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Seasonal and interannual variability in Gulf of Maine hydrodynamics: 2002–2011

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ABSTRACT

In situ observations including long-term moored meteorological and oceanographic measurements and multi-year gulf-wide ship survey data are used to quantify interannual variability of surface wind, river runoff, and hydrographic conditions in the Gulf of Maine during summers 2002–2011. The cumulative upwelling index shows that upwelling (downwelling)-favorable wind conditions were most persistent in 2010 (2005) over the 10-year study period. River discharge was highest in 2005; peak runoff occurred in early April in 2010 as opposed to late April to middle May in other years. Moored time series show that coastal water temperature was 0.5–2 °C warmer than average in summer 2010, and about 2 °C colder than average in 2004. Coastal salinity in April 2010 was the lowest in the 10-year study period. Both moored Acoustic Doppler Current Profiler (ADCP) current measurements and dynamic height/geostrophic velocity calculations based on gulf-wide ship survey data show May–June 2010 had one of the weakest alongshore transports in the western Gulf of Maine during the 10-year study period, likely associated with intrusions of warm slope water and fresher-than-usual Scotian Shelf water. Comparisons of coastal currents to the Paralytic Shellfish Poisoning (PSP) closure maps resulting from *Alexandrium fundyense* blooms suggest a linkage between alongshore transport and the downstream extent of toxicity.

1. Introduction

The Gulf of Maine (GOM) off the U.S. northeast coast is a marginal sea (Fig. 1) having a large-scale cyclonic mean circulation (Bigelow, 1927; Brooks and Townsend, 1989; Lynch et al., 1996, 1997; Pettigrew et al., 2005). The nearshore flow known as the Maine Coastal Current (MCC) flows southwestward along the coast from the Bay of Fundy. Downstream, one branch of this current often veers offshore of Penobscot Bay. The remaining portion continues southwestward, as it is fed by river runoff from the Penobscot, Kennebec, Androscoggin, and Merrimack Rivers. The current bifurcates further downstream, one branch flowing through the Great South Channel (GSC) toward the Middle Atlantic Bight (MAB), and the other flowing northeast to Georges Bank.

While these mean circulation patterns are well known, significant variability has been observed on synoptic to interannual time scales. Both local forcing (i.e., tides, wind, heat flux and rivers) and upstream/deep ocean forcing contribute to such hydrodynamic variability (e.g., He and McGillicuddy, 2008; Keafer et al., 2005; Lynch et al., 1997; Mountain and Manning, 1994; Pettigrew et al., 2005; Xue et al., 2000). Pettigrew et al. (2005) showed that during a three-year study period (1998–2000), there was significant disconnection between eastern and western segments of MCC in 1998, as compared to a more connected coastal flow in 2000, with 1999 being an intermediate case. Further analysis of the kinetic structure of the flow showed such variability is an outcome of the modulation of both wind forcing and river discharge. Moreover, eddies and meanders may affect the near-shore current variance at times (Churchill et al., 2005). The drifter study by Manning et al. (2009) suggested while the mean coastal current is centered near 100-m isobath, its path can deviate fairly frequently due to effects of wind forcing and small-scale baroclinic structures. Modeling studies (Aretxabaleta et al., 2009; Li et al., this issue) also revealed significant interannual variability in the strength and transport pathways of the coastal current.

In addition to local forcing, inflows into the Gulf of Maine from the Scotian Shelf and through Northeast Channel (NEC) have been found to be highly effective in modulating the GOM interior hydrography from time to time (e.g., Bisagni and Smith, 1998; Brown and Irish, 1993; Houghton and Fairbanks, 2001; McGillicuddy et al., 2011; Smith et al., 2001, 2012). Mountain and Manning (1994) studied the seasonal cycle and interannual

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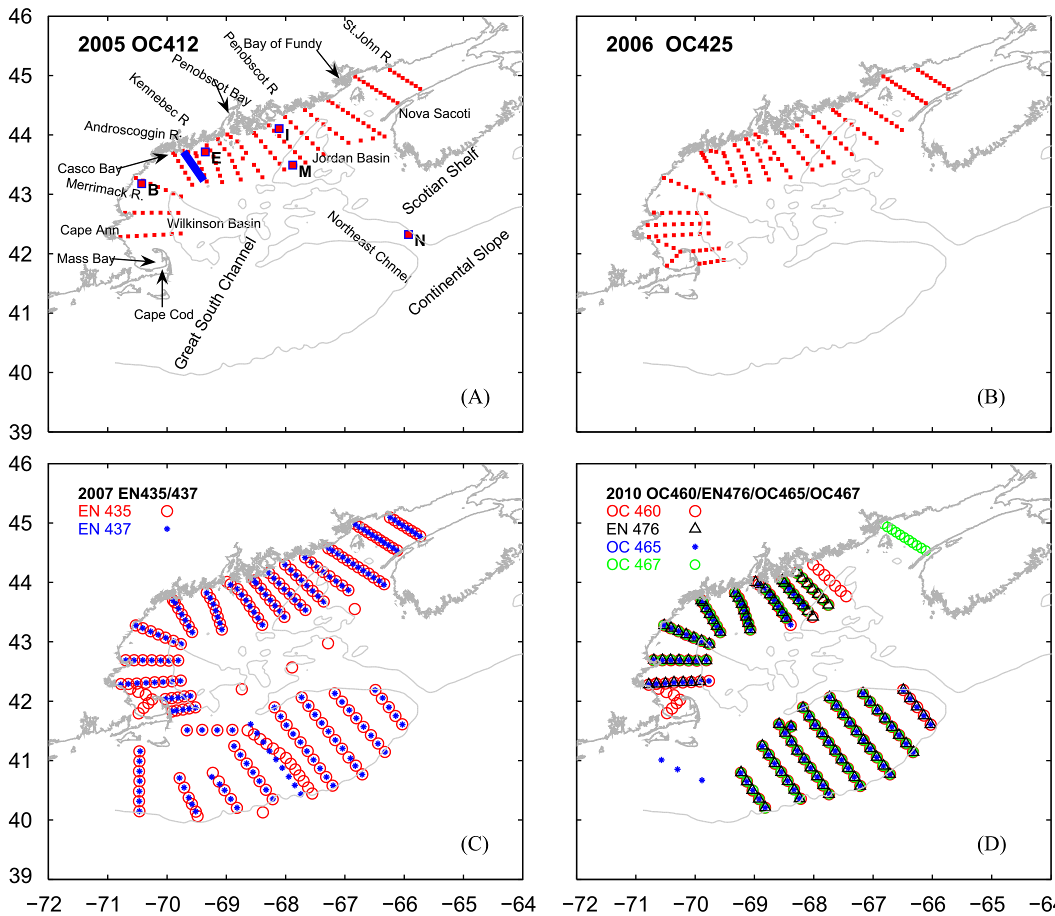

Fig. 1. Locations of the NERACOOS buoys (pink squares) and CTD stations (red dots) of gulf-wide ship surveys (A) *Oceanus* 412 in 2005, (B) *Oceanus* 425 in 2006, (C) *Endeavor* 435/437 in 2007 and *Oceanus* (D) 460/465/467 and *Endeavor* 476 in 2010, respectively. Also shown is the 200-m isobath. The blue solid line indicates the transect off Casco Bay that is used for computing alongshore transport shown in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variability in coastal hydrography. In the eastern Gulf the salinity cycle is dominated by the winter influx of low salinity Scotian Shelf water, as opposed to that in the western Gulf, which is heavily influenced by the local runoff in spring. Because of the phase differences in temperature and salinity cycles, the western GOM is more stratified in spring and summer. On decadal time scales, there was less variability in temperature (1–2 °C) during the period 1977–1987, compared to observed fluctuations of 4–6 °C in 1960s. Further analysis confirmed that the temperature variability was driven by both local heat flux and boundary inflows with an advective origin (Mountain et al., 1996). Townsend et al. (2010) found lower nitrate but higher silicate concentrations in the GOM interior beginning in the 1970s, likely due to increased freshwater inflow from the Scotian Shelf. As such, the coastal current system in recent decades is comprised of a greater portion of relatively nutrient-poor, cold shelf waters and less of the nutrient-rich, warm slope waters that were previously thought to dominate the nutrient flux into the gulf.

Long-term moored meteorological and oceanographic observations (with hydrographic observations becoming available in July 2001) taken by a regional marine buoy network, along with multi-year gulf-wide ship surveys of the Gulf of Maine Toxicity (GOMTOX) project and predecessor programs, have provided a new opportunity to quantify the interannual variability of the GOM hydrodynamics in recent years. Focusing on the late spring and summer periods (April 1–August 1), we use these observations to investigate the interannual variations in local wind forcing, river discharge, and the gulf-wide hydrographic conditions during 2002–2011. One of our objectives is to provide an updated knowledge of regional coastal hydrography that can complement Pettigrew et al. (2005) and other earlier studies (which were based on ship survey data and Gulf of Maine Ocean Observing System observations prior to 2005), and discuss the possible causes to such variability during the past 10 years. In addition, a number of earlier studies have illustrated that changes in atmospheric forcing, gulf hydrography and coastal circulation have significant impacts on the timing and magnitude of annually-occurring *Alexandrium fundyense* blooms and shellfish toxicity in the gulf (e.g., Anderson et al., 2005; He et al., 2008; Li et al., 2009; McGillicuddy et al., 2011; Thomas et al., 2010). In this regard, a particular motivation of this research is to better quantify the seasonal and interannual variations in the Gulf of Maine hydrodynamics to provide a foundation for understanding the intrinsic linkage between regional hydrodynamics, *A. fundyense* blooms, and the distribution of the associated toxicity along the coast.

2. Methods

The majority of long-term time series observations used in this study during 2002–2011 were obtained from moorings of the Gulf of Maine Ocean Observing System (now part of the Northeastern Regional Association of Coastal and Ocean Observation Systems [NERACOOS], http://www.neracoos.org, e.g., Pettigrew et al., 2011), including hourly observations of surface wind speed and direction, ocean temperature, salinity and velocity. We focused on

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