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Modelling the Drift of Lobster Larvae off Southwest Nova Scotia.

Modélisation de la dérive des larves de homard sur la côte sud-ouest de la Nouvelle-Écosse.

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Abstract

The potential source of the lobster larvae in the Lobster Bay off southwest Nova Scotia is examined by modelling larval drift. Larvae are inserted at a fixed depth into a climatological circulation model from known spawning sites on Georges, Browns and German banks in the offshore of the Gulf of Maine and within Lobster Bay itself. Drift tracks are determined during the summer under varying directional but steady amplitude winds as well as weekly varying winds based on 1988 observations. The model indicates the possibility of particle exchange among many of the offshore (> 50 m isobath) release sites (e.g. Browns, German and Georges Bank) but the probability is low. Few larvae from the offshore banks are found to make it into the inshore zone (< 50 m) of Lobster Bay because of the existence of convergence at the tidal-mixing front over Lurcher Shoals. Based upon our drift model results to date, it would appear that the most likely source of lobster larvae for the inshore area of Lobster Bay is local production. In the deeper midshore region off Lobster Bay, the primary sources of larvae lobster appear to be from German Bank and Browns Bank. Few, if any, of the modelled larvae are transported from Georges Bank towards southwest Nova Scotia. It must be cautioned, however, that these results have not included the effects of vertical migration of the larvae, possibility of directional swimming by the larvae, temperature-dependent larval stage durations, or realistic wind fields.

Résumé

On tente d’établir la source des larves de homard dans la baie Lobster, située sur la côte sud-ouest de la Nouvelle-Écosse, en modélisant leur dérive. Des larves issues de frayères connues sur les bancs Georges, Browns et German, situés dans les eaux profondes du golfe du Maine, ainsi que dans la baie Lobster ont été mises en circulation à une profondeur fixe dans un modèle de circulation climatologique. Les trajectoires de dérive pendant l’été ont été établies dans des conditions de vent de direction variable mais d’amplitude constante, ainsi que de conditions de vents variant chaque semaine d’après des observations faites en 1988. Le modèle a révélé la possibilité d’un échange de particules entre de nombreux sites hauturiers (isobathe > 50 m) de mise en circulation (p. ex. bancs Browns, German et Georges), mais il est peu probable que cela soit le cas. On a établi que peu de larves provenant des bancs hauturiers sont transportées vers les eaux côtières (< 50 m) de la baie Lobster à cause de l’existence d’une convergence au niveau du front de brassage de marée sur le haut-fond Lurcher. D’après les résultats du modèle de dérive, il semble que la production locale soit la source la plus probable de larves de homard pour les eaux côtières de la baie Lobster. Dans la zone semi-hauturière plus profonde située au large de cette baie, les principales sources de larves semblent être les bancs German et Browns. Peu, sinon aucune, des larves modélisées sont transportées du banc Georges vers le sud-ouest de la Nouvelle-Écosse. On doit toutefois rappeler que ces résultats n’incluent pas les effets de la migration verticale des larves, la possibilité qu’elles nagent dans une direction particulière, la durée des stades larvaires, dépendante de la température, ou les champs de vent.

Introduction

Recent studies in the Gulf of Maine have suggested that there is a strong relationship between the abundance of settling lobsters in an area and subsequent recruitment to the commercial landings (Incze et al., 1997). This lead to a conclusion reached at the joint US-Canada workshop on lobster research in the Gulf of Maine, held in St. Andrews, N.B., in November 1998, that the interannual variability in recruitment is therefore strongly linked to larval supply. This supports our earlier study which found a positive correlation (r = 0.61) between stage IV production in the southern Gulf of St Lawrence from the Northumberland Strait 15-year larval surveys between 1949 to 1963 and adjacent lobster landings lagged 4 or 8 years (Harding et al., 1982). The principal sources of larvae for various lobster grounds in the Gulf of Maine are, at present, unclear but the larval release sites are generally well known. The fate of hatched larvae depends on the local current regime and environment in the release area and downstream before settlement. The larval duration in the water column depends on the thermal properties of environment and also on their food supply. Larval depth selection and horizontal swimming behaviour of the final planktonic stage could substantially modify predictions of trajectories based entirely on residual drift modelling (Incze et al., 1997).

As part of CLAWS I (Canadian Lobster Atlantic Wide Study) we undertook to model the spatial and temporal relationships of larval lobsters starting with known larval hatching and release sites, including subsequent drift and/or swimming (in the case of stage IV), and ending in predicted settlement areas in the Canadian sector of the Gulf of Maine/Bay of Fundy region. This involves the incorporation of information on larval development and behaviour with larval release sites in an improved 3-D finite-element, shelf circulation model to predict possible drift or retention scenarios. The main area of concern is whether offshore hatching grounds around Georges, Browns or German Bank (Fig. 1) are primary sources of larvae for recruitment to inshore regions off southwestern Nova Scotia and where do those larvae that hatch inshore settle. The predictions from the circulation model can be verified by the results of tracking GPS-ARGOS buoys and larval lobsters, moored current meter results and known distributions of stage IV lobster concentrations.

This paper presents improvements to the existing circulation model through better resolution of the near-surface wind-driven layer. This was carried out because the later stage lobster larvae are mostly found in the upper few metres of the ocean. Our efforts to date have focussed on the identification of drift patterns from lobster spawning areas at fixed vertical levels in summer fields for various steady wind conditions. In addition, weekly varying winds from 1988 have been used to explore the differences in drift tracks between larvae hatched at different times during the season. Some facets of larval behaviour (e.g. vertical movements, swimming, etc.) and physiology (projected “real-time”, temperature-derived, larval development) will be incorporated into this circulation model in the near future.

The Model

Description

Our study uses 3-d summer flow fields from the finite-element numerical models applied to the Scotian Shelf and Gulf of Maine in recent GLOBEC (Global Ocean Ecosystem Dynamics) and PERD (Panel for Energy, Research and Development) studies. The primary model is the prognostic advanced-turbulence model QUODDY4 developed at Dartmouth College (Lynch et al. 1996; Naimie 1996) and recently used to obtain climatological seasonal-mean and M_2 velocity fields for the western and central Scotian Shelf (Hannah et al. 2001; Shore et al. 2000). It is used in a "prognostic refinement" mode; i.e. the model adjusts the density field from its initial state in order to be dynamically consistent with the flow field. Within the CLAWS I project, the model was improved to include more realistic physics in the very near surface layer (upper few meters). This was carried out because of the potential importance of wind-driven drift of lobster larvae within this layer, particular the later stage larvae. It was achieved by using QUODDY4 together with several other models, including the linear model FUNDY5 (Naimie and Lynch 1993) recently used to describe the regional response to wind stress (Greenberg et al. 1997), the 1-d advanced turbulence model NUBBLE (Naimie 1995), and analytical solutions for the surface log layer (top 1 m) within the Ekman layer (Madsen 1977). The Madsen model suggests an additional wind-induced drift component in the top meter that is 0.4% of the wind velocity. These additions provide a more realistic near-surface current structure. Incorporating the order 10-cm vertical resolution required to resolve the surface log layer directly into the 3-d nonlinear model was considered to be not worth the extra computational demand in view of other unresolved physics (e.g. waves) in the near-surface region, hence the reason for the combination of models.

Climatological drift simulations of lobster larvae are carried out by combining the summer-mean and M_2 tidal flow fields obtained from the prognostic advanced-turbulence 3-d model under forcing by summer-mean density and wind stress (0.02 Pa towards 32 degrees, i.e. predominantly southwesterly winds). The density field was estimated from the historic hydrographic database assembled at the Bedford Institute (Petrie et al. 1996). The procedure for estimating the density field and the summer field (estimated for 1 August) appear in Loder et al. (1997). The simulated flow field is similar to the summer field modelled by Hannah et al. (2001) except for the addition of increased turbulence in the surface Ekman layer through altered surface boundary conditions. The latter are considered to be more realistic. The mean currents include a climatological wind-driven Ekman layer in the upper 5 m overlying the flows driven by tides and the pressure gradients associated with density and wind forcing.

Potential drift pathways of lobster larvae in the 3-d flow fields are identified by numerically tracking particles at fixed depths using the program DROG3D (Blanton 1995). Mean and tidal flow components are used with random horizontal kicks included to represent unmodelled flow components (Hannah et al. 1998). The latter are modelled by assuming a horizontal diffusivity of 25 m^2s^{-1}, which represents background turbulent velocities. This leads to a slightly larger spread in the drift tracks but does not significantly alter the flow patterns.

Flow Fields

The modelled climatological circulation averaged over the top meter and at 10 m is shown in Fig. 2. The main features are consistent with previously published reports of the observed mean circulation including the anticyclonic circulation around Georges Bank with particular intense flows on the northern edge, a cyclonic circulation over the central Gulf of Maine, a southwestward flow along coastal Maine, an intensified northward flow over Lurcher Shoals off southwest Nova Scotia, and an anticyclonic gyre over Browns Bank. On the Scotian Shelf, the predominant southwestward flow at 10 m is consistent with the historic view of the circulation. The strong eastward flow in the top meter is the Ekman response to the mean southwesterly winds. The flows along the shelf edge and farther offshore in the slope water region are not well resolved. The model was originally developed to examine shelf dynamics and circulation patterns. The Gulf Stream was not modelled and the strong northeastward flow off the shelf (Fig. 2) is not considered realistic. Also because of the shelf emphasis, the model only has crude resolution of both the shoreline and near shore topography; therefore, the very nearshore currents may differ substantially from the true flows.

Comparison with Current Observations

Comparisons have been made between the model circulation under climatological conditions and moored (Eulerian) current observations over the shelf (Naimie 1996; Hannah et al. 2001). These studies show good qualitative and generally reasonable quantitative agreement between model and observed currents, including on Georges Bank, Browns Bank, and the outer edge of Lurcher Shoals. In spite of these agreements, slight differences in direction in key areas could cause large differences in actual and predicted particle tracks. It is thus important to compare particle tracks with drifting buoy data. The corresponding model field for spring has been found to be in general agreement with the mean flow over Browns Bank inferred from drifters drogued at 10 m (Shore et al. 2000; Smith 1989). Further, modeled tracks of particles released on Browns have been compared to drifters released from the Bank during the CLAWS I cruise in August 1998 (Fig. 3). The model tracks show some recirculation on Browns Bank but with substantial movement off the Bank on the north side. Model particles exiting on the northwestern side of the Bank tended to flow relatively rapidly to the north while those exiting from the northeast side moved eastward and at a slower rate. Drift buoys released in 1998 show similar behaviour. Good quantitative agreement has also been shown between model and observed drift tracks drogued at 10 m during a strong wind event in 1998 on Browns Bank. The model was run with the appropriate storm winds and the Ekman layer depth was adjusted to reflect these increased wind speeds. Our conclusion is that the model does a reasonably good job in recreating the near surface currents and drift patterns within the Gulf of Maine and on the southwestern Scotian Shelf. Flows at the shelf edge off Browns Bank in summer, over the continental slope, close inshore and in the Bay of Fundy are considered less reliable.

Modeling Larval Drift

To determine the possible sources of larvae to the region off southwest Nova Scotia, particles were released in the model flow field and advected for specified durations of up to 60 d. Developmental times for larvae under the observed climatological temperature fields range from approximately 30 d to just over 60 d depending on the temperature. Warmer temperatures reduce the duration of the larval stages. The larvae were released at a specific depth or depth layer and were not allowed to vertically migrate. We specified four separate release regions, one on each of Georges Bank, Browns Bank, and German Bank and in Lobster Bay (Fig. 4). On Georges Bank larvae were released on the northern flank in depths between 60 and 100 m based upon lobster surveys taken during the 1980s and 1990s (Harding et al. 2000). On Browns Bank they were released on its western side also in depths of 60-100 m, again based upon larval surveys presented in Harding et al. (2000). Model particles were seeded every kilometer in both horizontal directions resulting in a total of 568 being released on northern Georges Bank and 649 on western Browns Bank. German Bank and Lobster Bay releases covered the entire Bank and Bay, respectively. For these regions we seeded particles every 1.5 km resulting in 622 particles released over German Bank and 537 particles within the Lobster Bay region. Particles were tracked using the model currents averaged over the top meter, averaged over the top 5 m, and at 10 m. The first two are within the Ekman layer and so are strongly affected by the wind, with the magnitude of the dependency decreasing with depth. The 10 m depth is below the Ekman layer in the case using the climatological winds and hence the wind response at this depth is primarily through pressure gradients set up by the wind.

In addition to tracking model particles, we calculated the percentage of particles released from each of the above four areas that ended up in the inshore, midshore and offshore (within the Gulf of Maine) regions off southwest Nova Scotia as well as those that were found on Georges Bank or in the Bay of Fundy-coastal Maine region for the 3 different release depths (Fig. 4). For this exercise we used drift durations of 30 days. Particles that were driven onto the model shoreline were considered trapped in the inshore area and not tracked any farther.

We began by tracking particles using the climatological circulation field based upon the summertime means of both the density field and winds, and M_2 tidal forcing. We later explored the sensitivity of the drift tracks to winds from different directions.

Climatological Runs

Georges Bank

Particles released on the north flank of Georges Bank within the top meter flowed eastward, being entrained into the well-known Georges Bank anticyclonic gyre (Fig. 5). Example trajectories through 60 days are shown in the panels on the left in Fig. 5. The colours indicate position of release with the green tracks being released furthest to the east, red furthest west, and yellow in between. The panels on the right of Fig. 5 show the position of all of the particles at the end of 15 (blue) and 30 days (red). After rounding the eastern tip of Georges Bank the flow bifurcates near the southeastern edge of the Bank, with some particles moving offshore and eastward while the remaining particles flow southwestward along the edge of the continental shelf. A similar pattern emerges for the 0-5 m layer but with a greater percentage of the particles flowing southwestward. There is no evidence in either layer of recirculation on Georges Bank. This contrasts with the particles at 10 m where the majority is caught within the anticyclonic gyre and few particles move offshore. No particles from Georges Bank tracked within the top meter and top 5 m were within the Browns Bank region after 30 days of drift, although after 15 days some particles were located at the southern tip of Browns. Although fewer particles released at 10 m move off Georges, a small number do reach the southern flank of Browns after 15 d and offshore of German Bank after 30 days. Because of the strong tidal flows on Georges Bank and the possibility that the time of lease might affect the drift tracks, we released particles into the model flows at two different (opposite) stages of the tide. No significant difference was observed, however.

For particles released in the top meter and top 5 m, most where found outside of our designated areas of interest. Indeed, they were either transported off the shelf into the slope water region or advected southwestward towards the Middle Atlantic Bight. Three percent of the particles in the top meter remained on Georges while approximately 19% did so in the top 5 m (Fig. 6). At 10 m, over 80% of the particles remained on the Bank with less than 1% reaching the midshore region off southwest Nova Scotia.

Browns Bank

Particles released within the top meter and top 5 m on the southwestern edge of Browns Bank were transported eastward, many of them off the Bank (Fig. 7). This is in large part an Ekman response to the mean southwesterly winds. In contrast, below the Ekman layer (10 m), the primary movement was to the north to northwest. Most of the particles continued on a northward path, remaining just offshore of the 100 m isobath of Lurcher Shoals. After 30 days the leading edge of the particles had reached the mouth of the Bay of Fundy and by 60 days many particles were headed southwestward, caught within the Maine Coastal Current system.

As on Georges Bank, most of the particles released in the top meter and top 5 m after 30 days were not located in any of our regions of interest. Indeed, most were swept off the shelf and out into the slope water. Less than 2% of the particles in the top meter were located in the midshore region and 11% of those in the top 5 m (Fig. 6). In contrast, almost 70% of the particles at 10 m were located in the midshore region. Just over 1% of the particles made it to the Bay of Fundy/Coastal Maine region and the remainder were advected to locations outside of our main area of interest.

German Bank

On German Bank, the example trajectories show predominantly northward flow towards the Bay of Fundy with particles in the top meter and top 5 m reaching the vicinity of Cape St. Marys (Fig. 8). At 10 m, there is significant flow into and around the outer Bay of Fundy and extensive alongshore flow to the southwest off the coast of Maine. The reduced distance travelled by particles in the upper layers is largely due to particles reaching the coastline around Digby Neck, but also influenced by the wind-induced currents, which tend to oppose the mean current driven by tidal rectification and density gradients. The plots of the particle positions after 15 and 30 days show that some particles in both the top meter and the top 5 m would be advected to the east of German Bank towards and onto the Scotian Shelf. This again is due principally to the Ekman response to the mean southwesterly winds.

Approximately 95% of the particles released in the top meter and 85% in the top 5 m from German Bank were in the inshore region after 30 days (Fig. 6). These were all located in St. Marys Bay while none were transported into Lobster Bay. A small percentage in both layers remained in the midshore region and some made it to the Fundy/Maine region. In contrast, 94% of the 10 m releases were transported into the Fundy/Maine region and only a small percent made it to the inshore (4%) or offshore (<1%) regions or remained in the midshore region (<2%). The lack of transport into Lobster Bay is associated with a tidal mixing front lying along the 50-80 m isobath off the southwestern end of Nova Scotia.

Lobster Bay

From Lobster Bay, the example trajectories show significant offshore movement of particles in the top meter and top 5 m out across Lurcher Shoals (Fig. 9). The trajectories then tend to flow northward towards the Bay of Fundy with many coming ashore around Cape St. Marys. The particle positions also reveal that many go ashore within Lobster Bay. A small percentage of the particles are transported south and then eastward to the Scotian Shelf. At 10 m, there are also significant numbers that both remain within Lobster Bay and reach Cape St. Marys, but many that make it into the Bay of Fundy and then southwestward along the coast of Maine. Although a few particles end up south of Lobster Bay near the 100 m isobath, none are advected towards the Scotian Shelf.

At all three depths, the majority of the particles from Lobster Bay remain in the inshore region after 30 days, over 90% in both the top meter and top 5 m and approximately 54% at 10 m (Fig. 6). Thirty to thirty-five percent remain within the Lobster Bay region (extending from Cape Sable to just north of Lobster Bay proper; see Fig. 4) and around 60% are advected to the region between Cape St. Marys and Yarmouth. Fewer than 2% and 4% in the top meter and top 5 m, respectively, are located within the midshore and approximately 2% in the Fundy/Maine regions. At 10 m, 5% of the particles are located in the midshore region after 30 days and over 40% reach the Fundy/Maine region. It should be noted that the case of the Lobster Bay releases are considered less realistic than the others because of limited model resolution in the Bay and particles not being advected once they reach the model coastline.

Sensitivity to Wind Forcing from Different Directions

Not surprisingly, the response in the Ekman layer in the climatological cases was significantly influenced by the wind. This, together with the knowledge that there can be considerable variability in wind speed and direction, both from year to year and on a daily to weekly time scales, led us to examine how dependent the particle tracks might be to changes in wind direction. Therefore, wind sensitivity simulations were carried out by adding flow fields from the linear 3-d model for wind forcing and upstream inflow (Greenberg et al. 1997; Hannah et al. 2001) to seasonal-mean and M2 tidal flow fields from the prognostic model. In this case, the seasonal-mean solution was forced by tides and density gradients only, and the entire wind stress was used in the linear model. The use of the linear model allowed an improved representation of the surface Ekman layer (inclusion of log layer; increased Ekman depth in tidally-weak areas) through the specification of a 3-d eddy viscosity field based on the advanced-turbulence model and additional theoretical considerations. It also enormously reduced computational demand in the wind sensitivity studies.

To explore the possibility that winds from different directions may help transport larvae towards southwest Nova Scotia, the linear FUNDY5 model was used to obtain 3-d velocity fields for a steady wind stress of 0.05 Pa in eight different directions, using the composite eddy viscosity field. These velocity fields were combined with the prognostic climatological solution run with no wind to obtain realistic 3-d monthly-mean current fields under alternative wind forcing ("wind sensitivity" fields). Particle simulations of 1-month duration were carried out for each of the four release areas and for three different depths (0-1 m, 0-5 m, 10m). Results are reported here for 4 orthogonal wind directions (from northeast, southeast, southwest and northwest), which illustrate how drift both within and below the surface Ekman layer depends on wind direction. Although such winds do not persist over the entire summer, these runs show how strong winds could affect the larval transport. We examine the response to these different wind directions for releases from Georges and Browns Banks.

Georges Bank

The locations of particles released on northern Georges Bank (see Fig. 4) after 14 and 28 days are shown as a function of wind direction in Fig. 10. As expected, particles in the Ekman layer (top meter and top 5 m) show varying responses depending upon wind direction. On the other hand, below the Ekman layer (10 m), there are much smaller differences in the responses.

Northeasterly winds tend to move a large percentage of the particles in the Ekman layer into the central Gulf of Maine and those that remain in the anticyclonic gyre on Georges Bank are in shallower waters than in the climatological wind case. Southeasterly winds push the particles in the Ekman layer towards southwest Nova Scotia. A large number reach Cape St. Marys but few make it inshore between Cape Sable to Cape St. Marys, including into Lobster Bay. A high percentage of the particles released in the top meter are within the midshore area after 14 d but after 28 days have moved to the area off the coast of Maine. For particles in the top 5 m, most end up in the midshore area with a few reaching into the inshore area. The southwesterly wind case is qualitatively similar to that described in the climatological case. In the southerly wind case (not shown), there is some drift of the 0-1 m particles to the Scotian Shelf, with fewer reaching the inshore area or remaining in the midshore area.

Northwesterly winds tend to push the particles in the Ekman layer farther to the southwest than in the climatological case. No particles are found north of Georges Bank after either 14 or 28 days. The positions of particles released at 10 m show predominant transport within the anticyclonic gyre on Georges Bank with a few particles making it offshore in the case of either southeasterly or southwesterly winds, and a few moving north of the Bank under northwesterly winds. None make it into the midshore or inshore areas off southwest Nova Scotia.

Browns Bank

As expected and seen on Georges Bank, particles released on southwestern Browns Bank (See Fig. 4) below the Ekman layer show less variability in their flow patterns under winds from different directions than those released within the Ekman layer (Fig. 11). Most of the former move from Browns Bank into the midshore and offshore regions to the north. Northeasterly winds promote the longest drift tracks with many particles reaching the Bay of Fundy or the coastal current off Maine after 28 days. Southwesterly winds produce the shortest drift tracks and those farthest from the coast of Nova Scotia.

Drift tracks of particles released within the Ekman layer are highly dependent upon the wind direction. Northeasterly winds pushed most of the particles in the top meter well offshore to the west of the Bank and in the top 5 m to the northwest. Southwesterly winds drove the particles to the east and southeast, respectively while northwesterly winds forced them to the west and south where they eventually became entrained into the Georges Bank gyre. Winds from the southeast, however, pushed the particles released in the top meter into the midshore and inshore (St. Marys Bay) areas after 14 days and the inshore area and the coasts of Maine and New Brunswick after 28 days. Particles in the top 5 m moved into both the inshore and midshore regions with many after 28 days reaching the Bay of Fundy. However, few particles moved into Lobster Bay even in the southeast wind case.

Summary of Wind Sensitivity Runs

The above results reveal the potential of a large effect of wind on lobster larvae transport and so the results from the climatological cases must be viewed with caution. In spite of the unrealistic winds used in these sensitivity scenarios, the results do confirm that the chances of lobster larvae from Georges Bank reaching the inshore areas off southwest Nova Scotia are slim. Only under consistent southeasterly winds would lobster larvae from Georges Bank have a chance of making it towards southwest Nova Scotia. Those that do and remain in our area of interest would be located in the midshore area with a few making it inshore. Most would be transported to the Bay of Fundy with smaller numbers making it into St. Marys Bay and some to the Atlantic coast of Nova Scotia northeast of Cape Sable. The results also suggest that the only drift pathway from

Browns Bank to the inshore area occurs in the surface Ekman layer with southeasterly winds, and even then, there is little drift into Lobster Bay.

Variable Winds: 1988 Case Study

Given the sensitivity of the near surface flows to the wind direction, we next modelled particle tracks using weekly wind stresses from NOAA buoy 44005 in the Gulf of Maine during the summer of 1988. This year was chosen because of the availability of lobster larvae surveys and drifter releases from Georges Bank. In addition, there was a complete set of available wind data. Winds were relatively strong and fairly persistent from the south-southwest. Simulations of 4-weeks duration were carried out for the Georges and Browns Bank release areas, for six different starting weeks (July through early August). We released particles at the 3 standard depth intervals in both locations and also examined particle tracks in the top 10 cm for the Georges Bay case. For display purposes, results are plotted only for larvae released in weeks 27, 29 and 31 (first and third weeks of July and second week of August; Fig. 12). These are representative of the weeks not plotted. There is generally low probability of particles released within the Ekman layer on northern Georges Bank being found in the inshore or midshore areas off southwestern Nova Scotia, after drifting for 28 days. This result held in additional sensitivity studies with increased background horizontal turbulence. There was significant transport of larvae in the top 10 cm from Georges Bank towards Browns Bank within 7 to 14 days of release but by 28 days most of the particles had been transported to the east of Browns Bank. Below the Ekman layer at 10 m depth, a few larvae do make it to the midshore region (see week 27, for example).

A similar analysis was undertaken with releases from Browns Bank (Fig. 13). Particles released within the Ekman layer tended to be transported eastward. Consistent with the climatological case, particles released at 10 m moved off the Bank to the north with most located within the midshore zone after drifting for 28 days.

The conclusions reached using the weekly 1988 winds are similar to those based upon the climatological winds. That is, there is a very low probability of lobster larvae from Georges Bank reaching the areas off southwest Nova Scotia. Larvae released on Browns Bank at 10 m would primarily occupy the midshore region after a drift duration of 4 weeks, but most of the larvae in the surface layers would be advected eastward.

We do not expect large differences between years given that the summer winds tend to be reasonably persistent. The mean wind for the years 1979 to 1994 (note no data from buoy 4405 are available for 1980 and 1982) show variations primarily in amplitude rather than direction (Fig. 14). Those years that are most different tend to stronger westerly component, which would tend to push more larvae in an offshore direction from both Georges Bank and Browns Bank. However, this does not take into account the possibility of intense storms that could move larvae long distances in relatively short time periods. The ultimate fate of such larvae would depend upon the wind directions.

Frontal Structure

In spite of the accumulation of larvae in the midshore region under several different wind directions from releases on Browns and German Banks, few larvae make it to the inshore region between Cape Sable and south of St. Marys Bay in the model simulations. This arises from a cross-frontal surface convergence in the tidal-mixing front between the vertically well-mixed waters in the inshore zone off western Nova Scotia and the stratified waters of the midshore zone.

The temperature and density contours from the summertime mean hydrography in a cross section offshore of Lobster Bay are shown in Fig. 15. In depths of 50 to 75 m (approximately 40 km offshore) there is a density front which is also seen in the thermal structure. Inshore of these depths the waters are relatively well mixed due to the turbulence caused by the friction between the intense tidal currents and the ocean floor. Offshore of these depths the water is highly stratified. The alongshore velocity throughout most of the water column on both sides of the front is primarily northward (positive; out of the page). There is some southward movement near bottom on the outer half of the section and just inshore of the front. The across-shelf velocities suggest convergence in the vicinity of the front with shoreward flow (positive; eastward) on the offshore side of the front and offshore flow (negative; westward) on the inshore side of the front. This convergence acts to prevent particles from moving onshore and accumulating in the inshore region. For the predominant southwesterly winds, the eastward-southeastward wind driven component of near surface flow amplifies the onshore drift towards the front, but is weaker than the offshore density-driven flow or the inshore side of the front.

Discussion and Summary

Drift pathways are strongly dependent on the vertical (depth in relation to Ekman layer structure) and horizontal (in relation to bank gyres) release positions. Wind influences are strongest in the upper 5 m, but can be important and different below the Ekman layer. There are indications of particle exchange among many of the offshore (> 50 m isobath) release sites (e.g. Browns, German and Georges Bank) but only for a limited range of wind directions in some cases and hence of low probability. There is limited drift into the inshore (< 50 m) zone in the vicinity of Lobster Bay off southwest Nova Scotia because of the existence of convergence at the tidal-mixing front over Lurcher Shoals. Based upon our drift model results to date, it would appear that the most likely source of lobster larvae for the inshore area of Lobster Bay is local production. For the inshore area around St. Marys Bay, particle modelling suggests larvae could come from Lobster Bay and German Bank with some from Browns Bank. In the midshore region, the primary sources would seem to be German Bank and Browns Bank. Few, if any, of the modelled larvae are transported from Georges Bank towards southwest Nova Scotia.

Observational data of near-surface drift, although limited, provide support for these conclusions. Recent extensive drifting buoy experiments on Georges Bank

(Limeburner and Beardsley 1996, Naimie et al. 2001) indicate little drift at 10 m towards southwest Nova Scotia. Also, historical surface drift studies off southwest Nova Scotia (Bumpus and Lauzier 1965, Harding and Trites 1988) and limited drift buoy studies (Smith 1989 and our CLAWS studies in 1997 and 1998) show little tendency for near-surface flow into the inshore zone of Lobster Bay, including from Cape Sable to Yarmouth.

Nevertheless, our conclusions on lobster larval drift from model simulations must be viewed with caution. They are based upon drift at a particular depth or within a given depth level, and hence ignore daily vertical migration of the larvae or that different larval stages generally occupy different depth ranges (Harding et al., 2000). In addition, we neglect upwelling and downwelling of the water column that could move larvae vertically and eddy variability such as that seen on northern Georges Bank and along the Lurcher Shoals front that could move them horizontally. Full temporal variability in the wind forcing, including diurnal sea breezes in the coastal area (e.g. Incze et al. 2000), has not yet been included. Also, our conclusions are based primarily upon a drift duration of 28-30 days. This is less than the expected larval duration (hatching to half way into stage four when they are expected to settle). Based upon the temperature-dependent stage durations published by Mackenzie (1988) and long-term monthly mean temperatures around the Gulf of Maine (Petrie et al., 1996), we estimated the larval durations for releases on June 15, July 1 and 15 and August 1 throughout the Gulf of Maine assuming no advection. They suggested larval durations of 25-35 days in the western and central Gulf of Maine and 30-50 days on Georges Bank and Browns Bank with the longer durations for the larvae that were released earliest. In the midshore area, the larvae would take 50-60 days to develop and on Lurcher Shoals 60-80 days. Indeed, it is questionable whether larvae on Lurcher Shoals could survive if they had to exist that long. Finally, we have ignored the possibility of directional swimming of the larvae. Cobb et al. (1989) suggested a mean swimming speed of 0.18 ms^{-1} with a range of 0.07-0.24 ms^{-1}. At such speeds larvae occurring at the front on Lurcher Shoals could cover the approximately 40 km to Lobster Bay in a little over 3-4 days of continuous swimming, after taking into account the mean offshore counter current on the inshore side of the front. This is well within their estimated energy reserves (Sasaki 1984) although is most likely that the larvae would not swim continuously but rather stop to feed. Such a mechanism to reach the nearshore region requires that the larvae know what direction to swim. That they possess such abilities is unclear.

Still our modelling studies do suggest that few if any larvae are advected into Lobster Bay and adjacent inshore areas if hatched on Georges, Browns or German Bank. This together with the result that upwards of 30-35% of the larvae produced in Lobster Bay would remain there after 30 days leads us to conclude that local production is the most likely source of lobster larvae in Lobster Bay. We examined available temperature records from the inshore areas of Lobster Bay and St. Mary’s Bay. They are several degrees warmer in summer than those found on Lurcher Shoals and the lobster larval duration under such conditions would be 30-60 days based on Mackenzie’s temperature-dependent stage durations, and hence the larvae should survive. The warmest waters (of order 16°C near surface) are found close to shore with a strong thermal gradient towards the colder offshore waters as one proceeds out of the Bay. Our conclusion of the reliance on local lobster production in Lobster Bay is also consistent with the high numbers of stage I larvae found in larvae surveys undertaken there in 1996 and in the outer reaches in 1998. However, few older stages were found in these surveys. The sampling in 1996 occurred late in the summer and thus the absence of these later stages could not be explained by sampling too early. One possible explanation is that the later stages were simply in unsampled locations (close to shore) that year or perhaps the later stages do not survive within Lobster Bay. If the latter, then perhaps the adult lobsters in the Lobster Bay region are ones that settle in the midshore region and migrate inshore sometime prior to recruitment. Also, we acknowledge that we have not explored other possible source regions outside of the four in this study, i.e. Georges, Browns and German banks and Lobster Bay.

Another conundrum is that the model suggests that many larvae from Lobster Bay, German Bank and from Browns are advected into St. Marys Bay. This, however, is a region of low lobster catches. While this could be explained by low larval or juvenile survival in this region, this has not been established.

Future work under the CLAWS II program will focus upon incorporating temperature-dependent stage durations for the lobster larvae, stage-dependent depths, time-varying winds for all years where possible and exploring the possibility of directional swimming by the larvae.

Acknowledgements

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References

Blanton, B. 1995. DROG3D: User’s manual for 3-dimensional drogue tracking on a finite element grid with linear finite elements. Report in Program in Marine Sciences, University of North Carolina, Chapel Hill, N.C., 13 pp.

Bumpus, D. F. and L.M. Lauzier. 1965. Surface circulation on the continental shelf of eastern North America between Newfoundland and Florida. Am. Geogr. Soc. Ser. Atlas Mar. Environ. Folio 7: 4 p., 8 plates.

Cobb J.S., D. Wang, D.B. Campbell, P. Rooney. 1989. Speed and direction of swimming by postlarvae of the American lobster. Trans. Amer. Fish. Soc. 118:82-86.

Greenberg, D.A., J.W. Loder, Y. Shen, D.R. Lynch and C.E. Naimie. 1997. Spatial and temporal structure of the barotropic response of the Scotian Shelf and Gulf of Maine to surface wind stress. J. Geophys. Res. 102: 20897-20915.

Hannah, C.G., C.E. Naimie, J.W. Loder and F.E. Werner. 1998. Upper-ocean transport mechanisms from the Gulf of Maine to Georges Bank, with implications for *Calanus* supply. Cont. Shelf Res. 17: 1887-1911.

Hannah, C.G., J.A. Shore, J.W. Loder and C.E. Naimie. 2001. Seasonal circulation on the western and central Scotian Shelf. J. Phys. Oceanogr. 31: 591-615.

Harding, G.C. and R.W. Trites. 1988. Dispersal of *Homarus americanus* larvae in the Gulf of Maine from Browns Bank. Can. J. Fish. Aquat. Sci. 45: 416-425.

Harding, G.C., W.P. Vass and K.F. Drinkwater. 1982. Aspects of larval American lobster (*Homarus americanus*) ecology in St. Georges Bay, Nova Scotia. Can. J. Fish. Aquat. Sci. 39: 1117-1129.

Harding, G., K. Drinkwater, P. Vass, J. Pringle, A. Fraser, J. Prena, J. Loder, C. Hannah and J. Shore. 2000. Review of the distributional and ecological studies on larval lobster as it pertains to their dispersal in the Canadian sector of the Gulf of Maine. Working Paper, Lobster RAP held in Dartmouth during February 2000.

Incze, L.S., R.A. Wahle and J.S. Cobb. 1997. Quantitative relationships between postlarval production and benthic recruitment in lobsters, Homarus americanus. Mar. Freshwater Res.48: 729-743.

Incze, L.S. and C.E. Naimie. 2000. Modeling the transport of lobster (*Homarus americanus*) larvae and postlarvae in the Gulf of Maine. Fish. Oceanogr. 9:99-113.

Limeburner, R. and R.C. Beardsley. 1996. Near surface recirculation over Georges Bank. Deep Sea Res. II. 43: 1547-1574.

Loder, J.W., G. Han, C.G. Hannah, D.A. Greenberg and P.C. Smith. 1997. Hydrography and baroclinic circulation in the Scotian Shelf region: winter versus summer. Can. J. Fish. Aquat. Sci. 54 (Suppl. 1): 40-56.

Lynch, D.R., J. Ip, C.E. Naimie and F.E. Werner. 1996. Comprehensive coastal circulation model with application to the Gulf of Maine. Cont. Shelf Res. 16: 875-906.

Madsen, O.S. 1977. A realistic model of the wind-induced Ekman boundary layer. J. Phys. Oceanogr. 7: 248-255.

MacKenzie, B.R. 1988. Assessment of temperature effects on interrelationships between stage durations, mortality and growth in laboratory-reared *Homarus americanus* Milne Edwards. J. Exp. Mar. Biol. Ecol. 116: 87-98.

Manning, J. and G. Strout. 2001. Georges Bank winds: 1975-1997. Deep-Sea Res. II 48: 115-135.

Naimie, C.E. 1995. On the modeling of the seasonal variation in the three-dimensional circulation near Georges Bank. Ph.D. Thesis, Dartmouth College, 266 p.

Naimie, C.E. 1996. Georges Bank residual circulation during weak and strong stratification periods-prognostic numerical model results. J. Geophys. Res. 101: 6469-6486.

Naimie, C.E. and D.R. Lynch 1993. FUNDY5 Users' Manual. Numerical Methods Laboratory, Dartmouth College, N.H. 40 p.

Naimie, C.E., R. Limeburner, C.G. Hannah and R.C. Beardsley. 2001. On the geographic and seasonal patterns of the near-surface circulation on Georges Bank from observed and simulated drifters. Deep-Sea Res. II. 48: 501-518.

Petrie, B., K. Drinkwater, D. Gregory, R. Pettipas and A. Sandström. 1996. Temperature and salinity atlas for the Scotian Shelf and the Gulf of Maine. Can. Tech. Rep. Hydrogr. Ocean Sci. 171: 398 p.

Sasaki, G.C. 1984. Biochemical changes associated with embryonic and larval development in the American lobster *Homarus americanus* Milne Edwards. PhD. Thesis, MIT/WHOI, WHOI-84-8: 457 p.

Shore, J., C.G. Hannah and J.W. Loder. 2000. Drift pathways on the western Scotian shelf and its environs. Can. J. Fish. Aquat. Sci. 57: 2488-2505.

Smith, P.C. 1989. Circulation and dispersion on Browns Bank. Can. J. Fish. Aquat. Sci. 46: 539-559.

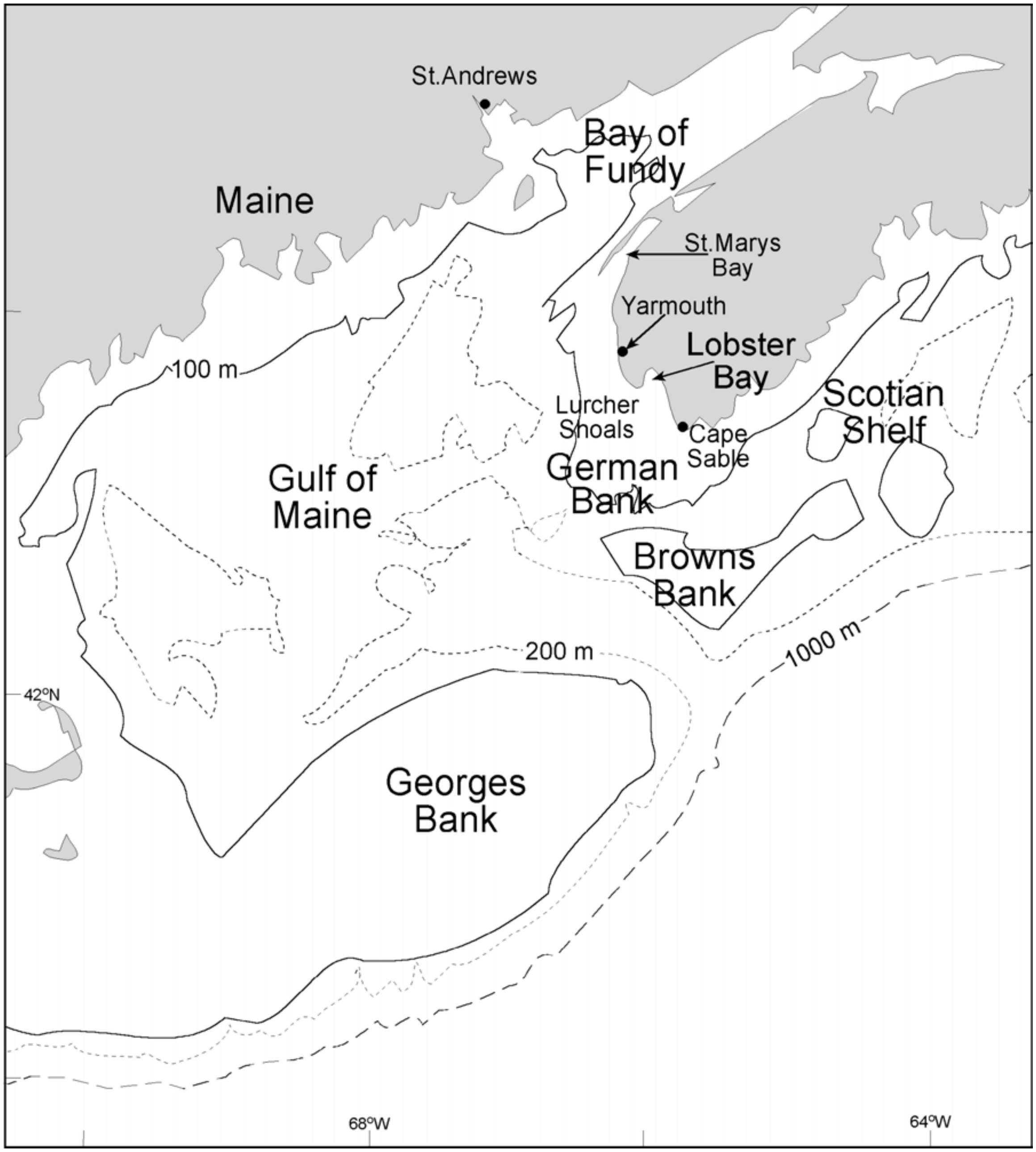

Fig. 1. The study area in the Gulf of Maine.

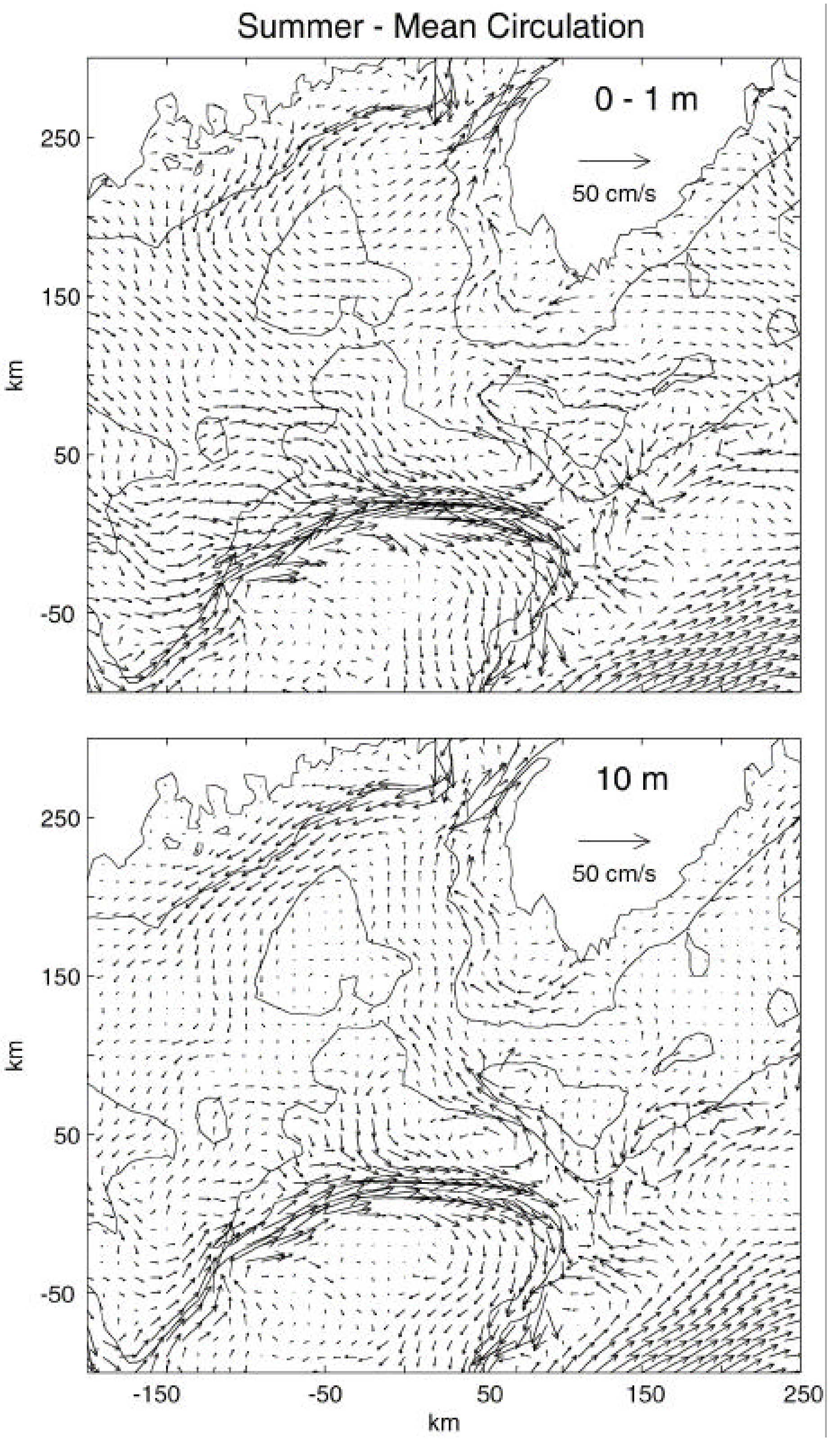

Fig. 2. The summer mean currents in the top meter (top panel) and at 10 m from the circulation model using M_2 tides, climatological winds and density fields.

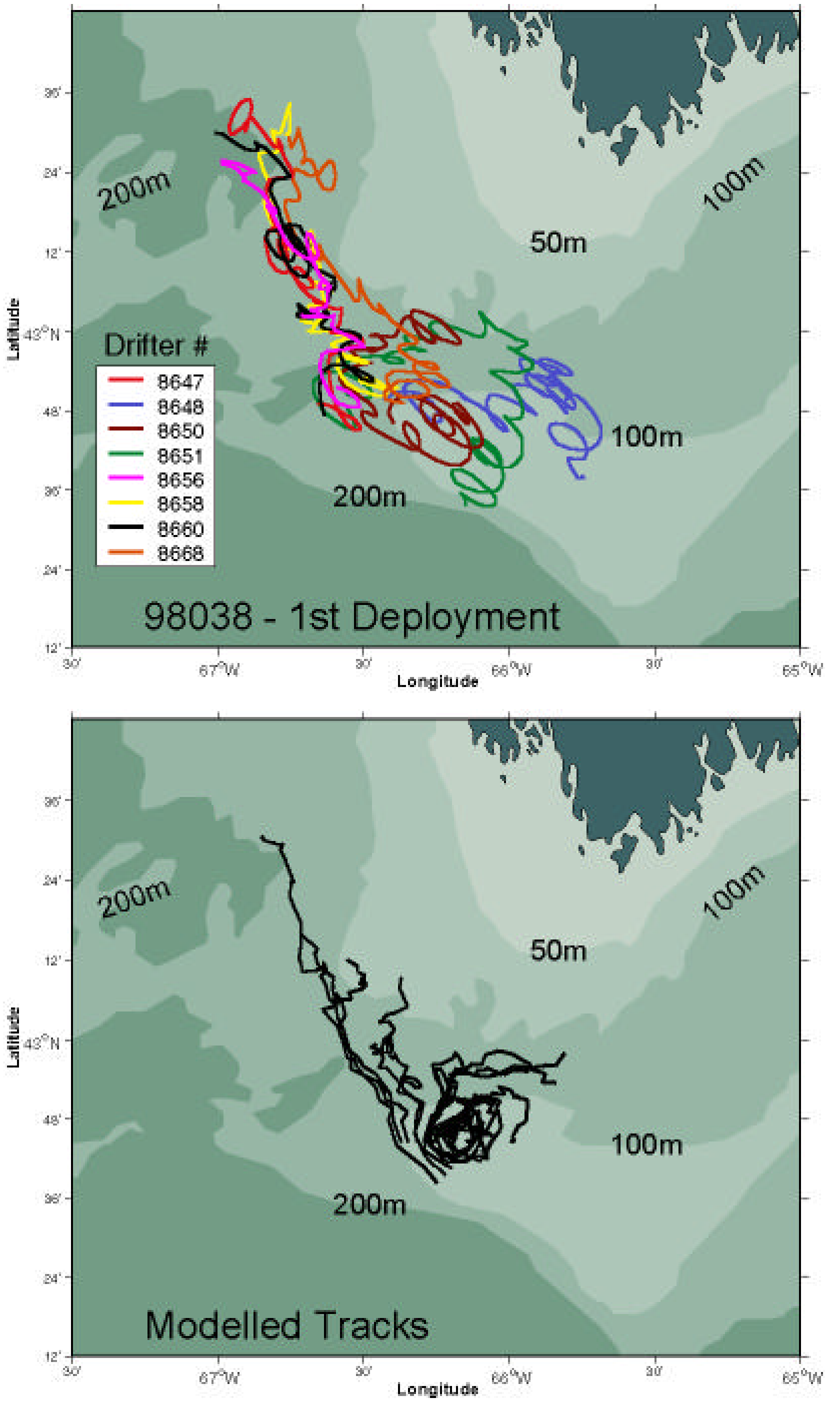

Fig. 3. Drift tracks over a duration of approximately 2 weeks of drift buoys drogued at 10 m from August 1998 (top panel) and model particles at 10 m using the climatological current field (bottom panel) released in the vicinity of northwestern Browns Bank

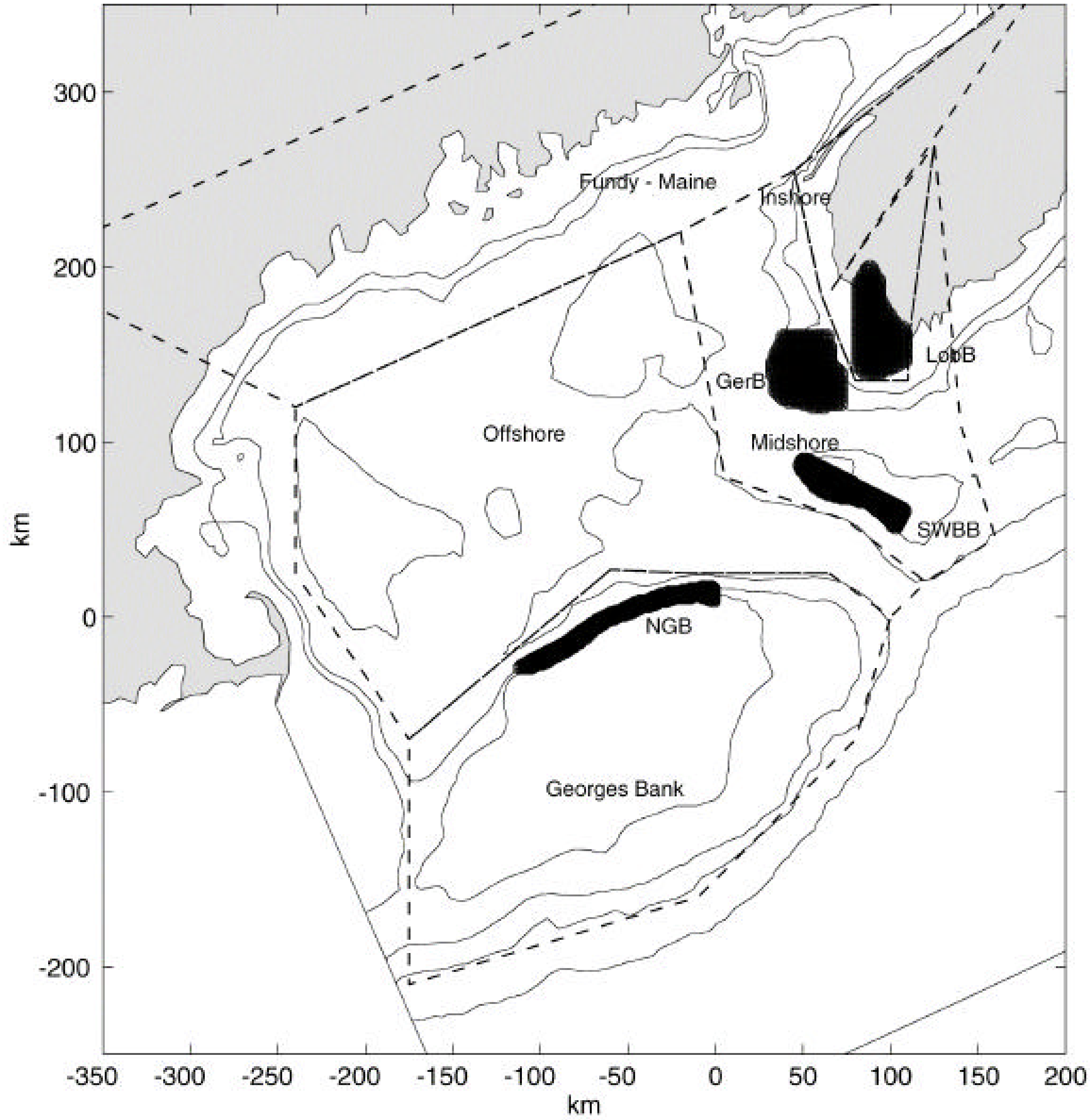

Fig. 4. Gulf of Maine showing the release sites and subareas for particle counting of modelled lobster larvae drift.

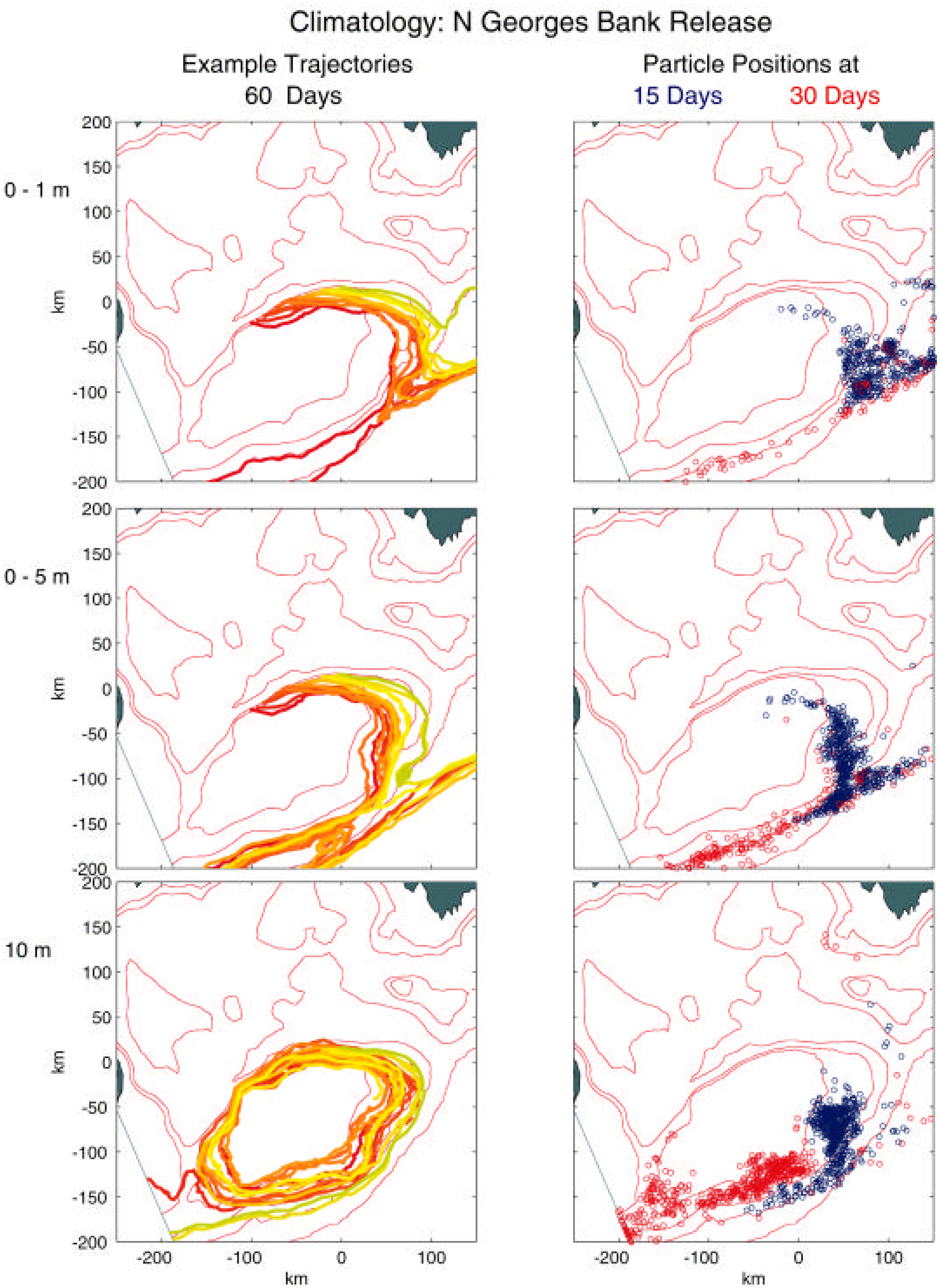

Fig. 5. Example particle trajectories of 60 days duration (left panels) and the location of all particles after 15 and 30 days (right panels) from releases on the northern flank of Georges Bank at depths of 0-1 m, 0-5 m and 10 m.

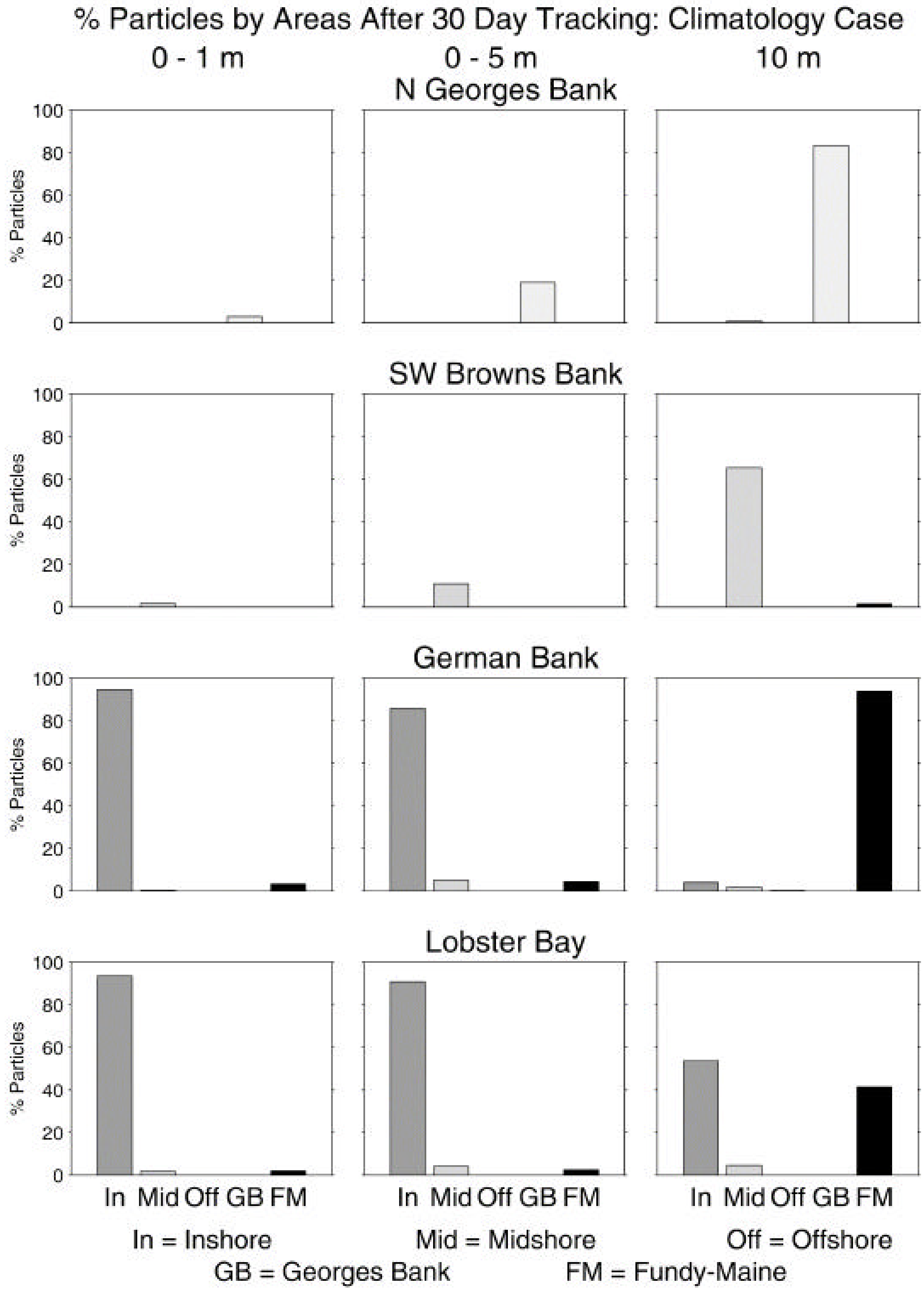

Fig. 6. The number of particles expressed as a percentage of the total released that are within a given subarea after 30 days of drift as a function of release site (rows) and depth (columns). The subarea names are given at the bottom of the figures and their geographic boundaries are shown in Fig. 4.

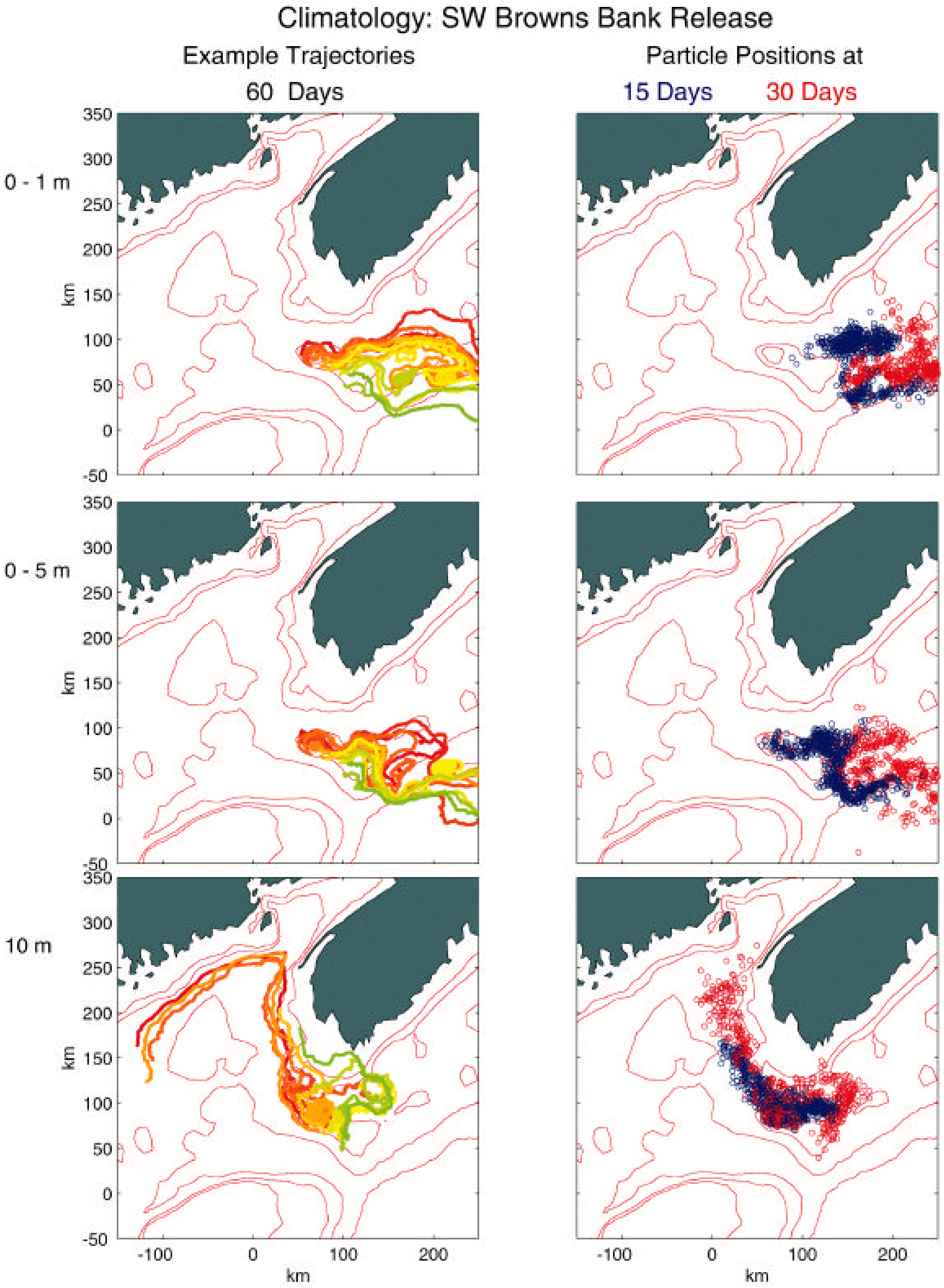

Fig. 7. Example particle trajectories of 60 days duration (left panels) and the location of all particles after 15 and 30 days (right panels) from releases on the southwest flank of Browns Bank at depths of 0-1 m, 0-5 m and 10 m.

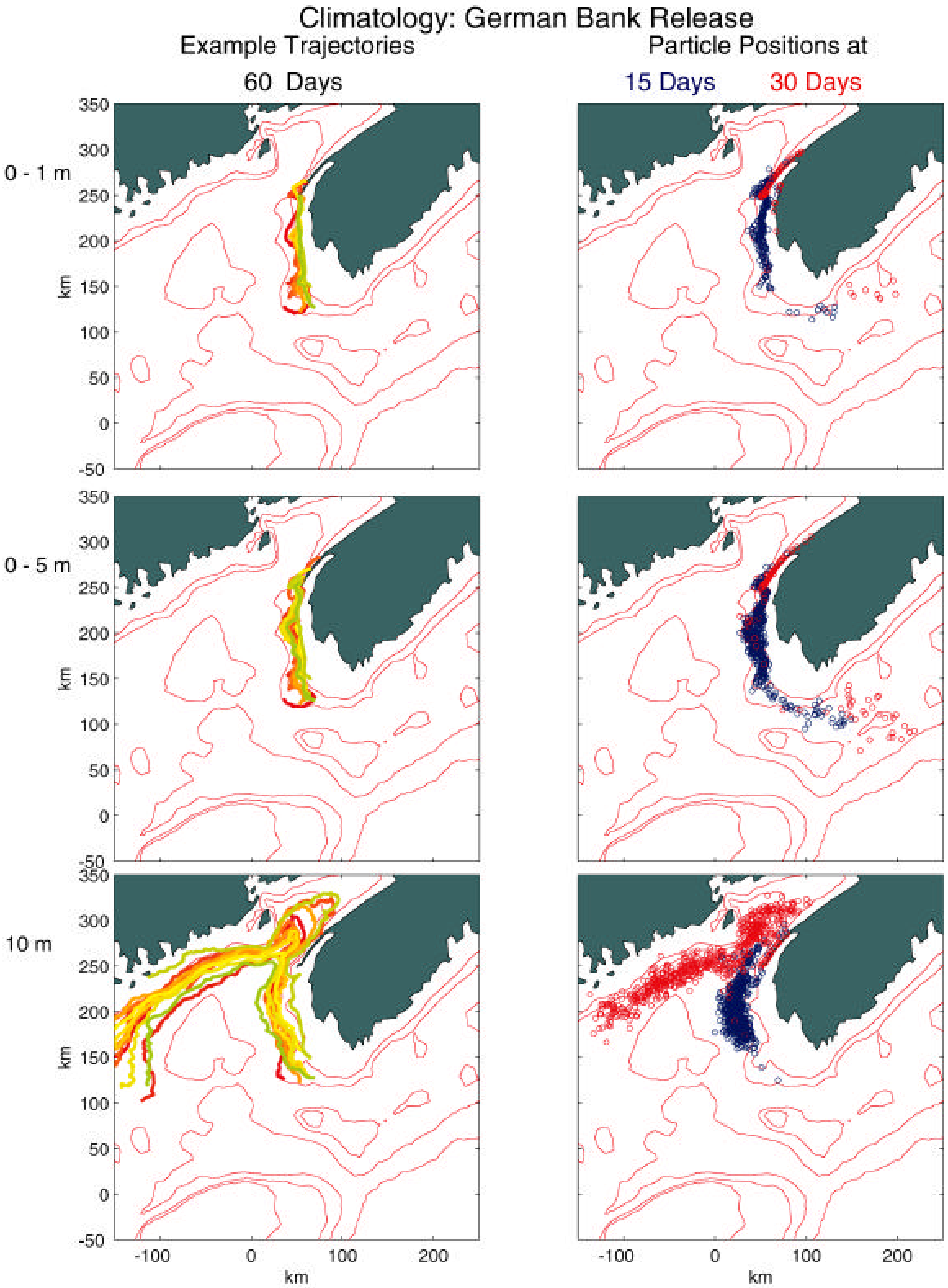

Fig. 8. Example particle trajectories of 60 days duration (left panels) and the location of all particles after 15 and 30 days (right panels) from releases on German Bank at depths of 0-1 m, 0-5 m and 10 m.

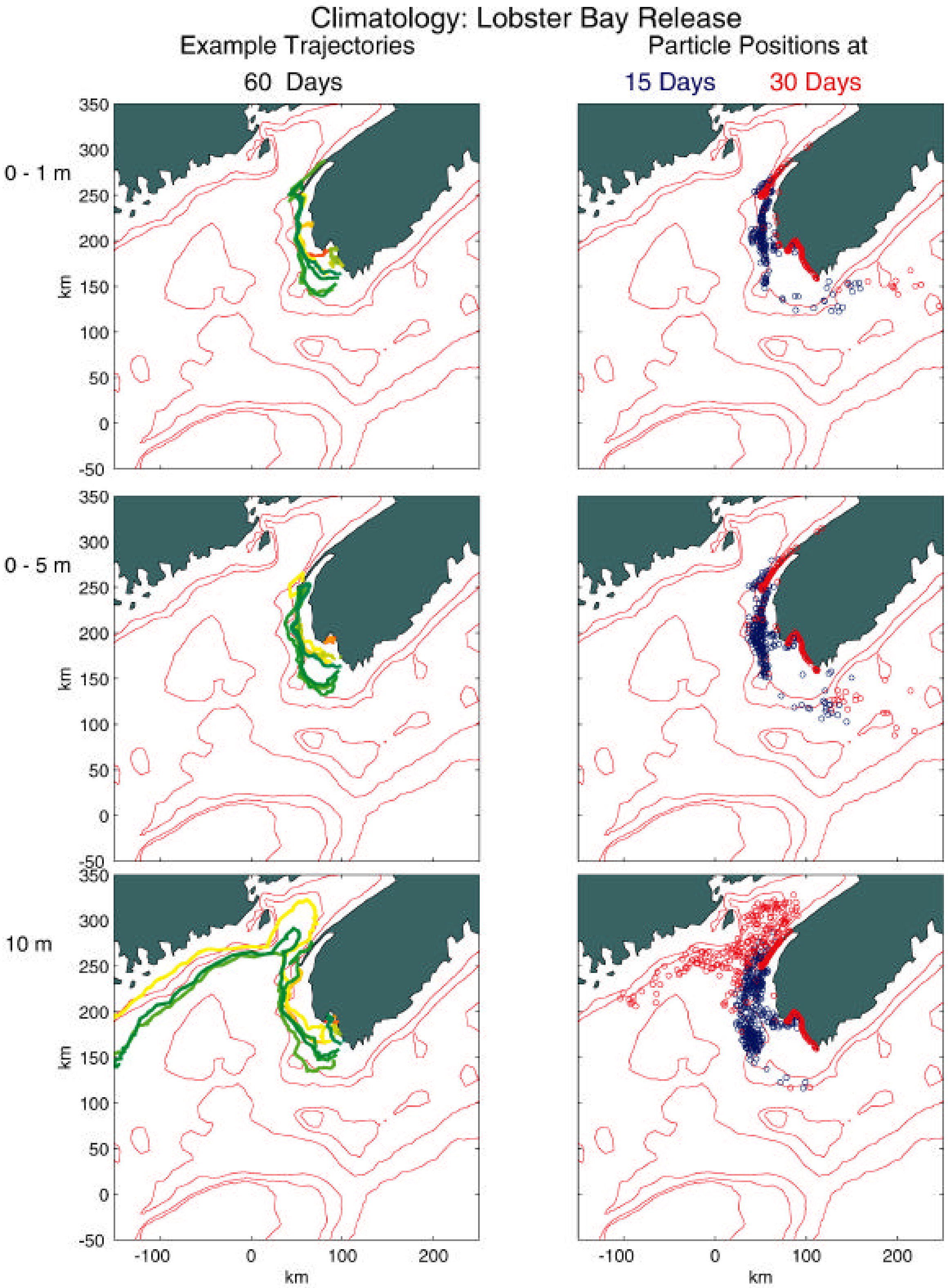

Fig. 9. Example particle trajectories of 60 days duration (left panels) and the location of all particles after 15 and 30 days (right panels) from releases in Lobster Bay at depths of 0-1 m, 0-5 m and 10 m.

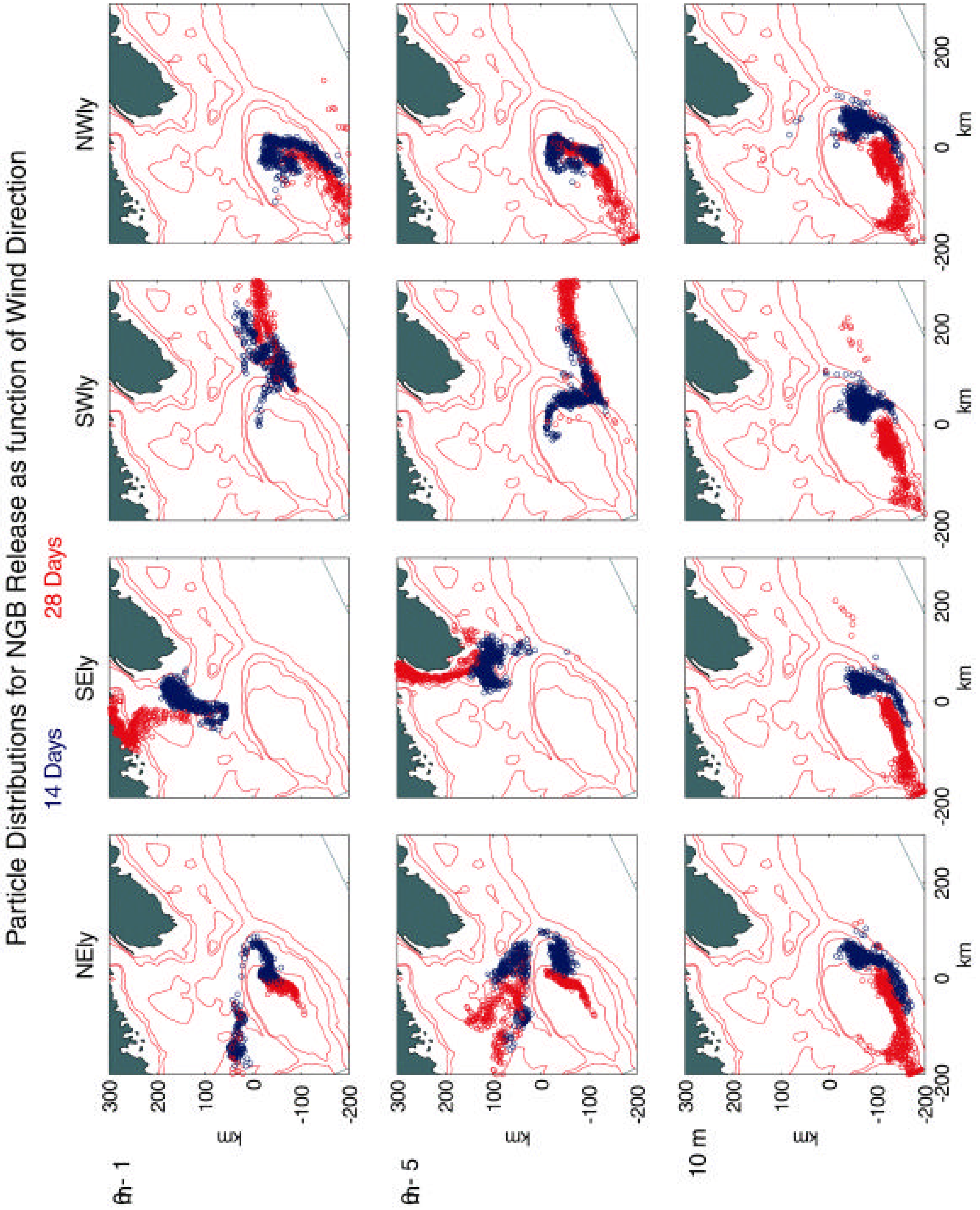

Fig.10. The location of all particles released on northern Georges Bank after 14 and 28 days as a function of wind direction and depth.

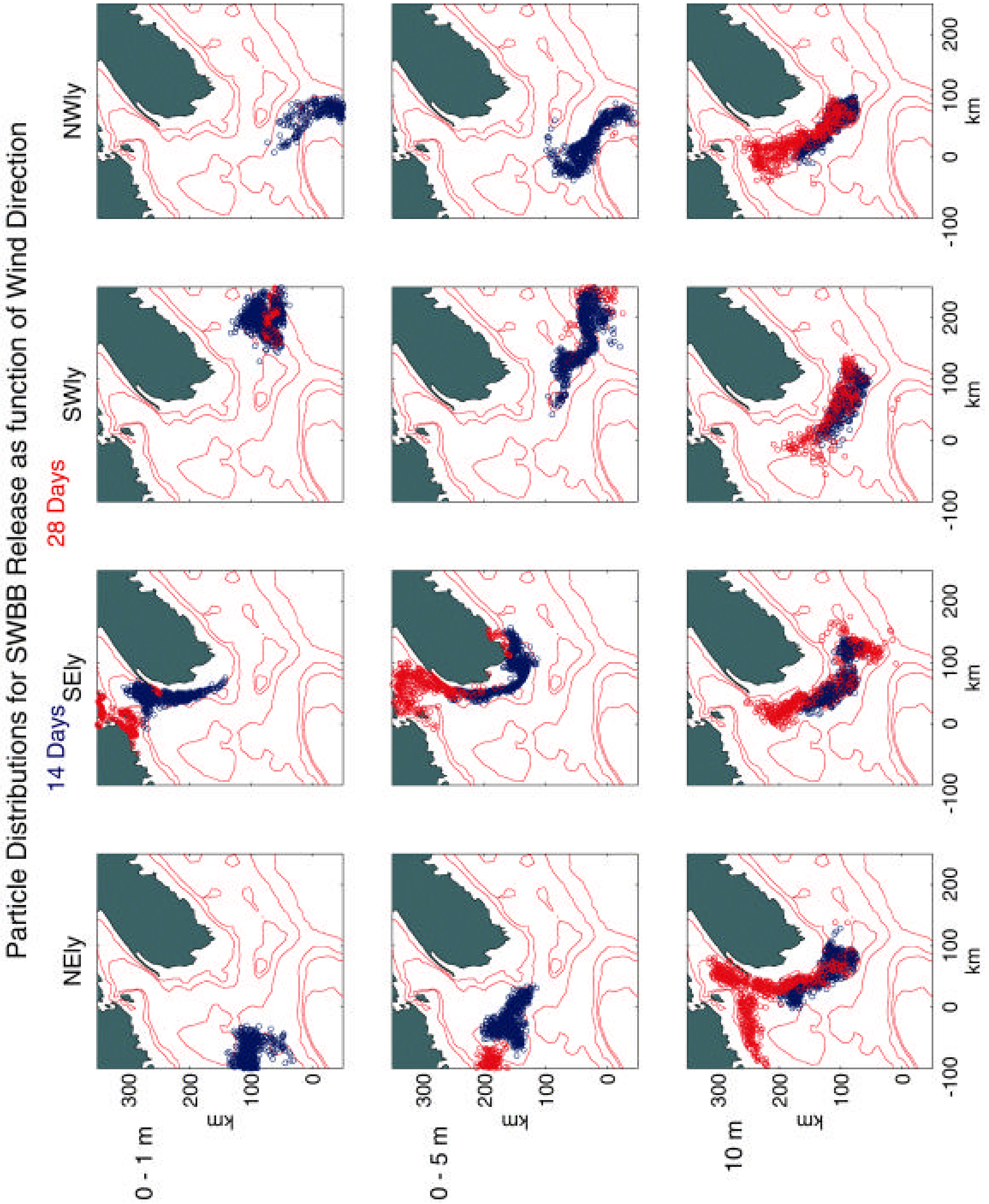

Fig. 11. The location of all particles released on southwestern Browns Bank after 14 and 28 days as a function of wind direction and depth.

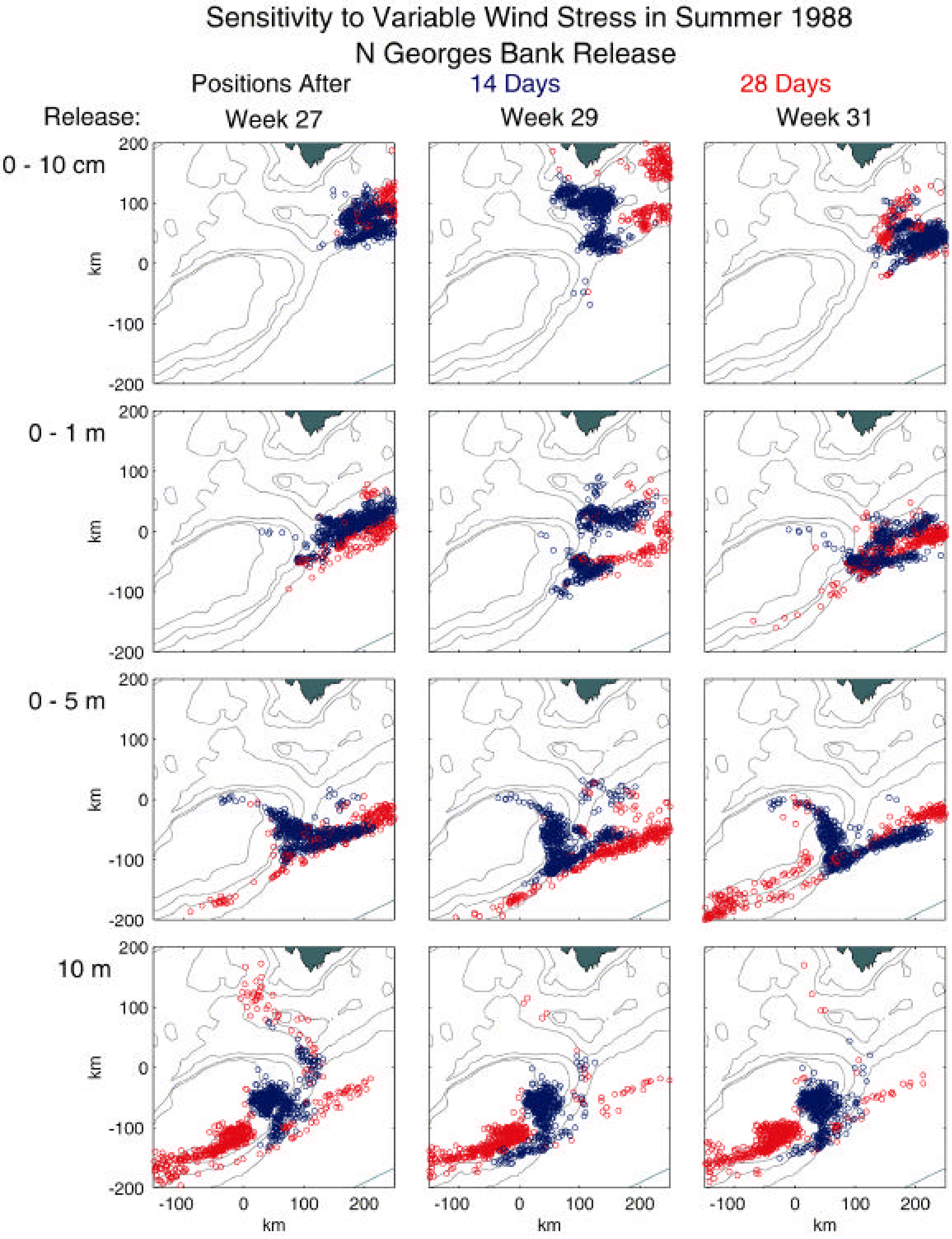

Fig. 12. The location of all particles released on northern Georges Bank after 7, 14 and 28 days as a function of the time of release and depth. Weekly winds from 1988 were used in the simulation.

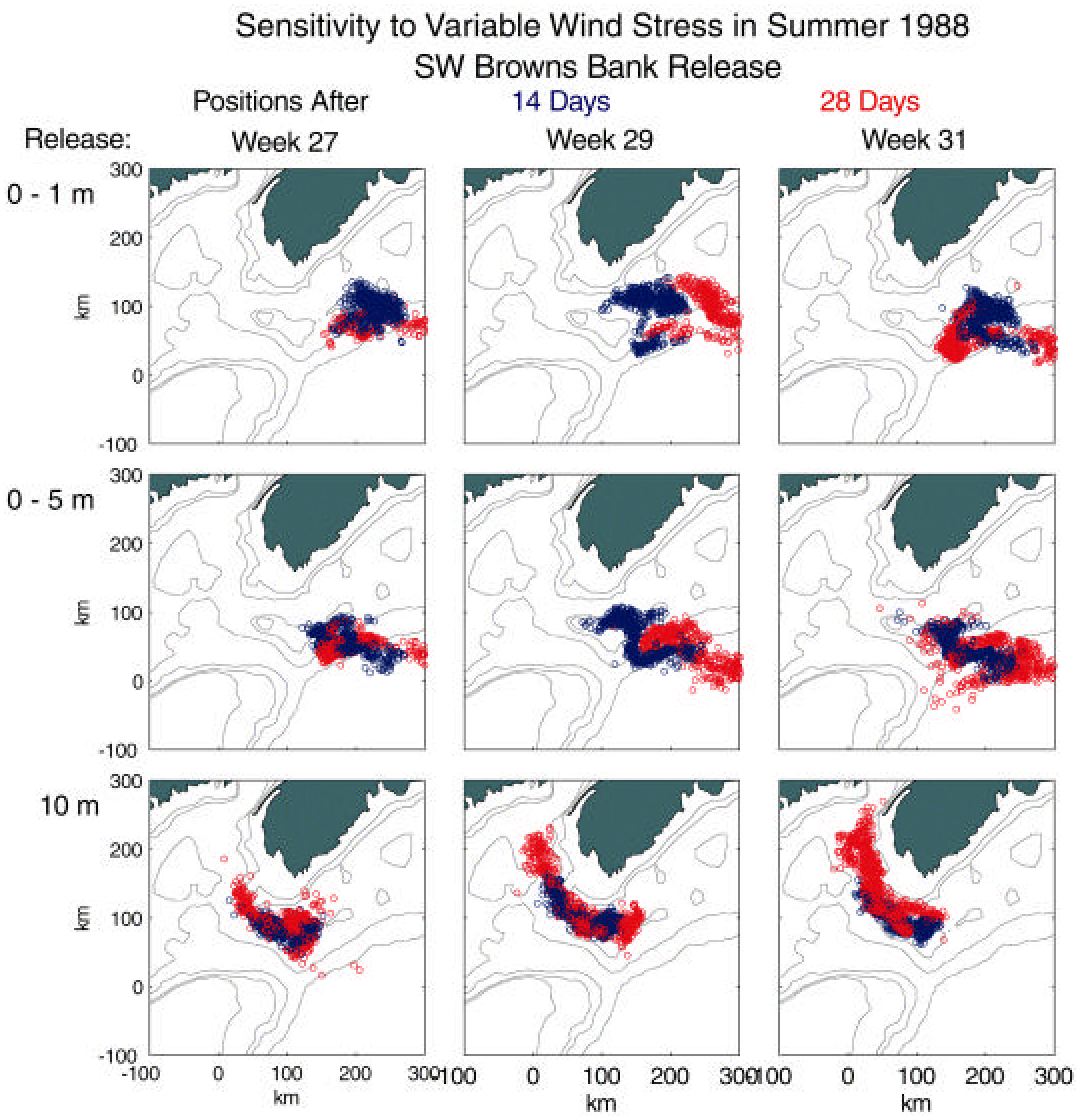

Fig. 13. The location of all particles released on southwestern Browns Bank after 7, 14 and 28 days as a function of the time of release and depth. Weekly winds from 1988 were used in the simulation.

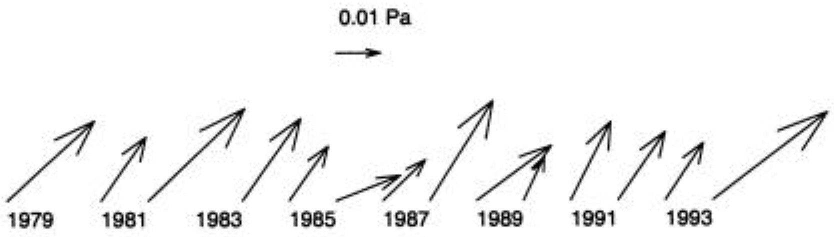

Fig. 14. The mean summer wind stress (in Pa) from 1979 to 1994 from the NOAA buoy 44005 in the Gulf of Maine (Manning and Strout 2001).

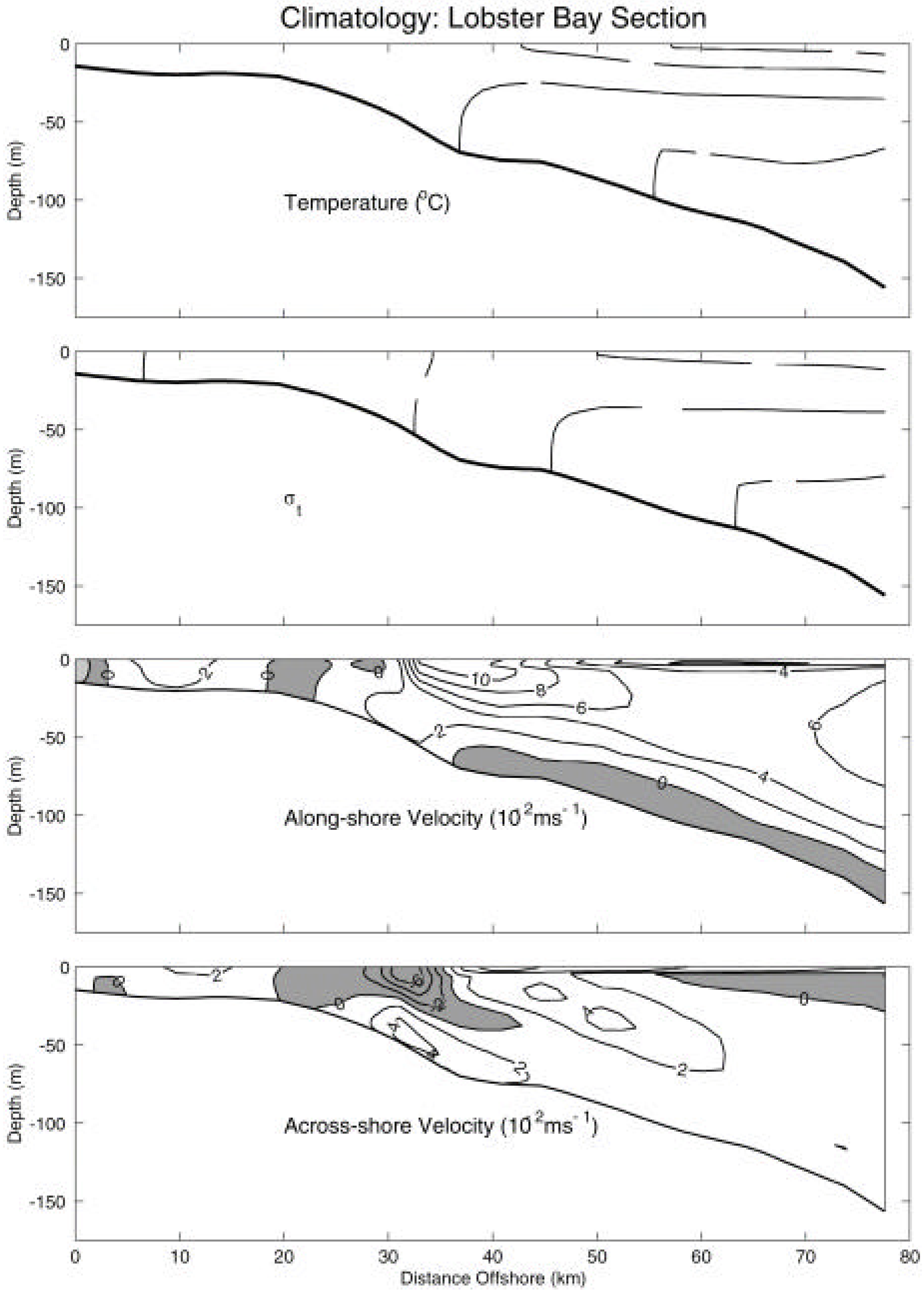

Fig. 15. Contours of the temperature, density, alongshore and across-shore speeds along a transect offshore from Lobster Bay based on the mean summertime hydrographic conditions and model currents. Positive (negative) alongshore speeds indicate a predominantly northward (southward) direction whereas positive (negative) cross-shore speeds indicate principally eastward or onshore (westward or offshore) movement. Negative speeds of both alongshore and cross-shore currents are shaded.