

The ecological impact of the Great Salinity Anomaly in the northern North-west Atlantic

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ABSTRACT

In a number of recent papers Cushing has advocated that the Great Salinity Anomaly (GSA), which entered the northern North Atlantic in the early 1970s, adversely affected the recruitment of a number of deep-water fish stocks of this ocean. Cushing envisages that a temperature anomaly accompanying the GSA slowed and/or delayed growth in the spring phytoplankton bloom which sequentially affected zooplankton growth and fish recruitment. We test a number of hypotheses relating to Cushing's picture, focusing on the waters of the West Greenland, Labrador and Newfoundland Shelves. We find that, south of Greenland waters, there were no significant temperature anomalies corresponding to the GSA. In addition we show that stability of the shelf waters increased during the GSA, casting doubt on the contention that the phytoplankton bloom was delayed by retardation of the spring stabilization of the water column due to the influence of cold water. Our analysis indicates that the food chain coupling of environment to recruitment (climate to phytoplankton to zooplankton to fish) is not strong in the study region.

Key words: Great Salinity Anomaly, climate and fisheries, recruitment

1 INTRODUCTION

The 'Great Salinity Anomaly' (GSA, hereafter) of the North Atlantic is perhaps the most conspicuous climate event reported for this ocean (see Dickson *et al.*, 1988, for a thorough description of the GSA). An incursion of fresh, cold polar waters via the Denmark Strait, in the late 1960s, introduced a great slug of low-salinity water into the circulation of the northern North Atlantic. This mass eventually propagated through a full circuit of

the northern North Atlantic, apparently returning to Icelandic waters in the early 1980s (Dickson *et al.*, 1988). The ecological effects of this event have not received a complete treatment; however, Cushing (1988, 1990a,b) has claimed that the GSA depressed recruitment in a wide range of deep-water fish stocks.

Cushing (1988, 1990a,b) has noted that the salinity decrement during the GSA was not itself likely to be ecologically significant. Rather, Cushing posits that the GSA waters, being of polar origin, were sufficiently cool to adversely affect plankton production. Three possible pictures of the food chain impact of the GSA are proffered by Cushing. (i) Decreased water temperatures inhibited phytoplankton growth with subsequent reductions in zooplankton growth and fish recruitment. (ii) The cold-water anomaly delayed stabilization (stratification) of the water column, retarding and reducing the spring bloom, with attendant decreases in zooplankton growth and fish recruitment. (iii) A delayed phytoplankton bloom (again due to reduced stability associated with cold water) produced a zooplankton peak appearing too late to provide an adequate food supply for larval fish, causing poor recruitment. This last view is an example of the match/mismatch hypothesis (Cushing, 1969, 1990a).

A recent marine ecology text, Mann and Lazier (1991), has highlighted the importance of Cushing's GSA work, although these authors do note that "...the story has many loose ends." In keeping with this latter thought, we will attempt to test a number of hypotheses which are antecedent to or concomitants of Cushing's account of the GSA and recruitment in the North Atlantic.

In this paper we will focus on the northern North-west Atlantic (Fig. 1), which we take to extend from the Grand Banks to West Greenland. This region has been selected because the GSA was very pronounced in these waters (Dickson *et al.*, 1988). (Note that the GSA was also very strong in the vicinity of Iceland; accounts of GSA-related ecological events in Icelandic waters are available in Thórdardóttir, 1977, and Ástthórsson *et al.*, 1983).

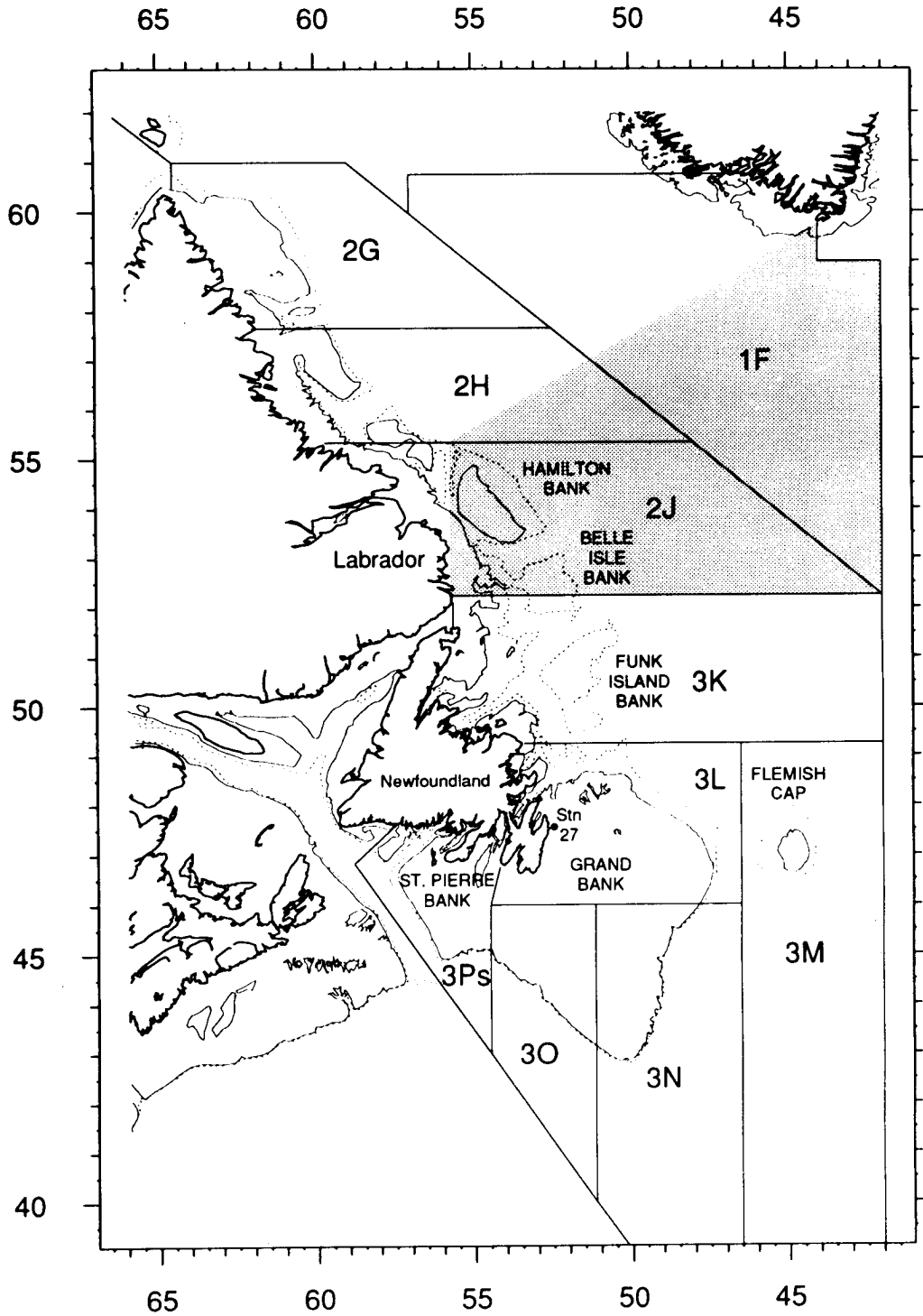
Our treatment will include an analysis of both oceanographic and ecological data. A major goal of this paper is an attempt to decide whether or not there is sufficient evidence to identify an impact of the GSA on

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Figure 1. Map of the study region, with the NAFO zones (only 1F is shown for NAFO zone 1; the remaining subzones 1A through 1E lie along the West Greenland coast). The 200 m (solid line) and 300 m (dotted line) isobaths are shown. The stippled areas of Regions 1 and 2 indicate the portions of these zones for which continuous plankton recorder coverage was available (Robinson et al., 1973, 1975).



Atlantic cod (*Gadus morhua*) recruitment in the northern North-west Atlantic. Cod has been selected for this analysis owing to the existence of long, reliable recruitment records for this species. Moreover, cod is a spring spawner, suggesting that the match/mismatch hypothesis may be very relevant to the year class success of Atlantic cod.

We will attempt to provide answers to six key questions. (i) Why did Cushing's analysis show no effect of the GSA on the important Northern cod stock (regions 2J3KL in Fig. 1)? (ii) Can salinity serve as a proxy for temperature, allowing us to interpret the GSA as a great temperature anomaly (temperature being more directly related to ecosystem variability)? (iii) Is there a significant relationship between phytoplankton levels and salinity or temperature in the northern North-west Atlantic? (iv) Was water column stability significantly reduced during the GSA, with possible subsequent effects on phytoplankton levels? (v) Can it be shown that the timing of peak phytoplankton and zooplankton abundance were anomalous during the GSA? (vi) Is there evidence for the food chain linkage of climate and recruitment anomalies?

2 DATA AND METHODS

2.1 Oceanographic data

The GSA was most pronounced in near-surface waters (Dickson *et al.*, 1988) and thus our analysis will focus on surface or near-surface (above the halocline and the thermocline) data. Much of the salinity and ocean temperature data to be presented is from Station 27 (Fig. 1), a standard sampling site for the Grand Banks. Profiles have been acquired at Station 27 irregularly at an average rate of about twice per month over more than three-and-a-half decades. Myers *et al.* (1990) and Petrie *et al.* (1992) have shown that Station 27 provides an excellent representation of interannual oceanographic variability for the eastern Newfoundland and southern Labrador Shelves.

In addition to the Station 27 data we will present salinity data for the southern Newfoundland Shelf, regions (see Fig. 1) 3Ps (represented by the box 45–47°N, 54.5–57°W) and 3NO (represented by the box 44.5–46°N, 51–54.5°W). The data were extracted from the NODC (National Oceanographic Data Center) compact disc, and the salinities to be presented represent averages over the boxes specified above. We have selected the months July through September to represent summer salinity as data are abundant for these months.

A corresponding summer salinity series for Station 27

was prepared by averaging the salinity anomalies (anomalies were calculated to remove the seasonal cycle) for July through September and then adding the mean July–September salinity to these data.

2.2 Recruitment indices

Recruitment and spawning stock biomass (SSB) from virtual population analysis (VPA) calibrated with research survey and commercial catch per unit effort data were collated from the latest assessment documents: West Greenland – Anon. (1990); 2J3KL – Baird *et al.* (1992a); 3M – Wells *et al.* (1984); 3NO – Baird *et al.* (1992b); 3Ps – Bishop *et al.* (1991). No SSB data exist for region 3M.

One difficulty in using VPA results is that year classes of recruitment tend to be smeared together (Myers and Drinkwater, 1989; Bradford, 1991). This makes recruitment studies relying upon year-to-year variability difficult to interpret. Because of this problem, we have supplemented the VPA recruitment estimates with indices derived solely from research surveys. To extract the survey effects at age we have used a modification of a multiplicative catch-at-age model developed by Pope (1972), Cook (1989) and Shepherd and Nicholson (1991). A description of the method (Myers and Cadigan, 1991) follows.

In the analysis we consider only ages at which commercial fishing mortality is small. The number of fish of age a caught in survey i in year y ($C_{y,a,i}$), is assumed to be the product of the catchability ($Q_{a,i}$), the survival to age a (P_a), the recruitment in year $y - a$ (R_{y-a}) and an error term ($\exp(\varepsilon_{y,a,i})$). Recruitment can be estimated via straightforward statistical analysis, after log transforming the multiplicative catch relation:

$$C_{y,a,i} = q_{a,i} + p_a + r_{y-a} + \varepsilon_{y,a,i} \quad (1)$$

The lower case letters represent the log-transformed variables and parameters. Note that $q_{a,i}$ and p_a are confounded in the above equation, and therefore we only attempt to estimate the sum of these two parameters. If the same survey vessel was used throughout the survey period, we estimated a year class effect for each year class, r_{y-a} , and age effect for each age used in the analysis, which is the sum of $q_{a,i}$ plus p_a .

Equation (1) is a simple analysis of variance problem with year class and age effects. If the error variance is approximately constant, then the year class effects can be estimated using any standard analysis of variance programs. The estimates of the year class effects, r_{y-a} , are used as relative recruitment indices (Shepherd and Nicholson, 1991). These will be on a log scale.

In our analysis we used ages 2 to 6 from the fall surveys

and 2 to 7 from the spring surveys. The exception was the USSR (3M) survey for which only ages 1 to 3 were available. The research vessel survey data for 2J3KL, 3NO, and 3Ps can be found in the above-cited assessment documents. The Flemish Cap area (3M) was surveyed by the former USSR from 1962 to 1982 (Konstantinov, 1983). There are no research survey data for the West Greenland stock during the period of interest.

2.3 Plankton data

As in Cushing (1988, 1990a,b), we will employ the continuous plankton recorder data (CPR) for the northern North-west Atlantic presented in Robinson *et al.* (1973, 1975). These data were available for standard areas, designated in Robinson *et al.* as Regions 1,2,3, which are now known as NAFO zones 1,2,3 (Fig. 1). CPR data for these regions were limited to standard routes (of merchant ships, ocean weather ships and coast guard vessels). Region 3 was sampled fairly broadly, while coverage of Regions 1 and 2 was limited to the stippled area indicated in Fig. 1. For the sampling period for the North-west Atlantic (1961–1972), CPR tows were carried out once per month.

The phytoplankton data consist of a 'greenness' index. For a zooplankton index we have used the abundance of *Calanus finmarchicus* because the eggs, nauplii and copepodite stages of this zooplankton serve as the food for larval cod and other fish species of the northern North Atlantic (Cushing, 1982; Runge, 1988; Pepin, 1990). We will present data for the copepodite stages I–IV; the later stages (V–VI) achieve peak abundance in the upper water column in late winter, when the overwintering stock surfaces, and are thus not relevant to our analysis. In the analysis to come we will employ the normalized deviations of the total phytoplankton or zooplankton caught in each year, available from Robinson *et al.* (1973). The normalization consists of subtracting the long-term mean of each series and dividing by its standard deviation.

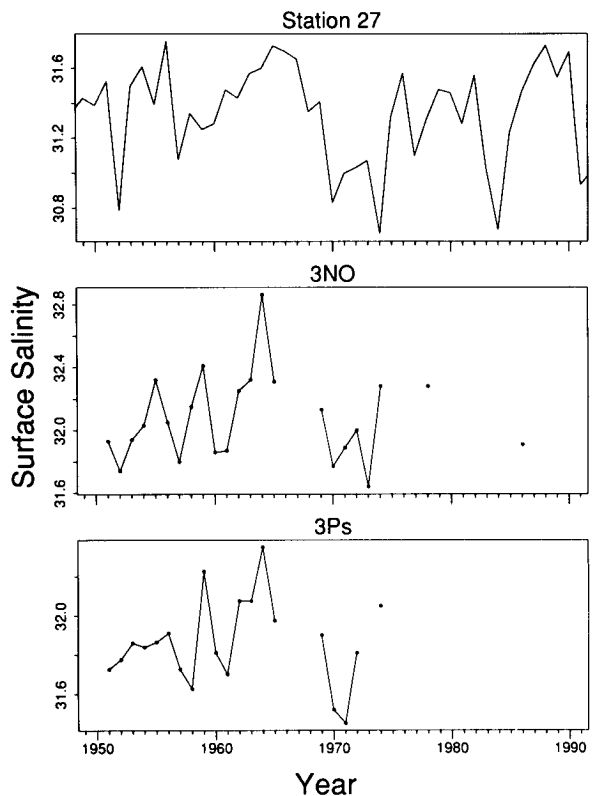
3 IMPACT OF THE GSA IN THE STUDY REGION

In this section we will proceed sequentially through the six questions posed in the introduction.

3.1 Timing and extent of the GSA in the study region

It is notable that Cushing found that recruitment of Northern cod (regions 2J3KL) was *not* significantly lower during the passage of the GSA; this is puzzling because the GSA was very pronounced in the waters

Figure 2. Summer (July through September) near-surface (upper 20 m) salinities for Station 27, the shelf waters of region 3NO and the shelf waters of region 3Ps. Salinities are given in psu.

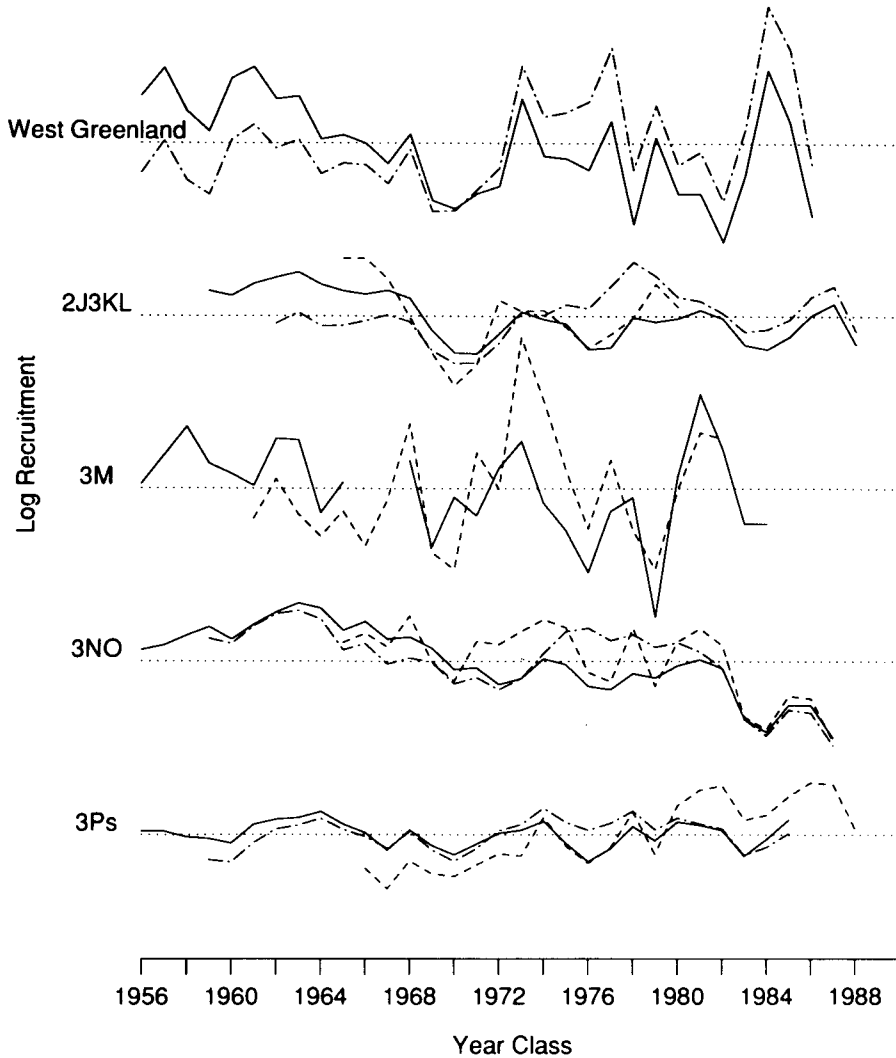


harbouring the Northern cod. Moreover, Cushing omitted region 3Ps from his analysis, claiming that the GSA did not influence the waters of 3Ps. These gaps have prompted us to re-examine the questions of the timing and extent of the GSA; in particular we will reconsider the timing of the GSA in relation to the recruitment series.

Based on the work of Dickson *et al.*, Cushing chose the interval 1971–73 to represent the period of the GSA passage for the Grand Banks. (Following Dickson *et al.* we will refer to the time of the salinity minimum associated with the GSA as the period of passage of the GSA.) Cushing found that, while the recruitment of 3NO cod was significantly diminished during 1971–73, the recruitment of Northern cod was not significantly abnormal during 1971–73, leading one to ask why the GSA affected 3NO cod but not 2J3KL cod.

We have reconsidered the salinity data used to define the passage of the GSA through the Grand Banks zone. In Fig. 2 we show the summer salinities (0–20 m) from Station 27 and for zones 3Ps and 3NO. The three

Figure 3. Recruitment indices for the five major cod stocks of the northern North-west Atlantic. The solid lines represent recruitment estimates from virtual population analysis. The long-dash, short-dash lines show the VPA data divided by the spawning stock biomass. The dashed lines designate recruitment estimated from a multiplicative model (see text) applied to survey data.



records show great similarity, each displaying a peak in the mid 1960s, with a rapid decline to the GSA minimum. All three records exhibit local minima during 1970–71. (The subsequent minima in 1973 and 1974 in 3Ps and at Station 27, respectively, apparently do not reflect the passage of the GSA because, according to the Dickson *et al.* chronology, the GSA had largely exited Grand Banks waters by 1973–74.) The passage of the GSA is clear in all three records, producing a strong salinity drop (roughly 0.7 psu) in each series. For the Grand Banks waters, the peak GSA years are clearly 1970–71 (not 1971–73 as specified by Cushing). Moreover, it is evident that the GSA did indeed influence the waters of 3Ps.

We may now reconsider the recruitment data in the light of our re-analysis of the salinity data. In Fig. 3 we have plotted the recruitment time series for the five major cod stocks under consideration. (Note that the GSA passed through West Greenland waters during the period 1969–70; Dickson *et al.*, 1988). For the West Greenland, 2J3KL and 3Ps cod stocks the indices are fairly consistent in showing minima in 1969–70, 1970–71, and 1970, respectively. For these stocks the recruitment minimum is in phase with the salinity minimum. The 3NO stock does not exhibit a conspicuous minimum which is common to all three indices for this stock. The 3M stock exhibits a fairly distinct recruitment minimum in 1969–70. The 3M cod spawn on

Flemish Cap (Fig. 1) and for the waters over this bank there was a salinity minimum in 1971–72 (Keeley, 1982). Thus, for 3M cod the recruitment minimum is about 2 years earlier than the interval of minimum salinity associated with the passage of the GSA.

For three of the five cod stocks examined, there is an apparent correspondence between the recruitment and salinity minima. It is clearly important that the 3Ps stock be included in the analysis, and it is essential that the timing of the GSA's maximum influence through the study area be firmly established.

Thus the answer to the first question posed in the introduction is that there was indeed a correlation of the GSA with low recruitment of Northern cod. Our more detailed analysis has shown that the entirety of the Grand Banks, including the 3Ps zone, appears to have experienced a synchronous freshening which peaked in 1970–71, in quite close synchrony with the recruitment minima for both Northern and 3Ps cod.

3.2 Is salinity a proxy for temperature?

Cushing (1988) states, in reference to the ecological impact of the GSA, "Of itself there is no reason to believe that reduced salinity should affect recruitment." To account for the surmised influence of the GSA on recruitment it must be supposed that the salinity decrement was accompanied by a reduction in temperature of the affected waters (Cushing, 1988, 1990a,b). The mechanisms accounting for the impact of a cold anomaly on recruitment are briefly recounted in the introduction. This fresh-cold correspondence seems plausible – the GSA was the consequence of an outbreak of polar (fresh, cold) waters into the northern North Atlantic. Here we will determine if there is a tendency for covariation of salinity and temperature in the northern North-west Atlantic.

Stein and Messtorff (1990) have recently presented quite long records of temperature and salinity on the Fylla Bank transect, off West Greenland. It is apparent from their Fig. 3, a display of 25 years of summer temperature and salinity data averaged over the upper 200 m of the water column, that temperature and salinity are related. In fact the two series are quite strongly correlated ($r = 0.62$), with the expected relationship that relatively fresh periods tend to be cold.

For the Grand Banks area, the high-quality, high-resolution Station 27 data afford an excellent oppor-

tunity to test for the interrelation of temperature and salinity. In Fig. 4 we present monthly surface (the depth where the GSA signature is strongest) temperature and salinity anomalies from Station 27. Figure 4(b) is the scatter plot of these monthly data. In Fig. 4(a) the monthly data have been smoothed (with a 13 month lowess smoother) for purposes of visual clarity. The correlation between the two series is weak ($r = -0.06$) and opposite to that expected if advection of polar waters is a major influence.

The temperature and salinity records show conspicuously different behaviour during the GSA phase of the records. During 1970 and 1971, the temperature anomalies were generally positive, while the salinity anomalies were negative. This is contrary to what would be expected if temperature was strongly influenced by the intrusion of fresh, cold polar waters associated with the GSA. Thus, the warm anomalies at Station 27 during 1970 and 1971 reveal that the GSA had little influence on the temperature of the waters of the Grand Banks. In fact, salinity is more influenced by advection of anomalies from remote sources than is temperature; we elaborate on this in the next paragraph.

Petrie *et al.* (1991) have analysed the annual harmonic of the seasonal cycles of surface temperature and salinity for the region extending from southern Labrador to the southern tip of the Grand Banks. They find that the temperature cycle is essentially in phase throughout this region and is dominated by the seasonally varying surface heat flux (which penetrates diffusively into the water column). (Below about 50 m depth, where the water is relatively insulated from the surface heat flux, advective effects are apparent; see Fig. 2 of Petrie *et al.*, 1991). By contrast, the seasonal salinity variations showed a progressive delay in phase from north to south, indicating the effect of a periodic encroachment of fresh water from the north. Myers *et al.* (1990) have shown that much of this fresh water results from ice melt on the North-east Newfoundland and Labrador Shelves. These results explain the decoupling of the temperature and salinity anomalies seen in Fig. 4; the near-surface temperature responds principally to thermal forcing from the atmosphere, while the near-surface salinity variations are generated by advection of waters from the north. Thus, the GSA is clearly apparent in the salinity record but there is no signature of this event in the Station 27 temperature record.

Figure 4. (a) The smoothed monthly surface temperature and salinity anomaly series for Station 27 (Fig. 1). (b) Scatter plot of the monthly Station 27 surface temperature and salinity anomalies.

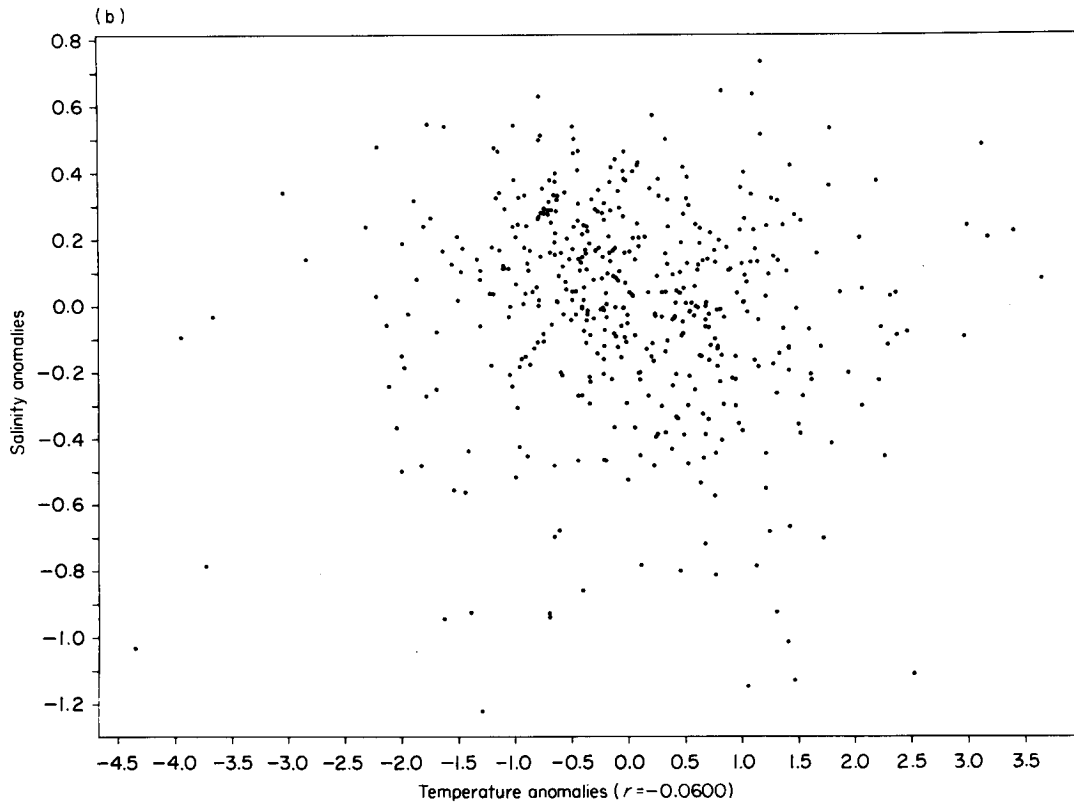
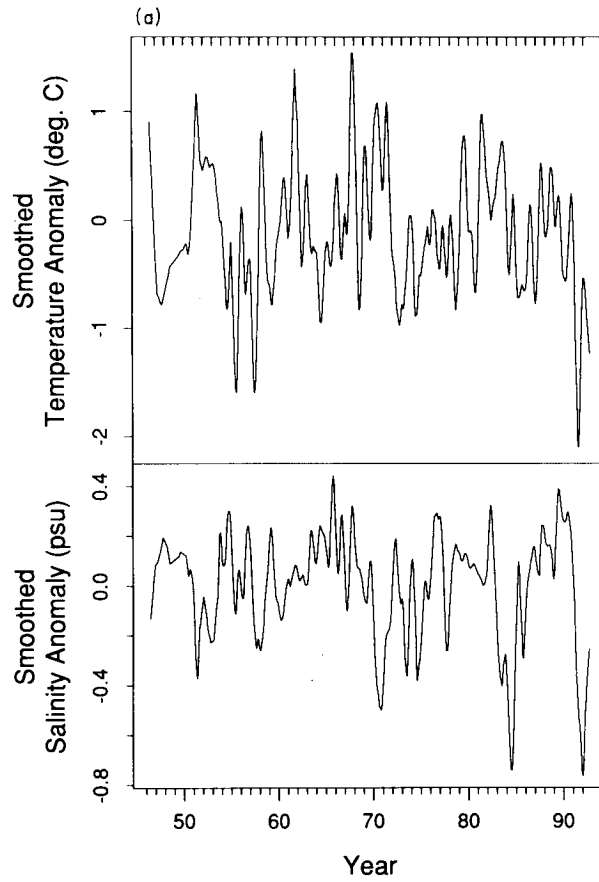
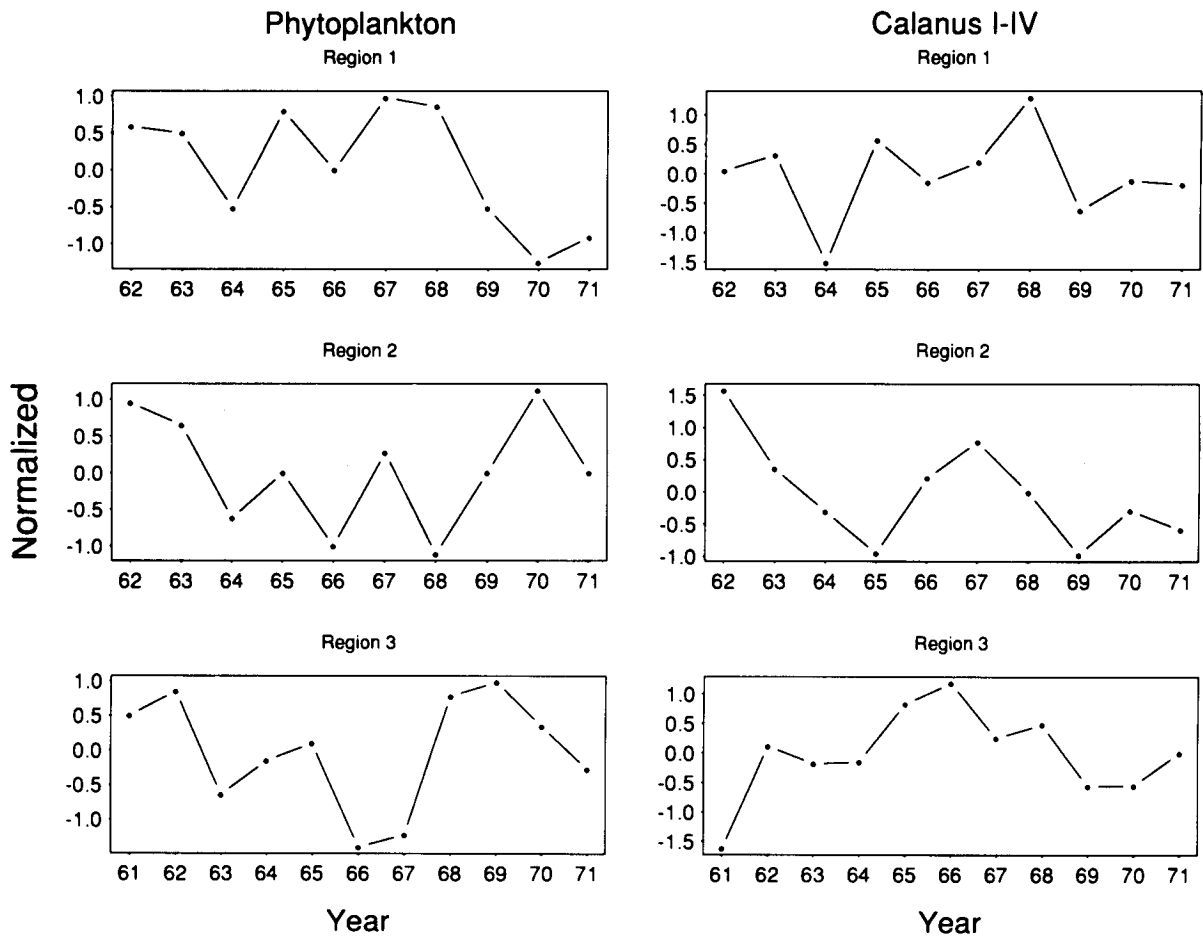


Figure 5. Annual CPR abundance series for phytoplankton and the copepodite stages I–IV of *Calanus finmarchicus*. The abundances have been normalized by removing the mean and dividing by the standard deviation. From Robinson *et al.* (1973).



We can answer the second question set out in the introduction in the negative: salinity is not generally a proxy for temperature in the northern North-west Atlantic. The analysis in this subsection demonstrates that hypotheses explaining the surmised impact of the GSA on recruitment as a temperature effect are not viable.

3.3 Salinity, temperature and phytoplankton levels

Cushing (1988, 1990a,b) has noted shifts in phytoplankton levels in the northern North-west Atlantic, based on continuous plankton recorder (CPR) data, perhaps corresponding to the passage of the GSA. In this subsection we will explore the relationships between salinity, temperature and phytoplankton abundance in more detail. Figure 5 shows the CPR phytoplankton (greenness) series, along with the abundance records for *Calanus* which will be referred to later.

The phytoplankton records shown in Fig. 5 show little tendency to covary: the correlation between the records for regions 1 and 2 is $r = -0.22$; the correlation between the records for regions 2 and 3 is $r = 0.19$. It is not clear why the records should be so weakly related.

Most interestingly, phytoplankton levels drop sharply in region 1 from 1968 to 1970, approximately coincident with the passage of the GSA. Phytoplankton levels also drop in regions 2 and 3, 1–2 years after the noted decrease in region 1. This delay is roughly consistent with the time required for the GSA to propagate from region 1 to regions 2 and 3.

It appears superficially plausible, based on Fig. 5, that the GSA induced significant reductions in phytoplankton levels in the northern North-west Atlantic, in accord with Cushing's hypothesis. However, the picture is not so simple. Because Station 27 provides a reasonably representative data set for the shelf waters of

regions 2 and 3 (Myers *et al.*, 1990; Petrie *et al.*, 1992), we have compared the surface salinity records from this station to the phytoplankton records from these zones. In Fig. 6(a,b) we show the scatter plots of the phytoplankton data with the spring and summer surface salinities. The relationship is opposite to that posited by Cushing; we find, using the complete records available, that high phytoplankton levels are (weakly) associated with low salinity.

Recall that Cushing's rationale for considering salinity in the analysis was the presumption that salinity could serve as a proxy for temperature (we have shown that this is not the case). It is therefore worthwhile to test for a relationship between temperature and phytoplankton levels. This we have done (Fig. 6c,d), and it is clear that there is no consistent, convincing relationship of phytoplankton with ocean temperature.

The third question raised in the introduction can be answered: in the northern North-west Atlantic, there does not appear to be a consistent (or at least readily interpretable) relationship between phytoplankton standing stock and salinity or temperature.

3.4 Water column stability and the GSA

Cushing proposed that the GSA reduced water column stability (the vertical density gradient) in the spring of the GSA years. At the low temperatures encountered in the bloom period in the northern North-west Atlantic it is salinity which controls density; temperature is largely irrelevant to water column stability. Thus the GSA should enhance stability. Lazier (1980) has noted this effect in the waters of the central Labrador Sea, at ocean weather station Bravo. He found that the GSA increased stability sufficiently to greatly limit the depth of the convectively mixed layer formed in the winter. We have found that the shelf waters also show an augmentation of stability in the GSA years, an effect which is most apparent in early spring; in Fig. 7 we have plotted the series of the March values of the stability parameter $\rho(50\text{ m}) - \rho(0\text{ m})$, where ρ is the density of sea water. It is clear that there was a very strong stability enhancement in the years 1970 and 1971.

Cushing assumed that strong stratification early in the spring should favour strong growth and high abundances of phytoplankton. However, the opposite effect was observed in Icelandic waters. Thórdardóttir (1977) and Ástthórsson *et al.* (1983) have shown that phytoplankton levels dropped dramatically in oceanographic sections north of Iceland during the GSA passage through Icelandic waters. These authors have conjectured that this suppression of phytoplankton growth was a result of augmented water column stability inhibiting nutrient re-supply of the photic layer by mixing pro-

cesses. Such an effect could account for the markedly lower phytoplankton levels in region 1 in 1969 to 1971 (Fig. 5).

The fourth question given in the introduction can be given a definite response: the spring stability was *enhanced, not reduced*, for the northern North-west Atlantic during the GSA, as a result of salinity being the dominant influence on density for the cool waters of this region. The stability augmentation during the GSA could have reduced available nutrient levels, unfavourably influencing phytoplankton production.

3.5 Timing of the plankton burst

As stated in the introduction, Cushing has noted that GSA-mediated shifts in timing of the plankton bloom might account for any apparent influence of the GSA on recruitment, exemplifying the match/mismatch hypothesis. We will directly examine the plankton data to determine whether or not such a shift occurred. In Fig. 8 we show year-month contours of phytoplankton and *Calanus finmarchicus* I–IV abundance, again based on CPR data for region 3 (Robinson *et al.*, 1975). (The corresponding data for regions 1 and 2 are not available.)

In Fig. 8(a) it is apparent that the timing of the onset of the spring phytoplankton bloom was quite constant over the length of the record, although there was a conspicuously early initiation in 1968. There is a weak trend apparent; the phytoplankton peak seems to arrive generally earlier toward the end of the 1960s.

Fig. 8(b) shows that the peak abundance of *Calanus finmarchicus* I–IV was achieved quite consistently about 1 month after the peak of the phytoplankton bloom. There do not appear to be any systematic shifts in the timing of the maximum abundance of this species, over the available record length. In 1971, a GSA year, the peak was unusually early.

In response to the fifth question in the introduction, there does appear to be a shift in the *Calanus* peak in 1971, a GSA year. However, there is no evidence for a corresponding change in the timing of the phytoplankton peak, which would be required if the full match/mismatch hypothesis holds.

It is not clear whether plankton abundance or plankton burst timing is more important to recruitment. In both 1970 and 1971, the peak GSA years in region 3, there were anomalies in the *Calanus* record (low abundance in 1970, an early peak in 1971). These features could account for the observed poor recruitment of Northern cod in 1970–71 and 3Ps cod in 1971. In the next subsection we will consider the plankton abundance records in more detail.

Figure 6. Scatter plots of the normalized CPR phytoplankton data for regions 2 and 3 versus (a) spring surface salinity at Station 27, (b) summer surface salinity at Station 27, (c) spring surface temperature at Station 27, (d) summer surface temperature at Station 27.

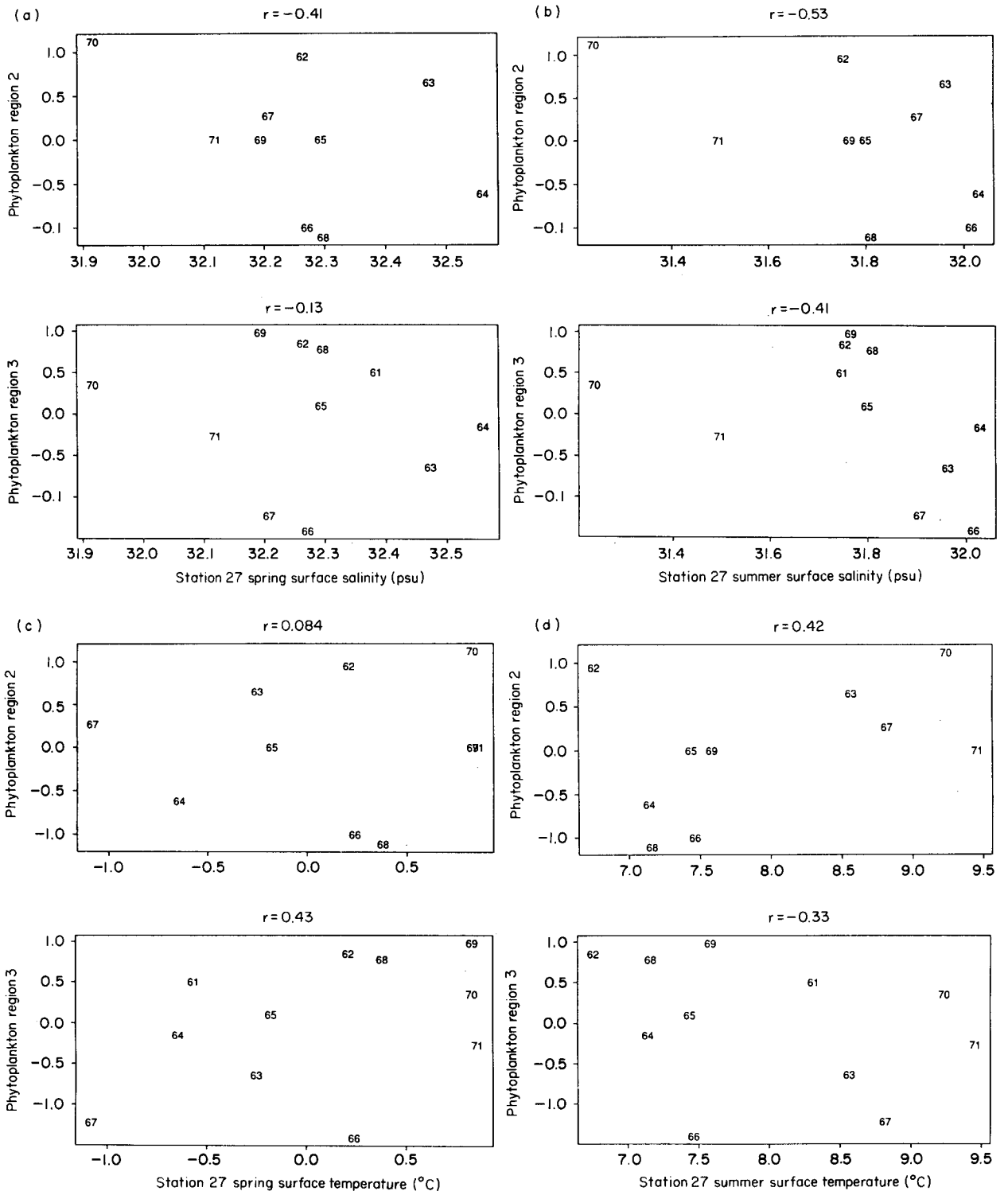
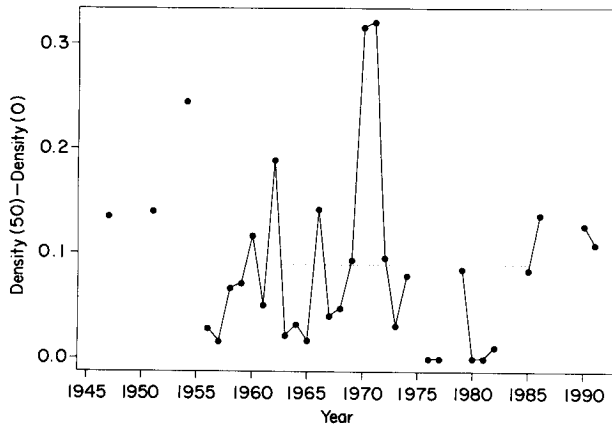


Figure 7. March stability [$\rho(50\text{ m}) - \rho(0\text{ m})$, kg m^{-3}] at Station 27.



3.6 Food chain linkage of climate and recruitment?

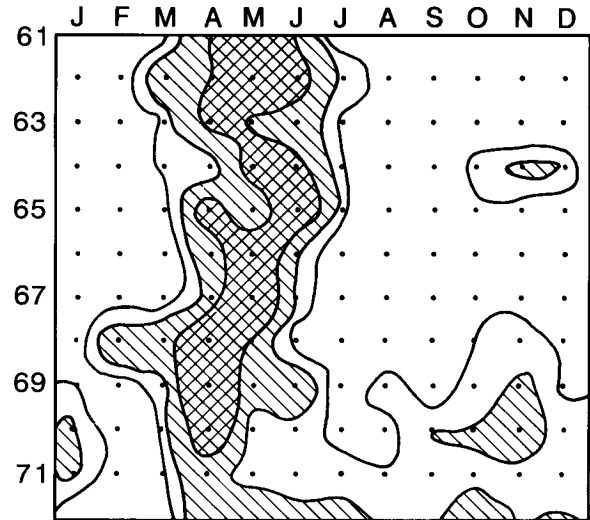
In the introduction we noted that Cushing has proposed that the impact of the GSA, in effect, propagates up the food chain, eventually influencing recruitment. In this subsection we will scrutinize this picture, testing for covariation of zooplankton and phytoplankton abundances and also of recruitment with zooplankton abundance.

The CPR data of Robinson *et al.* (1973), shown in Fig. 5, were used to test for a link between the abundances of zooplankton (*Calanus* I-IV) and phytoplankton in our study region. We found the following correlations: region 1, $r = 0.62$; region 2, $r = 0.30$; region 3, $r = -0.46$. Given that the two largest coefficients have opposite signs, it is fair to say that there is no evidence of a consistent relationship between phytoplankton and zooplankton abundances.

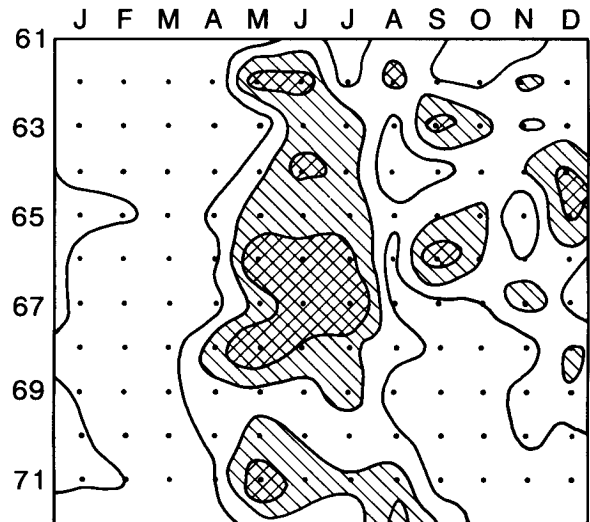
Figure 9 presents a summary of the relationship between interannual variability in cod recruitment and *Calanus* I-IV standing stock for the northern North-west Atlantic. In view of the large cod stock size changes in the period analysed it seemed advisable to use raw recruitment divided by spawning stock biomass as the recruitment index, where possible. There was not a complete virtual population analysis of the Flemish Cap stock for the period during which plankton data were available. However, there is a juvenile survey carried out by the former USSR that does provide an index of recruitment for the region (Konstantinov, 1983). We used the number of age 3 cod caught per trawling hour in the surveys as our index of recruitment. There is no reliable estimate of the spawning stock biomass for the region.

There is a positive relationship between recruitment

Figure 8. Month-year contours of the abundance of (a) phytoplankton (greenness index, contours at 2,4,6) and (b) *Calanus finmarchicus* I-IV (number per CPR sample, contours at 42,83,155). Adapted from Robinson *et al.* (1975).



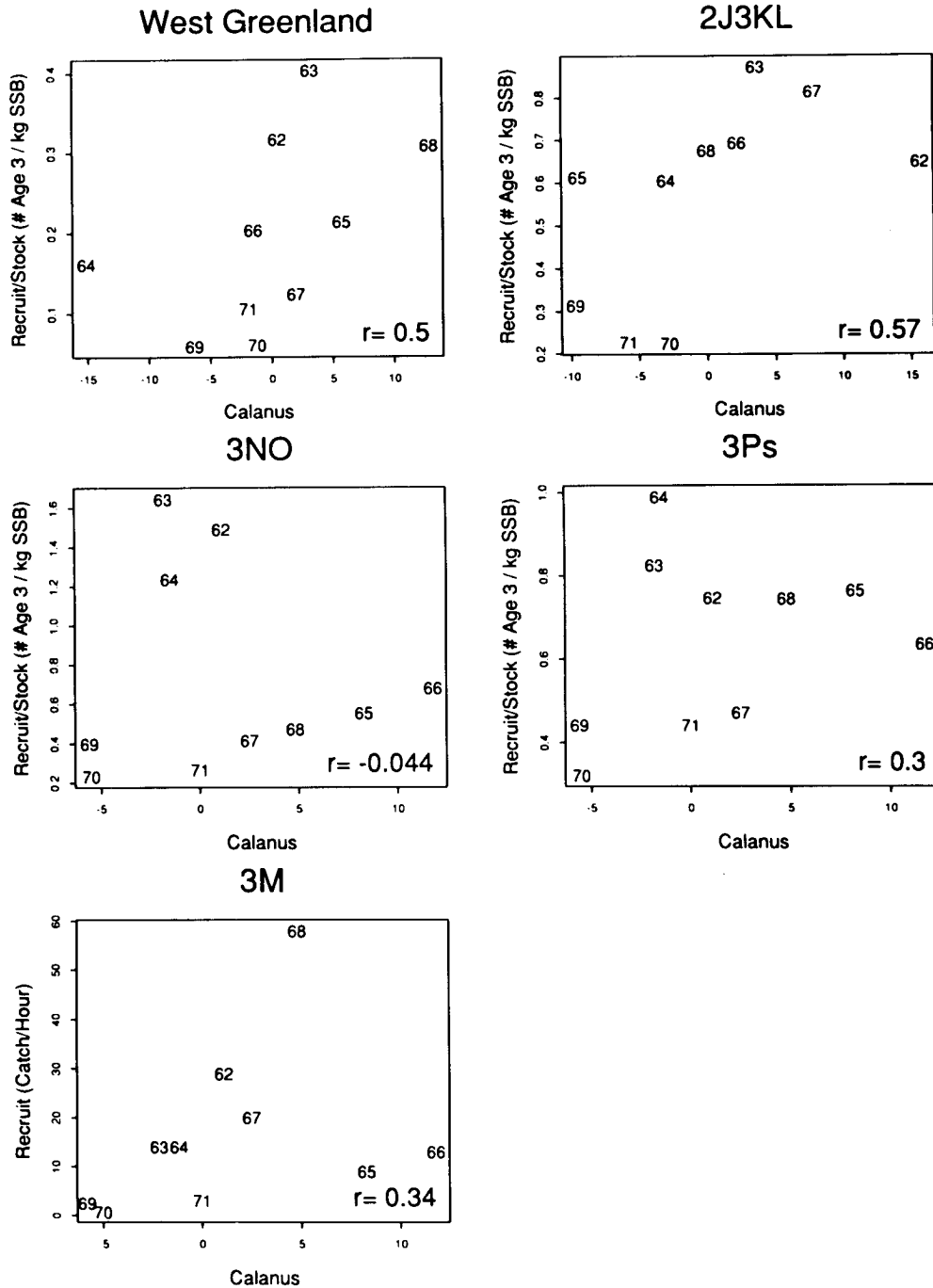
Phytoplankton - Colour



Calanus finmarchicus I - IV

and *Calanus* for four of the five regions (Fig. 9). Although none of these correlations meets the $p < 0.05$ criterion, we can test the general hypothesis of a relationship by combining probabilities from each individual test (Fisher, 1954, 21.1). Fisher's method is based upon the fact that the logarithm of the probability (for the correlation coefficient) is distributed as $-\frac{1}{2}\chi^2_{(2)}$,

Figure 9. Scatter plots of recruitment versus the *Calanus finmarchicus* I-IV annual abundance index (Fig. 5). For the West Greenland, 2J3KL, 3NO and 3Ps stocks the (VPA) recruitment was scaled by dividing by the spawning stock biomass. For the 3M stock the recruitment series is derived from the young fish survey of Konstantinov (1983); recruitment was not scaled as spawning stock biomass figures were not available.



and upon additive properties of the χ^2 distribution. That is, the sum of the natural logarithm of the probability for n correlation coefficients is distributed as $-\frac{1}{2}\chi^2_{[2n]}$. This allows the results of one-sided tests to be

combined, and the results tested using a χ^2 distribution. A test of the general hypothesis does yield a positive, albeit not compelling, relationship ($p = 0.038$). This relationship is not sufficiently strong to warrant an

assertion that *Calanus* can serve as a link between climate and recruitment.

4 CONCLUSIONS

We have attempted to clarify the ecological significance of the GSA in the northern North-west Atlantic by probing a number of questions derived from Cushing's (1988, 1990a,b) analysis. In this section we offer a consolidation of our findings.

Our examination of the timing and extent of the GSA has led us to revise the date of passage of the GSA through Grand Banks waters, from 1971–73 to 1970–71. Moreover, it is clear that the GSA did influence the waters of the 3Ps zone. With these refinements, we find that the GSA years corresponded to minima in the recruitment of Northern (2J3KL) and 3Ps cod. The recruitment of 3NO cod does not show a conspicuous minimum for years near the GSA period. Thus recruitment of three cod stocks (2J3KL, 3Ps and West Greenland), out of five, in the northern North-west Atlantic, showed a reduction in the peak GSA years.

Cushing (1988, 1990a,b) proposed the following chain of events: the presence of abnormally cool GSA waters delays and/or reduces the spring bloom (due to inhibited growth or reduced stratification), resulting in weak and/or retarded zooplankton growth, finally causing poor recruitment due to low zooplankton abundance or because of a mismatch of larvae to the zooplankton peak. We have shown that, south of Greenland, the GSA did not correspond to significantly lower water temperatures, and we have found that water column stability was enhanced (not reduced) during the GSA. Moreover, there appears to be little evidence for the marine food chain serving as a link between climate anomalies and recruitment anomalies (our analysis, like Cushing's, is limited to the short CPR data series for this region). These results show that there is no evidence for a plankton-mediated impact of the GSA on recruitment.

Cushing has claimed that the surmised effect of the GSA on recruitment was detectable well downstream of our study region. However because there is very strong thermal forcing of the ocean by the atmosphere in the northern North Atlantic Ocean, the temperature signature corresponding to the GSA was strongly modified, and in fact was eliminated by the time the GSA reached the Newfoundland Shelf. Consequently, it is unlikely that the GSA had a significant ecological impact after leaving the boundary waters and entering the subpolar gyre of the North Atlantic.

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