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Wind-Driven Currents and Larval Fish Survival

by

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Abstract

We test the hypotheses that the survival of fish eggs and larvae is reduced by wind-driven
transport off the continental shelf. A simple Lagrangian model including Ekman dynamics
and vertical migrating larvae is developed to determine the cross-shelf movement of eggs and
larvae in a two-layer stratified ocean. Wind stress calculated from 6 hr geostrophic winds
for 1946 to 1986 are used in the study. Vertical migration is simulated by moving larvae
into and out of the mixed layer diurnally and is found to significantly reduce the chances
of horizontal advection by Ekman transport. No relationships are found between simulated
Ekman transport of eggs and larvae and subsequent recruitment in the 10 Northwest Atlantic
stocks investigated.

1 INTRODUCTION

Wind stress is one of the most important driving forces for currents on continental shelves (see Allen
1980, Winant 1980, Csanady 1982, for reviews). In that physical processes can effect recruitment of
marine fish species (Shepherd et al. 1985), it follows that changes in wind patterns may partially
account for the observed recruitment variability of some fish stocks. The mechanisms through
which wind may effect recruitment are many. Offshore Ekman transport driven by longshelf winds
could carry eggs and larvae off the shelf where survival is poor. An alternative hypothesis is that
onshore Ekman transport carries larvae to their inshore nursery grounds which improves their
chances of survival. Near the coast during periods of offshore Ekman transport upwelling occurs,
raising nutrient levels in the euphotic zone which may increase larval survival through enhancement
of the food supply (Bakun 1985). The primary response to longshelf winds is downwind longshelf
currents which may increase or decrease the advection of eggs and larvae from an area depending
on the strength and direction of the mean flow. This process appears to be particular important
in the California current (Chelton 1981). Available evidence indicates that cross-shelf winds are
generally of secondary importance in driving shelf circulations (Allen 1980) and, therefore, their
effect on recruitment is expected to be minimal except for eggs or larvae in the neuston. The
turbulence produced by the wind, which scales as the cube of the wind stress, causes vertical
mixing, thereby introducing nutrients into the euphotic zone and in turn this may enhance larval
survival through increased primary production. On the other hand, mixing may lead to mechanical
stress on the eggs and larvae or disperse the food source for the larvae (Bakun and Parrish 1982;
Peterman and Bradford 1987), both of which would lower larval survival. Figure 1 summarises
these various effects of wind on eggs and larvae.

Fig. 1

　　In this paper we restrict ourselves to an examination of wind-driven offshelf transport of eggs
and larvae and its possibility as a source of interannual recruitment variability for several species
off eastern Canada. Earlier studies off the eastern seaboard of the U. S. (Nelson et al. 1976) and
off California (Bailey 1981) found evidence that interannual variation in marine fish recruitment is
related to variations in wind-induced Ekman transport. Our approach has been to develop a simple
Lagrangian model of egg and larval drift based on Ekman transport. Data-driven simulations of
egg and larval transport are carried out for years between 1946 and 1986 for which recruitment
data are available. We use the results from each year's simulation model and compare it with
observed recruitment in that year. On each day during the spawning season, eggs are assumed to
be released at a specific location on the shelf. The cross-shelf position of the eggs and larvae are
then tracked for the duration of the egg and larval stages. Their trajectories are based on Ekman

transport calculated from 6-hr geostrophic wind data. The result from each year's simulation is the integral of the paths for each individual day, weighted by the proportion of eggs estimated to be spawned that day.

The model is described in Section 2 of the paper, followed by a presentation of the model results in Section 3. In section 4 we compare the model with results with the recruitment time series. In the discussion we examine patterns of interspecific variability of larval strategies with respect to Ekman transport.

2 THE MODEL

2.1 Physical Considerations

A long, straight coastline is assumed parallel to the y-axis (Fig. 1) with a distance to the shelf-slope front of B. Beyond approximately 10 km from the shore, a longshelf wind stress produces Ekman transport (M_x) to the right of the wind of a magnitude given by

$$M_x = \frac{\tau_y}{\rho f},$$ (1)

where f is the Coriolis parameter, τ_y is the y component of the wind stress, and ρ is the density of sea water. The momentum imparted by the wind stress is not evenly distributed over the entire water column but is limited to a surface frictional layer. If the upper layers are turbulent, the depth of this layer, h_e, is given by

$$h_e \approx \frac{0.4}{f} \left(\frac{|\vec{\tau}|}{\rho} \right)^{\frac{1}{2}},$$ (2)

Stratification can restrict the downward transfer of wind-induced momentum and reduce the Ekman layer depth. Under stratified conditions the Ekman layer is generally confined to approximately the depth of the upper mixed layer, h. The cross-shelf velocity (u) in the Ekman layer is then estimated from

$$u = \frac{M_x}{h_e}, \quad \text{if} \quad h_e \ll h,$$ (3)

$$u = \frac{M_x}{h}, \quad \text{if} \quad h_e > h.$$ (4)

This is referred to as a slab model because the velocities are assumed to move uniformly within the layer. The results from such models compare well with observations (Gordon 1982).

Six-hr geostrophic winds for the period 1946 to 1986 were obtained from the Canadian Atmospheric Environment Service at the grid points on the Scotian and southern Labrador shelves (Fig. 2). The data are reliable estimates of the wind over the region (Swail et al. 1984); however, they have greater directional persistence than the measured surface winds. This is the most complete data set available. Unfortunately, the data from Jan. and Nov. 1981 and Jan.-June 1983 were missing. The geostrophic estimates were adjusted by applying a constant reduction of 20% in the wind speed and 20° cyclonic rotation (Swail, V., personal communication, AES, Burlington, Ontario). The wind stress ($\vec{\tau}$) was calculated from the adjusted winds using

Fig. 2

$$\vec{\tau} = \rho_a c_d(|\vec{w}|)|\vec{w}|\vec{w}$$

where ρ_a is the density of air, $\vec{w}$ is the wind velocity, and c_d is an empirically determined drag coefficient. We used a drag coefficient determined empirically by Large and Pond (1981), i.e.

$$10^3 c_d = \begin{cases} 1.14, & \text{if } 4 < |\vec{w}| < 10 ms^{-1} \text{ ;} \\ 0.49 + 0.65|\vec{w}|, & \text{if } 10 \le |\vec{w}| < 26 ms^{-1}. \end{cases}$$

Two versions of the model were considered. In the first version we assumed that the depth of the mixed layer varied only seasonally, and calculated cross-shelf velocities from $u = M_x/h$. In the second version, we calculated cross-shelf velocities from Eq. 3 and 4. The first version is often a good approximation to velocities calculated using the wind-dependent Ekman layer depth (equation 3) particularly during periods of strong winds, or during the summer when the mixed layer is shallow and $h_e > h$. The annual variability in the depth of the upper mixed layer was estimated from monthly mean temperature and salinity data compiled by Drinkwater and Taylor (1982) for the Scotian Shelf (Fig. 3) and was fixed for all years. A similar seasonal mixed layer depth was estimated for the Labrador Shelf from data compiled by Drinkwater and Trites (1986). The use of fixed seasonal mixed layer depths may underestimate the cross-shelf current velocities in years of light winds and overestimate them during years of strong winds.

Fig. 3

In the 2-dimensional model we are using, volume conservation requires that the cross-shelf Ekman transport must be balanced by an equal volume of water flowing in the opposite direction below the mixed layer. We assumed that the return flow (u^*) occurs uniformly below the mixed layer, i.e.

$$u^* = \frac{-uh}{D - h},$$ (5)

where D is the depth of the shelf. On the Scotian Shelf, D was taken as the mean depth of the Shelf (115 m) and on the Labrador and northern Newfoundland shelves D was taken as a constant 200 m. The model of the return flow may not be correct. The compensating flow may occur in a much shallower zone such as a bottom Ekman layer or just below the mixed layer. Also on the shelves it is likely that the flow is 3-dimensional rather than 2-dimensional and that all or part of

the required return flow occurs on another portion of the shelf. Lacking the data to adequately resolve the problem we chose the simplest conceptual model.

2.2 Biological Considerations

Eggs are assumed to be spawned a distance A offshore. Let $x(t,s)$ be the distance from the coast of an egg or larvae spawned at time s which has drifted for a time t. If an egg or larvae remains in the upper mixed layer and away from the coast then

$$x(t,s) = A + \int_0^t u(t')dt', \qquad (6)$$

since

$$x(0,s) = A.$$

and where $u(t)$ be the depth-averaged velocity of the upper mixed layer due to Ekman transport. When the egg or larvae are transported near to the coast, they are assumed to remain within the near-shore zone until under the influence of an offshore Ekman transport.

Many fish and crustaceans have larvae that undergo vertical migration below the upper mixed layer. In such cases we may rewrite (6) as

$$x(t,s) = A + \int_0^t \tilde{u}(t')dt', \qquad (7)$$

where $\tilde{u}(t')$ is the velocity experienced by a vertically migrating larvae. We consider larvae that is below the mixed layer during the night and within the mixed layer at night. Therefore,

$$\tilde{u}(t) = \begin{cases} 0, & \text{if } x(t,s) = 0 \text{ and } u(t) \leq 0; \\ u(t), & \text{if } x(t,s) > 0 \text{ and } t \text{ is during the night;} \\ u^*(t), & \text{if } x(t,s) > 0 \text{ and } t \text{ is during the day.} \end{cases} \qquad (8)$$

Two separate modeling exercises were carried out. First, we investigated the general seasonal and interannual variability of larval drift by calculating the time histories of the cross-shelf movement of eggs and larvae assuming spawning every day from 1946 to 1986. The spawning site was taken to be 100 km offshore. The number of spawning days for which eggs and subsequent larvae were retained within 50 and 100 km offshore of the spawning site were determined for 3 cases: (i) 30 d and (ii) 60 d drift without vertical migration and (iii) 60 d drift with vertical migration. Second, we investigated the response of specific stocks taking into account their season of spawning, their development rate, and whether they undergo vertical migration. The proportion of eggs and larvae retained within 50 and 100 km offshore of the spawning site were calculated as an index of Ekman transport.

The timing and distribution of seasonal spawning for 10 stocks (Table 1) in the Northwest Atlantic for which recruitment data was available were determined from (1) seasonal ichthyoplankton surveys (Sherman et al. 1984; O'Boyle et al. 1984; Markle and Frost 1985; and Bonnyman 1981) and (2) seasonal surveys of spawning activity (Liem and Scott 1966, Colton et al. 1979, Martin and Drewry 1978, Fitzpatrick and Miller 1979, Scott 1983, Sinclair and Tremblay 1984). Estimates of the length of the larval period were based upon laboratory data on the temperature dependent development times of eggs and larvae (Culliney 1974, Laurence 1974, Martin and Drewry 1978) and upon observed differences in the peak spawning activity and the period of peak larval abundance (Table 2). These estimates are crude; the data they were based upon were sometimes inconsistent. One source of uncertainty is the natural year-to-year variability in spawning times and developmental rates of larvae due, for example, to changes in the ambient water temperature. There is insufficient information, however, to calculate a different spawning function and larval duration for each year.

The vertical distribution of the eggs and larvae relative to the upper mixed layer were available from discrete-depth tow on ichthyoplankton surveys.

Table. 1

Table. 2

3 RESULTS

3.1 General Response

Offshelf Ekman transport occurs mainly in summer on the Scotian Shelf (Fig. 4) when the wind stress in directed primarily longshore (Thompson and Hazen 1983) and the mixed layer is shallowest. Larvae within the mixed layer in July would be transported beyond 100 km of their spawning site about 30% of the time. Those larvae that underwent vertical migration, however, were never transported beyond 100 km (Fig. 4).

Fig. 4

The seasonal response of the larvae on the Labrador shelf to Ekman transport was similar to that of the Scotian shelf but of a reduced amplitude (Fig. 4c). This reduction is primarily due to the lower frequency of longshore winds producing offshelf Ekman transport. The offshelf transport in winter is less on the Labrador shelf because the predominant winds are from the northwest which drives onshore Ekman transport. There are few years when a larvae would be expected to reach 100 km offshore from its spawning site. Larvae that vertically migrate generally move only short distances in the offshore direction from where they spawn.

The interannual variability in offshelf transport of larvae in January and June is displayed in Fig 4. Transport is minimum in winter and maximum in the summer. Much of the summertime variation is on decadal time scales, e.g. there was a much greater probability of being transported offshore during the 1970's than in the 1950's.

The robustness of these conclusions to the choice of the depth over which the Ekman transport is distributed was tested by comparing the results using the mixed layer depth to one with a wind-dependent Ekman layer depth (equation 2,4). Little difference was found (Fig. 4) indicating our original choice of the mixed layer depth is an adequate approximation.

3.2 Specific Responses

The proportion of the larvae spawned that was retained within 50 and 100 km offshore of the spawning site for 10 stocks are shown in Table 3. We assumed cod and haddock do not vertically *Table. 3* migrate below the mixed layer and in only one year were more than 50% of the larvae beyond 50 km offshore of the spawning location. These are overestimates of the effect of offshelf transport because many cod and haddock larvae are found in the region of the pycnocline, which should reduce their offshelf transport.

If redfish larvae were in the upper mixed layer they would suffer large mortality from Ekman transport (Table 3), however, the available evidence indicates they are found in the region of the pycnocline. For the two stocks that vertically migrate only a small portion of the larvae are advected beyond 50 km. The larvae of argentine and American plaice, which do not spawn in the summer, should not be advected offshore.

4 EFFECTS ON RECRUITMENT

4.1 Statistical Methods

We now test whether offshelf Ekman transport may be responsible for a significant portion of the observed variability in recruitment of various stocks. To do this we regressed recruitment indices against our Ekman transport estimates. The residuals from this regression are checked for autocorrelation using a Durbin-Watson test. One sided significance tests were used on each regression because we were testing the *a priori* hypothesis that offshelf Ekman transport reduced larval survival. If autocorrelation in the residuals was significant at the 0.10 level, the regression was repeated using regression with autocorrelated residuals. As the assumptions of an ordinary least squares regression could not always be met, the analysis was repeated using a nonparametric *methods. The test we used is the ordering test, which is equivalent to Kendall's rank correlation* coefficient (Sokal and Rohlf 1981).

4.2 Recruitment Data

Time series of spawning stock biomass and recruitment data for 10 stocks (Table 1) came from research surveys and sequential population analysis. Sequential population analysis includes virtual population analysis (Gulland 1965), cohort analysis (Pope 1972), and related techniques which reconstruct populations from catch at age. Sequential population analysis tends to smear estimates of recruitment year classes together because of ageing errors, i.e. the year classes before and after a strong year class will be overestimated, and the strong year class will be underestimated. This problem also occurs for research vessel data, but to a much lesser extent.

The errors in estimating recruitment from research surveys will generally be less autocorrelated than the SPA, *unless there is a change in survey methods or ageing errors are large. With the* exception of the surveys for capelin abundance, which were from acoustic surveys, and silver hake from 4VWX, which were from directed larval surveys, all the research survey data came from bottom trawls. Ages of fish from the research vessel surveys were determined by otoliths except for argentine and redfish whose ages were estimated from length frequencies.

For several stocks there were reliable estimates of spawning stock biomass (Table 1). For these stocks, we attempted to remove the effect stock size by using the residuals from a stock recruitment relationship as the index of recruitment in the analysis. The stock recruitment we examined was

$$R = \alpha S^\beta$$

where R is the recruitment index, S is the estimate of spawning stock and α and β are the fitted parameters. The above function was fit using a linear regression of the logarithmically transformed data.

If a reliable spawning stock biomass was not available, then a square root transformation was applied to the recruitment data before the regression analysis.

4.3 Results

In no case was there a statistically significant relationship between recruitment and our Ekman transport indices.

5 DISCUSSION

Our model results suggest that Ekman transport does not strongly influence the survival of fish eggs and larvae and that larvae undergoing diurnal vertical migrations below the mixed layer have

a much restricted cross-shelf motion compared to those spending all their time in the upper mixed layer. In our model we assumed a 2-dimensional mass balance with the surface Ekman transport compensated by a return flow that is equally distributed in a lower layer extending from the bottom of the mixed layer to the ocean floor or 200m, whichever is less. As stated earlier, such a model may not be realistic. The return flow may occur in a shallow bottom Ekman Layer (Kundu 1977) or even elsewhere on the shelf, i.e. 3-dimensional effects may be important. Thus, the model may overestimate the influence of vertical migration by overestimating the strength of the lower layer return flow. It is clear, however, that vertical migration is likely to reduce the extent of the cross-shelf transport of larvae.

The physical component of our larval drift model is oversimplified, e.g. no consideration of longshelf drift, idealised vertical current structure, and a fixed seasonal variability in the depth of the mixed layer. Similarly the biological component was also simplified by fixing the spawning period and larval critical period. Therefore, care must be taken in interpreting the results. It is interesting to note, however, that our general conclusion of minimal larval drift due to Ekman transport is consistent with the findings of Power (1986) in a simulation model of Anchovy larvae off the California coast.

5.1 Among Species Comparisons

Offshelf Ekman transport is probably not an important source of the variability in recruitment because species have evolved adaptations to reduce its effect. One reason this is possible is that the season of offshelf Ekman transport is predictable (Fig. 4). Other sources of offshelf advection (e.g. Gulf Stream warm core rings) are not strongly correlated with the seasonal cycle. This is one reason which may explain the relative importance of Gulf Stream warm core rings for recruitment variability (Myers and Drinkwater 1986, in press).

There are several life history adaptations that will mitigate offshelf transport of eggs and larvae. For egg retention, Parrish et al. (1981) discuss the following strategies: ovoviviparous reproduction, anadromy, benthic eggs, spawning in seasons or locations with low probability of offshelf transport. For planktonic larvae there are fewer options; offshelf transport may be reduced if larvae are in a region of low offshelf transport, such as the pycnocline (Winant and Olson 1976; Kundu 1977), or if larvae vertically migrate.

We should thus expect vertical migration and residence in the region of the pycnocline to be common in regions and seasons with large offshelf transport. We predict that residence in the mixed layer for long periods of time should be rare in such regions.

We compiled data on the vertical distribution, spawning season (high or low transport) and predominant spawning locations (slope, shelf, inshore) to thest this hypothesis (Table 4). Conclusions from different studies were not always consistent. We have identified ambiguities where they occur. These categories are not meant to be exhaustive, i.e. some species appear to migrate diurnally within mixed layer (Kendall and Naplin 1981). Furthermore, the data on vertical migration is confounded by net avoidance during the day.

There are four species whose larvae are resident in the mixed layer and vertically migrate; two of these spawn during the summer, when offshelf Ekman transport is large, and two spawn in other seasons (Table 4). This is not consistent with our above hypothesis. The adults of these four species are pelagic and wide-rangeing. Pelagic species may be less susceptible to loss from the population if advected off the shelf.

The three species from the Atlantic coast spawn on the slope (redfish, argentine, and Atlantic halibut) have adaptations which reduce offshelf transport, i.e. they are ovoviviparous or the eggs are in the region of the pycnocline.

6 ACKNOWLEDGMENTS

7 Figure legends

Fig. 1. Possible effects of wind on larval fish survival.

Fig. 2. Regions used in the analysis and the location of the grid where the Ekman transport indices were calculated.

Fig. 3. Depth of mixed layer for the Scotian shelf.

Fig. 4. Results of model predictions for the proportion of larvae retained within 50 km (—) and 100 km (···) offshore. The seasonal model is the average proportion transported beyond the range from 1946 to 1986. In all cases the months refer to the month the eggs or larvae began drifting. Scotian shelf with seasonal mixed layer depth (a), Scotian shelf with variable Ekman depth (b), and Labrador shelf with seasonal mixed layer depth (b).

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Table 1. Recruitment data used in the analysis. The location of the stock is given by the North Atlantic Fisheries Organization (NAFO) designation. The method used to obtain the recruitment data is from Sequential Population Analysis (SPA) or from research vessel (RV) surveys. For the RV surveys, the ages that were used for the analysis are given in parenthesis. The data sources are: NAFO Scientific Research Council Documents or Canadian Atlantic Scientific Advisory Committee (CAFSAC) Research Documents.

NAFO	Years	Method	Source
Cod (*Gadus morhua*)			
2J3KL	58-81	SPA	Baird and Bishop, CAFSAC Res. Doc. 87/42
4VsW	57-85	SPA	Sinclair and Smith, CAFSAC Res. Doc. 87/72
4X	47-83	SPA	Campana and Sinclair, CAFSAC 87/30
Haddock (*Melanogrammus aeglefinus*)			
4VW	47-84	SPA	Zwanenburg and Fanning, CAFSAC Res. Doc. 87/103
4X	61-84	SPA	O'Boyle and Wallace, CAFSAC Res. Doc. 87/101
Redfish (*Sebastes sp.*)			
4VWX	69-85	RV(1+2)	Zwanenburg and Hurley, CAFSAC Res. Doc. 87/35
American Plaice (*Hippoglossoides platessoides*)			
4V	66-84	RV(3+4)	Neilsen and Perley, CAFSAC 86/48
Silver Hake (*Merluccius bilinearis*)			
4VWX	69-83	SPA	Fanning et al., NAFO SCR Doc. 87/56
Herring (*Clupea harengus*)			
4WX	64-84	SPA	Stephenson et al., CAFSAC 87/75
Argentine (*Argentina silus*)			
4VWX	68-83	RV(2)	Dale and Halliday, CAFSAC Res. Doc. 87/19

Table 2. The proportion of eggs that were assumed to be spawned in each month. Cod from NAFO divisions 4VsW and 4X begin to spawn November and December of the year previous to their nominal year class.

NAFO	Nov	Dec	Jan	Feb	Mar	Apl	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cod														
2J3KL	0	0	0	0	.50	.50	0	0	0	0	0	0	0	0
4VsW	.30	.30	.25	.15	0	0	0	0	0	0	0	0	0	0
4X	0	.15	.15	.05	.40	.20	.05	0	0	0	0	0	0	0
Haddock														
4VW	0	0	0	0	.10	.40	.40	.10	0	0	0	0	0	0
4X	0	0	0	.10	.35	.50	.05	0	0	0	0	0	0	0
Redfish														
4VWX	0	0	0	0	0	0	.05	.30	.30	.30	.05	0	0	0
American Plaice														
4VWX	0	0	0	0	.25	.25	.25	.25	0	0	0	0	0	0
Silver Hake														
4VWX	0	0	0	0	0	0	.05	.15	.30	.30	.15	.05	0	0
Herring														
4WX	0	0	0	0	0	0	0	0	0	.80	.20	0	0	0
Argentine														
4WX	0	0	0	0	.33	.34	.33	0	0	0	0	0	0	0

Table 3. The proportion of larvae from 1946-1986 advected a distance B from the shore if larvae are spawned a distance A from the shelf. The assumed critical period, T_{crit}, and whether the larvae are assumed to undergo vertical migration (V.M.) is also given. The spawning period is given in Table 2. See text for details.

		Assumptions			Proportion Advected			
NAFO	A	B	T_{crit}	V.M.	$P < 50$	$50 \leq P < 80$	$80 \leq P < 95$	$95 \leq P$
Cod								
2J3KL	160	210	60		0	0	3	97
4VsW	160	260	45		0	0	0	100
4VsW	160	210	45		3	26	8	63
4X	160	260	45		0	0	0	100
4X	160	210	45		3	5	18	74
Haddock								
4VW	160	260	45		0	0	8	92
4VW	160	210	45		0	20	50	30
4X	160	260	45		0	0	0	100
4X	160	210	45		0	7	5	88
Redfish								
4VWX	160	210	50		72	10	5	13
American Plaice								
4VWX	160	260	50		0	13	2	85
Silver Hake								
4VWX	160	210	30	yes	0	0	0	100
Herring								
4WX	160	260	90	yes	5	5	0	90
Argentine								
4VWX	160	260	50		0	0	0	100

TABLE 4. Spawning location, egg strategies, and larval strategies, for species on the East and West Coasts of North America. Egg strategies have been classified as resident in the region of the pycnocline (PY.), resident in the mixed layer (M.L.), Benthic (B.), or ovoviviparous (OVI.). The same classification applies to the larval stage; however, only three of the categories are relevant.

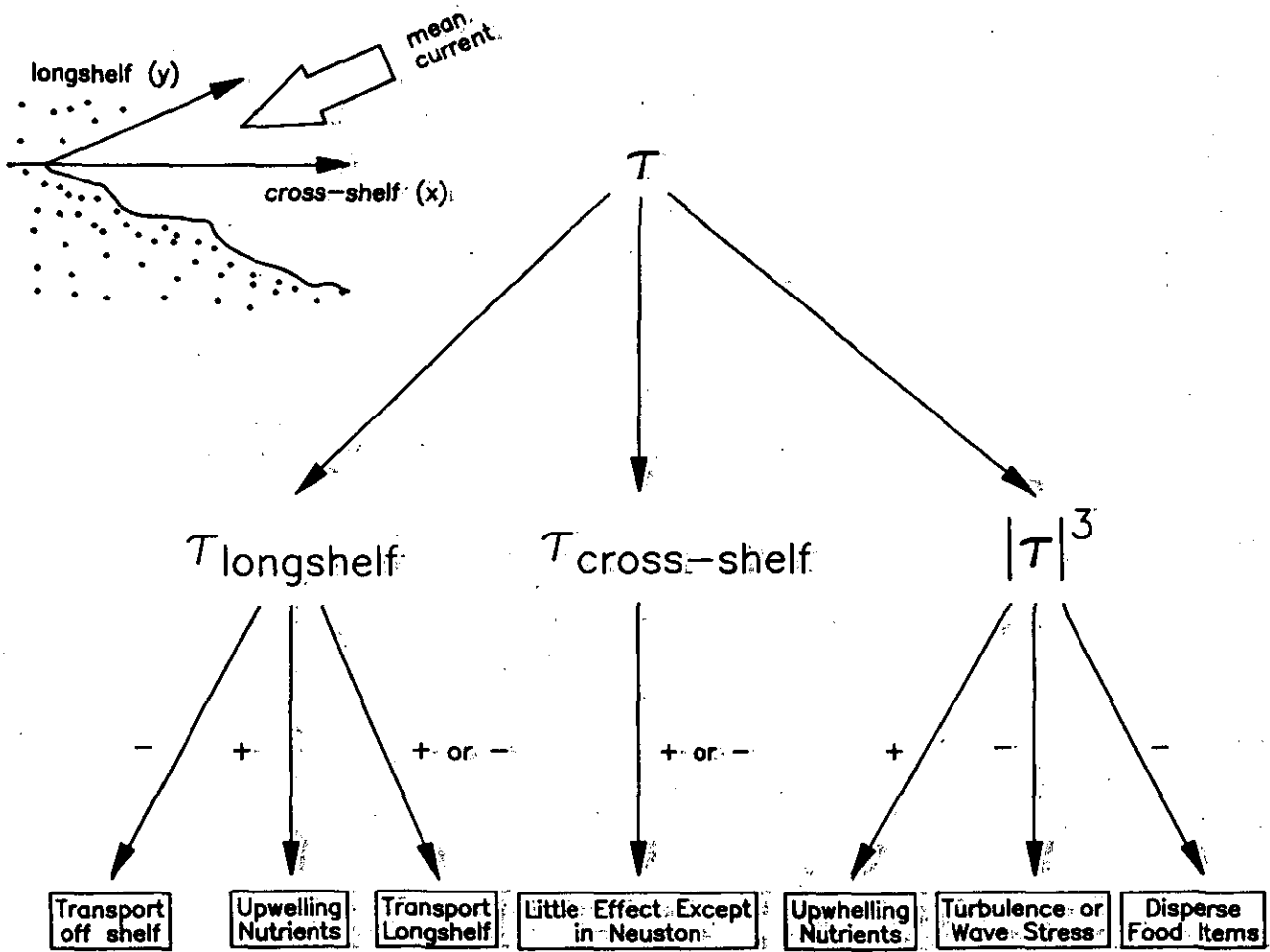| Scientific Name	Common Name	Spawning	Egg Strategy	Larval Strategy	References
MID ATLANTIC BIGHT TO SCOTIAN SHELF (FALL/WINTER/SPRING)					
Argentina silus	Atlantic argentine	slope	PY.	?	Southward & Bary 1980
Auxis sp.	Frigate mackerel	shelf	?	M.L.	Kendall & Naplin 1981, Fritzsche 1978
Ammodytes sp.	Sand lance	shelf	B.	V.M.	Sherman et al. 1984, Fritzsche 1978
Brevoortia tyrannus	Atlantic menhaden	shelf	M.L.	M.L.?	Hardy 1978, Nelson et al. 1977
Clupea harengus	Atlantic herring	shelf	B.	V.M.	Jones et al. 1978, Wood 1971
Gadus morhua	Atlantic cod	shelf	M.L.	PY. ML?	Hardy 1978, Lough 1984
Melanogrammus aeglefinus	Haddock	shelf	M.L.	PY. ML?	Hardy 1978, Miller et al. 1963, Lough 1984
Myoxocephalus octodecemspinosus	Longhorn sculpin	inshore	?	V.M.	Colton et al. 1979, Fritzsche 1978
MID ATLANTIC BIGHT TO SCOTIAN SHELF (SUMMER [UPWELLING])					
Citharichthys arctifrons	Gulf stream flounder	shelf	M.L.	V.M.	Kendall & Naplin 1981, Markle & Frost 1984,
Glyptocephalus cynoglossus	Witch flounder	shelf	pelagic	V.M.	Sameoto & Lewis 1979, Martin & Drewry 1978
Paralichthys oblongus	Fourspot flounder	shelf	M.L.	V.M.	Kendall & Naplin 1981, Martin & Drewry 1978
Hippoglossus hippoglossus	Atlantic halibut	slope	PY.	?	Haug et al. 1984
Limanda ferruginea	Yellowtail flounder	shelf	M.L.	V.M.	Martin & Drewry 1978, Smith et al. 1977,
Merluccius bilinearis	Silver hake	shelf	M.L.	PY.,V.M.	Kendall & Naplin 1981, Sameoto & Lewis 1979
Scomber scombrus	Atlantic mackerel	shelf	M.L.	M.L.	Murray et al. 1983, Liem & Scott 1966
Scophthalmus aquosus	Windowpane flounder	shelf	pelagic	V.M.	Markle & Frost 1984, Sameoto 1984
Sebastes spp.	Redfish	slope	OVO.	PY.	Sameoto & Lewis 1979, Kelly & Barker 1961
Tautogolabrus adspersus	Cunner	inshore	M.L.	V.M.	Fritzsche 1978, Harding et al. 1986
Urophycis chuss	Red hake	?	?	?V.M.	Markle et al. 1982
Urophycis tenuis	White hake	shelf	pelagic	?V.M.	Hardy 1978, Markle et al. 1982
Etropus microstomus	Smallmouth flounder	inshore	M.L.	V.M.	Kendall & Naplin 1981, Martin & Drewry 1978
Glyptocephalus cynoglossus	Witch flounder	inshore	pelagic	V.M.	Sameoto & Lewis 1979, Martin & Drewry 1978
Peprilus triacanthus	Butterfish	shelf	M.L.	V.M.	Kendall & Naplin 1981, Martin & Drewry 1978
Pomatomus saltatrix	Bluefish	shelf	M.L.	M.L.	Kendall & Naplin 1981, Hardy 1978

longshelf (y)

mean current

cross-shelf (x)

$\mathcal{T}$

$\mathcal{T}_{\text{longshelf}}$

$\mathcal{T}_{\text{cross-shelf}}$

$|\mathcal{T}|^3$

$-$ $\quad$ $+$ $\quad$ $+$ or $-$ $\qquad$ $+$ or $-$ $\qquad$ $+$ $\quad$ $-$ $\quad$ $-$

| Transport off shelf | Upwelling Nutrients | Transport Longshelf | Little Effect Except in Neuston | Upwhelling Nutrients | Turbulence or Wave Stress | Disperse Food Items |

Fig. 1.   Possible effects of wind on larval fish survival.
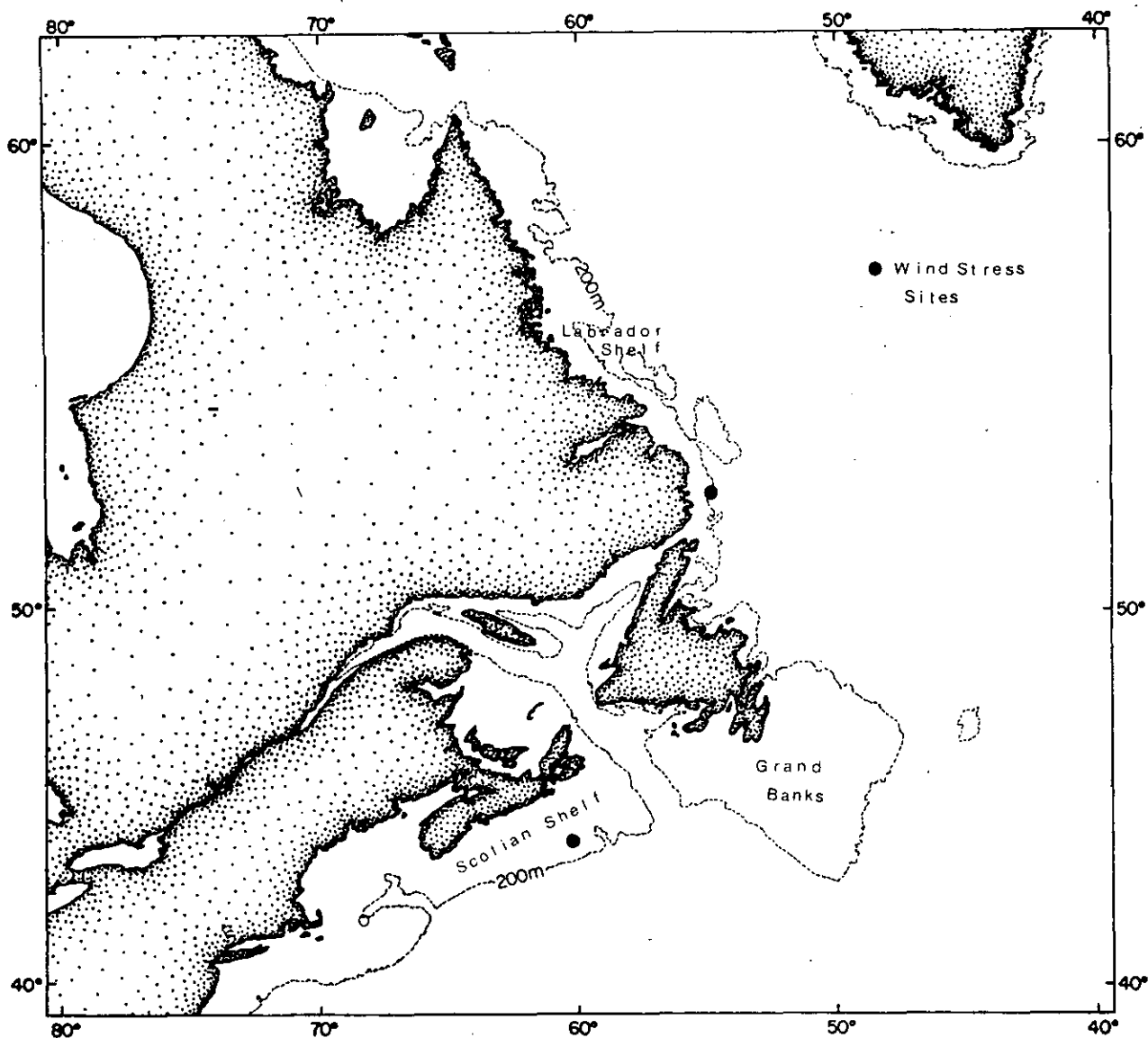
Fig. 2. Study region showing the location of the wind stress
sites where Ekman transport indices were calculated.
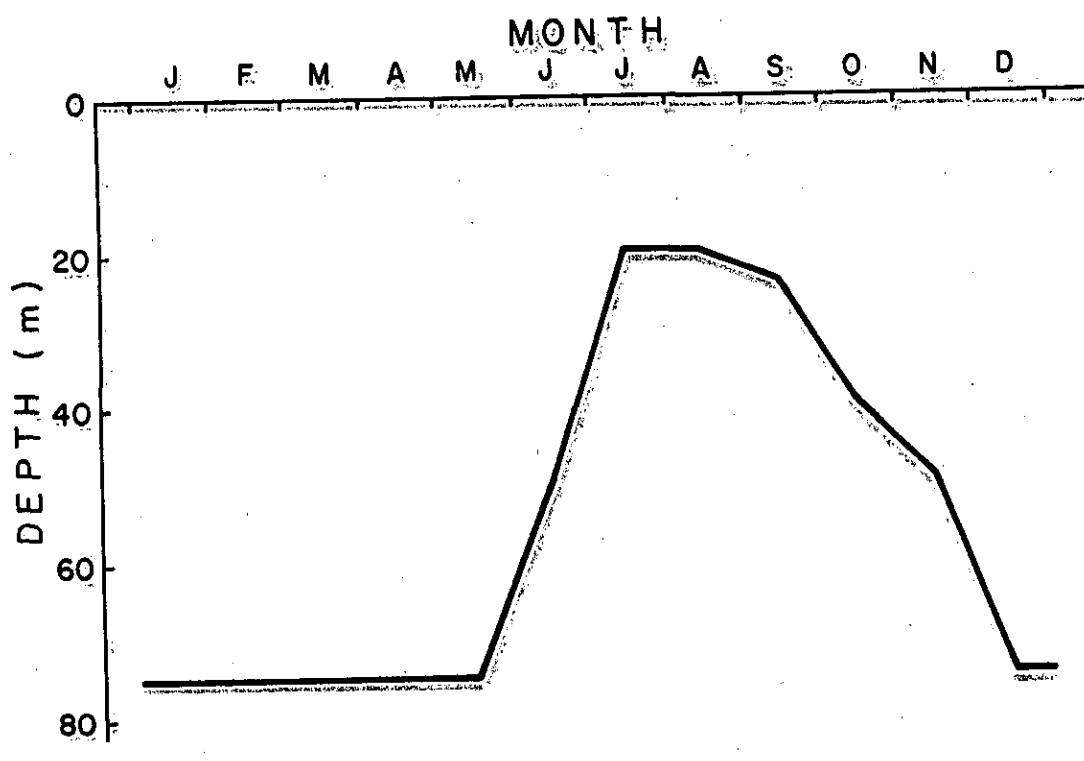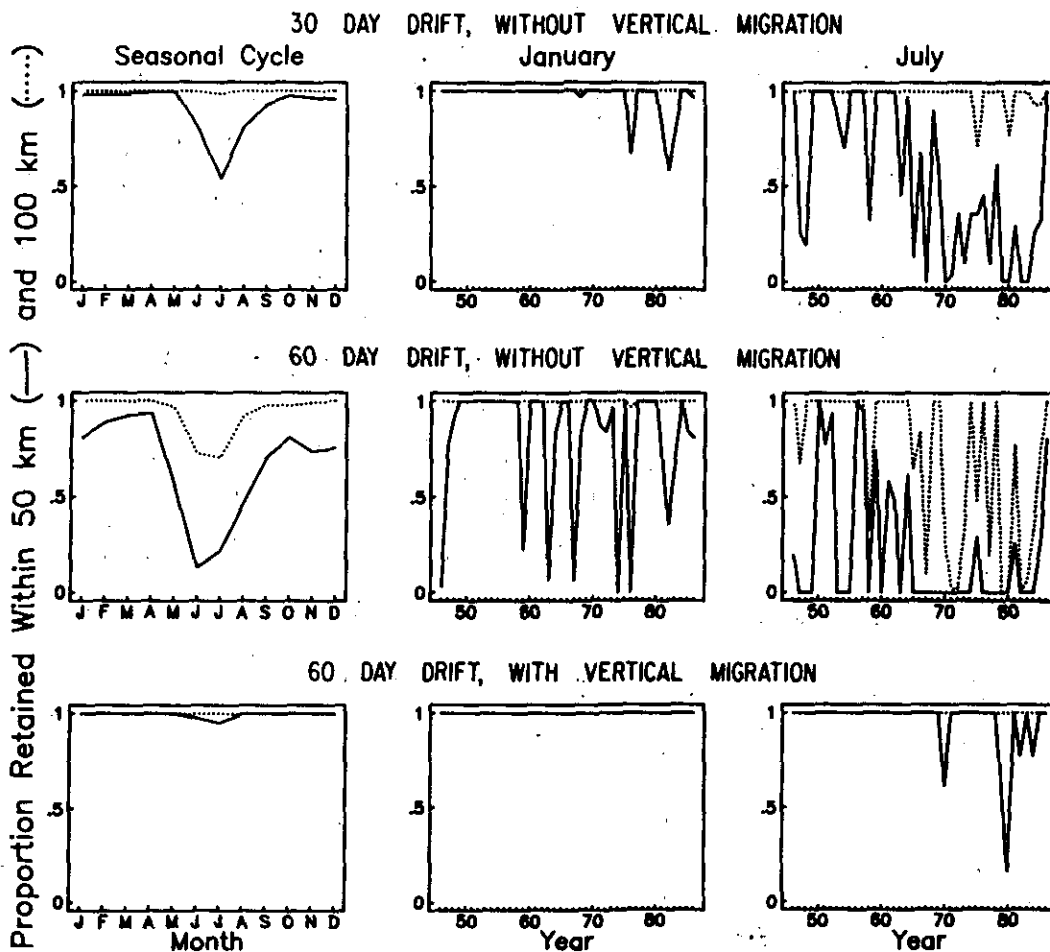
Fig. 3.   Mixed layer depth.

Fig. 4a. Model predictions for the proportion of larvae retained within 50 km (——) and 100 km (...) offshore. The seasonal model is the average proportion transported beyond the range from 1946 to 1986. In all cases the months refer to the month the eggs or larvae began drifting. The results are for the Scotian Shelf using the seasonal mixed layer depth.
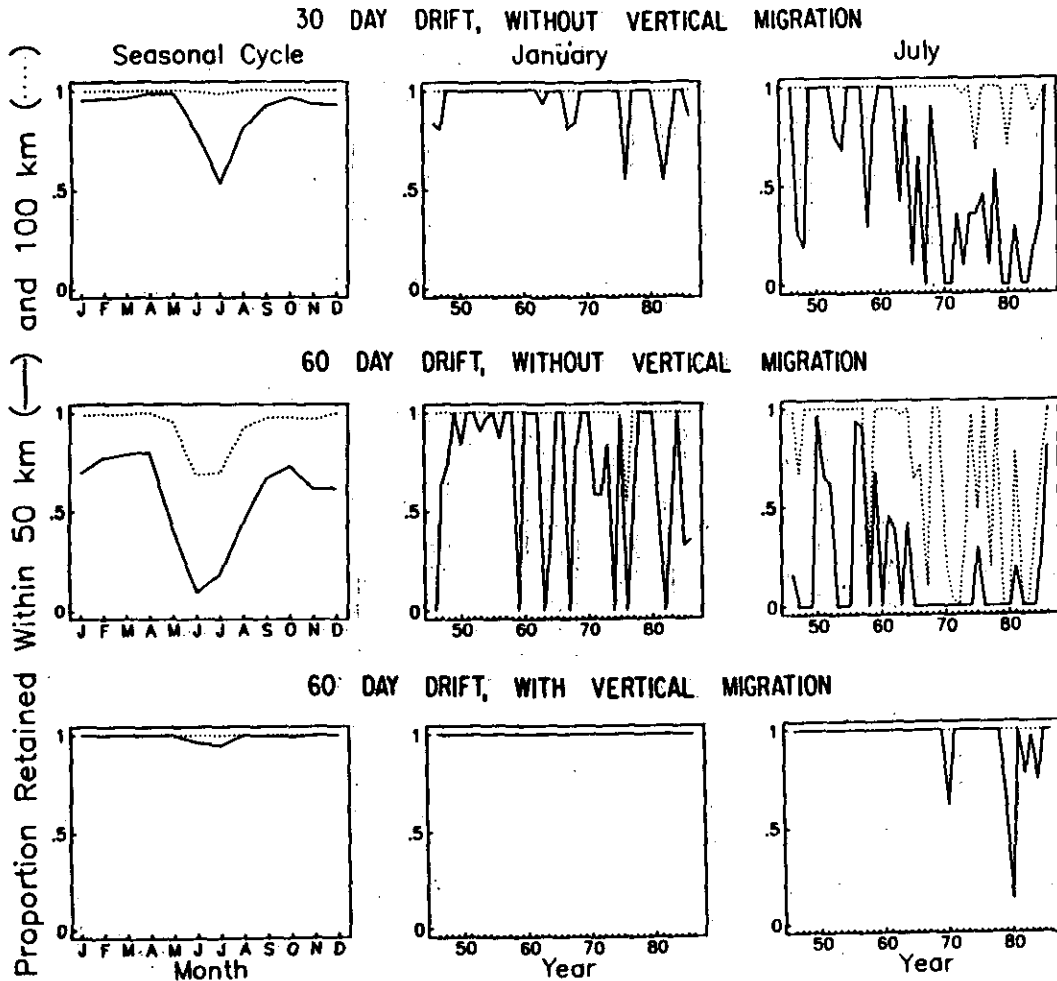
Fig. 4b. Model predictions for the proportion of larvae retained within 50 km (——) and 100 km (...) offshore. The seasonal model is the average proportion transported beyond the range from 1946 to 1986. In all cases the months refer to the month the eggs or larvae began drifting. The results are for the Scotian Shelf using a wind-dependent Ekman depth.
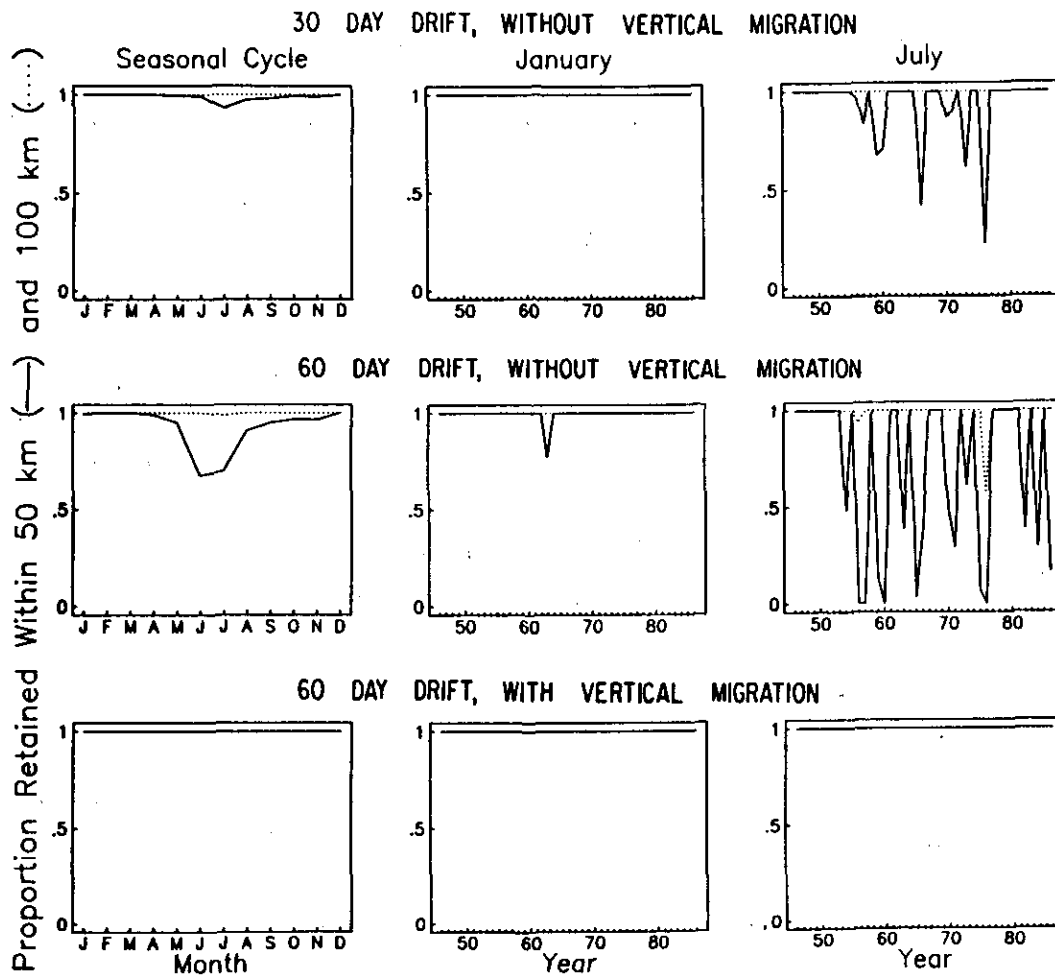
Fig. 4c. Model predictions for the proportion of larvae retained within 50 km (——) and 100 km (...) offshore. The seasonal model is the average proportion transported beyond the range from 1946 to 1986. In all cases the months refer to the month the eggs or larvae began drifting. The results are for the Labrador Shelf using the seasonal mixed layer depth.