Comparison between numerically simulated and observed drifter trajectories on Georges Bank.

Christopher E. Naimie, Richard Limeburner, Charles G. Hannah, and Robert C. Beardsley


Theme Session - GLOBEC: Results from Interdisciplinary Programmes in the North Atlantic (T)

Abstract:

We establish the level of agreement between the modeled and observed near-surface Lagrangian circulation on Georges Bank, through comparisons of numerically simulated and observed 10 meter deep drifter trajectories. The observational data set consists of 36 long-term drifters, deployed on Georges Bank at various times of the year, during the 1995 USGLOBEC Field Program. The numerical drifters trajectories are computed based upon the seasonal circulation as predicted by the Dartmouth Circulation Model, under climatological forcing. The observed and numerical drifter patterns indicate well organized anticyclonic around-bank flow on the northern flank, Northeast Peak, and southern flank throughout the year. The key to recirculation on the bank is the seasonality of the northward flow in the Great South Channel. Winter months are characterized by little northward flow; while there is significant northward flow in the Great South Channel in the summer. During the summer months, both observed and numerical drifters indicate a minimum recirculation time on Georges Bank of roughly 40 days. The modeled drifter trajectories generally predict a seasonal climate consistent with the observed drifters, though the effects of weather events on the observed drifters are not captured by the numerical simulations.

Christopher E. Naimie: Dartmouth College, Hanover, NH, 03755, USA [tel: +1 603 646 2119, fax: +1 603 646 3856, e-mail: christopher.naimie@dartmouth.edu].

Richard Limeburner: Woods Hole Oceanographic Institution, Clark 343A, MS #21, Woods Hole, MA, 02543, USA [tel: +1 508 289 2539, fax: +1 508 457 2181, e-mail: rlimeburner@whoi.edu]

Charles G. Hannah: Bedford Institute of Oceanography, P.O. Box 1006, Dartmouth, N.S., B2Y 4A2, Canada [tel: +1 902 426 5961, fax: +1 902 426 7827, e-mail: channah@emerald.bio.dfo.ca]

Robert C. Beardsley: Woods Hole Oceanographic Institution, Clark 343B, MS #21, Woods Hole, MA, 02543, USA [tel: +1 508 289 2536, fax: +1 508 457 2181, e-mail: rbeardsley@whoi.edu]
I. Introduction:

The sub-tidal flow over Georges Bank (Figure 1) is often described as a clockwise eddy or gyre. Huntsman (1924) was one of the first to note that the mean flow tended to be cyclonic over the deep basins and anticyclonic over the offshore shoals along the North American northeastern shelf. His chart indicated clockwise circulation around Georges Bank. This idea was enhanced by the analysis of Bigelow (1927). Walford (1938) discussed the non-tidal recirculation over Georges Bank after analyzing drift bottle data in relation to the survival of haddock eggs and larvae.

Later, Bumpus and Day (1957), Day (1958), and Bumpus (1973) used data from lightships and the results of drift bottle studies to establish a strengthening of the Georges Bank gyre during the summer months as a result of stratification, and interruptions in the gyre circulation during strong wind events. Bumpus (1976) reported on the use of radio tracked drifters over Georges Bank, and Butman et al. (1982) reviewed long-term Eulerian and Lagrangian current measurements to demonstrate clearly the clockwise flow pattern around Georges Bank inferred by Bigelow (1927), Bumpus (1973), and Bumpus (1976). These direct observations suggest that the residual clockwise circulation is a permanent feature of the regional circulation, and that some fraction of the shelf water that flows southwestward along the southern flank of Georges Bank turns and flows northward through the center and eastern side of the Great South Channel (GSC) to feed the narrow jet on the northern flank of Georges Bank and recirculate around the bank.

Butman et al. (1987) summarized the observed seasonal circulation on Georges Bank and reviewed the processes believed to drive the low-frequency circulation and affect its seasonal variability. They described how topographic tidal rectification [Loder (1980)] drives a clockwise circulation around Georges Bank throughout the year. However, the strength of the around-bank Eulerian circulation varies dramatically from the winter to summer months, with peak around-bank speeds increasing from 20 (15) cm s\(^{-1}\) to 40 (25) cm s\(^{-1}\) on the northern (southern) flank and displaying distinct seasonal changes which cannot be explained by tidal rectification. During the weakly stratified winter months, a strong surface wind stress contributes to an off-bank near-surface flow toward the south and reduces the recirculating northward flow on the eastern side of Great South Channel. The wind stress is significantly weaker during the strongly stratified summer months, when a tidal front at the transition region from vertically well-mixed to stratified conditions (about the 60 m isobath [Loder and Greenberg (1986)]) enhances the clockwise circulation around the bank. Seasonally varying inputs from far-field effects such as through-flow from the Scotian Shelf, interaction with the Gulf Stream (e.g. warm core rings), and the dynamics of the shelf/slope front also modify the circulation throughout the year.

More recently, Limeburner and Beardsley (1996) examined data from near-surface drifters deployed in the Great South Channel in late spring of 1988 and 1989 which became entrained in a clockwise recirculating gyre on Georges Bank during the stratified season (i.e. May-October). They found that eight drifters made a total of sixteen circuits around the bank, with an average drifter speed of 12 cm s\(^{-1}\) and an average recirculation time of 48 days. In general, the drifters moved faster over the northern and southern flanks of the bank, where average speeds were 15 and 13 cm s\(^{-1}\), respectively. These drifters followed a relatively narrow track around much of the bank, though there appeared to be a number of preferred paths over the Northeast Peak.

A fundamental objective of circulation modeling endeavors within the USGLOBEC program is to determine the seasonal evolution of bank-scale circulation patterns. Through the calculation of realistic circulation fields, understanding of the dominant physical processes is enhanced and the basis for advances in coupled physical/biological modeling is established. One outcome of mod-
eling efforts to date has been the computation, evaluation, and archival of climatological mean circulation fields which partition the annual cycle into six bimonthly periods. Naimie (1995) and Naimie (1996) detail the favorable comparisons between these solutions and available Eulerian circulation measurements, while Horne et al. (1996) indicate basic agreement between microstructure observations and model predictions of tidally-driven turbulence.

Our present aim is to demonstrate that numerical drifters tracked in the modeled climatology provide a description of the Lagrangian circulation on Georges Bank which is consistent with the observed large-scale drifter trajectories observed during the 1995 USGLOBEC Field Program. The primary objective of this observational component of the program is to characterize the recirculation over Georges Bank - both its spatial and temporal structure and variability, and integrate this physical characterization with biological observations to formulate a coherent description of the Georges Bank ecosystem. This Lagrangian understanding of the circulation is important because it will i) provide estimates of residence time over the Bank which directly relate to the ability of the system to retain nutrients and biota, ii) provide direct observations of where the water actually goes (i.e., the primary transport paths through important spawning grounds and the preferred regions where Bank water is exported), and iii) lead to a better understanding of the physics of the recirculation and improve our ability to model this dynamic system.

We begin with a summary of the numerical modeling strategy and illustration of the computed near-surface Eulerian circulation. This is followed by an overview of the 1995 USGLOBEC long-term drifter observational program. Next, we present direct comparisons between numerically simulated and observational drifters. We conclude with a brief summary.

II. Modeled Climatological Eulerian Circulation:

The modeled circulation is represented by 3-D velocity fields for each of six bimonthly periods: January/February, March/April, May/June, July/August, September/October, and November/December. These fields provide realistic estimates of the mean and M2 tidal velocity fields for the Gulf of Maine and Georges Bank region; subject to forcing from the regionally-dominant M2 tide, mean wind stress, and baroclinic and barotropic pressure gradients.

Circulation Model

A detailed description of the Dartmouth Circulation Model is presented in Lynch et al. (1995). Using a time-stepping finite element method algorithm, the model solves the nonlinear, three-dimensional, shallow water equations with the conventional Boussinesq and hydrostatic assumptions. The version of the model employed determines the baroclinic pressure gradient from a prognostically evolving density field. Vertical mixing is parameterized in terms of eddy mixing coefficients, which are determined using level 2.5 advanced turbulence closure [Mellor and Yamada (1974); Galperin et al. (1988); Blumberg et al. (1992)]. Variable grid spacing was employed in all spatial dimensions, providing vertical resolution of order 1 m in the surface and bottom boundary layers and horizontal resolution of order 0.5 km over the steep flanks of Georges Bank. Throughout the simulations; the 3-D mesh remained fixed in horizontal extend but was adjusted vertically to track the movement of the free surface. All aspects of the numerical simulations, including the time-step of approximately 45 seconds, were identical to those reported in Naimie (1996).

For each bimonthly period, the initial density field was determined from the historical temperature and salinity data base maintained at the Bedford Institute of Oceanography [see Naimie
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et al. (1994, hereafter NLL94). The initial conditions for velocity were taken from the corresponding NLL94 diagnostic (fixed density) bimonthly solutions. The climatological mean wind stress was estimated as described in NLL94 from the Comprehensive Ocean-Atmosphere Data Set (Woodruff et al. (1987)).

Eulerian Circulation

The circulation model predicts that an anticyclonic seasonal-mean circulation exists throughout the year around the periphery of Georges Bank (see Figure 2), consistent with the year-round influence of tidal rectification. Another noteworthy similarity between all bimonthly periods is the tendency for southeastward flow of a few cm s⁻¹ near the geographic center of the bank, which appears to be supplied by the northern flank jet. Just to the northeast of this feature, we note that a relatively quiescent zone persists throughout the year.

During the weakly-stratified winter months (January/February and March/April bimonthly periods): i) the anticyclonic circulation is narrowly confined to regions of steep topography on the northern and southern flanks, ii) there is little northward flow in the Great South Channel; resulting in a total recirculating transport under 0.06 Sv, and iii) the effects of the northwesterly winds are evidenced by the cross-bank component of the near-surface circulation on the northern flank (especially in January/February). In the strongly-stratified summer months (July/August and September/October bimonthly periods): i) the anticyclonic circulation is intensified and broadened on the northern flank, ii) the more intense jet extends from inside the 60 m isobath to approximately the 200 m isobath on the Northeast Peak and southern flank sections, iii) there is a northward flow of approximately 10 cm s⁻¹ in the Great South Channel; resulting in a total recirculating transport of approximately 0.25 Sv, and iv) there is little suggestion of any influence from the weak climatological winds. The May/June circulation field indicates the interplay of increased stratification and reduced wind stress, while the November/December field indicates the converse.

III. 1995 USGLOBEC Long-term Drifter Observational Program:

A total of 36 drifters with drogues centered at a depth of 10 m were deployed over Georges Bank during the 1995 USGLOBEC field program. As displayed in Figure 4, groups of 5 drifters were deployed on the crest of Georges Bank during the months of January, February, March, April, and November. During the month of June, 5 drifters were released in a line extending from the southwestern to northeastern extremes of the bank. In July, 5 drifters were released on the northern flank in a line directed along the bathymetric gradient. Finally, a single drifter was released on the crest of the bank in October. Drifter locations were recorded at approximately 1.5 hour intervals. For display purposes, all plots contained herein have been low-pass filtered such that the average daily locations of the drifters are shown.

A composite view of the drifter trajectories is displayed in Figure 3. This figure illustrates i) the general preference for along-bank transport, ii) apparent recirculation on the crest of the bank, iii) an exit region for drifters at the southwestern extent of the bank (i.e. drifters continuing along the continental shelf toward the Mid-Atlantic Bight, and iv) complex interactions of a limited number of drifters with the Gulf of Maine (Northwest Atlantic) to the northwest (southeast) of the bank.

Monthly observed drifter trajectories are displayed in Figure 4; where we plot trajectories for drifters deployed prior to the beginning of each month. As a result of this plotting strategy, there are no trajectories for the month of January. The four drifters displayed in the February panel
are four of the five deployed during January (the fifth drifter deployed in January had already been advected out of the region by the first of February). Similarly for the remaining months, the number of drifters advected out of the region during a particular month is equal to the number of trajectories plus the deployment sites for that month minus the number of trajectories for the subsequent month.

IV. Observation and Model Lagrangian Circulation Comparisons:

Numerical Drifter Simulations

To facilitate direct comparison of the modeled and observed Lagrangian circulation, Numerical drifters were tracked at 10 m below the undisturbed free surface in the seasonal-mean and $M_2$ circulation fields. The numerical drifter tracking methodology employed is described in Blanton (1995). At the beginning of each month, a numerical drifter was deployed at the location of each observational drifter within the domain (i.e. at the + symbols in Figure 4). Trajectories for the numerical drifters were subsequently computed for the ensuing month.

Monthly Drifter Trajectory Comparisons

As for the observed drifters, the numerically simulated drifters indicate the following general tendencies: i) anticyclonic circulation throughout the year, ii) seasonally varying advection scales, iii) export of drifters from Georges Bank to the southwest, iv) tendency for drifters to remain on the crest of Georges Bank during the winter months (January-April), v) evidence of recirculation in the summer months (July-October) with a recirculation time of approximately 40 days, vi) apparent transition from winter to summer (summer to winter) conditions during the May-June (November-December) time-frame.

However, there are a number of noteworthy differences between the trajectories of corresponding observed and numerical drifters; many of which appear to be directly linked to processes not modeled in the numerical simulations (i.e. episodic wind events, gulf stream eddies, etc.): i) In February, the numerical drifters all proceed along the southern flank and are advected out of the region along the continental shelf break (Figure 5). However, the observational drifters are all advected off Georges Bank to the southeast, where they are entrained in a gulf stream eddy (Figure 4). Examination of wind records on Georges Bank during the January-February 1995 period indicates that this is most likely a response to a series of episodic wind events. ii) In the July-August time-frame, recirculating drifters are observed to undergo southward advection either to the west of or over the 60 m isobath (Figure 4), while their numerical counterparts tend to continue eastward along the northern flank with more of a preference to turn southward at approximately the 80 m isobath (Figure 5). iii) Throughout the year, observed drifters are affected by circulation features in regions around the periphery of Georges Bank which are not reproduced by the modeled climatological circulation fields. iv) In a few instances numerical drifters are either trapped in very localized circulation features (see single drifters in the July and August panels of Figure 5 for example) or remain stationary (see eastmost deployment site in April panel of Figure 5), while their observed counterparts undergo significant advection. v) Finally, there are also cases where advection of a numerical drifter greatly exceeds and/or undergoes a significant diversion from its observational counterpart (consider the northwestern most drifter in the April panel of Figures 4 and 5 for example).

Seasonal Composite Lagrangian Description
To present a bank-wide description of the Lagrangian circulation, we determine the seasonal averages of observed and modeled drifter velocities for 24 subregions of Georges Bank. Our definition of subregions (see Figure 6b) consists of three elliptical rings of eight cells. The rotational orientation of the subregions was selected to provide direct measures for northern flank, Northeast Peak, southern flank, and Great South Channel velocities. As part of our statistical record keeping, we compile the number of daily intervals for which drifters are located within each subregion and the number of trajectory segments per subregion (e.g. a drifter with horizontal location confined to a single subregion for 10 days would yield 10 daily intervals for that subregion and a single trajectory segment).

The annual composite for the observational drifters (Figure 6) reinforces the fidelity of the observations to the conventional wisdom regarding the climatological circulation. There is a bank-scale anticyclonic circulation with clockwise Lagrangian currents in excess of 10 cm s$^{-1}$ on the northern flank and Northeast Peak, a southwestward flow on the southern flank and at the shelf break, and a hint of recirculation in the Great South Channel. Panels a, c, and d of Figure 6 indicate that there are a significant number of observations for each subregion.

Having introduced our data processing strategy for the annual composite, we now proceed with quantification of the observed and modeled drifter results for the winter and summer periods. The winter composite results (Figures 7 and 8) support earlier discussions regarding the individual drifter trajectories. They also provide additional information regarding the observability of the bank-scale circulation, whereby both modeled and observed drifters indicate that very similar regions of the Northeast Peak and the Great South Channel are essentially unobserved (shaded areas in panel b of the respective figures). The modeled and observed circulation is very similar for subregions with some portion inside the 60 m isobath, and there is no sign of recirculation in the Great South Channel in either case. All but one of the observed drifters which exit the region appear to do so under the influence of wind events of episodic wind events during February, while every numerical drifter which exits the bank continues southwestward along the continental shelf. Caution must be exercised here to emphasize that the absence of particle trajectories in a particular region is not a sufficient condition to support the conclusion that there is no tendency for drifters to enter that subregion; given the limited set of observations.

The most dramatic feature of the summer composite results (Figures 9 and 10) is the strength of the bank-scale recirculating gyre. The structure of this gyre is very similar for the observed and modeled circulation as are the unobserved regions of the southern flank and bank crest (shaded subregions in panel b of the respective figures), the intensity of the maximum clockwise Lagrangian currents on the northern flank and Northeast Peak (in excess of 20 cm s$^{-1}$), and the northward component of the flow in the center GSC subregion. As previously mentioned, the observed trajectories suggest that the inner limb of the southward flow on the Northeast Peak occurs inside the 60 m isobath, while the model trajectories suggest it lies nearer the 80 m isobath.

V. Concluding Remarks:

The Lagrangian circulation as described by numerical drifters deployed in climatological model-generated circulation fields is generally consistent with the observations from the 36 long-term drifters deployed during the 1995 USGLOBEC Field Program. Both of these products are also in overall agreement with the description of the bank-scale circulation resulting from earlier observational and modeling studies. In particular, the circulation on the bank is best described as an anticyclonic gyre with a seasonally dependent propensity for recirculation which is limited by the northward flow in the Great South Channel. The northward flow is essentially absent dur-
ing the weakly-stratified winter months and is a persistent feature of the circulation during the strongly-stratified summer months.

Episodic events, such as atmospheric weather conditions or interactions between the fluid on Georges Bank and its surroundings, have significant effects on a subset of the observed drifters. While these dynamics are not included in the model-generated circulation fields, their existence does not dominate the overall observation/model comparisons. Therefore, the underlying seasonally-dependent forcings from tidal dynamics, turbulent mixing, stratification, external pressure gradients, and climatological atmospheric conditions appear to be important in establishing the physical environment controlling observations from the 1995 USGLOBEC long-term drifter program.

However, episodic events can have important effects on the fate and transport of nutrients and biota on Georges Bank. Efforts are currently underway to incorporate more realism into our circulation models, through the use of observations to improve our specification of initial conditions as well as the evolution of atmospheric and horizontal boundary forcing. As a component of these studies, we will address some events which our present study has indicated result in significant discrepancies between the observational and model results. Most notably, the effect of non-climatological wind forcing on the observed drifters during January-February 1995.

Acknowledgements:
We thank Daniel Lynch and Justin Ip for their contributions to the development of the prognostic circulation model, Brian Blanton for providing the particle tracking software, and Francisco Werner for his contributions to both the circulation model and the particle tracking software. This work was jointly funded by NSF and NOAA, under the USGLOBEC program. Additional support for model development was provided by the Office of Naval Research.

References:


Figure 1: Map of the Georges Bank/Gulf of Maine Region. Abbreviations on the map indicate the geographic locations for the following regions on Georges Bank: northern flank (NF), Northeast Peak (NEP), southern flank (SF), and Great South Channel (GSC). All subsequent figures focus on a more localized view in the vicinity of Georges Bank.
Figure 2: Bimonthly climatological Eulerian circulation at a depth of 10 m, as predicted by the Dartmouth Circulation Model. Contour lines of the 60, 100, and 150 m model topography and a north-south line through the Great South Channel (located at 69.0°W) indicate the geographic location of Georges Bank.
Figure 3: Composite of observed long-term drifter trajectories (thin lines) on Georges Bank during 1995. The heavy lines indicate the geographic location of Georges Bank, as explained in Figure 2.
Figure 4: Monthly observed long-term drifter trajectories and deployment sites on Georges Bank during 1995 USGLOBEC Field Program. Trajectories (heavy lines) are included for drifters which were located on Georges Bank at the beginning of each month (+'s indicate initial positions). Deployment sites during each month are indicated by the *'s. The first(second) number in parentheses indicates the number of drifters trajectories(deployment sites) for each month.
Figure 5: Monthly modeled climatological drifter trajectories on Georges Bank. Model drifters were released at locations coincident with the starting positions for the observed drifters (i.e. the plus signs in Figure 4.) and tracked at a constant depth of 10 m for one month.
Figure 6: Average observed daily drifter velocities for 24 subregions of Georges Bank during 1995. Panel a) contains the drifter segments used for each subregion. Panel b) displays the average subregion velocities. Panel c) reports the number of daily intervals for which velocities were averaged for each subregion, while panel d) reports the number of trajectory segments for which velocities were averaged for each subregion. By not including daily intervals during which drifters crossed subregion boundaries, we have disregarded 23.99% of the available 2601 daily intervals.
Figure 7: Average observed daily drifter velocities for 24 subregions of Georges Bank during the winter months of 1995 (i.e. January-April). Panel layout is identical to Figure 6, with panel a) displaying the corresponding monthly trajectories from Figure 4, postprocessed into subregions. Subregions with less than two trajectory segments are shaded in panel b). By not including daily intervals during which drifters crossed subregion boundaries, we have disregarded 24.33\% of the available 596 daily intervals.
Figure 8: Average numerically simulated climatological drifter velocities for 24 subregions of Georges Bank during the winter months (i.e. January-April). Panel layout is identical to Figure 6, with panel a) displaying the corresponding monthly trajectories from Figure 5, postprocessed into subregions. Subregions with less than two trajectory segments are shaded in panel b).
Figure 9: Average observed daily drifter velocities for 24 subregions of Georges Bank during the summer months of 1995 (i.e. July-October). Panel layout is identical to Figure 6, with panel a) displaying the corresponding monthly trajectories from Figure 4, postprocessed into subregions. Subregions with less than three trajectory segments are shaded in panel b). By not including daily intervals during which drifters crossed subregion boundaries, we have disregarded 26.55% of the available 919 daily intervals.
Figure 10: Average numerically simulated climatological drifter velocities for 24 subregions of Georges Bank during the summer months (i.e. July-October). Panel layout is identical to Figure 6, with panel a) displaying the corresponding monthly trajectories from Figure 5, postprocessed into subregions. Subregions with less than three trajectory segments are shaded in panel b).