A View of Physical Mechanisms for Transporting Harmful Algal Blooms to Massachusetts Bay

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ABSTRACT

Physical dynamics of Harmful Algal Blooms in Massachusetts Bay in May 2005 and 2008 were examined by the simulated results. Reverse particle-tracking experiments suggest that the toxic phytoplankton mainly originated from the Bay of Fundy in 2005 and the western Maine coastal region and its local rivers in 2008. Mechanism studies suggest that the phytoplankton were advected by the Gulf of Maine Coastal Current (GMCC). In 2005, Nor'easters increased the cross-shelf surface elevation gradient over the northwestern shelf. This intensified the Eastern and Western MCC to form a strong along-shelf current from the Bay of Fundy to Massachusetts Bay. In 2008, both Eastern and Western MCC were established with a partial separation around Penobscot Bay before the outbreak of the bloom. The northeastward winds were too weak to cancel or reverse the cross-shelf sea surface gradient, so that the Western MCC carried the algae along the slope into Massachusetts Bay.

1. Introduction

Harmful Algal Blooms (HABs) of *Alexandrium fundyense* (*A. fundyense*) have become a serious environmental problem in the Gulf of Maine (GoM) coastal regions since 1972, particularly along the western shelf stretching from Maine into Massachusetts (Mass) Bay (*Geraci et al.*, 1989; *White* et *al.*, 1989; *Franks and Anderson*, 1992; *Anderson et al.,* 2005; *McGillicuddy et al.,* 2005). As the bloom develops, this dinoflagellate produces the neurotoxin saxitoxin that can lead to paralytic shellfish poisoning (PSP) when consumed in contaminated shellfish.

Impacts of regional and local physical processes on HABs in the GoM have intensively explored in the last decades, including its relationship with the seasonal and interannual variability of water temperature, stratification, winds and lights and oxygen, etc (*Anderson*, 1980; *Anderson et al.*, 1987; *Shumway et al.*, 1988; *McGillicuddy et al.,* 2003). It is really challenged to predict the outbreak of HABs since the growth of *A. fundyense* from a cyst stage was relevant to complex physical-biological interaction processes (*Anderson*, 1997).

Mass Bay is a semi-enclosed coastal region with the water supplies mainly from the northern shelf of the GoM. While the geography of Mass Bay sometimes isolates it from the large-scale HABs in the GoM, two serious HAB events occurred there in Mass Bay in May 2005 and May-June 2008 (Fig. 1). Comprehensive observational and modeling analyses were conducted for the 2005 bloom event, which suggested that while the regional bloom was initialized by a high concentration of *A. fundyense* cysts in the western GoM sediments, two mechanisms contributed to the advection of high concentrations of *A. fundyense* cells into Mass Bay. Several strong downwelling-favorable wind events (Nor'easters) (Fig. 2) intensified the two branches of the Gulf of Maine Coastal Current (GMCC), the Eastern MCC (EMCC) and Western MCC (WMCC)

(Churchill et al., 2005; Pettigrew et al., 2005), and to a lesser extent higher than normal coastal river discharge combined to form a continuous strong, along-shelf current from the Bay of Fundy region to Mass Bay (*He and McGillicuddy*, 2008; *He et al., 2008*). During May 15-16 2008, over half of Mass Bay was covered by an intense *A. fundyense* bloom (Fig.1). Winds during May were generally weak and towards the northeast (upwelling-favorable) (Fig. 2), clearly not a primary driver to transport *A. fundyense* cells from the western shelf into Mass Bay (Fig.2). Near-surface drifters released in May 2005 and May 2008 followed quite different paths (Fig. 3). A drifter deployed over the western Maine shelf on May 13, 2005 followed the intensified GMCC and moved quickly toward the Mass coast in 2005, while a drifter deployed outside of Mass Bay on May 28, 2008 moved into the GoM and towards the Bay of Fundy.

The contrast in wind forcing in May 2005 and May 2008 suggests that strong southwestward wind forcing may not be the primary physical mechanism that transports high concentrations of *A. fundyense* cells into Mass Bay. What is the difference of current features during the period of 2005 and 2008 HABs? Except wind-induced transport, were there other physical processes that could transport *A. fundyense* to Mass Bay?

In this paper we use the simulated hindcast data from the Northeast Coastal Ocean Forecast System (NECOFS) to investigate the physical mechanisms that can transport *A. fundyense* cells (which normally occur in the upper 30 m of the water column) into Mass Bay during the May 2005 and 2008 bloom periods. The simulation results have provided us insights into these questions.

2. Data and Methods

NECOFS is an integrated atmosphere-ocean model forecast system designed for the northeast US coastal region covering a computational domain from the south of Long-Island

Sound to the north of the Nova Scotian Shelf. The system includes 1) the mesoscale meteorological model WRF (Weather Research and Forecasting model); 2) the unstructured grid Finite-Volume Community Ocean Model and Surface WAVE model with configuration for the Gulf of Maine/Georges Bank /New England Shelf (FVCOM-GOM and FVCOM-SWAVE); 3) the Massachusetts Coastal Waters domain FVCOM (Mass-Coastal FVCOM) and 4) fully wave-current coupled coastal inundation model systems for Scituate Harbor and Boston Harbor, MA, and Hamption-Seabrook Estuary, NH.

The NECOFS has been used with data assimilation to create an archive of hourly hindcast fields of water elevation, three-dimensional (3-D) velocities, temperature and salinity for the period 1978-present (http://fvcom.smast.umassd.edu/necofs/). The hindcast simulation includes 1) the surface net heat flux, wind forcing, precipitation minus evaporation and river discharges, 2) the inflow of the cool and lower salinity water from the upstream Scotian Shelf, and 3) interaction with the Gulf Stream as well as data assimilation of SST, SSH and T/S profiles for a domain covering the entire northeast coastal region. The hindcast fields have successfully captured the spatial and temporal variability of the physical field in the region, with support from publications including *Cowles et al*. (2008) for vertical mixing and subtidal currents; *Chen et al.* (2011) for tidal elevations/currents; *Sun* (2014) for drifter trajectories; *Li et al.* (2015) for water stratification; *Sun et al.* (2016) for CODAR-derived surface currents; *Chen et al.* (2016), *Zhang et al.* (2016a,b) for the upstream region in the Arctic Ocean.

In this paper, first we "reverse" track model surface drifters from their initial positions in the Mass Bay blooms to determine the original source of the blooms observed in 2005 and 2008. The reverse tracking was done using the FVCOM offline Lagrangian particle-tracking method (*Chen et al.,* 2013). The particle trajectories were calculated by a fourth-order Runge–Kutta time-stepping scheme with second-order accuracy. A random walk-type process is included to simulate subgrid-scale turbulent variability in the current field (*Chen et al.*, 2012). By reproducing the same results in 2005 as previous studies (*He et al*., 2008), we then examine 2008 and construct momentum balances to identify the dominant physical mechanisms.

3. Results

3.1. Reverse Particle Tracking

A major bloom was first observed in the northern area of Mass Bay during May 10-16 2005; by May 28 it covered much of Mass and Cape Cod Bays (Fig. 1). In 2008, the bloom was detected inside Mass Bay around May 15-16. To examine the advection patterns during these two years, we released 55 particles in the NECOFS flow fields at the surface on May 17, 2005 and on May 15, 2008 and tracked them backward in time for 14.5 days (Fig. 4).

In 2005, 15 particles can be traced back to near the Bay of Fundy, while others back to rivers along the western GoM coast. This result is consistent with previous analysis, demonstrating that 1) the downwelling-induced mechanism proposed by *He and McGillicuddy* (2008) and *He et al*. (2008) played a significant role in transporting *A. fundyense* cells along the Maine coast to Mass Bay, and 2) freshwater discharge of local rivers along the coast may have contributed to the Mass Bay bloom.

In 2008, however, similar experiments show that many particles ended up over the southern half of the western GoM shelf and slope. Other particles were tracked back to local rivers but none back to the Bay of Fundy area. We do not have observational data showing whether the primary bloom outbreak in 2008 occurred over the western half of the Maine shelf and slope. However, the reverse particle tracks support the hypothesis that the bloom did not originate in the Bay of Fundy/eastern Maine shelf and slope area. The reverse tracks do support the hypothesis that areas around local rivers may be important sources of the blooms observed in Mass Bay in both years. Estuarine-shelf interaction processes, clearly implicated in the syntheses of *Franks and Anderson* (1992), have not been included in recent GoM HAB model studies.

3.2. Physical Mechanism for Advection Process

The critical issue raised here is: what physical mechanisms transport the bloom from the western GoM shelf and slope to Mass Bay during the 2008 period of northeastward (upwelling-favorable) winds?

The mean NECOFS-predicted surface circulation in the western GoM in both May 2005 and 2008 was dominated by southwestward along-shelf currents in the western GoM to Mass Bay region (Fig. 5). The only difference between years was in intensity and cross-shelf horizontal scales. In 2005, currents were much stronger and covered the entire shelf, while in 2008 currents were strongest along the slope and weaker over the mid- and inner-shelf. The westward and eastward trajectories of drifters, deployed on May 13, 2005 and May 28, 2008, respectively (Fig. 3), represent the surface (1-m) Lagrangian currents over the shelf for 2005 and in the interior of the GoM for 2008. The trajectories were influenced by the temporal and spatial variation of the surface wind. The model particles, released at the surface at the same time and positions that drifters were deployed, followed quite similar paths as drifters. This result helps convince us that the NECOFS-produced flow fields are realistic for both years, and the southwestward slope current could readily advect the bloom that appeared on the western shelf to Mass Bay in 2008.

What were the physical mechanisms driving the along-shelf currents in 2005 and 2008? In 2005, the persistent downwelling-favorable alongshore wind clearly intensified the along-shelf current (*He et al.*, 2008). During the 2008 bloom in Mass Bay, however, the wind-induced Ekman transport was offshore, which would tend to slow down the southwestward along-shelf current over the western shelf. *Franks and Anderson* (1992) suggested that during spring and summer the buoyancy-induced currents over the shelf could carry *A. fundyense* cells southward along the slope. The strength of this current was influenced both by the wind and volume of freshwater discharge from the rivers. This mechanism was supported by reverse-tracked particle trajectories that predicted the water sources from local rivers. Here we explore these dynamics in more detail through a momentum balance analysis.

Momentum balances for subtidal currents were computed using the May 2005 and 2008 NECOFS hindcast fields. The balance averaged in time and distance along the cross-shelf transect A (located ~ 100 km upstream of Mass Bay) show that the dominant cross-shelf (*y*-direction) balance was geostrophic, between the Coriolis term (*fu*), the barotropic (surface) pressure gradient ($g\partial\zeta/\partial y$), and the baroclinic pressure gradient ($1/\rho\partial p/\partial y$) in both years (Fig. 6). In 2005, the downwelling-favorable Nor'easters produced a strong onshore Ekman transport which increased the cross-shelf sea level gradient and greatly enhanced the southwestward barotropic transport along the shelf and slope. The buoyancy-induced baroclinic pressure gradient set the vertical shear in the along-shelf geostrophic current. The resulting mean along-shelf current in the upper 30 m in 2005 was ~ 25 cm/s (Fig. 5). In 2008, although ~ 50% weaker, the along-shelf flow was also southwestward through most of the water column, in geostrophic balance with a reduced cross-shelf pressure gradient (the upper water column mean was ~ 10 cm/s). Clearly, the weak and variable northeastward (upwelling-favorable) winds were unable to reverse the cross-shelf pressure gradient (and alongshelf flow) that had been built prior to May and thus prevent the southwestward transport of *A. fundyense* cells to Mass Bay.

4. Conclusions

Through an analysis of models and observations, we conclude that the mechanism leading to the occurrence of toxic HABs in Mass Bay in 2005 and 2008 were quite different. In May 2005, downwelling-favorable Nor'easters enhanced the along-shelf EMCC and WMCC, advecting an existing HAB along the coast from near the Bay of Fundy into Mass Bay (*He and McGillicuddy*, 2008; *He et al,* 2008). In May 2008, however, the Mass Bay HAB occurred during a period of upwelling-favorable winds. Our analysis shows that these winds were not strong enough to counteract the southwestward along-shelf currents in the WMCC driven by the existing cross-shelf pressure gradient and buoyancy forcing. The Mass Bay bloom likely originated near the rivers in southwestern Maine (e.g., *Franks and Anderson*, 1992). It is clear that the advection of existing HABs is a primary source of toxic phytoplankton along the GoM coast southwest of Maine (e.g., *Franks and Anderson, 1992; Anderson et al., 2005*). The dynamics underlying this alongshore advection are complex, involving an ever-changing balance between the buoyancy-induced coastal current (positive cross-shelf sea-level gradient), and the changing surface wind stress (positive and negative cross-shelf sea-level gradient). When these two forcings work together, there is extensive alongshore advection (e.g., in 2005). When the buoyancy-induced current is weak and/or the opposing wind stress is relatively strong or has strong cross-shelf gradients, the alongshore advection can be halted. Here we have shown a situation in which the opposing wind stress was not strong enough, and did not have enough spatial structure to counter the existing buoyancy-induced current, allowing the alongshore advection of a HAB into Mass Bay against the prevailing wind in 2008.

In both 2005 and 2008, the modeled particle trajectories tracked backward in time showed that the water in Mass Bay during the toxic bloom could be partially traced back to local rivers along the western coast of the GoM. *Zhao et al.* (2010) have examined the wetland-estuarine-shelf interaction in the Plum Island-Merrimack River complex (located near the Mass-NH boundary). Both observations and modeling revealed a re-circulation around the estuary-sound-shelf. Since the rivers were one of the major sources of nutrients near the surface and inner shelf region, attention should be paid on the estuarine-shelf interaction in future studies of HABs in the GoM.

It should be pointed out that this study focused mainly on the impacts of physical processes on the transport of *A. fundyense* after the outbreak of HABs. The physical and biological interaction mechanisms controlling the growth of *A. fundyense* are much complex, which required a significant effort on developing a coupled physical and geochemistry/ecosystem model that is capable of simulating the temporal and spatial variability of key physical and biological variables relevant to the life cycle of *A. fundyense.*

Acknowledgments

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Figure Captions

Figure 1: Distributions of the *A. fundyense* blooms observed in Mass Bay in May 2005 (dark orange: May 10-16; light orange: May 28) and May 2008 (dark orange: May 15-16). The 2005 distribution was redrawn from images from the website of WHOI. The 2008 distribution was redrawn from presentation presented by D. Anderson (WHOI) at the Massachusetts Water Resource Authority annual advisory meeting in 2009.

Figure 2: Time series of the 10-m wind velocity at the mid-point of the cross-shelf section shown in Figure 5. The wind values were obtained from the NECOFS hindcast archive.

Figure 3: Trajectories of surface (1-m) drifters tracked over the 2005 periods: May 13-July 6 (#55381) (blue line), and 2008 periods: May 28-August 12 (#85203) (red line). Drifter data were obtained from http://www.nefsc.noaa.gov/drifter/ with help from J. Manning (NOAA NMFS). Open circles: start locations; black dots: every 5- day location; gray level color lines: NECOF-simulated trajectories with daily re-sampling at the drifter's location.

Figure 4: Reverse trajectories of particles released at the surface at 12:00 EST May 17, 2005 (left panel) and 12:00 EST May 15, 2008. A total of 55 particles were released each year and total tracking time was 14.5 days. The number of tracks that reached the coast in different regions is shown in the white boxes along the Mass-Maine coast.

Figure 5: Distributions of NECOFS-produced monthly-averaged 40-hour low-passed subtidal near-surface currents for May 2005 (upper) and May 2008 (lower). Note the strong continuity of the GMCC in 2005 in comparison to the weaker connection between the EMCC and WMCC in 2008. The red line indicates the cross-shelf section where the momentum balance was computed. The light blue line is the 100-m isobath contour.

Figure 6: Cross-shelf and monthly-averaged momentum balance in the cross-shelf direction on the section shown in Figure 5 for May 2005 (left) and May 2008 (right).

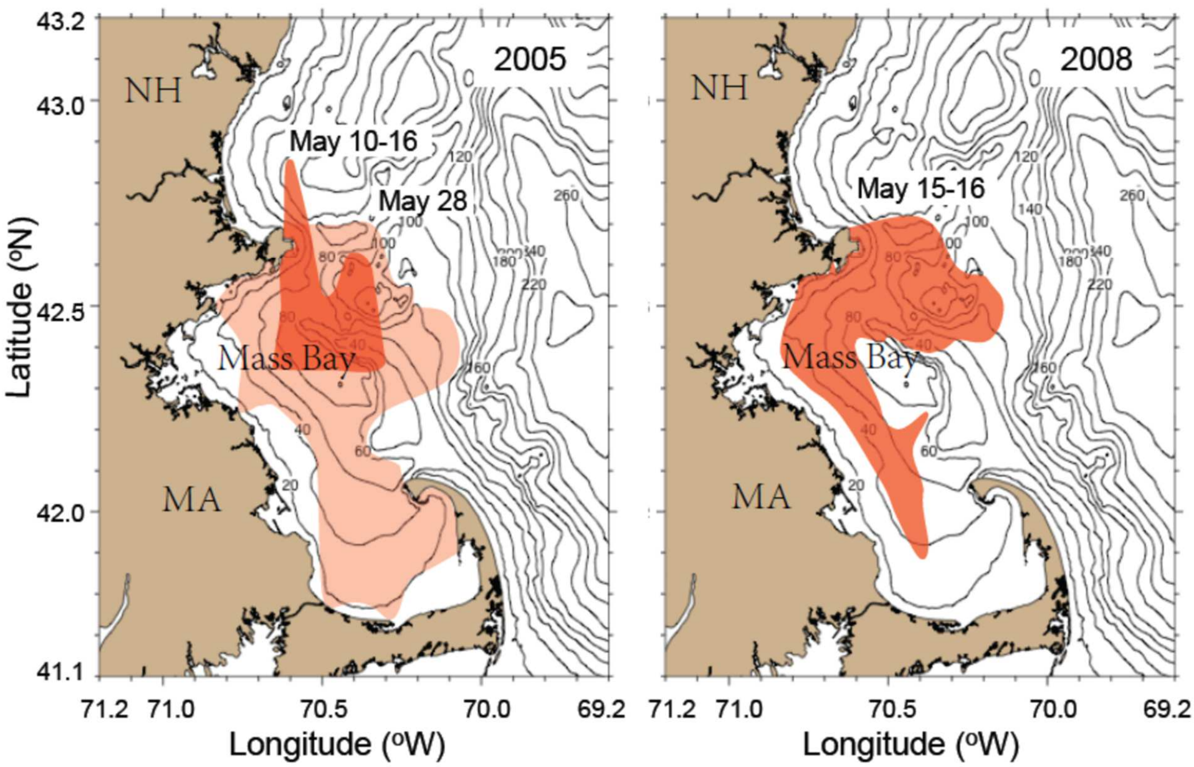

Fig. 1

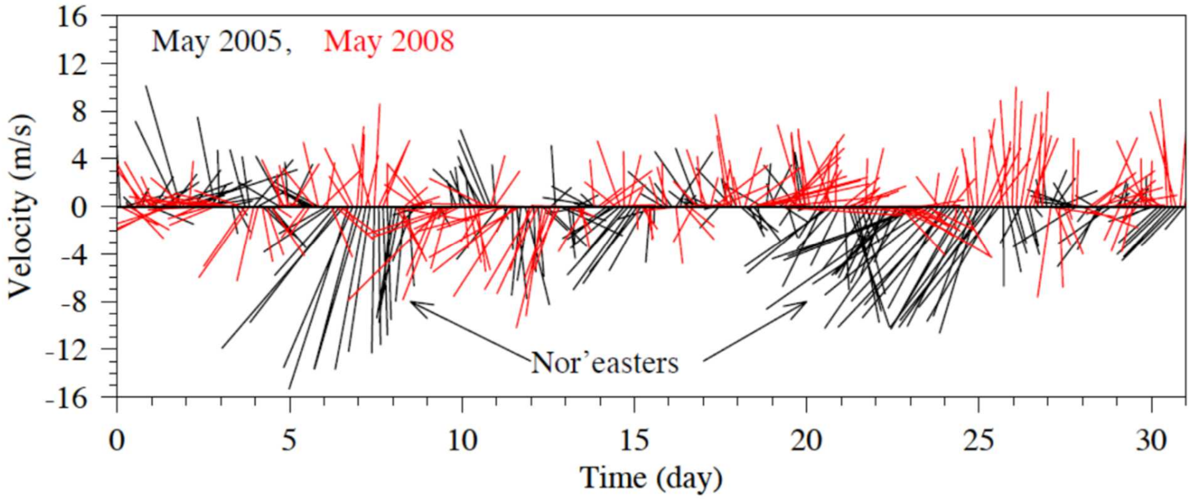
May 2005,
May 2008
Velocity (m/s)
16
12
8
4
0
-4
-8
-12
-16
Nor'easters
0
5
10
15
20
25
30
Time (day)

Fig. 2

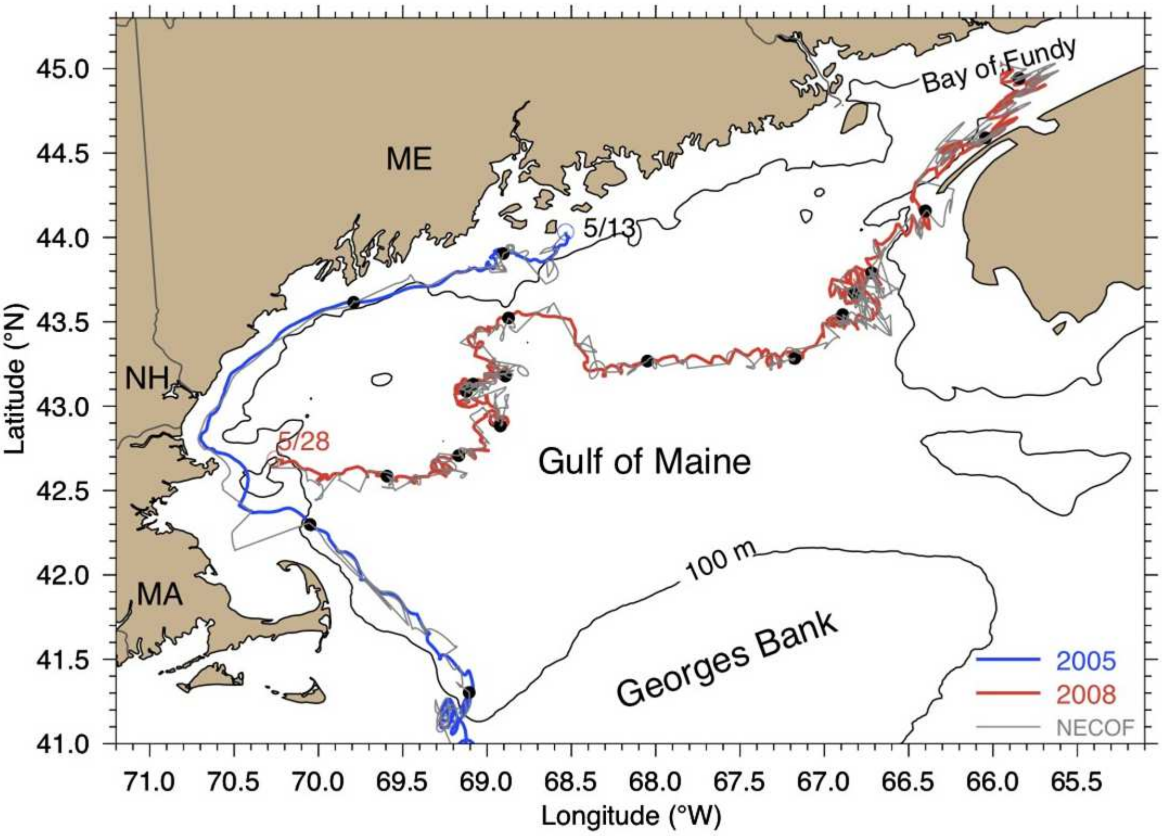
45.0
44.5
44.0
43.5
43.0
42.5
42.0
41.5
41.0
Latitude (°N)
71.0
70.5
70.0
69.5
69.0
68.5
68.0
67.5
67.0
66.5
66.0
65.5
Longitude (°W)
ME
NH
MA
5/13
5/28
Bay of Fundy
Gulf of Maine
100 m
Georges Bank
2005
2008
NECOF

Fig. 3

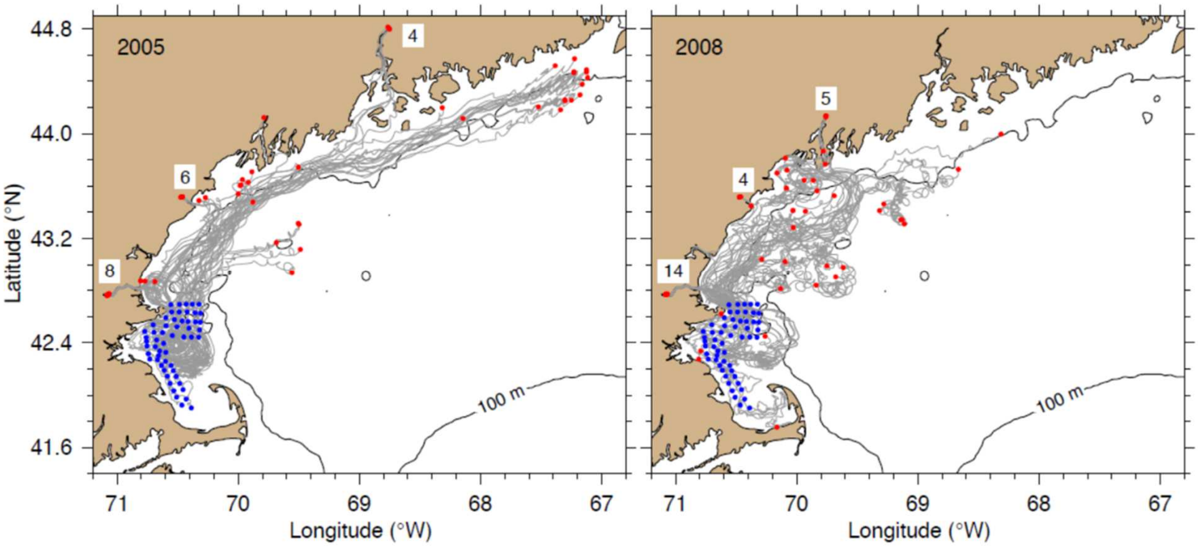
2005
2008
44.8
44.0
43.2
42.4
41.6
Latitude (°N)
71
70
69
68
67
Longitude (°W)
4
6
8
5
4
14
100 m
100 m

Fig. 4

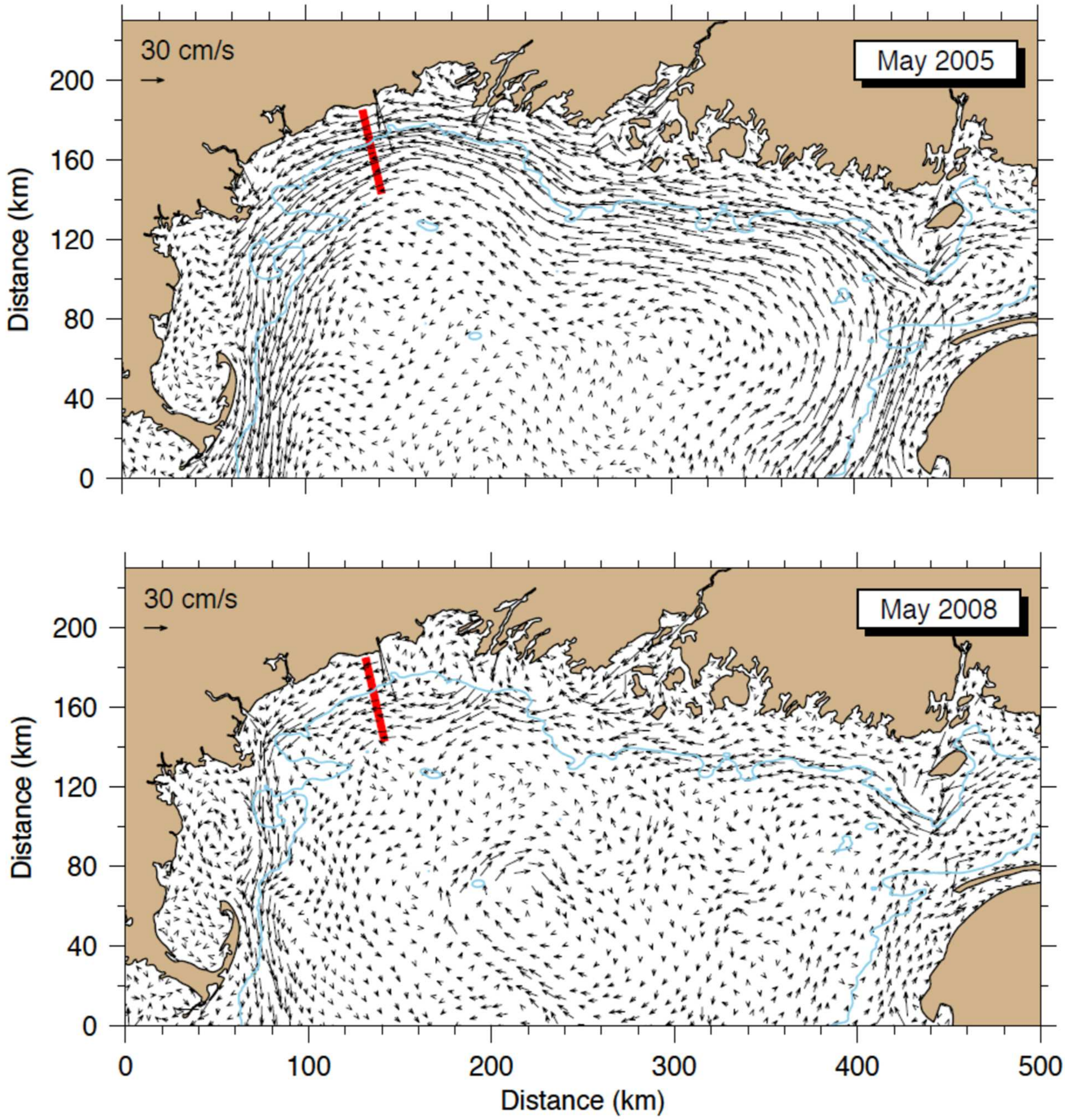
30 cm/s
May 2005
30 cm/s
May 2008
Distance (km)
Distance (km)
Distance (km)
0
40
80
120
160
200
0
100
200
300
400
500

Fig. 5

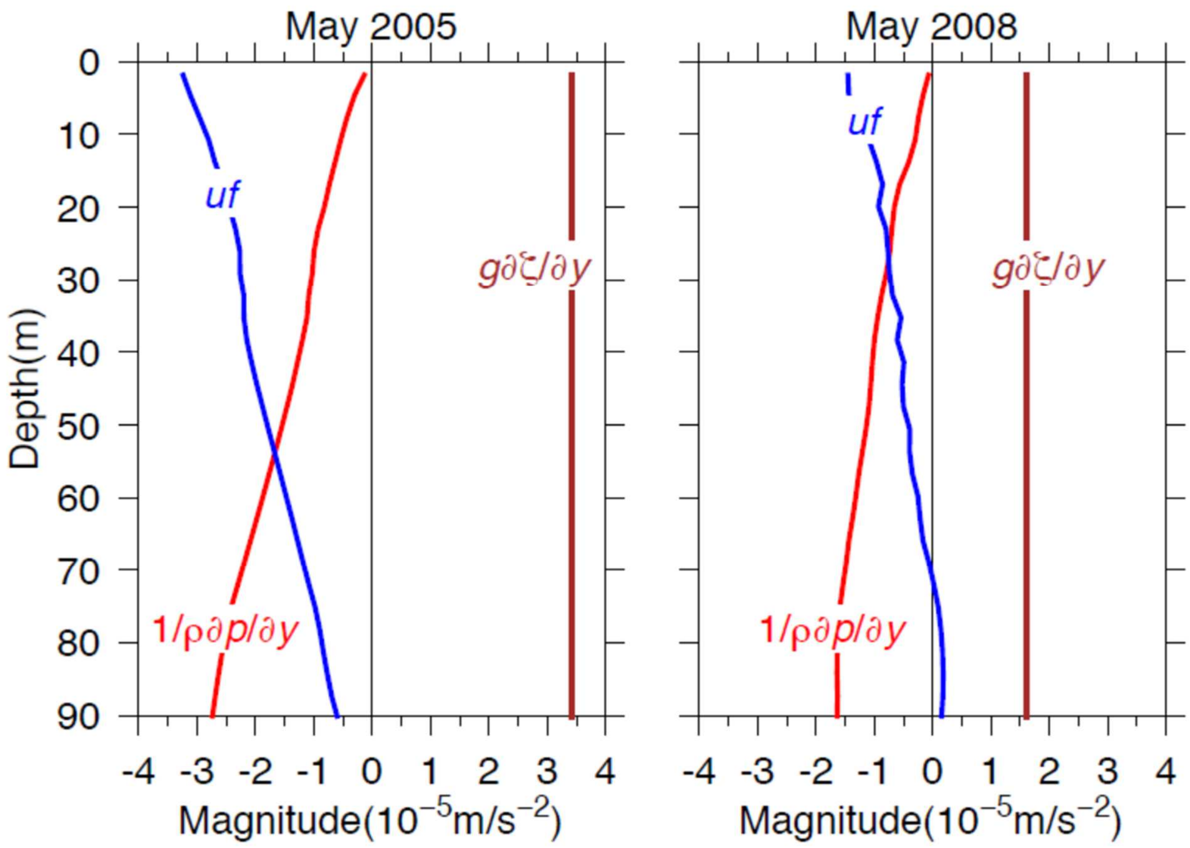
May 2005
May 2008
Depth(m)
0
10
20
30
40
50
60
70
80
90
uf
g∂ζ/∂y
1/ρ∂p/∂y
-4 -3 -2 -1 0 1 2 3 4
Magnitude(10^{-5}m/s^{-2})

Fig. 6