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Effects of Experimental Releases of Oil and Dispersed Oil on Arctic Nearshore Macrobenthos. I. Infauna

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ABSTRACT. An experimental subsurface release of chemically dispersed oil at Cape Hatt, northern Baffin Island, resulted in short-term, relatively high oil concentrations in the waters of two adjacent bays, whereas untreated oil released onto the surface of a third bay could not be detected in the water below a depth of 1 m. Diver observations revealed no apparent short-term effects of untreated oil on shallow water infauna, whereas marked acute effects on infauna, including emergence from the substrate and narcosis, were apparent in the dispersed oil bays within 24 h of the release. Analysis of systematic airlift samples at two depths (3 and 7 m) in the three test bays and a fourth (reference) bay during the open water seasons of 1980-83 (two pre-spill and four post-spill sampling periods) showed that most affected animals recovered.

Neither type of oil release caused any large-scale mortality of benthic infauna. Multivariate analyses showed no significant change in infaunal community structure, and effects attributable to oil were found in only 3 of 72 univariate analyses of density, biomass or size data for individual taxa. A progressive decrease in the condition of the filter-feeding bivalve *Serripes groenlandicus* in the reference bay (several km distant from the dispersed oil release) was apparently the result of exposure to dilute dispersed oil for several days. A similar effect on condition in the surface deposit-feeding bivalve *Macoma calcarea* was apparently caused by relatively low oil concentrations in the sediments of the dispersed *and* surface oil release bays. There were no apparent effects on recruitment in bivalve species with planktonic larvae, but density changes in the polychaete *Spio* spp. indicated that oil in the sediments of the surface oil release and dispersed oil release bays affected reproductive processes. Effects on the condition of the bivalves and on *Spio* spp. were still evident two years post-spill in 1983, the last year of sampling.

Key words: arctic infauna, oil effects, dispersed oil effects, experimental oil releases, Baffin Island, macrobenthos

RÉSUMÉ. Un déversement expérimental de pétrole chimiquement dispersé sous la surface au cap Hatt (au nord de l'île Baffin), a amené à court terme des concentrations de pétrole relativement élevées dans les eaux de deux baies adjacentes, alors que du pétrole non traité déversé sur la surface d'une troisième baie n'a pu être détecté dans l'eau à une profondeur supérieure à 1 m. Des observations en plongée n'ont révélé aucun effet apparent à court terme du pétrole non traité sur l'endofaune en eau peu profonde, alors que des effets très prononcés sur cette même endofaune, y compris l'émergence du substrat et la narcose, ont été notés dans les 24 heures suivant le déversement dans les baies où se trouvait le pétrole dispersé. Grâce à un système à air comprimé qui les fait remonter à la surface, des échantillons ont été prélevés systématiquement à des profondeurs de 3 m et de 7 m, dans les trois baies expérimentales et dans une quatrième baie témoin. Les échantillons ont été prélevés durant les saisons d'eau libre de 1980 à 1983 lors de deux périodes d'échantillonnage antérieures et quatre postérieures au déversement, et leur analyse a montré que la plupart des animaux affectés avaient retrouvé leur état normal.

Aucun des deux déversements de pétrole n'a causé une mortalité à grande échelle de l'endofaune benthique. Des analyses à variables multiples n'ont montré aucun changement notable dans la structure de la communauté endofaunique, et on a pu attribuer des effets au pétrole dans seulement 3 des 72 analyses à une seule variable de la densité, de la biomasse ou des données sur la taille permettant la classification des individus. Une baisse progressive de l'état du mollusque bivalve filtreur, *Serripes groenlandicus*, dans la baie témoin (située à plusieurs km du déversement de pétrole dispersé), était apparemment due à l'exposition au pétrole dispersé dilué, durant plusieurs jours. Le même effet sur l'état du mollusque bivalve dépositivore, *Macoma calcarea*, était apparemment causé par des concentrations de pétrole relativement faibles dans les sédiments des baies où avait été déversé du pétrole dispersé *et* dans celle ayant reçu le pétrole en surface. On n'a pas remarqué d'effets sur la repopulation par migration à partir des zones adjacentes des espèces bivalves en relation avec des larves planctoniques, mais des changements de densité chez les polychètes des genres *Spio* ont indiqué que les processus de reproduction ont été affectés par le pétrole présent dans les sédiments des baies où il avait été déversé en surface et sous forme dispersée. Les effets sur l'état des bivalves et sur les genres *Spio* étaient encore notables deux ans après les déversements de pétrole, soit en 1983, dernière année de la prise d'échantillons.

Mots clés: endofaune arctique, effets dus au pétrole, effets dus au pétrole dispersé, déversements expérimentaux de pétrole, île Baffin, macrobenthos

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INTRODUCTION

In a recent appraisal of the fate and effects of oil and dispersants in Canadian marine environments (Sprague *et al.*, 1981, 1982), several major data gaps were identified. These included the fate and effects of dispersants in general, the fate and effects of oil in the Arctic and knowledge of natural processes in the marine environment, particularly in the Arctic. In spite of early recommendations that field studies of oil effects be carried out (e.g., Moore and Dwyer, 1974; National Academy of Sciences, 1975), experimental field studies are still needed (Teal and Howarth, 1984).

The papers in this volume report results of the Baffin Island Oil Spill (BIOS) Project. The BIOS Project assessed the use of chemical dispersants on an oil slick in arctic nearshore waters by comparing the fate and effects of dispersed oil with those resulting from the option of allowing the untreated oil slick to contact the beach and be removed by natural processes. The effectiveness of various shoreline cleanup techniques was also evaluated in separate study areas. Sergy and Blackall (1987) summarize the rationale, design and overall results of the BIOS Project.

This paper describes effects of experimental oil releases on subtidal macrobenthos. Subtidal benthos are of interest in oil effects studies because they occupy the habitat most likely to be affected by dispersed oil. Also, they tend to be more sensitive to oil impact than are intertidal benthos, which are better adapted to withstanding natural environmental stress (Swedmark *et al.*, 1973; Cowell, 1974; Rice *et al.*, 1976; Hyland *et al.*, 1985). Despite this, the subtidal habitat has received much less attention than the intertidal habitat during studies of major oil spills (American Petroleum Institute, 1977; Percy, 1982). Furthermore, the few field studies involving experimental contamination with oil and dispersed oil (Levell, 1976; Hartwick *et al.*, 1982; Crothers, 1983) have examined the intertidal and not the subtidal zone.

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The subtidal communities in the BIOS study area are described in Snow *et al.* (1987). Oil effects on the relatively immobile infauna, predominantly bivalves and polychaetes, are reported here. Treatment effects on the motile epibenthos (crustaceans and echinoderms) and on macroalgae are reported in the following two papers (Cross *et al.*, 1987a,b). Infaunal benthos — i.e., animals that burrow in soft substrates — are important in arctic marine ecosystems because (1) they dominate soft-bottom benthic communities (Curtis, 1975; Thomson, 1982; Snow *et al.*, 1987), (2) they contribute to the diets of some vertebrates, e.g., walrus and bearded seals (Vibe, 1950; Mansfield, 1958; Lowry *et al.*, 1980), and (3) their burrowing activity reworks sediments, recycles nutrients and, at low oil concentrations, accelerates the weathering of sediment-bound oil (Gordon *et al.*, 1978). Infauna are particularly susceptible to oil impact because of their relative immobility — hence their inability to avoid oil. Also, infauna can be expected to be more vulnerable to the presence of oil than are organisms having a less intimate relationship with the substrate (Moore and Dwyer, 1974). The impact of oil on arctic infauna may be severe and long lasting because most species have slow growth rates, long life spans, pronounced reproductive periodicity and direct development (i.e., no planktonic larvae) (Thorson, 1936; Ockelmann, 1958; Dunbar, 1968; Chia, 1970; Baker and Crapp, 1974; Curtis, 1977).

METHODS

Study design and methods are described in Snow *et al.* (1987). Only a brief summary is given here. A discussion of possible sources of error and design rationale and evaluation is also given in Snow *et al.* (1987).

Four shallow embayments at Cape Hatt, northern Baffin Island, were selected as experimental bays (Fig. 1). During August 1981, approximately 15 m^3 of Lagomedio crude oil was applied to the surface of one bay (Bay 11), and 15 m^3 of dispersed oil (10 Lagomedio:1 Corexit 9527) was released underwater in another bay (Bay 9). The oil in both cases had been artificially weathered to remove 8% by volume. Surface oil in Bay 11 did not penetrate below 1 m depth in the 30 h following the release. The dispersed oil release, on the other hand, resulted in a severe exposure to benthos at 3 and 7 m depths in Bay 9, a lower and more realistic exposure in the third study bay (Bay 10) and very light exposure in the fourth (reference) bay (Bay 7). Details of the oil releases and of oil concentrations during the releases are given in Dickins *et al.* (1987) and in Humphrey *et al.* (1987) respectively.

Sampling of infauna was carried out in these bays during each of the two ice-free months (August and September) between September 1980 and August 1983; two of these six sampling periods (September 1980 and August 1981) preceded the experimental oil releases.

Three contiguous 50 m transects parallel to the shoreline were sampled at each of two depths (3 m, 7 m) in each of the four bays during five or six sampling periods. On each transect, eight randomly located replicate samples, each covering 0.0625 m^2, were collected using a diver-operated airlift fitted with a 1 mm mesh collecting bag. Mean depth of penetration of the airlift sampler into the substrate in each bay and period was 12.0-17.1 cm at 7 m depth and 6.0-14.6 cm at 3 m depth. Visual and tactile inspection of the sampling plots by divers ensured that all large individuals of deeply burrowing bivalves were collected. To enumerate infauna that emerged from the substrate, approximately 10 photographs, each covering 0.25 m^2, were taken at random locations along the transects in each bay within five days of the dispersed oil release.

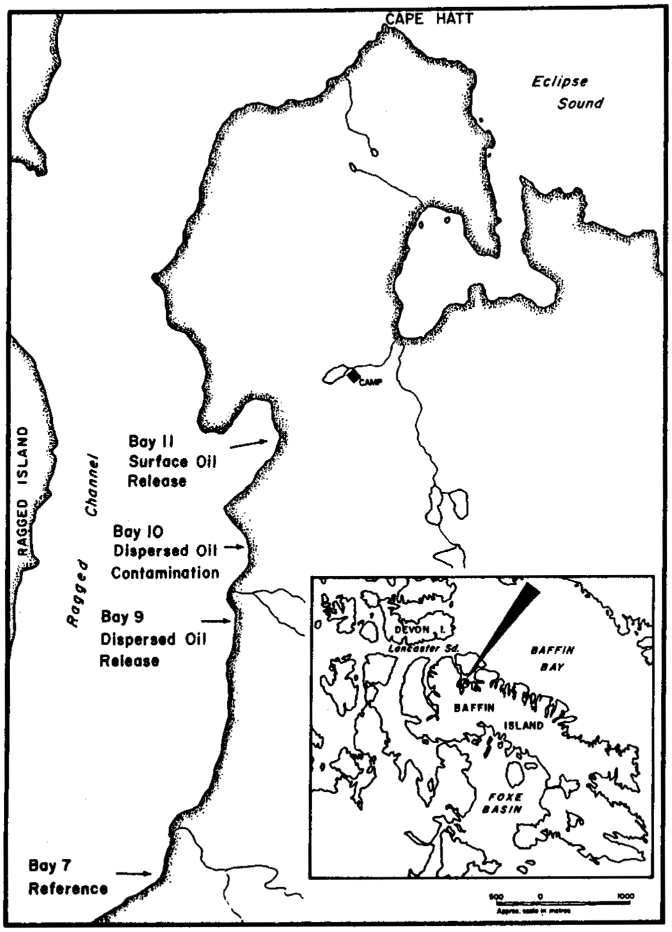

FIG. 1. BIOS site at Cape Hatt, Baffin Island, showing the locations of study bays and oil treatments applied in August 1981.

All animals retained on a 1 mm sieve were sorted from the airlift samples using (1) flotation and decantation of water to remove algae, detritus and most soft-bodied animals, (2) flotation in a zinc chloride solution (s.g. = 2.0) to separate bivalves and some soft-bodied animals from gravel, and (3) hand sorting under binocular microscopes to separate animals from algae and detritus. Specimens were identified to species where possible, counted and weighed (± 0.5 mg) after gently blotting dry (10% formalin wet weight, including mollusc shells but excluding polychaete tubes). Bivalve lengths and holothurian oral ring diameters were measured (± 0.5 mm). For each of four common species (*Mya truncata*, *Macoma calcarea*, *Astarte borealis* and *Serripes groenlandicus*), individual lengths and wet and dry weights (60°C until constant weight) were measured for a subsample of 50 individuals (where available) from each bay and period. Dry weights were not measured for *Serripes groenlandicus* collected in 1980.

To determine whether oil had an effect, temporal changes in the four bays were compared using three-factor (periods, bays and transects) fixed-effects analysis of variance (ANOVA), with transects nested within periods and bays. In statistical terms, a significant interaction between spatial and temporal effects indicated a possible oil effect (Green, 1979; see also Snow *et al.*, 1987). Because of the nested design, the among-transects term rather than the residual error term was used to test the significance of main effects (periods, bays) and of the interaction between the main effects. When interaction terms involving transects were non-significant ($P>0.05$), they were pooled with the transect term before testing for main effects. When interactions involving transects were significant ($P\leq0.05$), they were not pooled with the transect term, which was used alone as the denominator in the tests.

All data were log-transformed ($\log[x + 1]$) prior to analysis in order to reduce the skewness inherent in such data. Data from the two depths sampled were analyzed separately. Univariate ANOVA was applied to 28 and 33 density or biomass variables at 3 and 7 m depths respectively and to mean length data for four common bivalve species and the holothurian *Myriotrochus rinkii*. Multivariate analysis of variance (MANOVA) was used in order to examine variability in the benthic community as a whole. ANOVA and MANOVA were performed by the GLM procedure of the SAS computer program package (Helwig and Council, 1979; Freund and Littell, 1981). Factor analysis (BMDP4M; Dixon, 1981) was used to identify recurring groups of species and to reduce the number of variables in the MANOVA. At each depth, species selected for factor analysis were those that accounted for 0.9% or more of density. The principal components method was used to extract initial factors from the correlation matrix of log-transformed species abundance data, and final factors were generated by varimax rotation. The scoring coefficients so produced were applied to log-transformed species abundances to produce factor scores for all samples collected during all sampling periods. These factor scores were then used as dependent variables in MANOVA. An *a priori* decision was made to use Pillai's trace (see Green, 1979:174) as the overall test of significance in MANOVA.

The functional relationships between lengths and weights of dominant bivalve species were identified by analysis of scatter plots of the data and of residuals generated by regression analyses. Analyses of covariance (ANCOVA) with the corresponding function of length as the covariate were then used to test for differences among periods and bays in dry meat weight adjusted for differences in mean length among periods and bays. ANCOVA was carried out using the SAS GLM procedure (Helwig and Council, 1979; Freund and Littell, 1981).

The design of the experiment was unbalanced because there were no data from one bay (Bay 7) in the first pre-spill sampling period or from another bay (Bay 10) in the last post-spill sampling period. The unbalanced design necessitated the use of three different analytical procedures including three different combinations of bays and sampling periods (see Snow *et al.*, 1987), as results of a single analysis with two missing cells would have been ambiguous. In most parts of this paper, the results of only one analysis type are presented — the analysis including data from all four bays and excluding data from 1980 and 1983. However, when an oil effect was indicated only in one or both of the other two types of analysis, this fact is mentioned.

RESULTS

These results are based on the "optimal impact study design" of Green, (1979:70), in which the evidence for impact effects is a significant area-by-times interaction. Such an interaction would occur when temporal change in benthos was inconsistent among the study bays, each of which received a different oil treatment. Under the present study design, for such change to be considered significant in both statistical and practical terms, it would have to be large relative to variability within the bays. Within-bay variation included both variability among the transects (the "transect" term) and temporal variability that was not consistent among the transects (the "period-by-transect" term).

Significant periods-by-bays interaction terms could arise because of (1) actual effects of oil, (2) some other temporal change in only some bays, or (3) type I errors in statistical inference (such errors are expected when a large number of tests are done). The third possibility is discussed for this study in Snow *et al.* (1987), and the second is treated in general by Hurlbert (1984). Because the experimental oil releases were carried out in the field, it was not possible to randomly allocate oil treatments to replicate samples, nor was it practical to replicate oil treatments (i.e., to release oil in the same manner in two or more bays). Hence, we are guilty of "pseudoreplication" as defined by Hurlbert (1984), and it is not possible to reach unequivocal conclusions on the effects of oil. To reduce the possibility of committing type I errors or of confounding oil effects with natural changes that were inconsistent among bays, the nature of each significant interaction was examined in relation to the type of oil treatment (surface vs. dispersed) and the concentrations of oil, both in the water during and immediately after the oil releases and in the subtidal sediments during 1981 to 1983. Only if change in the benthos corresponded with change in oil concentrations was it concluded that a probable oil effect had occurred.

Community Structure

The species considered in analyses of community structure included 21 taxa representing 85% of total numbers of individuals at 3 m depth and 23 taxa representing 82% of total numbers at 7 m depth. At 3 m depth, five factors accounted for 65.1% of the variance represented by the 21 species variables. At 7 m depth, six factors accounted for 59.0% of the variance represented by the 23 species variables. Each of these factors represents an assemblage of species that tended to occur together and whose densities varied more or less proportionately; some factors also include species (those with negative signs) that tended to be absent or rare at locations where the other species were common. The species whose densities were strongly correlated with each factor are listed in Table 1, and the mean abundance (factor score) of each factor for each period/bay combination is presented in Figure 2.

No effects of oil or dispersed oil on community structure were detected in MANOVA at either depth ($P>0.7$ for period-by-bay interaction at both depths; Table 2). Univariate ANOVA, carried out for abundances (factor scores) of five species assemblages at 3 m depth and six assemblages at 7 m depth, indicated a possible effect of oil for only one assemblage, and only in one type of analysis (Table 2). This assemblage consisted mainly of the small polychaetes *Spio* spp., *Mediomastus* sp., *Pholoe minuta*, and *Capitella capitata* (Table 1). In general, its abundance increased progressively throughout the study period (Fig. 2). Inspection of the data indicated that one possible source of the observed interaction was larger negative factor scores in Bays 9 (dispersed oil release) and 11 (surface oil release) than in

TABLE 1. Results of factor analyses of 21 and 23 common infaunal benthic taxa at 3 and 7 m depths respectively in four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983

3 m depth

1. Variance explained		20.4%
Astarte juveniles	B	0.849
Thyasiridae spp.	B	0.779
Mya truncata	B	0.742
Tharyx marioni	P	0.636
Astarte borealis	B	0.612
Chaetozone setosa	P	0.533
Astarte montagui	B	0.532
Euchone analis	P	0.518
Cingula castanea	G	0.482
Retusa obtusa	G	0.413

2. Variance explained		17.3%
Myriotrochus rinkii	H	0.790
Pholoe minuta	P	0.743
Asabellides sibirica	P	0.686
Retusa obtusa	G	0.534
Cingula castanea	G	0.524
Astarte montagui	B	0.523
Astarte borealis	B	0.520
Euchone analis	P	0.454
Mya truncata	B	0.425

3. Variance explained		11.5%
Musculus discors	B	0.870
Musculus juveniles	B	0.814
Nereimyra punctata	P	0.681
Harmothoe imbricata	P	0.418

4. Variance explained		8.4%
Spio spp.	P	0.712
Capitella capitata	P	0.600
Harmothoe imbricata	P	−0.631

5. Variance explained		7.5%
Mediomastus spp.	P	0.714
Eteone longa	P	0.617
Chaetozone setosa	P	0.582

7 m depth

1. Variance explained		14.3%
Astarte montagui	B	0.857
Astarte borealis	B	0.806
Astarte juveniles	B	0.776
Nuculana minuta	B	0.509
Mya truncata	B	0.496
Praxillella praetermissa	P	0.493
Maldane sarsi	P	0.405

2. Variance explained		11.5%
Thyasiridae spp.	B	0.847
Macoma calcarea	B	0.801
Macoma juveniles	B	0.537
Serripes groenlandicus	B	0.432
Nuculana minuta	B	0.406

3. Variance explained		10.7%
Musculus juveniles	B	0.727
Musculus niger	B	0.699
Serripes groenlandicus	B	0.634
Retusa obtusa	G	0.453
Cingula castanea	G	0.450

4. Variance explained		9.3%
Spio spp.	P	0.768
Mediomastus sp.	P	0.704
Pholoe minuta	P	0.599
Capitella capitata	P	0.569

5. Variance explained		7.7%
Moellaria costulata	G	0.773
Trichotropis borealis	G	0.483
Cingula castanea	G	0.474
Scoloplos armiger	P	−0.468

6. Variance explained		5.5%
Pectinaria granulata	P	0.788
Maldane sarsi	P	−0.415

The values shown are the correlations between the log-transformed densities of various species (the original variables) and each of the factors determined in the analysis. Species whose densities were weakly correlated with a factor ($-0.4<r<0.4$) are not shown. Also shown is the variance explained by each factor expressed as a percentage of the variance of the original variables.
B = Bivalve; P = Polychaete; G = Gastropod; H = Holothurian.

Bay 10 (dispersed oil contamination) during September 1980 (Pre-spill Period 1); this clearly does not represent an oil effect. In general, the pre- to post-spill change that was not consistent among bays appeared to be an earlier, but less pronounced, relative increase in the abundance of this factor in Bay 10 than in Bay 9 or 11. This might be indicative of an oil effect, except that the clearest increase in the abundance of this assemblage occurred in Bay 7, the reference bay (Fig. 2). Therefore, the significant interaction term for the fourth assemblage at 7 m depth did not represent an oil effect.

Thus, according to our analyses, oil and dispersed oil did not affect infaunal community composition or the abundances of dominant species assemblages in the two years following the oil releases. Rather, most of the significant variation in all analyses was spatial, including both variation among transects within bays and variation among bays (Table 2; Fig. 2). Infaunal community structure in the study area changed during the four years of study at both depths studied. However, the lack of significant period-by-bay interactions shows that this temporal change was similar in each bay. The interval of greatest change was at some time between September 1981 and September 1982. However, the generally parallel trends in all bays indicate that this change in community structure was not related to the different oil treatments (surface vs. dispersed) or to the observed differences in oil concentrations in the water or sediments of the various study bays.

Distribution of Species

Immediate Effects of Surface and Dispersed Oil: During the surface oil release in Bay 11, diver observations and chemical monitoring showed that oil entered only the top metre of the water column. No effects on the benthos were noted at either 3 or 7 m depths during the oil release or the following two weeks. In contrast, the dispersed oil release produced marked short-term effects on the subtidal benthos at both depths in Bays 9 and 10, both of which received dispersed oil. In those two bays, dispersed oil concentrations reached >50 and 6 ppm respectively within 6 h of the release. Exposures during the 30 h following the release were approximately 300 and 30 ppm·h in Bays 9 and 10 respectively (Humphrey *et al.*, 1987). Infaunal benthos affected included bivalves (*Mya truncata*, *Astarte* sp., *Macoma* sp. and especially *Serripes groenlandicus*), large errant polychaetes (*Phyllodoce* sp.), ophiuroids, holothuroids, gastropods (including limpets) and sipunculids. Bivalves, polychaetes, holothurians and sipunculids that normally burrow were on the sediment surface, and many bivalves were gaping. Ophiuroids and gastropods were lying on the substrate in unnatural positions (e.g., upside down). Some individuals of each group responded unusually slowly when prodded, and others did not respond. In Bays 7 and 11, concentrations of dispersed oil reached 0.12 ppm (Humphrey *et al.*, 1987). No effects were noted in those two bays during observation periods several hours, two days and two weeks following the dispersed oil release.

Density and biomass of *Serripes groenlandicus* on the sediment surface in the study bays were estimated from randomly located photographs, each covering 0.25 m^2 of substrate. Airlift samples showed that this large bivalve was relatively abundant in the sediment at 7 m depth in all four bays. Very few individuals were observed on the sediment surface during any

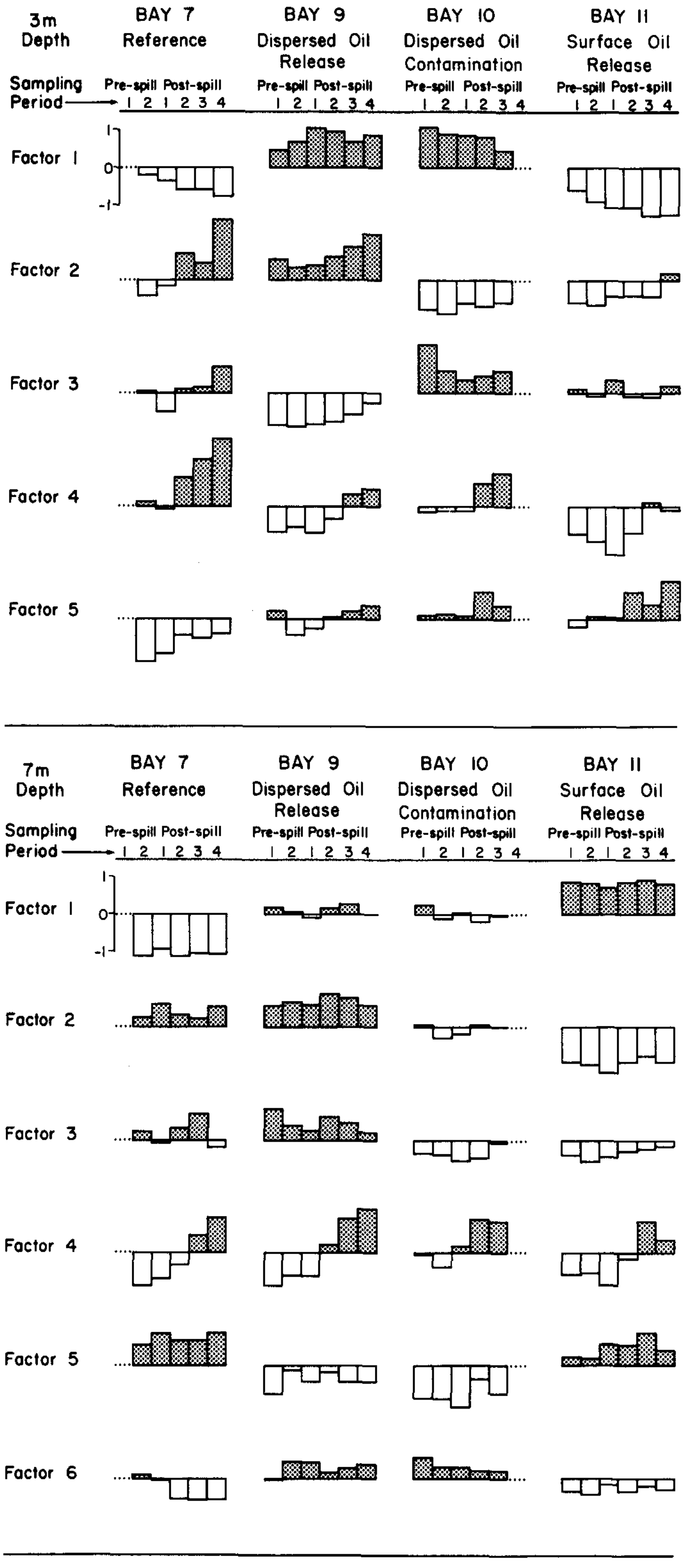

FIG. 2. Mean factor scores for each factor (species assemblage) in each period and bay at 3 and 7 m depths in four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983. Factors are shown in Table 1.

sampling period in Bays 7 and 11 or during pre-spill periods in Bays 9 and 10. In the latter two bays, however, densities of *S. groenlandicus* on the sediment surface on the second post-spill day represented 31 and 35% of pre-spill subsurface densities and 37 and 43% of subsurface biomasses respectively. In the 7-10 d following the oil release, numbers at the surface in Bays 9 and 10 decreased from 31 to 17% and from 35 to 9% respectively of subsurface numbers.

The decreases in densities of surfaced individuals were, in part, a result of predation by the urchin *Strongylocentrotus droebachiensis* (diver observations). This mortality must have represented only a small proportion of the population, however, as there was no significant decrease in densities of *Serripes groenlandicus* during post-spill airlift sampling (see below). Some individuals were attempting to rebury themselves as early as the second post-spill day. Most of the decrease in numbers of surfaced individuals was probably a result of recovery and reburial in the sediment.

Density and Biomass: Oil and dispersed oil released at Cape Hatt did not cause large-scale mortality of benthic animals during the two years following the oil releases; no statistical treatment of the data is required to demonstrate this (see Fig. 3). The purpose of statistical tests, rather, was to test for subtle oil-related changes in the densities or biomasses of infaunal animals. At 3 and 7 m depths, 28 and 33 infaunal species or group variables respectively were tested by ANOVA. The period-by-bay interaction term, the indicator of a possible oil effect, was significant ($\alpha = 0.05$) for only 3 (5%) of these 61 variables (Tables 3 and 4): densities of the polychaete *Spio* spp. at 3 m depth, and densities of total polychaetes and juveniles of the bivalve genus *Macoma* at 7 m depth.

The significant period-by-bay interaction for *Spio* spp. at 3 m depth was apparently attributable to changes in density between September 1982 and August 1983 that were not consistent among bays (Fig. 3). Densities in every bay were low during 1980 and 1981 and increased considerably between 1981 and 1982. However, in 1983 there was an increase in density in the reference bay but no increase in Bays 9 or 11 (Fig. 3). Implicit in the present study design is the assumption that temporal change in the reference bay is a natural occurrence that, in the absence of any treatment effect, would also be expected in the treatment bays. Thus, the lack of increases in *Spio* densities in Bays 9 and 11 can be interpreted as treatment effects. The occurrence of effects in both of those bays was probably attributable to increases in sediment oil concentrations in both bays between 1982 and 1983 (see Boehm *et al.*, 1987). Thus, it appears that oil contained in sediments, and originating from both types of oil release, had an adverse effect on *Spio* spp. 1-2 years after oiling.

Possible oil effects were also indicated for densities of polychaetes and juveniles of the bivalve *Macoma* at 7 m depth (Table 4). Inspection of the data (Fig. 3) indicates that the probable source of interaction in analyses of *Macoma* juveniles was a decrease and subsequent increase in density in Bay 11 between the second pre-spill and second post-spill sampling period (August 1981 and 1982). The source of the observed interaction in analyses of polychaete densities is less obvious, although density changes in Bay 11 during 1981 and 1982 were similar to those in *Macoma* juveniles (Fig. 3). In both cases, decreased densities in the first two post-spill weeks may have resulted from concurrent increases in the concentrations of oil in Bay 11 sediments (see Boehm *et al.*, 1987). However, it should be noted that (1) the observed changes in polychaete density were within the range of natural variability apparent in the reference bay and under pre-spill conditions, (2) the observed short-term pre- to post-spill density decrease in *Macoma* juven-

TABLE 2. Multivariate and univariate analyses of variance (MANOVA and ANOVA) for factor scores determined in factor analyses of infaunal density in four bays at Cape Hatt, northern Baffin Island, during August and September 1981 and 1982

			Source of variation and univariate df[a]				
Depth	Variable		Period 3,32	Bay 3,32	Period by bay 9,32	Transect (bay) 8,334	Per by trans (bay) 24,334
3 m	MANOVA						
	Pillai's trace	F ->	3.75	34.10	0.75	10.80	1.06
		P ->	0.000	0.000	0.867	0.000	0.327
		df ->	15,90	15,90	45,160	40,1670	120,1670
	ANOVAS						
	Factor 1		2.30 ns	105.93***	0.43 ns	8.27***	1.29 ns
	Factor 2		2.63 ns	15.98***	0.65 ns	14.27***	1.44 ns
	Factor 3		0.16 ns	11.47***	0.54 ns	15.23***	0.66 ns
	Factor 4		15.93***	17.00***	0.25 ns	15.07***	1.11 ns
	Factor 5		4.70**	13.22***	0.22 ns	9.02***	0.88 ns
7 m	MANOVA						
	Pillai's trace	F ->	2.38	24.83	0.87	3.50	1.11
		P ->	0.004	0.000	0.728	0.000	0.185
		df ->	18,87	18,87	54,192	48,2004	144,2004
	ANOVAS						
	Factor 1		0.53 ns	84.64***	0.36 ns	1.46 ns	1.13 ns
	Factor 2		0.35 ns	38.20***	0.50 ns	6.34***	1.03 ns
	Factor 3		1.48 ns	8.96***	0.28 ns	7.90***	0.80 ns
	Factor 4[b]		46.42***	10.88***	1.81 ns[b]	1.92 ns	1.40 ns
	Factor 5		1.59 ns	52.45***	1.64 ns	2.06*	1.05 ns
	Factor 6		0.81 ns	4.96**	0.39 ns	5.58***	1.36 ns

F-values are shown with significance levels (ns = $P>0.05$; * $P\leq0.05$; ** $P\leq0.01$; *** $P\leq0.001$) for univariate analyses, and with actual probabilities for multivariate analyses.

[a] Period-by-transect (bay) interaction was pooled with transect (bay) effect to test bay, period and period-by-bay effects.

[b] In analysis excluding data from Bay 7 (reference) and including data from September 1980, the period-by-bay term was significant ($F = 2.39$; df = 8,30; $P = 0.040$).

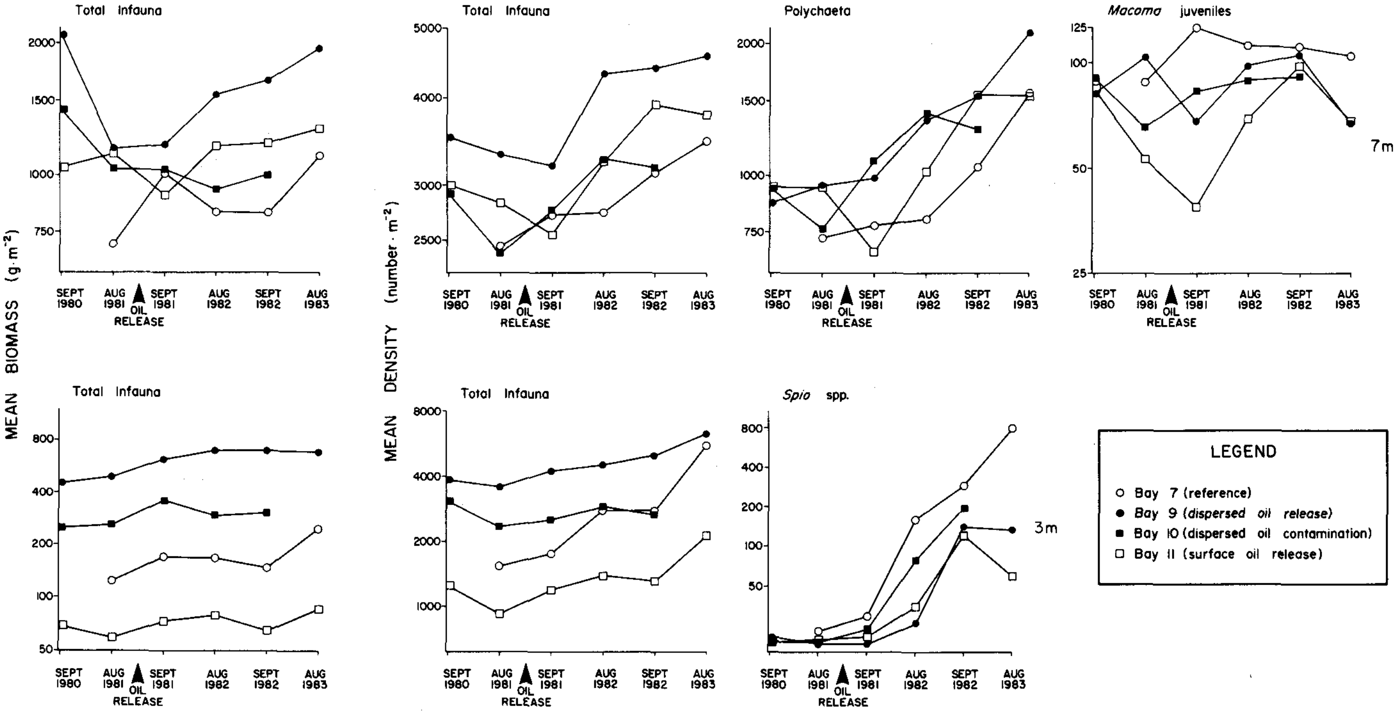

FIG. 3. Mean biomass and density of total infauna and mean density of each taxon where analysis indicated possible oil effects, in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods, September 1980-August 1983. Each symbol represents the back-transformed mean of log-transformed data from 24 replicate 0.0625 m^2 airlift samples for each depth, bay and period.

TABLE 3. Three-factor analyses of variance for the biomasses and densities of major taxa and dominant species of infauna at 3 m depth in four bays at Cape Hatt, northern Baffin Island, during August and September 1981 and 1982

		Source of variation and df[a]				
		Period 3,8 or 32	Bay 3,8 or 32	Period by bay 9,8 or 32	Transect (bay) 8,334	Per by trans (bay) 24,334
Biomass	Total infauna	0.61 ns	33.69 ***	0.06 ns	11.94 ***	0.96 ns
	Polychaeta	0.40 ns	14.19 **	0.36 ns	4.71 ***	1.66 *
	Bivalvia	0.51 ns	35.41 ***	0.06 ns	11.12 ***	0.89 ns
	Mya truncata	0.30 ns	31.17 ***	0.16 ns	9.02 ***	1.20 ns
	Astarte borealis	0.17 ns	12.85 ***	0.18 ns	20.63 ***	0.88 ns
	Astarte montagui	0.01 ns	4.94 *	0.02 ns	47.11 ***	2.06 **
	Macoma calcarea	0.17 ns	7.47 ***	0.50 ns	13.03 ***	0.63 ns
Density	Total infauna	4.51 **	44.96 ***	0.49 ns	6.53 ***	1.54 ns
	Polychaeta	7.40 **	22.20 ***	0.93 ns	2.73 **	1.91 **
	Pholoe minuta	0.78 ns	25.66 ***	0.14 ns	5.65 ***	1.45 ns
	Nereimyra punctata	0.98 ns	2.97 *	0.79 ns	16.01 ***	1.11 ns
	Euchone analis	0.69 ns	14.69 **	0.16 ns	7.83 ***	1.57 *
	Spio spp.[b]	7.11 *	53.91 ***	1.47 ns[b]	5.06 ***	2.60***
	Eteone longa	0.94 ns	8.84 ***	0.92 ns	3.84 ***	1.03 ns
	Chaetozone setosa	3.19 *	30.65 ***	0.23 ns	6.25 ***	1.02 ns
	Capitella capitata	1.15 ns	2.34 ns	0.20 ns	12.32 ***	1.17 ns
	Bivalvia	0.92 ns	45.78 ***	0.41 ns	11.10 ***	0.57 ns
	Mya truncata	1.10 ns	85.62 ***	0.37 ns	4.43 ***	0.58 ns
	Thyasiridae spp.	0.52 ns	41.41 ***	0.23 ns	12.31 ***	1.54 ns
	Astarte borealis	0.22 ns	21.00 ***	0.19 ns	16.82 ***	1.08 ns
	Astarte montagui	0.05 ns	24.14 ***	0.02 ns	35.98 ***	1.53 ns
	Astarte juveniles	0.83 ns	38.90 ***	0.56 ns	12.37 ***	1.12 ns
	Musculus discors	0.15 ns	13.46 ***	0.45 ns	13.50 ***	0.74 ns
	Musculus juveniles	0.14 ns	12.51 ***	1.34 ns	6.92 ***	0.59 ns
	Gastropoda	1.18 ns	72.32 ***	0.30 ns	5.25 ***	1.11 ns
	Cingula castanea	2.42 ns	110.63 ***	0.39 ns	8.11 ***	0.67 ns
	Retusa obtusa	2.91 *	56.74 ***	0.57 ns	1.71 ns	1.30 ns
	Holothuroidea					
	Myriotrochus rinkii	1.62 ns	17.12 ***	0.77 ns	4.36 ***	1.35 ns

F-values are shown with significance levels (ns = $P>0.05$; *$P\leq0.05$; ** $P\leq0.01$; *** $P\leq0.001$).

[a] Where period-by-transect (bay) interaction was ns, it was pooled with transect (bay) effect to test bay, period and period-by-bay effects; where period-by-transect (bay) was significant ($P\leq0.05$), transect (bay) alone was used to test main effects.

[b] In analysis excluding data from Bay 10 (dispersed oil contamination) and including data from August 1983, the period-by-bay interaction term was significant ($F = 11.39$; df = 8,6; $P = 0.004$).

iles was small, representing a difference between 75 and 56 individuals collected in August and September respectively, and (3) the density of *Macoma* juveniles in Bay 11 had increased to pre-spill levels by August 1982, the second post-spill sampling period.

Thus, our results suggest that the only oil effect on infaunal distribution that was of possible ecological significance was an adverse effect of oil in sediments on the polychaete *Spio* spp. In this case, density changes were substantial and could be related to changes in sediment oil concentrations. Possible oil effects indicated in analyses of polychaete and *Macoma* juvenile densities may represent chance effects. In any case, the observed density changes either were not distinguishable from natural variability (polychaetes) or were minor and transitory (*Macoma* juveniles). No oil effects were indicated for any of the 15 biomass variables or for 43 of the 46 density variables analyzed (Tables 3 and 4).

Population Structure

Analysis of mean lengths indicated possible size-related oil effects for *Mya truncata* at 3 m depth and for *Macoma calcarea* at 7 m depth (Table 5). No effects of oil on mean lengths were detected for *Astarte borealis* at either depth, for *A. montagui* or *M. truncata* at 7 m depth or for the holothurian *Myriotrochus rinkii* at 3 m depth.

For *Mya truncata* at 3 m depth, a possible oil effect was indicated only by the analysis that excluded data from Bay 10 and from September 1980 (Table 5). Likely sources of the observed interaction were the marked annual (September-August) decreases in mean size (1) in Bay 7 between 1981 and 1982 relative to increases in Bays 9 and 11 and (2) in Bay 11 between 1982 and 1983 relative to little change in Bays 7 and 9 (Table 6). In both cases, inspection of size-frequency data (Fig. 4; shaded portion = 3 m) indicates that annual decreases in mean size were a result of recruitment of small individuals to the populations (in this case, settlement of planktonic larvae). Recruitment was strong only in Bay 10 in 1980 (based on September data), was poor in each bay in 1981, was markedly improved only in Bay 7 (and somewhat improved in Bay 10) in 1982, and was relatively good in each of Bays 7, 9 and 11 in 1983 (Fig. 4). The pattern of recruitment in 1982 may indicate an effect of oil in the sediments of Bays 9 and 11 and, to a lesser extent, in Bay 10. However, the recruitment success in each bay in 1983, together with variability in recruitment during pre-spill

TABLE 4. Three-factor analyses of variance for the biomasses and densities of major taxa and dominant species of infauna at 7 m depth in four bays at Cape Hatt, northern Baffin Island, during August and September 1981 and 1982

		Source of variation and df[a]				
		Period 4,6 or 30	Bay 2,6 or 32	Period by bay 8,6 or 32	Transect (bay) 6,334	Per by trans (bay) 24,334
Biomass	Total infauna	0.51 ns	5.54 **	0.70 ns	3.33 **	0.76 ns
	Polychaeta	1.13 ns	3.58 *	0.52 ns	2.64 **	0.90 ns
	Bivalvia	0.53 ns	5.55 **	0.61 ns	3.30 **	0.81 ns
	Mya truncata	0.68 ns	1.48 ns	0.89 ns	2.44 *	0.59 ns
	Astarte borealis	0.47 ns	46.20 ***	1.20 ns	1.68 ns	0.81 ns
	Astarte montagui	0.44 ns	91.66 ***	0.29 ns	4.19 ***	0.77 ns
	Macoma calcarea	2.48 ns	16.69 ***	0.26 ns	3.54 ***	1.11 ns
	Serripes groenlandicus	1.63 ns	29.43 ***	0.39 ns	2.53 *	0.80 ns
Density	Total infauna	14.11 ***	14.83 ***	1.05 ns	1.64 ns	1.06 ns
	Polychaeta	—[b]	—[b]	2.46 *	2.76 **	1.01 ns
	Pholoe minuta	8.16 ***	20.46 ***	1.72 ns	2.78 **	0.92 ns
	Pectinaria granulata	0.62 ns	1.28 ns	0.26 ns	7.14 ***	1.17 ns
	Praxillella praetermissa	7.71 ***	11.61 ***	0.40 ns	1.85 ns	1.14 ns
	Spio spp.	36.72 ***	24.77 ***	1.90 ns	2.48 *	1.12 ns
	Capitella capitata	6.16 **	0.13 ns	0.86 ns	2.35 *	1.08 ns
	Maldane sarsi	0.14 ns	9.65 ***	0.52 ns	6.15 ***	1.21 ns
	Bivalvia	1.89 ns	11.40 ***	0.29 ns	2.47 *	1.21 ns
	Mya truncata	1.52 ns	6.66 **	0.34 ns	2.95 **	0.95 ns
	Thyasiridae spp.	1.66 ns	83.17 ***	0.20 ns	5.01 ***	0.94 ns
	Astarte borealis	0.03 ns	24.96 ***	0.86 ns	1.99 *	0.79 ns
	Astarte montagui	0.24 ns	71.51 ***	0.37 ns	5.01 ***	1.08 ns
	Astarte juveniles	0.99 ns	50.52 ***	0.41 ns	1.04 ns	1.31 ns
	Macoma calcarea	1.43 ns	33.99 ***	0.71 ns	3.79 ***	1.35 ns
	Macoma juveniles[c]	4.08 *	9.38 ***	1.90 ns[c]	2.49 *	0.81 ns
	Nuculana minuta	1.73 ns	30.71 ***	0.55 ns	2.01 *	0.83 ns
	Musculus niger	0.51 ns	34.01 ***	0.27 ns	2.47 *	0.38 ns
	Musculus juveniles	8.70 ***	26.92 ***	0.30 ns	5.24 ***	0.34 ns
	Serripes groenlandicus	0.79 ns	27.21 ***	0.25 ns	2.37 *	1.15 ns
	Gastropoda	5.12 **	23.77 ***	1.09 ns	2.32 *	0.80 ns
	Cingula castanea	3.04 *	21.72 ***	1.56 ns	2.79 **	0.94 ns
	Trichotropis borealis	0.86 ns	13.47 ***	0.48 ns	3.15 **	0.64 ns
	Retusa obtusa	1.84 ns	1.94 ns	1.45 ns	2.56 *	1.04 ns
	Moelleria costulata	7.10 ***	35.86 ***	1.40 ns	1.36 ns	0.65 ns

F-values are shown with significance levels (ns = P>0.05; *P≤0.05; ** P≤0.01; *** P≤0.001).

[a] Period-by-transect (bay) interaction was pooled with transect (bay) effect to test bay, period and period-by-bay effects.

[b] Interpretation of main effects confounded by significant interaction of period-by-bay term.

[c] In analysis excluding data from Bay 10 (dispersed oil contamination) and including data from August 1983, the period-by-bay interaction term was significant (F = 2.92; df = 8,30; P = 0.015).

TABLE 5. Results of analyses of variance on mean lengths (in each sample) of four bivalve species and mean oral ring diameter of the holothurian *Myriotrochus rinkii* in four bays at Cape Hatt, northern Baffin Island, during August and September 1981 and 1982

		Source of variation and numerator df						
Depth	Species	Period (df = 3)	Bay (df = 3)	Period by bay (df = 9)	Transect (bay) (df = 8)	Per by trans (bay) (df = 24)	Residual df	No. of samples
3 m	*Myriotrochus rinkii*	4.64 **	11.84 ***	0.68 ns	2.29 *	0.96 ns	305	353
	Astarte borealis	0.68 ns	1.31 ns	0.38 ns	6.37 ***	1.21 ns	215	262
	Mya truncata	1.64 ns	9.33 ***	1.60 ns[a]	3.83 ***	0.48 ns	260	308
7 m	*Astarte montagui*	0.91 ns	1.90 ns	0.44 ns	1.78 ns	1.37 ns	297	345
	Astarte borealis	0.50 ns	13.86 ***	1.17 ns	2.11 *	1.05 ns	319	367
	Mya truncata	1.04 ns	5.61 **	0.66 ns	3.43 ***	1.18 ns	324	372
	Macoma calcarea	1.77 ns	3.73 *	2.14 ns[b]	0.97 ns	0.57 ns	325	373

F-values are shown with significance levels (ns = P>0.05; *P≤0.05; ** P≤0.01; *** P≤0.001).

[a] In analysis excluding data from Bay 10 (dispersed oil contamination) and including data from August 1983, the period-by-bay interaction term was significant (F = 4.30; df = 8,32; P = 0.002).

[b] The period-by-bay interaction terms were significant in the analysis excluding data from Bay 7 (reference) and including data from September 1980 (F = 2.76; df = 8,32; P = 0.021) and in the analysis excluding data from Bay 10 and including data from August 1983 (F = 2.81; df = 8,32; P = 0.019).

TABLE 6. Mean lengths (mm) of six species of benthic infauna from four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983

		3 m depth				7 m depth			
Taxon	Period	Bay 7 Reference	Bay 9 Dispersed oil release	Bay 10 Dispersed oil contamination	Bay 11 Surface oil release	Bay 7 Reference	Bay 9 Dispersed oil release	Bay 10 Dispersed oil contamination	Bay 11 Surface oil release
Mya truncata	Pre-spill 1	—	12.7 ± 7.4 (371)	9.4 ± 7.6 (310)	8.5 ± 5.5 (81)	—	26.7 ± 14.4 (232)	18.2 ± 13.6 (195)	16.2 ± 13.0 (251)
	Pre-spill 2	13.1 ± 7.7 (60)	14.8 ± 7.1 (295)	14.9 ± 9.0 (149)	10.7 ± 6.5 (27)	19.0 ± 12.3 (125)	20.2 ± 12.1 (130)	21.9 ± 13.2 (90)	16.2 ± 12.0 (230)
	Post-spill 1	17.3 ± 7.4 (72)	15.9 ± 8.0 (358)	13.9 ± 9.2 (143)	10.1 ± 7.1 (39)	21.3 ± 13.7 (126)	22.0 ± 13.4 (102)	22.5 ± 12.7 (113)	17.8 ± 11.1 (191)
	Post-spill 2	12.5 ± 9.6 (105)	19.4 ± 8.4 (280)	16.2 ± 10.9 (131)	13.6 ± 7.2 (23)	21.9 ± 13.6 (127)	23.8 ± 11.4 (164)	22.3 ± 12.6 (132)	17.1 ± 10.7 (211)
	Post-spill 3	14.2 ± 9.8 (69)	18.0 ± 7.4 (334)	17.1 ± 10.6 (122)	10.4 ± 6.0 (37)	22.4 ± 14.0 (157)	24.1 ± 12.3 (170)	23.2 ± 10.8 (136)	18.5 ± 11.0 (223)
	Post-spill 4	13.7 ± 10.2 (131)	18.3 ± 9.1 (328)	—	5.8 ± 6.9 (34)	23.1 ± 13.9 (102)	29.6 ± 12.4 (129)	—	21.5 ± 12.2 (189)
Macoma calcarea	Pre-spill 1	—	11.6 ± 4.6 (53)	10.6 ± 4.1 (37)	15.0 ± 6.8 (8)	—	12.8 ± 5.4 (299)	14.8 ± 6.5 (164)	15.5 ± 6.6 (104)
	Pre-spill 2	16.2 ± 3.0 (11)	12.6 ± 5.3 (67)	14.4 ± 6.8 (18)	0	13.2 ± 5.1 (364)	13.2 ± 5.1 (265)	15.3 ± 6.6 (136)	13.2 ± 6.7 (99)
	Post-spill 1	14.6 ± 5.8 (18)	11.8 ± 5.2 (72)	11.5 ± 4.9 (24)	23.0 (1)	13.4 ± 5.1 (376)	12.6 ± 4.9 (298)	14.9 ± 6.5 (147)	15.5 ± 6.8 (81)
	Post-spill 2	14.3 ± 4.1 (13)	12.3 ± 4.9 (59)	15.5 ± 6.3 (34)	11.0 ± 3.5 (3)	13.8 ± 5.1 (369)	13.8 ± 4.7 (347)	14.9 ± 6.4 (222)	13.8 ± 6.9 (118)
	Post-spill 3	14.0 ± 5.2 (14)	11.7 ± 5.0 (86)	14.3 ± 5.5 (19)	16.7 ± 3.8 (3)	13.9 ± 5.0 (360)	13.7 ± 5.0 (291)	14.1 ± 6.1 (204)	13.4 ± 6.5 (159)
	Post-spill 4	17.6 ± 5.6 (18)	11.0 ± 5.2 (59)	—	20.5 ± 5.1 (4)	14.5 ± 4.8 (372)	14.6 ± 4.7 (311)	—	14.3 ± 6.7 (137)
Astarte borealis	Pre-spill 1	—	12.8 ± 7.5 (287)	12.4 ± 9.5 (48)	10.2 ± 6.8 (31)	—	12.4 ± 7.1 (653)	12.6 ± 8.4 (549)	13.3 ± 8.5 (572)
	Pre-spill 2	12.1 ± 7.4 (81)	12.9 ± 7.5 (357)	11.6 ± 8.5 (74)	9.1 ± 5.1 (21)	9.6 ± 5.6 (239)	12.2 ± 7.6 (431)	11.9 ± 7.6 (431)	13.8 ± 8.5 (566)
	Post-spill 1	13.8 ± 7.8 (76)	14.2 ± 7.7 (351)	16.0 ± 10.2 (132)	10.3 ± 6.2 (16)	10.4 ± 6.0 (286)	11.9 ± 7.0 (445)	13.9 ± 8.7 (377)	12.5 ± 8.1 (496)
	Post-spill 2	11.2 ± 7.6 (121)	12.6 ± 7.0 (382)	13.4 ± 9.4 (124)	9.6 ± 8.7 (16)	10.1 ± 6.1 (252)	13.1 ± 7.4 (560)	12.5 ± 8.6 (415)	13.7 ± 8.9 (549)
	Post-spill 3	13.0 ± 7.8 (89)	13.0 ± 7.7 (399)	12.5 ± 9.0 (88)	15.1 ± 10.5 (12)	10.0 ± 6.0 (274)	12.6 ± 7.2 (567)	12.9 ± 8.4 (374)	13.2 ± 8.5 (569)
	Post-spill 4	13.5 ± 7.9 (112)	13.4 ± 7.6 (445)	—	12.6 ± 7.7 (20)	10.7 ± 6.4 (227)	13.5 ± 7.3 (406)	—	14.4 ± 8.9 (514)
Astarte montagui	Pre-spill 1	—	11.0 ± 2.8 (217)	12.2 ± 3.0 (10)	10.7 ± 6.7 (3)	—	9.4 ± 3.7 (299)	9.3 ± 4.1 (239)	9.7 ± 3.8 (671)
	Pre-spill 2	9.6 ± 3.7 (24)	10.5 ± 3.1 (337)	10.7 ± 3.8 (13)	17.0 ± 0.0 (2)	8.7 ± 3.8 (64)	9.0 ± 4.2 (197)	10.2 ± 3.9 (237)	10.2 ± 3.8 (661)
	Post-spill 1	8.9 ± 4.2 (27)	10.7 ± 2.9 (422)	11.2 ± 2.8 (32)	0	9.5 ± 3.6 (66)	9.8 ± 3.7 (204)	9.7 ± 3.9 (301)	9.9 ± 4.0 (723)
	Post-spill 2	10.6 ± 3.3 (32)	10.6 ± 3.0 (327)	11.4 ± 3.8 (18)	12.0 ± 6.1 (3)	9.1 ± 4.2 (68)	9.3 ± 3.8 (246)	10.1 ± 3.9 (315)	9.5 ± 3.9 (747)
	Post-spill 3	11.3 ± 4.3 (23)	10.7 ± 2.9 (395)	9.1 ± 4.2 (13)	0	9.0 ± 3.7 (43)	9.4 ± 3.6 (279)	9.3 ± 3.6 (275)	10.0 ± 3.9 (769)
	Post-spill 4	10.2 ± 3.3 (24)	10.4 ± 2.9 (491)	—	0	10.6 ± 3.9 (58)	9.4 ± 3.7 (225)	—	10.2 ± 3.9 (761)
Serripes groenlandicus	Pre-spill 1	—	12.8 ± 5.9 (30)	13.5 ± 12.0 (2)	26.0 (1)	—	24.5 ± 15.2 (89)	29.0 ± 12.2 (34)	19.2 ± 9.2 (18)
	Pre-spill 2	0	16.0 ± 4.8 (30)	0	6.3 ± 3.9 (4)	15.3 ± 11.2 (37)	26.5 ± 12.8 (46)	28.1 ± 15.4 (21)	20.6 ± 10.4 (18)
	Post-spill 1	0	14.9 ± 10.9 (18)	10.0	0	19.9 ± 12.1 (37)	24.8 ± 11.6 (44)	18.8 ± 10.9 (18)	25.2 ± 12.3 (10)
	Post-spill 2	4.6 ± 1.5 (11)	17.4 ± 12.7 (24)	1.0 (1)	28.8 ± 17.7 (5)	15.6 ± 14.2 (65)	30.5 ± 13.0 (58)	22.6 ± 17.5 (24)	22.3 ± 14.6 (9)
	Post-spill 3	10.0 (1)	15.4 ± 10.8 (39)	0	(1)	15.7 ± 12.3 (58)	26.1 ± 14.8 (50)	15.8 ± 16.3 (23)	19.2 ± 13.7 (10)
	Post-spill 4	6.0 ± 2.9 (4)	9.2 ± 11.0 (25)	—	0	17.2 ± 14.3 (34)	30.3 ± 15.6 (43)	—	24.7 ± 15.5 (10)
Myriotrochus rinkii[a]	Pre-spill 1	—	2.3 ± 1.1 (519)	2.8 ± 1.0 (216)	2.7 ± 1.0 (139)	—	3.1 ± 1.0 (127)	4.0 (1)	3.6 ± 0.8 (40)
	Pre-spill 2	2.6 ± 0.9 (159)	2.3 ± 0.8 (417)	3.1 ± 0.8 (115)	2.7 ± 1.1 (142)	3.1 ± 0.8 (36)	3.1 ± 0.9 (48)	3.5 ± 0.7 (12)	3.5 ± 0.5 (6)
	Post-spill 1	2.4 ± 0.9 (176)	2.3 ± 0.8 (417)	2.8 ± 1.0 (202)	2.4 ± 1.0 (207)	3.0 ± 0.9 (6)	2.9 ± 0.8 (92)	3.5 ± 2.1 (2)	2.8 ± 0.9 (16)
	Post-spill 2	2.5 ± 1.1 (361)	2.6 ± 0.9 (523)	2.8 ± 1.0 (209)	2.9 ± 1.0 (144)	3.6 ± 1.0 (25)	3.1 ± 0.9 (120)	3.5 ± 0.7 (2)	3.7 ± 1.4 (7)
	Post-spill 3	2.3 ± 1.2 (263)	2.7 ± 0.8 (388)	2.7 ± 1.0 (223)	2.8 ± 1.1 (134)	3.6 ± 1.0 (18)	3.4 ± 0.9 (95)	4.0 (1)	2.7 ± 1.1 (11)
	Post-spill 4	2.1 ± 1.0 (503)	2.5 ± 1.0 (486)	—	2.7 ± 1.1 (309)	3.5 ± 1.6 (6)	3.1 ± 1.1 (61)	—	2.1 ± 1.5 (9)

Data are expressed as mean ± standard deviation; numbers in parentheses are number of individuals collected and measured.

[a] Diameter of calcareous oral ring.

sampling periods, suggests that recruitment in *Mya truncata* was not necessarily affected by the oil treatments.

The second possible size-related oil effect was indicated for *Macoma calcarea* at 7 m depth in each of the analysis types that included data from only three bays (Table 5). Inspection of the data, however, gives no indication that the inconsistencies in size changes among bays were attributable to the effects of oil. In Bays 7 and 9, a similar increase in mean size occurred throughout the study period (Table 6), and population structure was also similar in the two bays (Fig. 5). Mean size in Bay 10 was more or less constant over the study period and was greater than in Bays 7 and 9 (Table 6), apparently because of higher numbers of large individuals and lower numbers of small individuals (Fig. 5). The greatest period-to-period variability in mean size occurred in Bay 11. In that case, however, mean size would be more susceptible to random variation in the size distribution of large individuals because of small sample sizes. Most of the variability in population structure of *M. calcarea* at Cape Hatt was spatial (Fig. 5). Variability among periods was also evident, both between pre-spill sampling periods and among sampling periods following the oil releases in 1981.

Thus, it appears that the oil releases had no detectable effect on the population structure of four dominant bivalve species or of the holothurian *Myriotrochus rinkii*. Population structure varied among bays, between pre-spill sampling periods and among post-spill periods. There was evidence that changes in size or population structure were not consistent among bays, but there was no evidence that these inconsistencies were attributable to the oil treatments.

Weight-Length Relationships of Bivalves

Weight-length relationships of *Mya truncata*, *Macoma calcarea*, *Astarte borealis* and *Serripes groenlandicus* were expressed by power curves ($y = ax^b$), and analyses of covariance were then used to assess among-bay and among-period variations in (1) the slopes of the regression lines and (2) dry weights adjusted for length. Bay-by-period interactions were significant in the cases of regression line slopes for *A. borealis* and adjusted mean dry weights of *M. calcarea* and *S. groenlandicus* (Table 7). Each of those interactions indicates the possibility that oil affected weight-length relationships. There was no evidence of oil effects on the weight-length relationship in *M. truncata*.

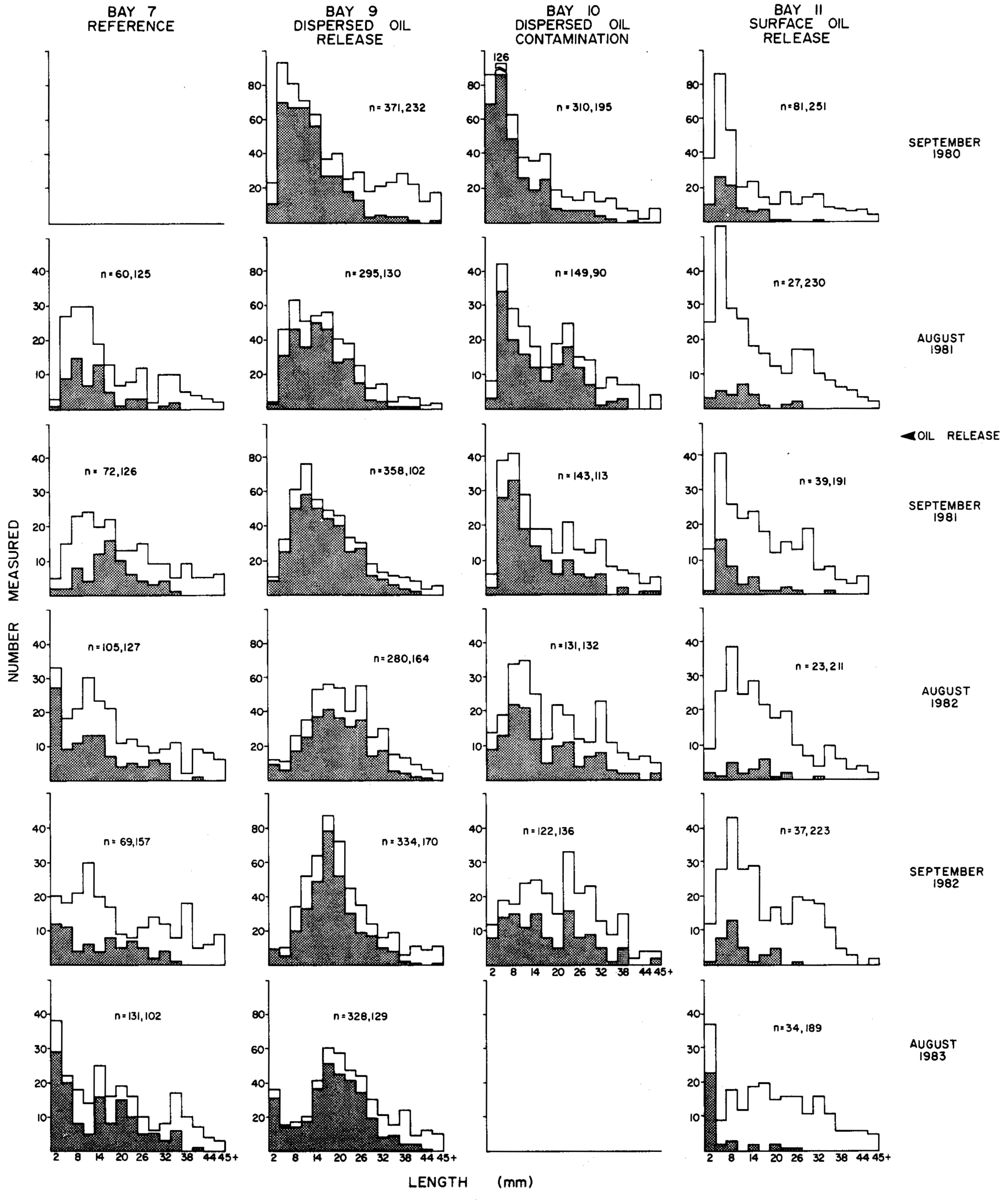

FIG. 4. Length-frequency distributions of *Mya truncata* at 3 and 7 m depths in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods, September 1980-August 1983. Sample sizes are given for 3 m depth (lower portion of each histogram), followed by 7 m depth (upper portion), and represent all undamaged individuals in 24 samples from each depth, bay and period. Note differences in vertical scales.

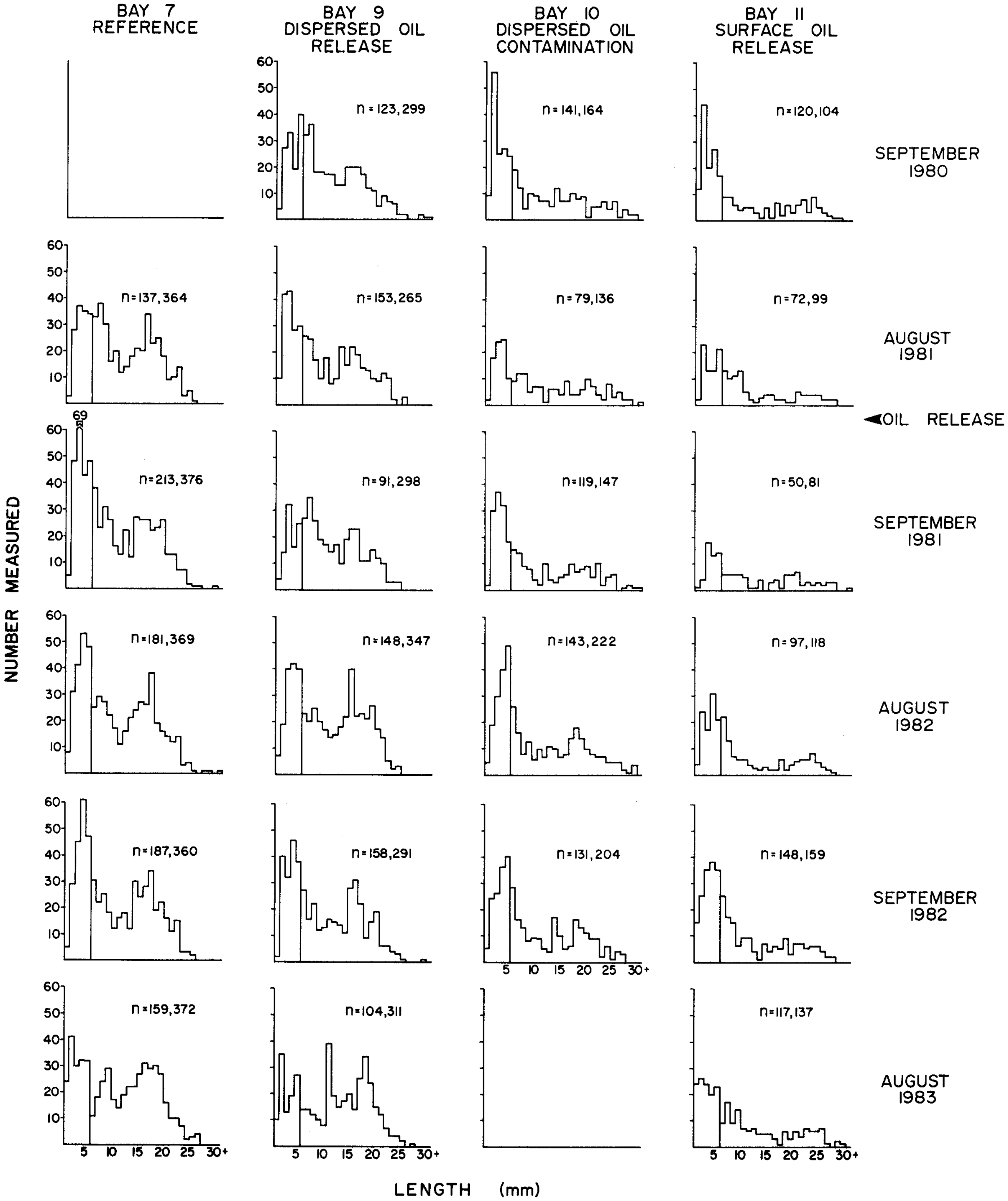

FIG. 5. Length-frequency distributions of *Macoma calcarea* (≥ 6 mm long) and *Macoma* juveniles (1-5 mm) at 7 m depth in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods, September 1980-August 1983. Sample sizes are given for *Macoma* juveniles, followed by *Macoma calcarea*, and represent all undamaged individuals in 24 samples from each bay and period.

TABLE 7. Analyses of covariance of difference in dry meat weight, using length as the covariate, for bivalves collected at 7 m depth in four bays at Cape Hatt, northern Baffin Island, during August and September 1981 and 1982

	Equality of group means				Equality of slopes			
Species	Period (df = 3)	Bay (df = 3)	Period by bay (df = 9)	Denominator df	Period (df = 3)	Bay (df = 3)	Period by bay (df = 9)	Denominator df
Astarte borealis	—[a]	15.89***	—[a]	745	3.27*	1.67 ns	1.99*	730
Macoma calcarea	4.41**	—[a]	2.96**	724	2.55 ns	9.18***	1.02 ns	709
Mya truncata	2.78*	—[a]	0.84 ns	797	0.94 ns	3.88**	1.07 ns	782
Serripes groenlandicus	7.55***	9.42***	3.70***	345	1.00 ns	0.85 ns	1.72 ns	330

F-values are shown with significance levels (ns = P>0.05; *P≤0.05; ** P≤0.01; *** P≤0.001).

[a] Results of "equality of group means" not shown because of heterogeneity of slopes.

The weight vs. length regression lines for *Astarte borealis* in each period and bay (Fig. 6) show little evidence of progressive change in slopes through time. The only such change occurred in large individuals in Bay 10; in this case the greatest apparent differences were those between the two pre-spill sampling periods. Hence, there is no evidence that either of the oil releases affected weight-length relationships in *A. borealis*.

The period-by-bay interaction effect in adjusted dry meat weight of *Macoma calcarea* is evident in Figure 7. In Bay 7, adjusted mean dry meat weight of *M. calcarea* increased between August and September in 1981 and 1982. In contrast, adjusted mean dry weight in Bays 9, 10 and 11 was relatively constant or decreased from August to September in both 1981 and 1982 (Fig. 7). The August to September increase in body tissue relative to length in Bay 7 probably represented a natural seasonal increase in storage materials that are necessary to meet metabolic requirements in winter. The lack of such an effect or its reversal in the other (oiled) bays may be attributable to the effects of oil in sediments.

Adjusted dry meat weights of *Serripes groenlandicus* show unexpected patterns (Fig. 7; data for Bays 10 and 11 are not included, because too few individuals were measured). In Bay 9, differences in weights among periods were small. In Bay 7, bivalves showed a progressive decrease in adjusted mean dry

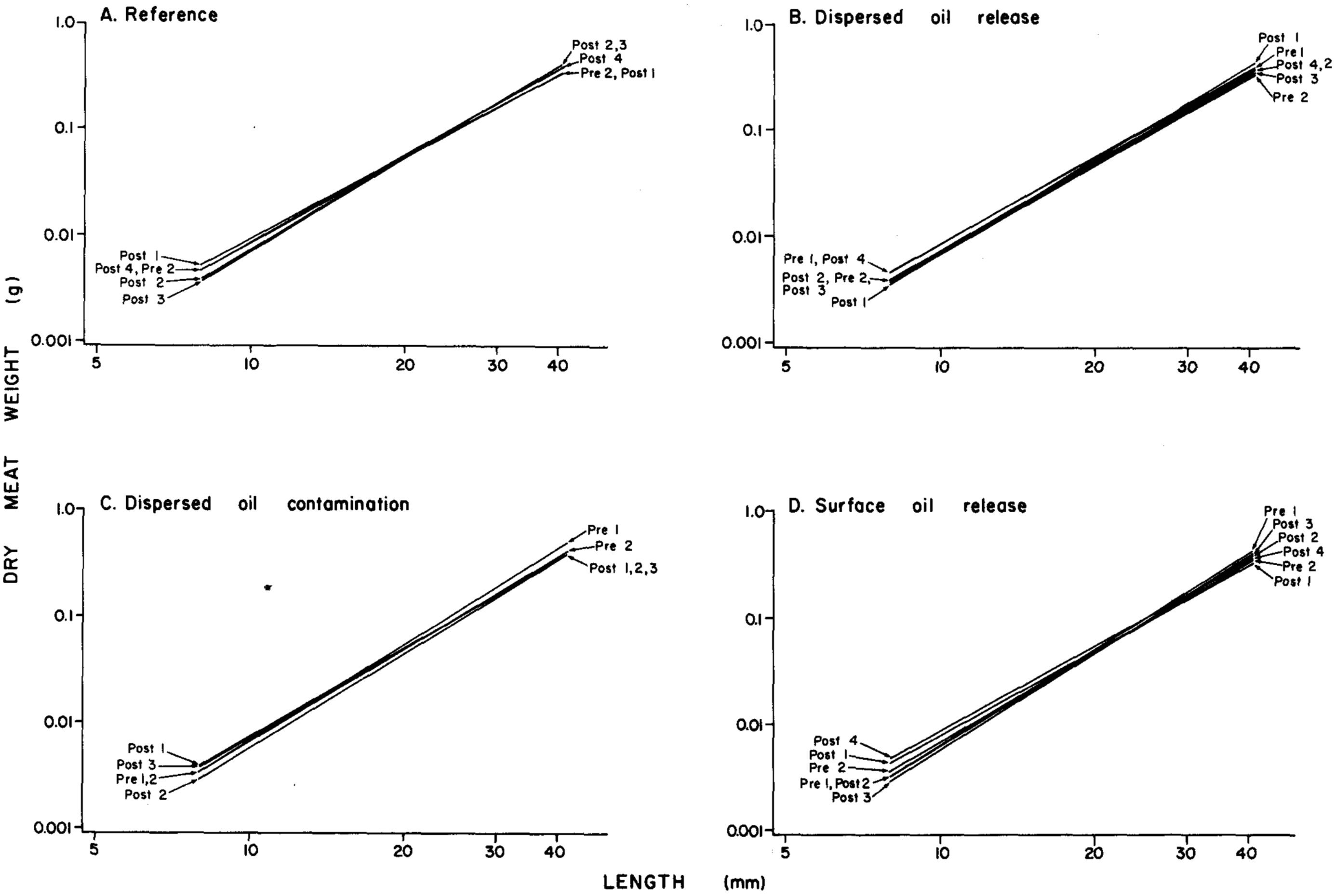

FIG. 6. Least square regression lines of dry meat weight vs. length for *Astarte borealis* in four bays at Cape Hatt, northern Baffin Island, during pre-spill sampling in September 1980 and August 1981 and during post-spill sampling in September 1981, August and September 1982 and August 1983.

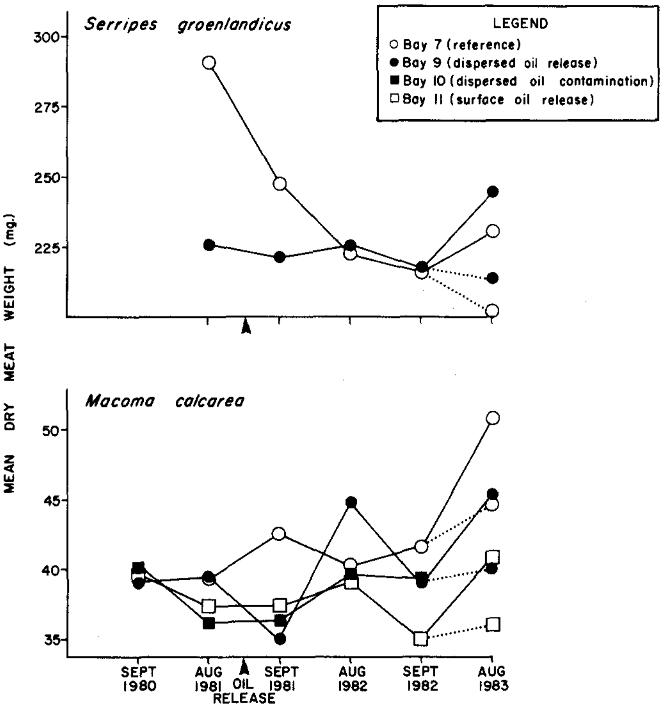

FIG. 7. Back-transformed adjusted group mean dry meat weights of *Macoma calcarea* and *Serripes groenlandicus* determined in analysis of covariance (see Methods). Animals were collected at 7 m depth in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods, September 1980-August 1983. Dotted lines show estimated correction for alcohol weight loss (see Snow *et al.*, 1987).

weight from the second pre-spill to the third or fourth post-spill periods (Fig. 7). These results were unexpected because Bay 7, the reference bay, received very low concentrations of dispersed oil. However, the body burden of hydrocarbons in *S. groenlandicus* collected in Bay 7 immediately following the dispersed oil release was similar to (in fact, somewhat higher than) that in specimens from Bay 9 (Boehm, 1983), which were exposed to much higher oil concentrations in the water column. Although the mechanism is not known, the decrease in "condition" of this bivalve can be interpreted as an effect of lengthy exposure to dilute dispersed oil.

DISCUSSION

Dispersed vs. Surface Oil Release

The primary objectives of the BIOS Project were to compare effects of dispersed and undispersed oil and to make inferences about the effects of dispersing oil with chemical agents. By design, and in reality, the exposure of benthos to chemically dispersed oil in the water column represented a "worst case" situation with respect to oil concentrations (Sergy and Blackall, 1987). Where dispersed oil concentrations as high as those at Cape Hatt have been reported during accidental or experimental spills, they have been restricted to the immediate vicinity of dispersant application (McAuliffe, 1977) or to very shallow depths (Nilsen, 1985) or have persisted for very short periods (Cormack and Nichols, 1977; McAuliffe *et al.*, 1981). At Cape Hatt, the duration of exposure to high concentrations of dispersed oil in the water column (6 h) was typical of that expected in most marine locations after an accidental spill.

Benthic animals were exposed to oil in the sediment as a result of both the dispersed and surface oil releases. The highest concentrations of oil in sediments, up to 119 ppm in Bay 11 during 1983, resulted from entry of untreated oil stranded on the beach into subtidal sediments during the second post-spill year (Boehm *et al.*, 1987; Owens *et al.*, 1987). During 1981 and 1982, particularly in the dispersed oil bays, sediment oil concentrations were low (<10 ppm) relative to those reported after major untreated spills. For example, Gundlach *et al.* (1983) considered sediments containing <15 ppm to have "little or no oil" following the *Amoco Cadiz* spill, and Sanders (1978) classified sediments containing 2.5-8 ppm as "marginally oiled and unoiled stations" after the *Florida* spill. Thus, long-term exposure of sediments to oil at Cape Hatt was far from "worst case."

Over the two years following the releases at Cape Hatt, there were detectable effects of oil on a small number of species, but neither untreated nor dispersed oil caused large-scale mortality of benthic infauna or significant change in infaunal community structure. This lack of major effects was unexpected in the case of dispersed oil, considering the severity of exposure. Similar results were obtained, however, in laboratory simulations of the dispersed oil release (Mageau *et al.*, 1987).

The lack of major effects was consistent, on the other hand, with the levels of oil in sediments. Evidence from previous laboratory studies indicates that concentrations of oil in sediments must be at least 1000 ppm to cause substantial mortality in bivalves, polychaetes and sipunculids (Gordon *et al.*, 1978; Roesijadi *et al.*, 1978; Roesijadi and Anderson, 1979; Augenfeld, 1980; Augenfeld *et al.*, 1980; Olla *et al.*, 1983, 1984). Such high concentrations are not unusual after accidental spills and have been reported to cause massive mortality and radical changes in community composition (e.g., in Wild Harbor, Massachusetts, where oil concentrations in subtidal sediments were 550-12 400 ppm following the grounding of the barge *Florida* — Sanders *et al.*, 1980). Chronic oil pollution has caused similar effects on benthos in sediments containing lower concentrations of oil, although the reported oil concentrations were higher than those at Cape Hatt. Addy *et al.* (1978, in Teal and Howarth, 1984) reported decreases in densities and numbers of benthic species at 10-25 ppm *aromatic* hydrocarbons in sediments near a storage tank in the Ekofisk oil field, and Armstrong *et al.* (1977) reported a severe reduction in numbers of benthic species and individuals at 18-21 ppm *naphthalenes* in sediments in a Texas oil field (equivalent to 96 ppm oil; Anderson *et al.*, 1978). Oil concentrations of 109 ppm in sediments of experimental enclosures resulted in substantial decreases in macrofaunal density and biomass (Elmgren *et al.*, 1980; Grassle *et al.*, 1981).

Size-Selective Mortality

The lack of significant effects on density and biomass for most species at Cape Hatt indicates that no size-selective mortality occurred. For several dominant species, this was confirmed by analysis of mean size data and inspection of size-frequency data. Possible oil effects were indicated in analyses of mean size data for the bivalves *Mya truncata* and *Macoma calcarea*, but inspection of the data showed that the observed variability in population structure and recruitment of pelagic larvae was not necessarily related to oil. Petersen (1978) also reported considerable variability in recruitment of *M. calcarea* among the years and locations studied in West Greenland, and it has been suggested that both of these species are subject to periodic spawning or periodic failure of larval development (Thorson, 1936:105; Ockelmann, 1958:242). Relatively high concentrations of oil in sediments did not affect recruitment of planktonic bivalve larvae either in field experiments (Anderson *et al.*, 1978; Hartwick *et al.*, 1982) or following accidental oil contamination of Chedabucto Bay, Nova Scotia (Gilfillan and Vandermeulen, 1978; Thomas, 1978).

Sublethal Effects

Exposure of marine invertebrates to oil may result in a number of sublethal physiological changes (see review by Connell and Miller, 1981), some of which may impair the ecological fitness of individuals (Bayne *et al.*, 1982) and become significant at population or community levels. Percy (1982) has termed those sublethal effects likely to have direct, ecologically significant consequences "critical effects" and considered effects on growth, reproduction and behaviour to be critical. In the present study, effects of oil on growth and reproduction were examined using data on mean size, size-frequency distributions and tissue growth. The only effects detected were changes in the condition (the ratio of dry tissue weight to shell length) of two of the four bivalves examined. Effects on reproductive processes in the polychaete *Spio* spp. were evident from density data. Our results concerning behaviour are restricted to field observations of short-term responses of infauna to the oil releases. Mageau *et al.* (1987) report detailed information on the behavioural responses of two infaunal species to simulations of the oil releases. Neff *et al.* (1987) report histopathologic and biochemical responses of bivalves to the oil releases.

Behaviour: Oil effects on infauna were noticeable on the first and second days following the dispersed oil release in 1981. At both 3 and 7 m depths in both the release bay and the adjacent bay, a variety of large infaunal invertebrates, particularly the bivalve *Serripes groenlandicus*, emerged from the substrate and/or assumed unnatural postures. Emergence of infauna (primarily bivalves) from the substrate has been observed previously following accidental spills (Thomas, 1973; Dow and Hurst, 1975) and during laboratory studies of oil toxicity (Taylor and Karinen, 1977; Roesijadi and Anderson, 1979; Stekoll *et al.*, 1980; Olla *et al.*, 1983, 1984; Mageau *et al.*, 1987).

Emergence of infauna from the substrate may reduce survival by increasing susceptibility to predation or to movement by currents into unfavourable habitats (Taylor and Karinen, 1977; Stekoll *et al.*, 1980; Olla *et al.*, 1984). After the oiling of Chedabucto Bay, N.S., in 1970, most *Mya arenaria* that left their burrows were eaten by predators (Thomas, 1973). In the present study, divers observed predation on surfaced bivalves by the urchin *Strongylocentrotus droebachiensis*, but the extent of infaunal mortality attributable to predation was slight. Our observations of reburial attempts, together with the lack of significant density decreases, indicate that most of the affected infauna must have recovered from narcosis and reburied themselves in the sediment. Reburial of surfaced bivalves within brief (2-7 d) recovery periods in clean water following exposure to oil has been reported previously for *Macoma balthica* (Taylor and Karinen, 1977) and for *Serripes groenlandicus* from the BIOS study area (Mageau *et al.*, 1987). The fate of soft-bodied infauna (e.g., large polychaetes and sipunculids) that emerged from the substrate is less certain, as these animals were too sparsely distributed to be adequately represented in the samples collected. However, in a previous field study most polychaetes (*Arenicola marina*) that were apparently moribund following exposure to dispersed crude oil recovered and continued to feed during the first post-spill week (Levell, 1976; Baker *et al.*, 1977). In laboratory experiments, the polychaete *Nereis virens* recovered after 96 h exposure to high concentrations (>5000 ppm) of oiled sediment (Olla *et al.*, 1984).

Condition: Condition indexes in two of the four bivalve species examined in the present study were apparently affected by the experimental oil releases. In *Macoma calcarea*, the normal seasonal (August-September) increase in tissue weight relative to length occurred only in the reference bay. *Macoma calcarea* is a deposit feeder (Ockelmann, 1958), and high concentrations of oil (275-800 ppm) were accumulated in its body tissues from sediments in the oiled bays during the two weeks following the oil releases (Boehm, 1983). In *Serripes groenlandicus*, tissue weight adjusted for length decreased progressively in the reference bay following the dispersed oil release. *Serripes groenlandicus* accumulated oil concentrations in that bay that were similar to those accumulated in Bay 9, in spite of the much lower exposure to oil, viz. 3 ppm·h with 0.12 ppm maximum in Bay 7, and 300 ppm·h with >50 ppm maximum in Bay 9 (Humphrey *et al.*, 1987). Perhaps the filtering activity of *S. groenlandicus* was not impaired in Bay 7 but was impaired in bays where dispersed oil concentrations were high (Boehm *et al.*, 1982; see also Mageau *et al.*, 1987). A similar phenomenon was reported by Clement *et al.* (1980), who found that the ability of *Macoma balthica* to concentrate Prudhoe Bay crude oil from seawater dispersions increased with decreasing oil concentrations, probably as a result of reduced siphon activity at high oil concentrations.

Thus, results of the present study indicate that the condition index in the deposit-feeding *M. calcarea* was affected by high oil concentrations in sediments, whereas that in the filter-feeding *S. groenlandicus* was affected by low oil concentrations in the water. The similarity of body burdens in *S. groenlandicus* from Bays 7 and 9, together with the decreased condition only in Bay 7, indicates the possibility that some factor other than oil may have caused the observed decrease in condition. However, it is also possible that the different exposure regimes (concentrations and times) affected uptake, metabolism or depuration in different ways and resulted in decreased condition only at low oil concentrations. If this is true, there are significant implications where harvestable resources may be exposed, as hydrocarbons were accumulated and condition was adversely affected in very low levels of dispersed oil (0.05 ppm) at relatively great distances (several km) from the dispersed oil source.

Oil in sediments has previously been reported to reduce condition indexes in *Macoma inquinata* (Roesijadi and Anderson, 1979), *Protothaca staminea* (Augenfeld *et al.*, 1980) and *Mya arenaria* (Thomas, 1978), albeit at much higher oil concentrations than those present at Cape Hatt. Long-term exposure to low levels of crude oil in water (0.3 and 3 ppm) has been reported to reduce condition index in *Macoma balthica* (Stekoll *et al.*, 1980). The authors attributed that and other indications of negative energy balance to a combination of reduced feeding and increased metabolism and concluded that such exposures would, in time, lead to population decreases. Indeed, both physiological changes and population effects were reported in *Mya arenaria* following the *Arrow* incident in Chedabucto Bay, N.S. In addition to initial massive mortality

(Thomas, 1973), long-term effects have included increased respiration rates; reduced filtration rates, assimilation ratios, condition indexes and growth of tissue and shell; and altered population structure (Gilfillan and Vandermeulen, 1978; Thomas, 1978; MacDonald and Thomas, 1982).

Reproduction: Effects of oil on reproductive processes may lead to changes in populations or communities, but such effects can be detected at the site of disturbance only for species lacking planktonic larvae. In the Arctic, many benthic species develop directly, probably including the polychaete(s) referred to as *Spio* spp. in the present study. In the Disko Bay area of West Greenland, *Spio filicornis* apparently spawned in autumn and winter, and eggs were brooded in tubes until spring. At that time the larvae, although capable of swimming, metamorphosed into benthic forms in the parental tubes (Curtis, 1977).

Oil in the sediments of the dispersed and surface oil release bays at Cape Hatt apparently inhibited a natural population increase in *Spio* spp. between 1982 and 1983. Assuming direct development, our results suggest (1) that breeding of mature adults or development of their offspring in the oiled bays was affected in autumn or winter 1982 or (2) that juveniles released onto oiled sediments in spring or summer 1983 were unable to survive. Although scant, the available literature tends to support the former interpretation. Rossi and Anderson (1976, 1978), in studies on the effects of fuel oil on the polychaete *Neanthes arenaceodentata*, reported that fecundity was suppressed at all concentrations tested, that hatching success was reduced at higher concentrations, but that rate of larval development to the feeding juvenile stage was not affected by any of the concentrations tested. Seawater-soluble fractions of crude oil reduced reproduction in another two polychaete species studied by Carr and Reish (1977).

SUMMARY OF CONCLUSIONS

1. The dispersed oil release caused immediate and widespread adverse effects, including emergence from the substrate, narcosis and death. Analysis of density data showed that most stressed animals recovered and that only a small proportion of the populations died.
2. Neither untreated oil released onto the water surface nor chemically dispersed oil released underwater resulted in massive mortality of infaunal benthos or any detectable change in community structure in the two years following the oil releases.
3. The lack of prolonged major effects of dispersed oil on infauna was unexpected, because benthos were exposed to oil concentrations in the water column considered to be "worst case" in terms of operational or experimental dispersant use in the field.
4. The lack of prolonged major effects of untreated or dispersed oil on infauna was consistent with observed concentrations of oil in subtidal sediments. Sediment oil levels were low relative to those expected for major (untreated) accidental spills. Levels expected for chronic low-level oiling were approached only after two years, when stranded untreated oil continued to leach off the beach and enter subtidal sediments.
5. Effects on infauna of the entry of stranded untreated oil into subtidal sediments were not apparent in the second post-spill year, but longer term effects of this process are not known.
6. Minor effects were found in only 3 of 72 analyses of density, biomass or size data for individual infaunal taxa. These effects, which either appeared or were still present in the second year after oiling, were:
    - a progressive decrease in the condition of the bivalve *Serripes groenlandicus*, which may have resulted from prolonged exposure to low concentrations of dispersed oil,
    - disruption of natural seasonal changes in the condition of the bivalve *Macoma calcarea* in sediments containing small amounts (<10 ppm) of untreated and dispersed oil, and
    - failure or retardation of a natural population increase in the polychaete genus *Spio* in sediments containing small amounts (<10 ppm) of untreated and dispersed oil.

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