# THE RESPONSE OF THE GULF OF MAINE COASTAL CURRENT SYSTEM TO LATE-SPRING NORTHEASTERLY WIND FORCING

Neal R Pettigrew and Huijie Xue
School of Marine Sciences
University of Maine, Orono ME 04469

The Gulf of Maine Coastal Current (GMCC), which extends from southern Nova Scotia to Cape Cod Massachusetts, has two principal branches; the Eastern Maine Coastal Current (EMCC) that extends along the eastern coast of Maine to Penobscot Bay, and the Western Maine Coastal Current (WMCC) that extends westward from Penobscot Bay to Massachusetts Bay. The GMCC is primarily a buoyancy-driven system with both principal branches increasing their transport in the spring and summer, and flowing southwestward against the mean wind forcing during this period. When the winds blow from the northeast they reinforce the buoyancy forcing rather than opposing it, and the response is a clear acceleration toward the southwest.

Under typical summer conditions the transport of the EMCC is significantly greater that the WMCC. The reduction of southwestward transport near Penobscot Bay is accomplished via an offshore veering of a variable portion of the EMCC that recirculates cyclonically within the eastern Gulf of Maine (Figure 1). The degree of summer recirculation versus leakage into the WMCC varies from nearly complete recirculation to nearly continuous through flow. Although the fundamental reasons for this circulation pattern and its variation are not confidently known, it is clear that the interplay of the barotropic and baroclinic along-isobath pressure gradients is a major contributor. These pressure gradients are associated with the Penobscot outflow and the transition from the tidally-mixed eastern shelf to the more vertically stratified western shelf.

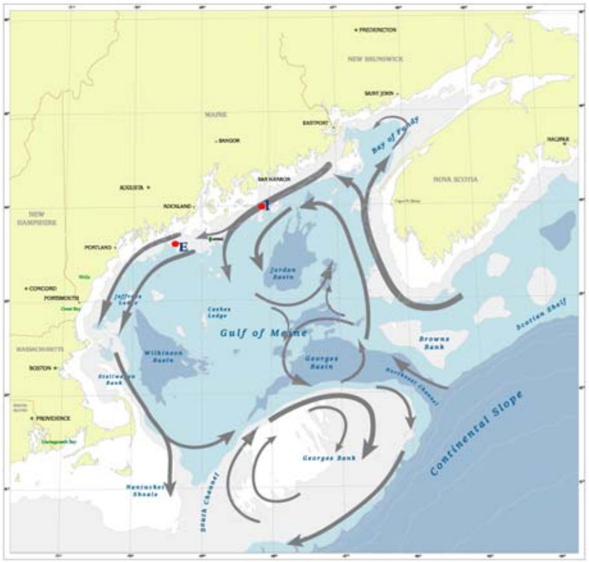

**Figure 1. Summer surface circulation schematic**

The degree of continuity, or leakage, between the EMCC and WMCC has important implications with respect to transport of planktonic organisms including the toxic red-tide dino-flagellate *Alexandrium* fundyense. Because Alexandrium is present in the core of the EMCC from late spring through early fall in most (if not all) years, its transmission southwestward along the shelf, versus its diversion offshore, or may be a key factor in the appearance of red tide outbreaks in the western coastal Gulf of Maine. While the factors controlling the continuity of the EMCC and WMCC are not well known, wind stress direction has a demonstrable effect. When winds blow from the northeast, both coastal currents accelerate toward the southwest with the WMCC transport often increasing more dramatically than the EMCC transport. This reduction of the EMCC/WMCC transport ratio is consistent with the notion that northeasterly wind forcing decreases, or even eliminates, the offshore veering of the EMCC, thereby enhancing the connectivity between the two principal branches of the GMCC.

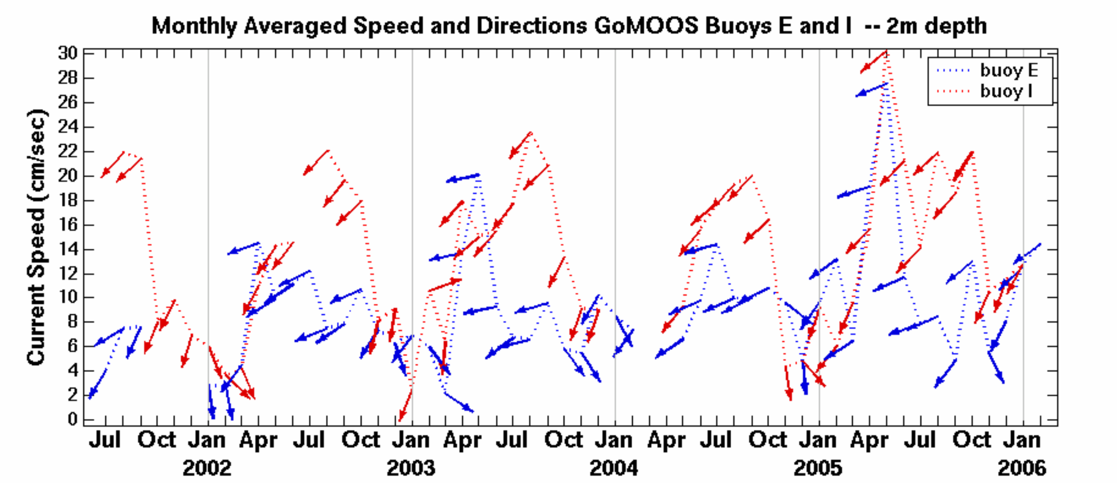

**Figure 2. Monthly averages of the surface current speed and direction at GoMOOS buoys I and E (see Fig. 1) that are located respectively in the EMCC and WMCC. Speed is plotted on the abscissa and direction is idicated by the unit vectors. The seasonal disparity of the strength of the EMCC and WMCC is an indicator of the offshore veering of the EMCC near Penobscot Bay. The anomaly in May of 2005, where the two currents are of equal strength, indicates flow through from east to west during this period.**

In the May and June of 2005, GoM was exposed to repeated northeasterly wind events unusual not so much for their strength, but rather for their late-season timing that occurred after the onset of the "red tide season" and the establishment of the summer circulation pattern characterized by offshore veering of the EMCC. Data from the GoMOOS buoy array and output from the operational GoMOOS nowcast /forecast circulation model provide an unprecedented chance to examine the effects of northeast wind events during the late spring in the GoM. Figure 3 shows the locations of the GOMOOS buoy and CODAR arrays, and Figure 4 shows daily averages of wind speed and direction for buoys E, B and A. Records from Buoy E are not shown because the wind sensor malfunctioned during the first episode.

Figure 4 shows that the May and June of 2005 were characterized by three distinct periods of northeast winds centered on with peaks around May 8, May 24, and June 15. The May wind episodes reached daily average peaks of 12 at buoys E and B, and 14 ms$^{-1}$ at buoy A in Mass Bay. The June episode was shorter lived and weaker at 8-9 m s$^{-1}$.

The corresponding daily-averaged surface current speeds (at 2m depth) for May and June 2005 for Buoys I, E, B, and A are shown in Figure 5. The strongest current response to the three wind episodes were observed at Buoy A, which also showed closer coupling with wind, less lag, and the surface currents reversing when the reversed after the strong northeasterlies. In contrast currents at Buoy I were uniformly southwestward regardless of wind direction, and showed little response to the June 15 event.

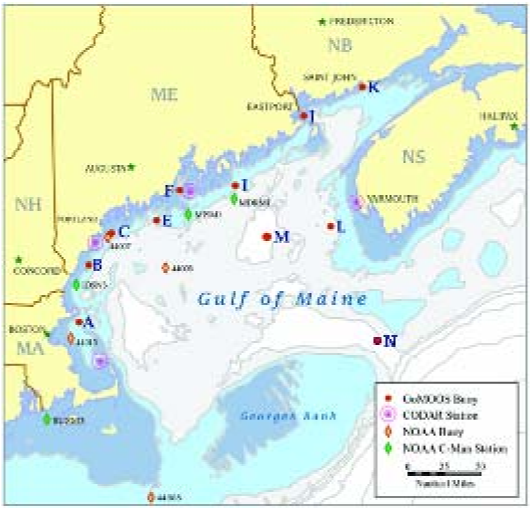

**Figure 3. Locations of GoMOOS buoys (red dots) and CODAR Staions (lavendar bullseyes.**

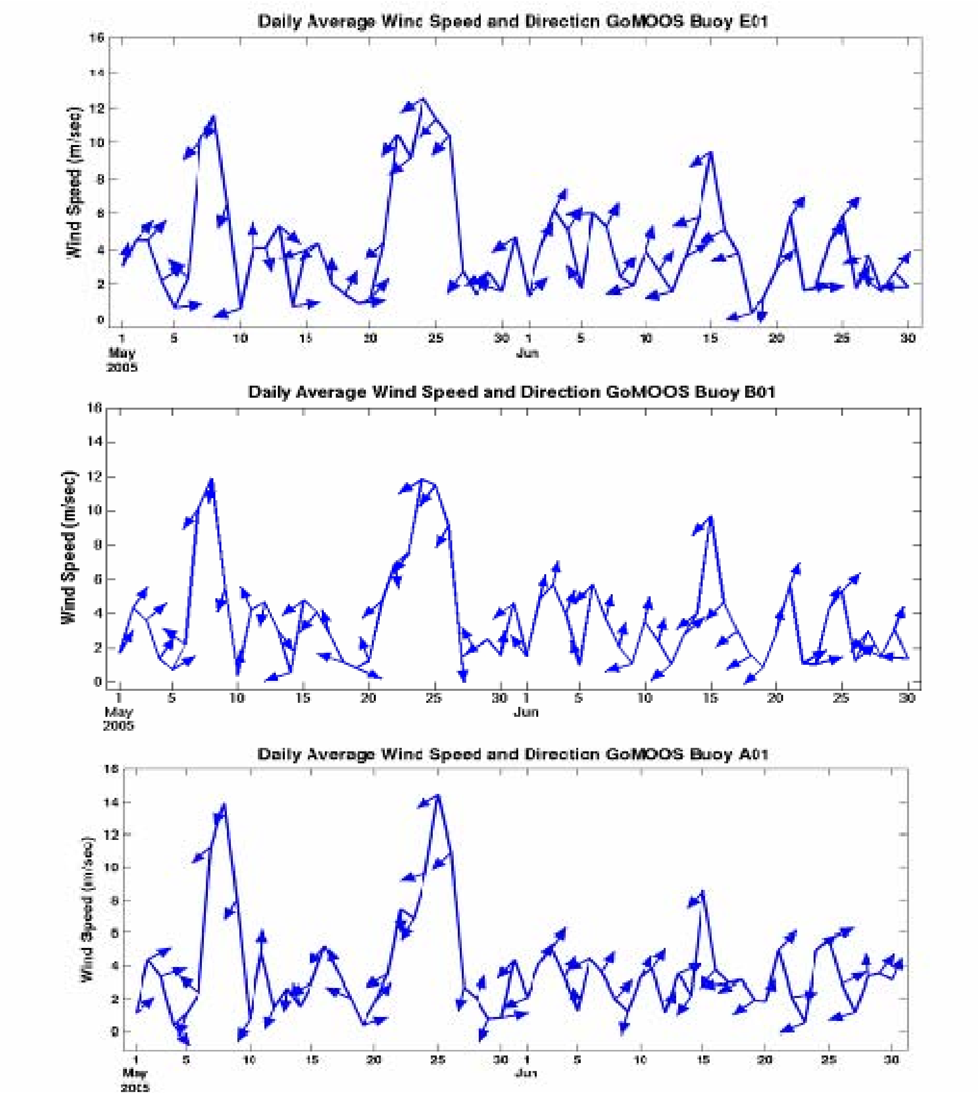

**Figure 4. Wind speeds and directions at Buoys E, B, and A during May and June 2005.**

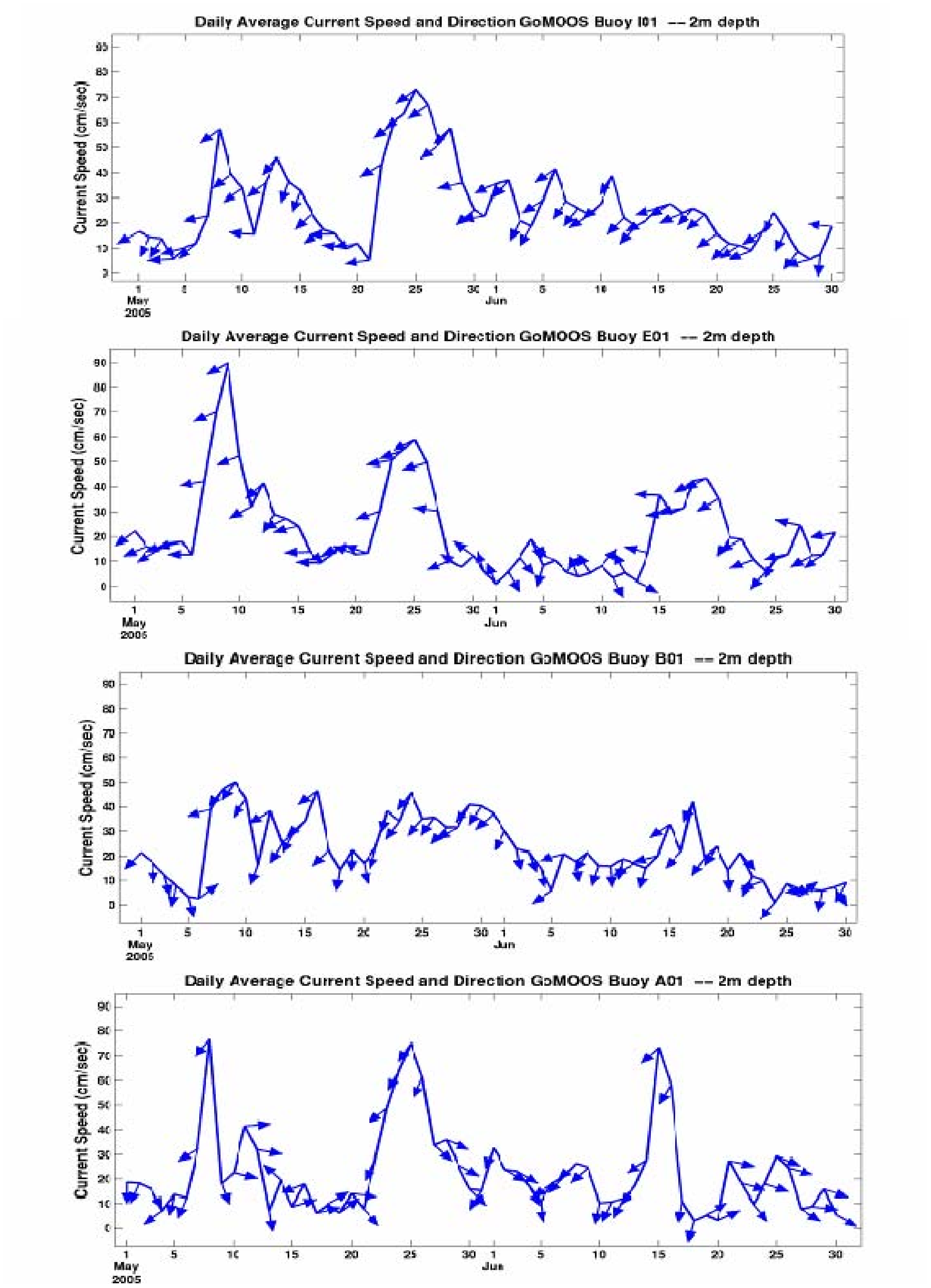

**Figure 5. Surface Current Speed and Direction for Buoys I, E, B, and A for May and June 2005. Response to the northeast winds were least apparent at Buoy B (and M and L, not shown) perhaps due to coastline orientation.**

During the June 15 2005 northeast wind, the three northernmost CODAR units were operating. Although these three stations are too far apart for the consistent overlapping of radials required for continuous surface current vector calculations under typical wave conditions, the high wind conditions provided idea wave conditions for extended range. A tidally-averaged CODAR derived surface current map is shown in Figure 6. The surface current map shows strong and extensive southwestward flow over the shelf from Isle au Haut to Biddeford and westward flow from Biddeford to the entrance of Mass Bay. It is notable the characteristic summer offshore veering the EMCC near Penobscot Bay is entirely absent, that (as observed by the buoys) the flow in the vicinity of Buoy I in the EMCC was relatively weak, and the flow in Jordan Basin ((near Buoy M) was NNW. This current map suggests that the surface flow east of Penobscot Bay and South of Biddeford had a significant shoreward component that would tend to bring the Alexandrium cells ashore. It also confirms that the cells from the EMCC, rather than being shunted offshore near Penobscot Bay, would flow westward into the WMCC. The sum of the physical data suggest strongly that northeasterly winds in the spring and summer are capable of disrupting the offshore veering of the EMCC that typically interrupts much of the southwestward transport in the vicinity of Penobscot Bay. This wind-induced flow through would carry Alexandrium cells from the EMCC father westward and could have substantially contributed to the widespread red tide outbreak that began in late spring of 2005.

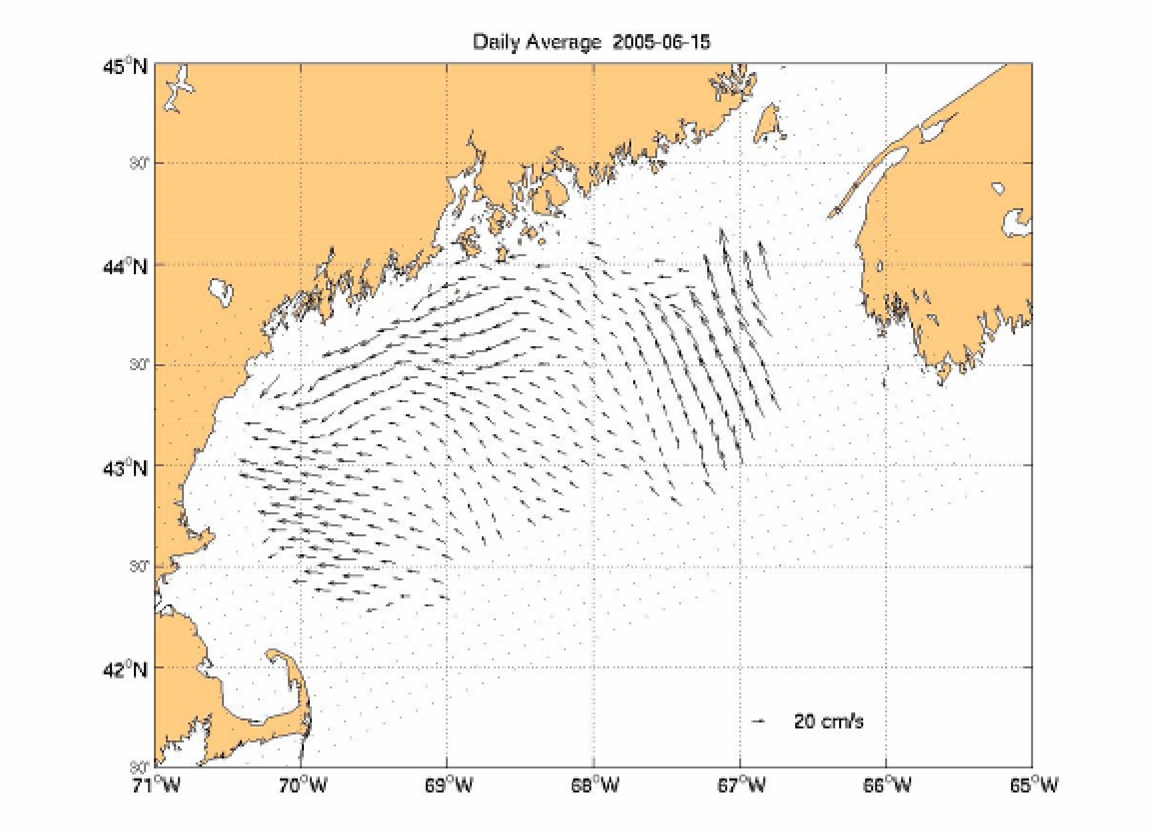

**Figure 6. Tidally-averaged CODAR surface current map for June 15, 2005 during the peak of the northeasterly wind event. Note the absence of the offshore flows near Penobscot bay that typically divert the EMCC water into the interior of the GoM during summer. Instead the current vectors suggest continuous flow from the eastern shelf to the western shelf.**

## Numerical Modeling Results:

The Gulf of Maine Ocean Observing System (GoMOOS) Nowcast/Forecast System (Xue et al., 2005) has provided daily nowcast and forecast of current, temperature, salinity and sea level in the Gulf of Maine since 2001. It provided timely estimates to aid strategic sampling program in the field during the outbreak of harmful algal bloom in Massachusetts Bay in May 2005

The numerical study focuses on two storm events in May 2005. Figure 7 compares the numerical meteorological nowcasts with the GoMOOS buoys winds. Results show that the model did an excellent job of simulating the wind field at the buoys locations. The wind had a strongly northerly component during the first Northeaster from 7-10 May, especially in the western Gulf of Maine, while it was more northeasterly and easterly during the second event from 21-27 May. Similar responses were found for both events with downwelling in Massachusetts Bay and acceleration of the Maine Coastal Current. Both events triggered strong mixing episodes and resulted in well-mixed water columns along much of the coast. Surface temperature decreased by 2-5 deg C, while the temperature at 50 m increased by 1-2 deg C. The resulting water temperatures were thus a combined product of the downwelling, vertical mixing, and advection of colder waters from the east. The stratification tended to reestablish quickly between events largely due primarily to surface heating. When compared with *in situ* observations, the model responses appeared to be somewhat weaker and more gradual especially during the onset of the first Northeaster.

Synoptic Description of the Storms – During the first storm event, the low began to form over the South Atlantic Bight on 6 May. It moved northeastward and intensified in the next 24 hours. Strong wind began to impact the Gulf of Maine on 7 May around 12:00 UST, estimated wind speed exceeded 10 m/s in Massachusetts Bay and was close to 15 m/s over Georges Bank. Wind was from the northeast over the western Gulf, but mostly from east over the eastern Gulf. The Gulf received considerable amount of rainfall. On 8 May, the low was situated south of the Gulf of Maine with strong wind (> 15 m/s) over the entire Gulf (stronger in the west than in the east), and changing from northerlies and northeasterlies in the west to northeasterlies and easterlies in the east. The cyclone continued moving eastward and wind speeds gradually diminished over the Gulf of Maine from ~ 10 m/s on 9 May to ~ 5 m/s on 10 May.

The second storm period was characterized by two back-to-back storms, one from 21 to 23 and another from 24 to 27 May, resulting in nearly a week strong winds. Northerly wind dominated in the former period, and northeasterly wind the latter. The maximum wind speeds during the storms were on the order of 17 m/s.

The comparison between modeled and observed currents is shown in Figure 8. The response to the storm winds is well rendered although the observed response was a bit sharper than the modeled winds. In general the eastward component was better modeled than the northward component, especially at buoys E and I. The model accurately shows the currents at E accelerating to speeds comparable to the currents at I, as observed in the data, and as is consistent with the conceptual model of the northeasterly winds “opening the gate” and allowing EMCC waters to flow southwestward into the WMCC region.

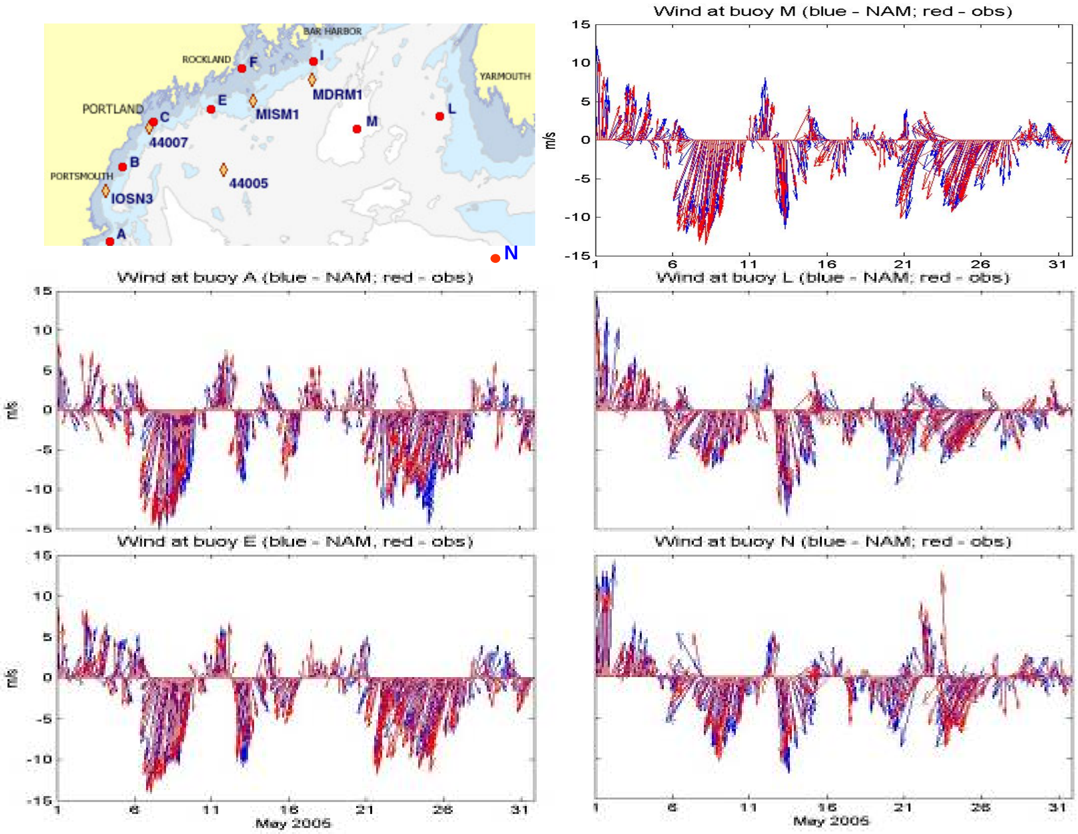

Fig 3. The Gulf of Maine Coastal Current (GMCC) accelerated in response to the Northeaster events (see buoy E and I). The increase in speed was found at all depths. Eastward velocity at buoy A reversed at depth, suggesting the presence of downwelling in Massachusetts Bay. In general, responses in the model were consistent with but weaker than the observed.