# Marine Ecosystems Response to Climate: NCEAS Workshop 1

## Objectives

A small meeting of the Marine Ecosystems Response to Climate (MERC) working group was held from April 17-25 at the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, CA. The meeting had three major objectives:

1. To resolve some of the physical and biological connections between Georges Bank (GB), the Gulf of Maine (GoM), and adjacent areas (Scotian Shelf, Slope Waters) during the1996-1999 time period. Specifically, the group focused its attention on how circulation and hydrographic changes observed during this period influenced phytoplankton and *Calanus finmarchicus* dynamics in the GoM/GB region.

2. To use retrospective analyses of time series data to provide a context for interpreting how such connections may be altered by the North Atlantic Oscillation (NAO) and modal shifts in the NW Atlantic's Coupled Slope Water System (CSWS).

3. To use SeaWIFS imagery to examine how feeding conditions may have impacted modal *Calanus* growth and egg production rates in the GoM and on GB.

In addition to these major scientific objectives, a subset of the participants worked on technical issues associated with analyzing acoustic and video plankton recorder data collected with BIo-Optical Multi-frequency Acoustic and Physical Environmental Recorder (BIOMAPER) II.

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## Working Group Summary

### *Introduction*

*Calanus finmarchicus* dominates the zooplankton biomass and secondary production in the ecosystems of the GoM/GB region from late winter through early summer. Despite its seasonal dominance, *C. finmarchicus* is an expatriate species in this region whose populations must be replenished every year or every few years by advection from some oceanic source. This latter feature makes it a good indicator of climate-driven changes in ocean circulation.

The seasonal cycles of *C. finmarchicus* in the GoM and on GB are linked, but often driven by different combinations of physical and biological processes. Below, we outline our hypotheses about how these processes operate during different seasons in the two ecosystems (Figure 1). First, we will focus on the typical or climatological seasonal cycle; then, we will describe anomalies from this seasonal cycle observed during the period from 1996–1999. Finally, we describe results from recent retrospective analyses of time series data to provide a climatological context for interpreting these observations.

### *Typical or Climatological Seasonal Cycle*

During a typical winter period (January to early March), the GoM population emerges from diapause and the egg production of its females is food limited. The GB population is dependent primarily on $G_0$ adults advected onto the Bank from the GoM. Once on GB, these females are no longer food limited and egg production commences. The $G_1$ animals on GB grow at rates determined primarily by temperature rather than food limitation.

During a typical early spring period (mid-March to early May), the vernal phytoplankton bloom occurs in the GoM, and the *C. finmarchicus* population is no longer food limited for either egg production or growth. The $G_1$ animals in the GoM now grow at rates determined primarily by temperature rather than food limitation. Both $G_0$ and $G_1$ animals are recruiting from the GoM to GB. It is also likely that the Scotian Shelf (SS) and perhaps the Slope Waters are now becoming important sources of animals recruiting to both the GoM and GB. Those recruiting to GB may arrive through SS crossover events or by transiting through NE Channel and Georges Basin before entering the Bank's circulation. Food limitation and predation increase significantly on GB during this period, reducing *C. finmarchicus* abundance as well as population egg production and growth rates.

During a typical late spring/early summer period (mid-May to early July), animals continue to recruit to the GoM and GB from the SS and Slope Waters. Those in the GoM become food limited and many late copepodites begin to descend into the diapause stock. In addition to recruitment from the SS and Slope Waters, the GoM continues to supply GB with recruits, especially via the "SCOPEX" pathway (one pathway leading from a bifurcation observed in Great South Channel). Food conditions improve on Georges Bank, and *C. finmarchicus* abundance as well as egg production and growth rates increase.

During a typical late summer/autumn period (August to December), the active *C. finmarchicus* population in the GoM begins to decline rapidly as advective supplies from upstream sources decrease, while losses to advection, predation, and the diapause stock increase. Despite these net losses, a small population remains active in the GoM throughout the period. The *C. finmarchicus* population on GB completely disappears for the reasons cited above. The size of the diapause stock in the GoM during autumn determines the abundance of $G_o$ animals recruiting to GB during winter. The supply of recruits from the GoM is an important determinant of *C. finmarchicus* population dynamics on GB until at least March.

*Anomalies from the Typical or Climatological Seasonal Cycle during 1996–1999*

Relative to the previous quarter century, the period from 1996–1999 was a very unusual time in the GoM/GB region. From the 1970's until 1995, the North Atlantic Oscillation (NAO) Index exhibited an unusually persistent, positive trend. The MARMAP decade of the late 1970's and early 1980's, in particular, was a time of strongly positive NAO conditions. During winter 1996, however, the NAO Index exhibited its largest single-year drop of the twentieth century, attaining a negative value not seen since the 1960's. This large drop in the NAO Index led to a large-scale reorganization of ocean circulation patterns in the NW Atlantic. To comprehend the magnitude of these changes, one must first understand conditions prior to the event.

The NW Atlantic's slope waters have been shown to respond as a coupled system to major changes in climate. During the positive NAO conditions of the past quarter century, this coupled slope water system (CSWS) has operated predominantly in its maximum modal state, with relatively warm and salty Atlantic Temperate Slope Water (ATSW) advancing northeastward along the shelf break and converging with Labrador Subarctic Slope Water (LSSW) at a front near the Gulf of St. Lawrence (Figure 2a). This advance of ATSW typically coincides with reduced transport in the Labrador Current and an enhanced hydrographic signature of Labrador Sea Water in the Deep Western Boundary Current.

After the NAO Index's large drop during 1996, the CSWS shifted to its minimum modal state, with relatively cold and fresh LSSW advancing along the shelf break, displacing ATSW offshore, and penetrating to the southwest as far as the Middle Atlantic Bight (Figure 2b). In addition to its advance along the shelf break, the LSSW also invaded the deep basins of the Gulf of Maine (GoM) and Western Scotian Shelf (WSS). By early winter 1998, LSSW had replaced the deep waters of Emerald Basin on the WSS and began entering the GoM through Northeast Channel. By early autumn 1998, the hydrographic properties of the GoM deep basins reflected the advective replacement and mixing that had occurred between the invading LSSW and the resident deep waters derived largely from ATSW.

The observed hydrographic changes were short-lived, however. The NAO Index's large drop during winter 1996 was a single-year event, and the Index returned to positive values for the remainder of the late 1990's. Likewise, the CSWS shifted back to its maximum modal state, with the Labrador Current weakening and the frontal boundary of the LSSW retreating northeastward along the Scotian Shelf. As the supply of LSSW to the region decreased, ATSW returned to its previous position adjacent to the shelf break and began supplying slope water to the deep basins of the GoM and WSS. By the end of 1999, hydrographic conditions in the GoM and WSS deep basins resembled those prior to the NAO-forced modal shift in the CSWS.

The NAO-driven changes in ocean circulation patterns observed during the late 1990's had dramatic impacts on the population dynamics of *C. finmarchicus* in the GoM/GB region. Although the drop in the NAO Index occurred during winter 1996, the seasonal cycles of *C. finmarchicus* in the ecosystems did not exhibit obvious anomalies until 1998.

The diapause stock observed in the GoM deep basins during autumn 1997 was not remarkable in general, although the abundance of diapausing copepodites in Jordan Basin was high. The spring bloom was delayed in the northern GoM and on the WSS during early 1998, but *C. finmarchicus* population growth on GB appeared strong and not limited by food. As the season progressed, food limitation set in on GB, and the *C. finmarchicus* population hit a severe bottleneck during April. It appears that the poor early-season growth conditions for phytoplankton in the GoM and on the WSS may have strongly impacted *C. finmarchicus* population growth in those source areas. It is also possible that the extension of LSSW down the continental margin cut off the supply of *C. finmarchicus* from the Slope Waters to the upstream population on the Scotian Shelf and/or directly to the Gulf of Maine through NE Channel. In any case, we suspect that poor recruitment from upstream sources led to a steady decline in the *C. finmarchicus* population on GB for the remainder of the year. Without a good supply source, the GoM population also declined rapidly, and this was evident in the extremely low diapause stocks observed in all three GoM deep basins during autumn 1998.

In contrast to 1998, the phytoplankton bloomed early in the GoM during winter 1999. Hence, the conditions for growth and egg production by *C. finmarchicus* were unusually good both in the GoM and on GB during winter. However, because of the poor supply of $G_1$ animals ascending from the diapause stock, *C. finmarchicus* abundance remained relatively low until March in both ecosystems. By early spring, however, recruitment from upstream sources appears to have opened the bottleneck, and *C. finmarchicus* populations in both the GoM and GB were able to return to abundance levels more in line with the typical or climatological seasonal cycle. This return to more typical conditions was reflected in the diapause stock observed during autumn 1999.

*Retrospective Analyses: Providing a Climatological Context for these Observations*

The oceanographic events observed during the late 1990's provide circumstantial evidence that the NAO can alter hydrographic conditions in the shelf ecosystems of the GoM/GB region and that these effects are mediated by modal shifts in the CSWS. To generalize from these observations, we now place them in the context of physical and biological time-series data collected from the GOM/WSS region over the past half century (Fig. 3).

From 1950 to 1999, the NAO Index exhibited considerable interannual variability (Fig. 3a). Against this background of interannual variability in the time series, two longer term patterns are apparent. During the decade of the 1960's, the NAO Index was in a predominantly negative phase, while during the subsequent three decades, it was in a predominantly positive phase. During the three decades of predominantly positive values, the NAO Index shifted to negative values on five occasions (1977, 1979, 1985, 1987, 1996), and each of these shifts was for only a year. Among the five single-year shifts in the NAO Index after the 1960's, only the one that occurred in 1996 stands out as an extreme event in the time series.

During the same 50-year period, a time series of the Regional Slope Water (RSW) Temperature Index[1] indicates that the CSWS has existed predominantly in its maximum modal state (Fig. 3b). The only extended period during this interval in which the CSWS existed in its minimum modal state occurred during the decade of the 1960's. After the 1960's, the CSWS appears to have shifted from its maximum to minimum modal state on only a few brief occasions, including 1981-83, 1988-91, and 1996-98.

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[1] *We use the Regional Slope Water Temperature Index as an indicator of the modal state of the CSWS, with positive values corresponding to maximum modal state conditions and negative values corresponding to minimum modal state conditions. The Regional Slope Water Temperature Index is the dominant component derived from a principal components analysis of ten slope water temperature anomaly time series from the GOM/WSS region. The time series correspond to mean annual slope water temperature anomalies between 150 – 250 m in Emerald Basin, Georges Basin, Jordan Basin, Wilkinson Basin, and from six geographic sectors overlying the region's continental slope. All hydrographic data were obtained from a database maintained at the Bedford Institute of Oceanography.*

From both 50-year records, we conclude that it is reasonable to associate positive (negative) phases of the NAO with maximum (minimum) modes of the CSWS. The decade-long negative phase of the NAO observed during the 1960's coincided with the only extended period in the record during which the CSWS existed in its minimum modal state. When the NAO shifted from a predominantly negative to a predominantly positive phase for the subsequent three decades, the CSWS also shifted to a predominantly maximum modal state.

While longer term phase changes in the NAO are positively associated with shifts in the CSWS's modal state, the relationship between the two is less clear on shorter time scales. The NAO Index and RSW Temperature Index are significantly correlated, but the time lag appears to be variable, with slope water temperature responses lagging changes in the NAO by one to two years. This finding is consistent with the response of the RSW Temperature Index to the extreme, single-year drop of the NAO Index in 1996. It is also consistent with linking the weaker modal shifts in the CSWS observed during 1981-83 and 1988-91 to changes from positive to negative values of the NAO Index in 1979 and 1987, respectively. Given the variable nature of the time lag, however, we do not feel that the evidence is strong enough to exclude the possibility that other non-NAO associated changes in the climate system may have triggered these weaker modal shifts in the CSWS.

Although we have provided evidence that the GOM/WSS's regional hydrography responds to climate-driven changes in the CSWS, this raises the question of whether or not *C. finmarchicus* responds consistently to such changes. A time series of the *Calanus finmarchicus* Abundance Index from the GOM provides evidence for such a biological response (Fig. 3c). With a variable time lag centered on three years, the *C. finmarchicus* Abundance Index is significantly correlated with the RSW Temperature Index. During the decade of the 1960's, when the NAO Index was predominantly negative and the CSWS was in its minimum modal state, slope water temperatures and *C. finmarchicus* abundance were relatively low. During the 1980's, when the NAO Index was predominantly positive and the CSWS was predominantly in its maximum modal state, slope water temperatures and *C. finmarchicus* abundance were relatively high. During each of the maximum to minimum modal shifts in the CSWS after 1980, *C. finmarchicus* abundance declined in subsequent years. The modal shift during 1981-83 preceded a large, single-year decline in abundance during 1983. The modal shift during 1988-91 preceded a large decline in abundance that persisted throughout the early 1990's. Then, after *C. finmarchicus* abundance began building up again during the mid-1990's, the NAO Index underwent its drop of the century during 1996. This event triggered the intense modal shift of the CSWS during 1997, which, in turn, led to very low abundances of *C. finmarchicus* observed during 1998.

## **APPENDIX***Analyses of Acoustic and Video Plankton Recorder Data*

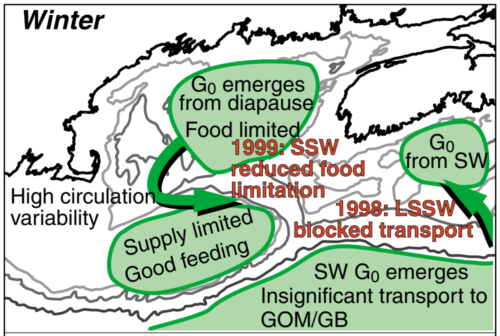
Data were collected with the BIo-Optical Multi-frequency Acoustic and Physical Environmental Recorder (BIOMAPER) II in Jordan Basin during cruise EN331 (December 1999). The analytical approach was to use video plankton recorder (VPR) data on the distribution and size frequencies of zooplankton to solve the acoustic forward problem at several frequencies. The forward problem estimates the volume backscattering coefficient that would be produced by a group of animals with a measured size distribution and abundance. These predicted volume backscattering coefficients then were compared with measured volume backcattering coefficients from each of BIOMAPER II's five acoustic frequencies in 10-m thick depth intervals between the surface and 210 m. The ratio of the expected:measured volume backscattering coefficient was then used to scale the observed acoustical data in order to produce taxon specific maps of the distributions of each taxon from the acoustic data. The approach appears to have utility, and preliminary examinations of other data from *Calanus finmarchicus* suggests that predicted volume backscattering accounts for 50-100% of observed scattering below 100 m. These analyses are continuing with production of a manuscript targeted for submission during July 2001.

## Figure Captions

Figure 1. The seasonal dynamics of *Calanus finmarchicus* in the Gulf of Maine and Georges Bank. For each season, the processes controlling the population abundance over the deep basins of the Gulf of Maine, on Georges Bank, the Scotian Shelf, and in the Slope Waters are indicated both graphically and as hypotheses.

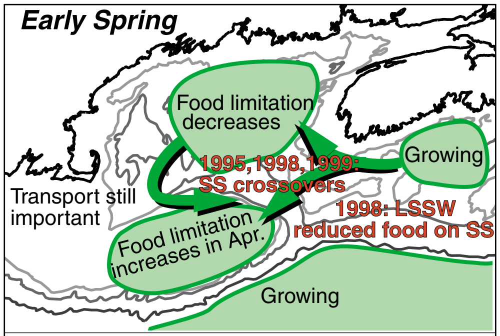
Figure 2. The distribution of the two main water masses during the two states of the Coupled Slope Water System (CSWS). When the CSWS is in its maximum modal state (a), warm Atlantic Temperate Slope Water (ATSW) is present through the region. In the minimum modal state (b), cold Labrador Subarctic Slope Water (LSSW) extends along the shelf as far as the Mid-Atlantic Bight. The numbered circles indicate the date when LSSW was first observed in the shelf basins following the NAO minimum in 1996: 1=September 1997, 2=January 1998, 3=February 1998, 4=August 1998 (Drinkwater et al., 2000).

Figure 3. Time series from the North Atlantic. a. Annual values of the winter NAO Index. b. Annual values of the Regional Slope Water Temperature Index. c. Annual values of the *Calanus finmarchicus* Abundance Index.



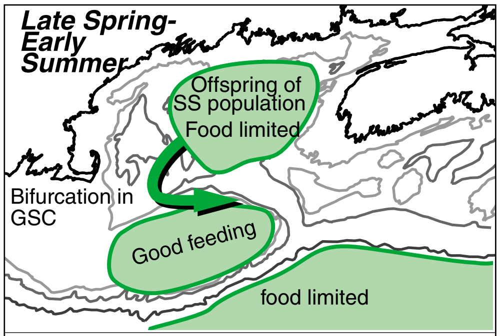
## Hypotheses

H1. GB is supply limited from GOM
H2. GOM food limited
H3. GB not food limited
H4. SS and SW not significant source of G0's for GB



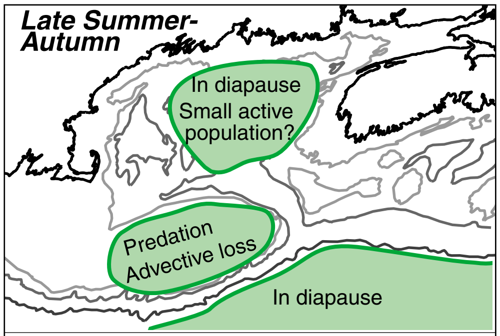
## Hypotheses

H1. Significant G1 (some G0, too) from GOM to GB
H2. Bloom in GOM reduces food limitation
H3. Food limitiation increases on GB in April
H4. SS crossovers significant source of Calanus to GB
H5. Predation increases on GB
H6. SW and SS contributions to GB population become more important



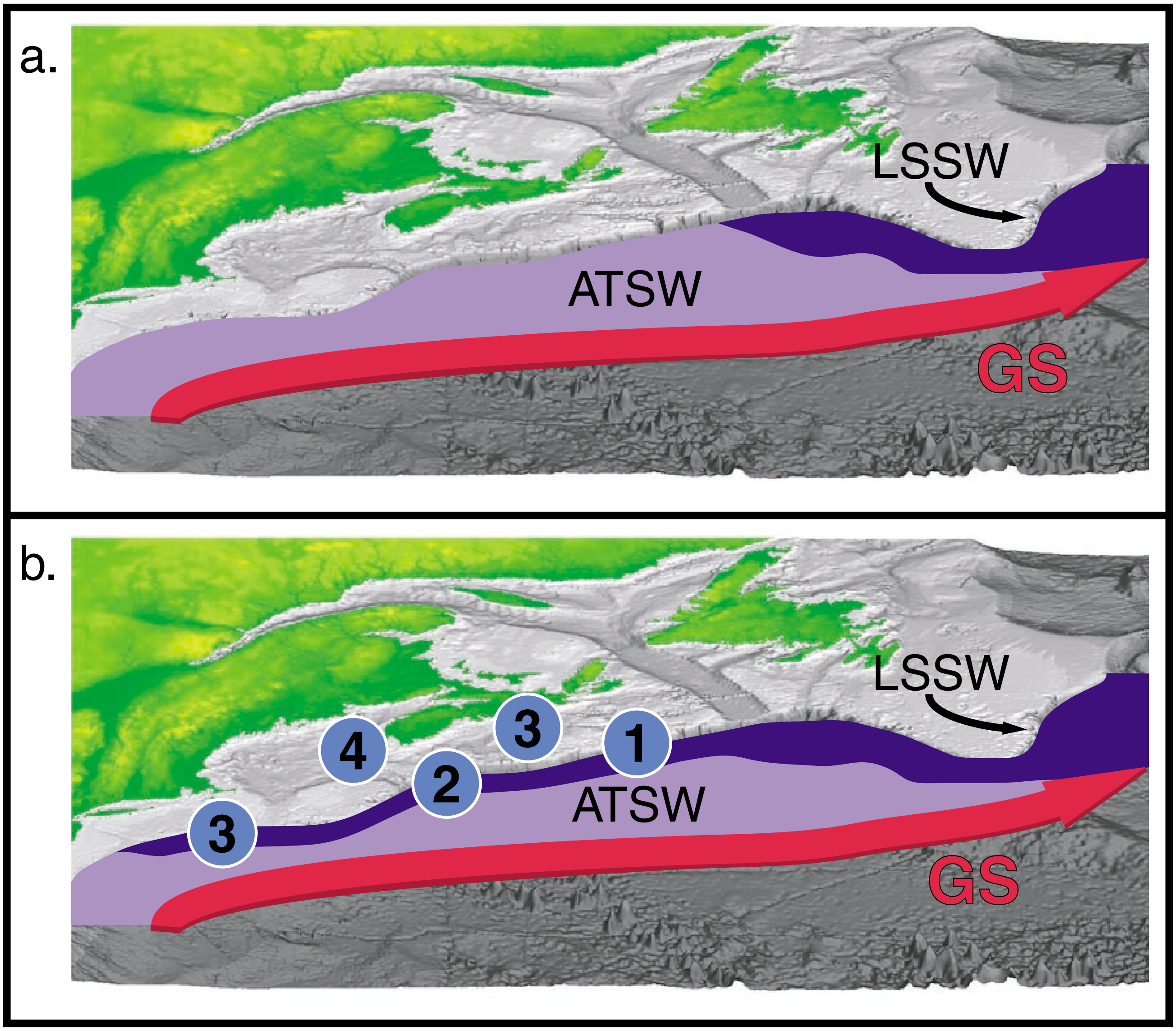
## Hypotheses

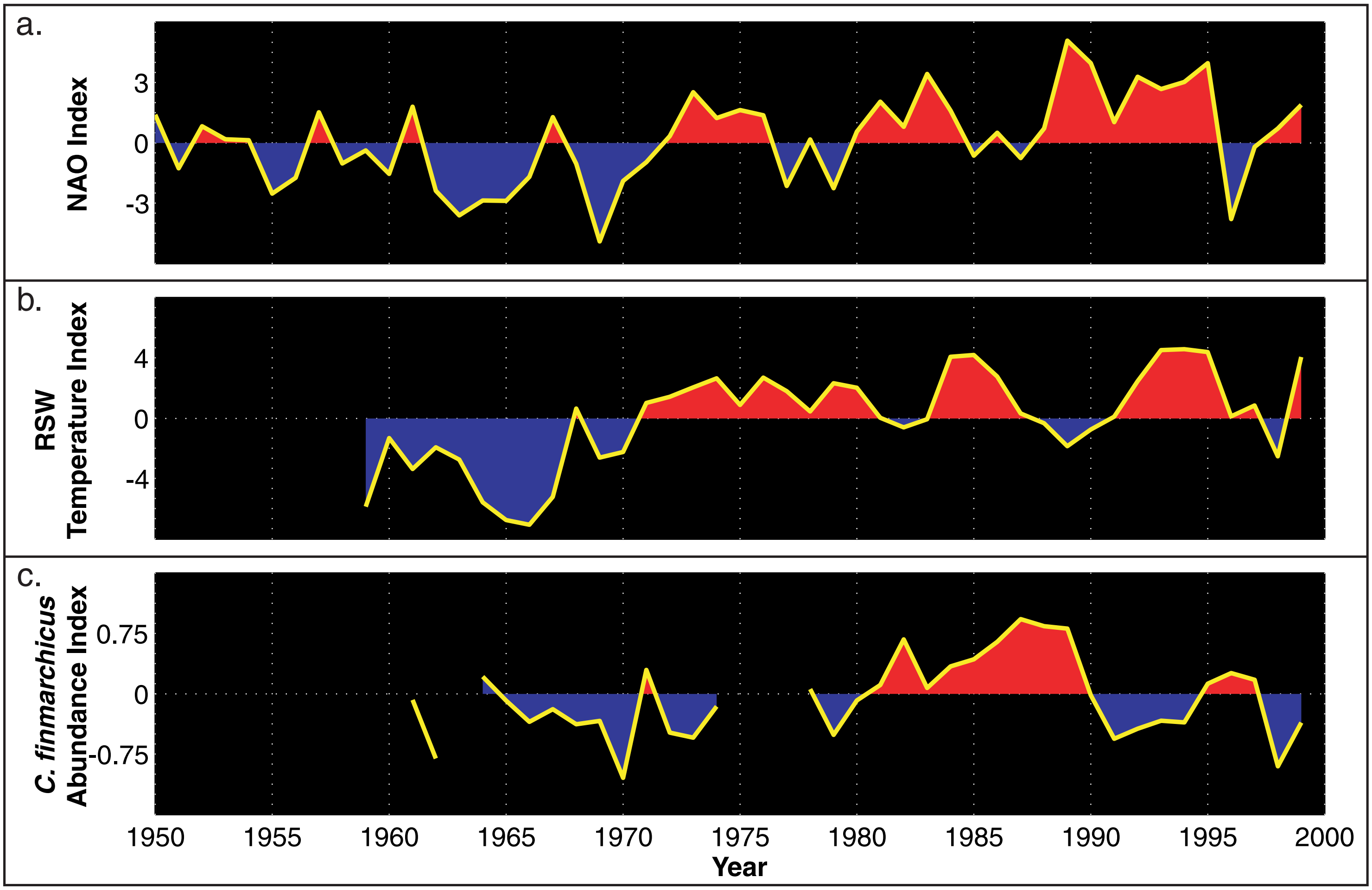
H1. GB is not supply limited—SCOPEX pathway
H2. GOM food limited again, diapause stocks begin to build
H3. GB not food limited
H4. GOM population dervied from SS and SW sources.



## Hypotheses

H1. Calanus disapppears from GB due to predation & advective losses
H2. Size of GOM diapause stock determined by SS spring and GOM summer conditions.
H3. Fall reproduction in GOM not a significant source of variability in winter recruitment to GB
H4. Predation during diapause not a signficant source of variability in winter recruitment to GB
H5. Variability in vertical distributions can lead to losses from GOM diapuase stock due to vertical mixing and subsequent advective loss.
H6. Vertical distribution of diapausing animals is determined by light penetration.


a.
LSSW
ATSW
GS
b.
LSSW
3
1
4
2
ATSW
3
GS


a.
NAO Index
3
0
-3
b.
RSW
Temperature Index
4
0
-4
c.
C. finmarchicus
Abundance Index
0.75
0
-0.75
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year