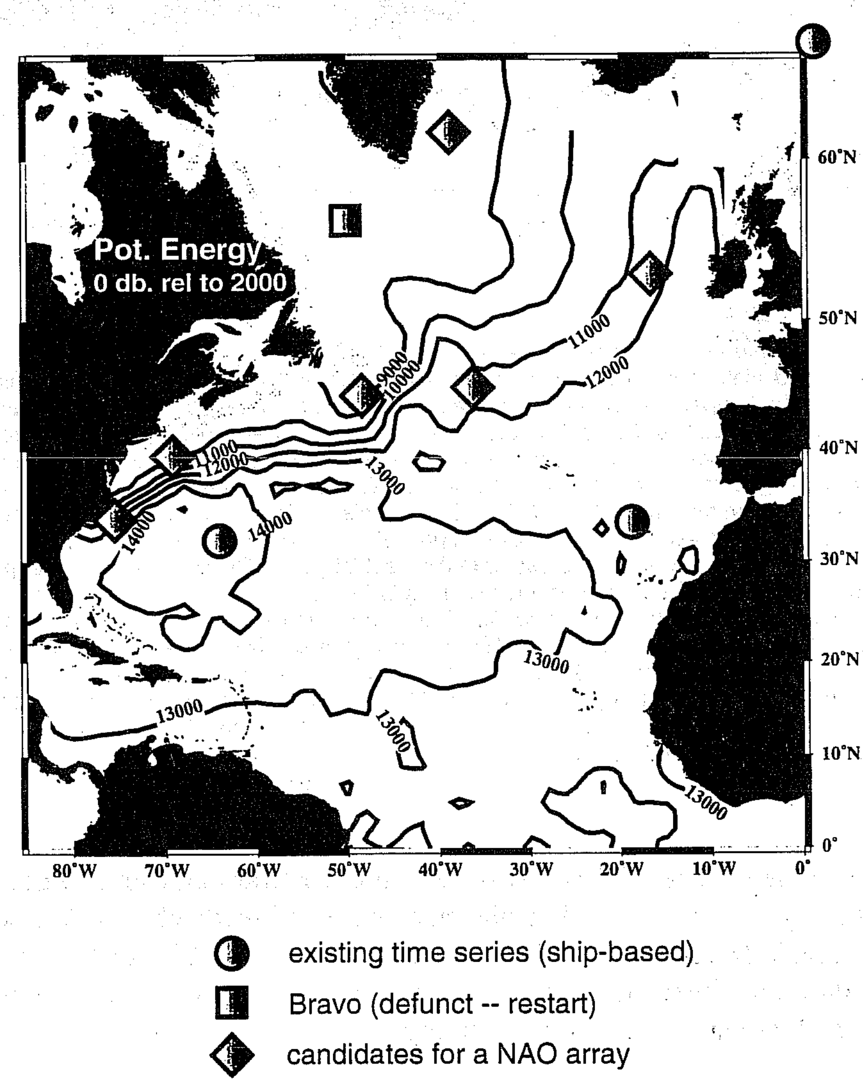

Figure 19. Potential energy anomaly 0 - 2000 db for the climatological average North Atlantic, a baroclinic transport streamfunction for that layer relative to 2000 db. The positions of a DecCen "NAO Array" of moored profiling CTDs are indicated by different symbols. In Figure 18, the time history of baroclinic transport from time-series at two of these locations is shown. A complete array would add tropical and subtropical sites south of 30 °N to include the whole-ocean fluctuations described by Kushnir (1994, 1996) and Sutton and Allen (1997).

Analagous to Figure 18, pairs of such moorings can simultaneously provide indices of baroclinic advection between key points in the transformation pipeline. We suggest a total of seven deep-moored profiling CTDs, [illustrated in Figure 19, though in strongly-sheared regimes, as some of these are, the spatial variability may need to be determined before a representative monitoring site can be chosen]:
Other pairings of these sites may of course turn out to have value. Together they should reveal the time lags of propagating warm water disturbances such as the warm anomaly of the 1950's and 1960's, or the southward return to the subtropical western boundary regime of the transformed products, as in the case of the recent southward invasion by a very cold and thick LSW layer. This "NAO Array" should therefore be directly aimed at the central question that links NAO to CLIVAR---- whether (and how) the ocean temperature field might feed back to encourage recurrent behaviour in the NAO.
Compared with the single Bermuda-BRAVO pairing available at present, the greater redundancy provided by this network will also be of value. Since there is no single spectral peak in the NAO, there might in fact be more than one feedback process involved. Further unknown processes are the draining of Labrador Sea Water from the center of the Labrador gyre by horizontal exchange processes, [the Labrador Current is observed to vary with the NAO; Myers, Helbig and Holland, 1989], the role of deep narrow boundary currents in transmitting the convective water mass signals into the oceans interior, and the fluxes of fresh water from run off and sea ice from the high latitudes. Most of these processes are not well captured in coupled models.

As currently envisaged, the evolution of temperature and salinity content in the mode water and thermocline that the "NAO Array" is designed to monitor will be supplemented by the following fieldwork components :

- a revived and updated "CAGE" experiment, in which a large volume of atmosphere and ocean [the North Atlantic] is cordoned off in attempt to budget its total heat content, and
- a lagrangian study which would enter the CAGE to follow mode waters around McCartney's transformation pipeline over a succession of winters, evaluating their subduction, obduction and transformation directly.
- repeat trans-ocean CTD Sections at critical locations to monitor the the upper-ocean flow along the subpolar gyre:subtropical gyre boundary, to monitor the source regions of North Atlantic Deep Water and the spreading Labrador Sea Water [LSW] plume, to monitor changes in the LSW (the end-point of the transformation pathway), to assess volumetric changes and formation rates of the intermediate and deep waters of the Atlantic and to establish any link between intensified mode water production and changes in the the intensity of the THC
- a program to monitor the Arctic response to NAO forcing by repeat trans-Arctic sections and by monitoring the Fram Strait ice-flux [Vinje in press]. The two main justifications are the apparent involvement of the NAO in hemispheric warming [a range of models predict that the *effect* of that warming will be maximal in the high Arctic; e.g. IPCC, 1996, their Figure 8.12], andthe fact that changes in the export of ice and freshwater from the Arctic to the open Atlantic will have potential effects on the production and characteristics of NADW.

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