WAVE CLIMATOLOGY INFLUENCING AQUACULTURE OPERATIONS IN COASTAL MAINE

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1. Introduction

Many parts of the world are witnessing the proliferation of aquaculture activities in nearshore and offshore waters (e.g. U.S.A., Canada, Scotland, Chile, and Japan). These activities involve structures like salmon cages and mussel rafts of various designs (Hartstein, 2005; Decew et al. 2005; Lee and Wang 2005); in the Gulf of Mexico, appendages on decommissioned oil platforms are being proposed as fish containment units.

Ocean waves constitute possibly the most significant of all the hydrodynamic factors affecting the behavior of these structures and the overall aquaculture operation. In some cases (e.g. Toothacher Bay, Maine), Panchang et al. (1997) have concluded that waves play the dominant role in cleansing the bay of settled net-pen wastes (excess fish food and fecal matter) and represent a factor in siting these operations. On the other hand, large waves can damage aquaculture structures, resulting not only in a financial loss but also in undesirable intermingling of wild and harvested species. One high-profile incident and the ramifications which included calls for a moratorium on the industry in Maine are described in an article titled “Escape Upsets Environmentalist” by B. Rayner in the March 2001 issue of “Fish Farming”; see also Schardt (2004). Wave-induced turbulence can also lead to detachment of mussels from rafts. Considerable research efforts are therefore being invested in understanding and predicting the wave-structure interactions associated with aquaculture units to enable proper design. (See special issue of IEEE Journal of Oceanic Engineering, January 2005, devoted to Open Ocean Aquaculture Engineering, which describes moored fish cage dynamics and mooring analysis of several structures under wave action).

Obviously, characterization of the wave climate in coastal regions is needed both for siting aquaculture operations and for designing the units. From an environmental water-quality standpoint, frequency of wave-induced re-suspension of settled wastes can lead to their being flushed out an embayment; from the standpoint of structural integrity, it may be noted that aquaculture units can sustain damage due to big waves and also possible low frequency swell (i.e. resonance, as noted by Fredriksson et al. 2003). Thus, detailed knowledge of the frequency of high wave action as well as the “extreme” wave conditions is needed, along with information regarding the wave velocities and wave periods. Unfortunately these data are rarely available for most coastal sites.

This paper describes the development of the requisite coastal wave climatology for some coastal regions in the Gulf of Maine, where aquaculture activity is widespread. While Perez et al. (2004) have articulated comparable goals for aquaculture near the Canary Islands, our methods constitute a generalization and a refinement of their techniques, and while we describe results for coastal Maine, are presented the methods described here may be adopted for other locations. Section 2 provides details about the two study areas and the available background wave information. Section 3 describes the modeling methodology used to obtain wave characteristics at an appropriately fine resolution as well as validation of the calculated wave heights. In order to obtain reasonably representative estimates of the frequency of high waves and also of the “extreme” events, the modeling was performed for a period of six and half years (July 1999 – December 2005) on a continuous basis. This extended duration, combined with the high spatial resolution, yields a large database on which we can perform two types of analyses. The first consists of an examination of the modeled data to determine typical and maximum wave conditions in different parts of the domain. Using water depths and the modeled wave height and peak periods estimates are obtained of wave-induced bottom velocities which can motivate re-suspension of settled wastes. This is described in Section 4. The second analysis, presented in Section 5, consists of estimating, from the modeled data at each grid point, the extreme wave conditions corresponding to specified recurrence intervals, say 30 years representing the design life of the cage. Concluding remarks are presented in section 6.

2. Site Description and Background Wave Data

Our work focuses on two prominent areas along the coast of Maine (Fig. 1). The first encompasses Blue Hill Bay, Frenchman’s Bay, and Belfast Bay; for simplicity we will call these the Penobscot Bay region (Fig 2). The second, Machias Bay region (Fig. 3), is near the Canadian border. Both domains have salmon farms and existing and expanding mussel raft operations.

The bathymetry in these areas is extremely complex and the coastline is fraught with numerous bays, islands, coves, etc. It may be surmised that wave propagation and growth in these area would be influenced by refraction and diffraction caused by the bathymetry and the islands, breaking, and frequent storm activity (wind effects). The tidal range in these regions is quite large, and it is likely that the wave propagation is influenced by tidal currents as well, although we have not considered that effect in the present work. As regards wave information sources, there were, until recently, only two NDBC buoys in coastal waters of the Gulf of Maine: buoy 44007 near Boston and buoy 44013 near Portland (Fig 1). Previous studies using models and buoy data show that the overall wave climate in the Gulf of Maine is highly energetic (Panchang et al. 1999; Panchang et al. 1999; Panchang and Li 2006). At the location of the two aforementioned buoys, Panchang et al. (1999) estimated that the significant wave heights (SWH’s) with a 2% chance of being exceeded in any year were greater than 9 m (translating to maximum wave heights of approximately 18 m). These buoys have been augmented by the deployment of additional buoys as part of the Gulf of Maine Ocean Observing System (GOMOOS). However, buoys can provide only “spot” measurements which are obviously not representative of

Maine's extremely complex coastal topography; furthermore the buoy data are inadequate for extracting climatological information, owing to the fact that the buoys have been deployed only in recent months.

Wave predictions for the Gulf of Maine are in fact produced by NOAA's National Center for Environmental Prediction, but as part of a large scale simulation for the entire western north Atlantic. The well-established and validated energy-balance mathematical models WAVEWATCH is used for this purpose along with simulated windfields. For a large domain such as the western north Atlantic, the resolution must necessarily be coarse and a grid of about 25 km is used by NOAA (http://polar.ncep.noaa.gov/waves/main_table.html). Obviously, for the stated aquaculture applications, the resulting information is much too coarse for representing the intricacies of coastal Maine which encompasses over 3500 miles of coastline with complicated bathymetric and geometric variations. The Army Corps of Engineers' WISWAVE models also do not provide the desired resolution, nor are their data available for many time periods.

3. Fine - grid coastal modeling

In their effort to develop the wave climatology for aquaculture applications around the Canary Islands, Perez et al. (2003) identified grid points where the Spanish Department of Maritime Climate (SDMC) provided forecasts for the North Atlantic. These points are approximately 25 km apart. Perez et al. (2003) assumed that the near-shore aquaculture sites experienced the same wave conditions as those that prevailed at the SDMC grid points; no attempt to modify these waves for local bathymetric effects (refraction, diffraction, decay, and growth) on scales less than 25 km was made. That approach would clearly be inappropriate for the domains shown in Figs 2 and 3.

To accommodate local geometric and growth effects, we extend NOAA's coarse-resolution (approximately 25 km) outer ocean predictions to the near-shore areas by performing high-resolution (0.5 km) simulations on the individual Penobscot Bay and Machias Bay domains. For this purpose, we resorted to the third generation wave-prediction model SWAN (Simulating Wave in the Nearshore), developed at the Technical University of Delft (Booij et al. 1999; Ris et al. 1998; and Ris et ai. 1999). The model is based on the following spectral action balance equation:

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N + \frac{\partial}{\partial \theta}c_\theta N = \frac{S}{\sigma} \qquad (1)$$

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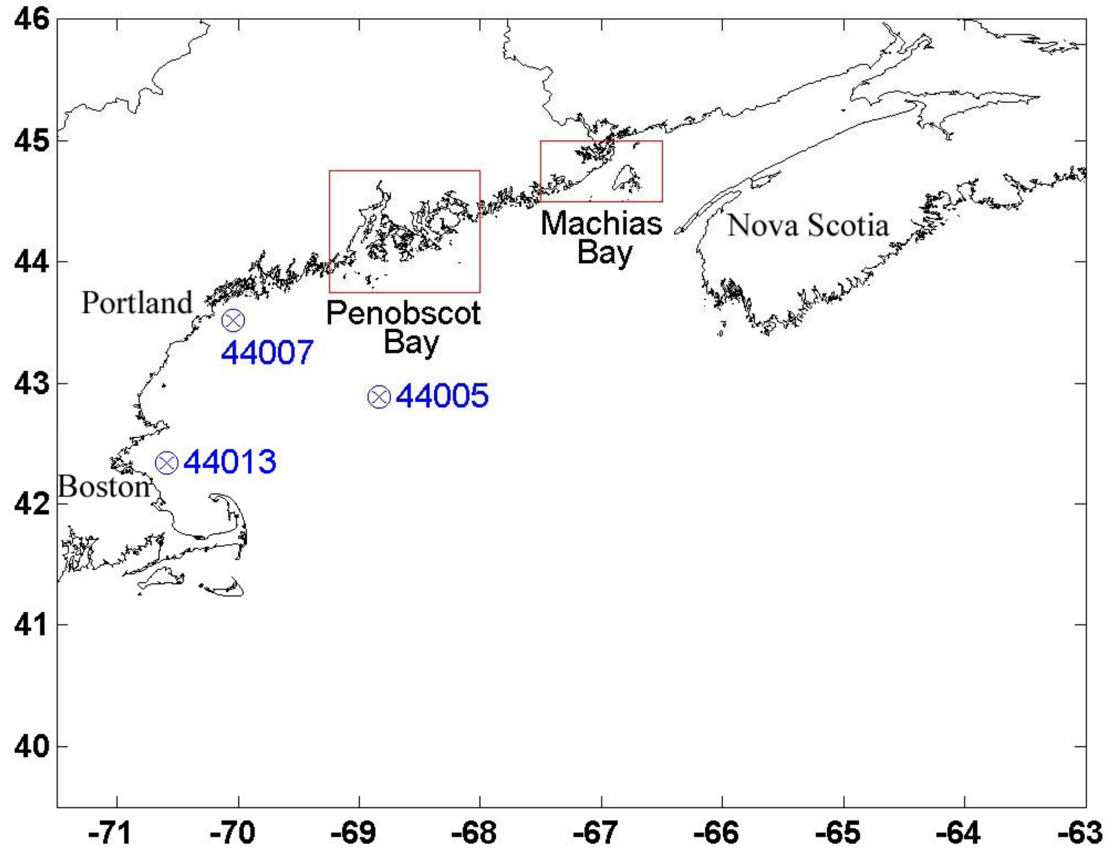


Fig 1. Gulf of Maine and Location of the NDBC buoys.

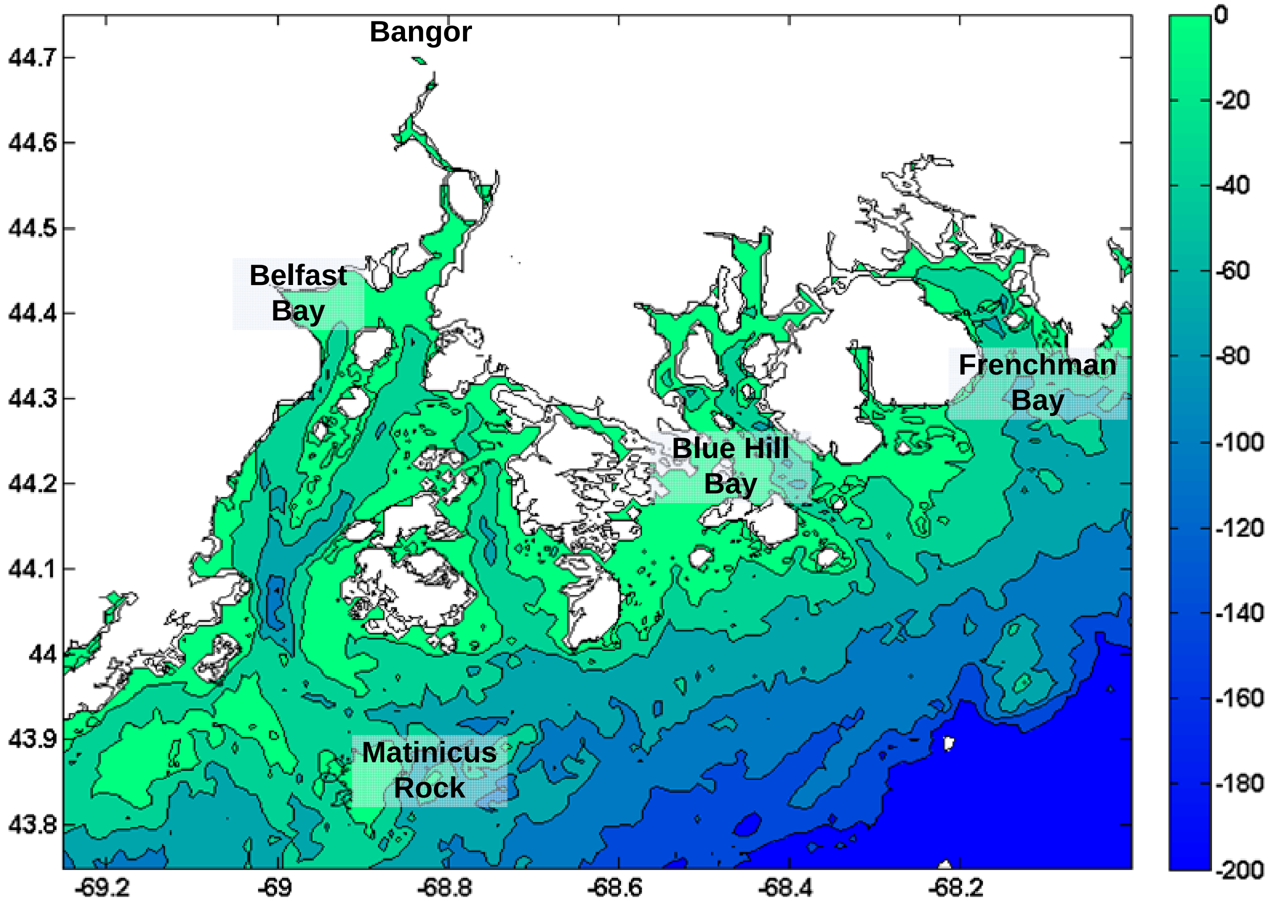


Fig 2. Penobscot Bay and bathymetry in meters

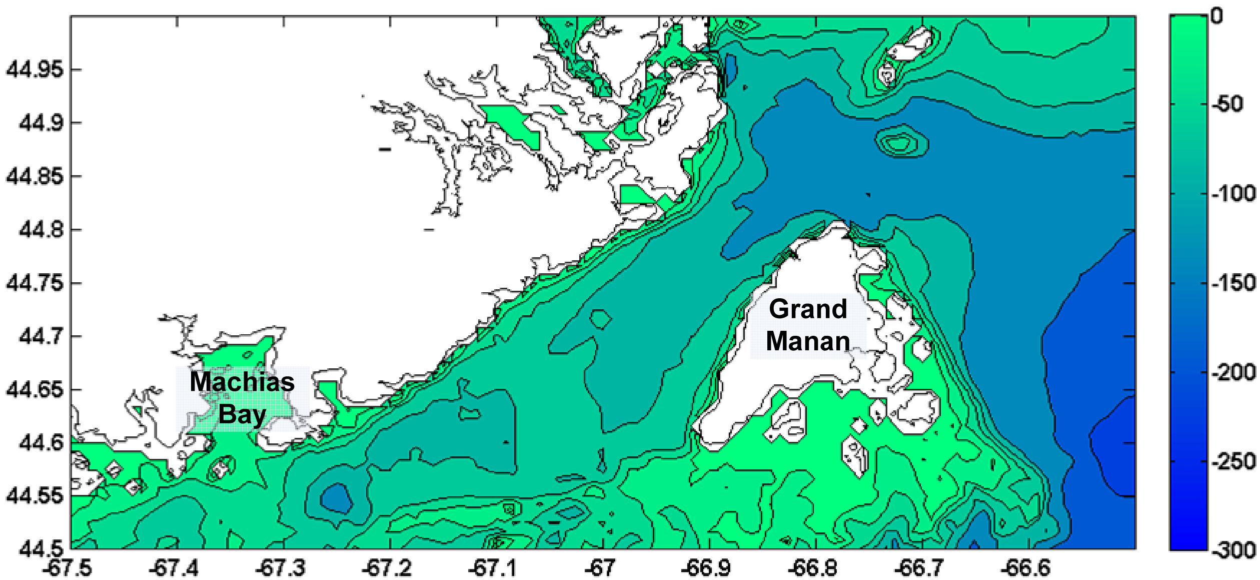


Fig 3. Machias Bay and bathymetry in meters

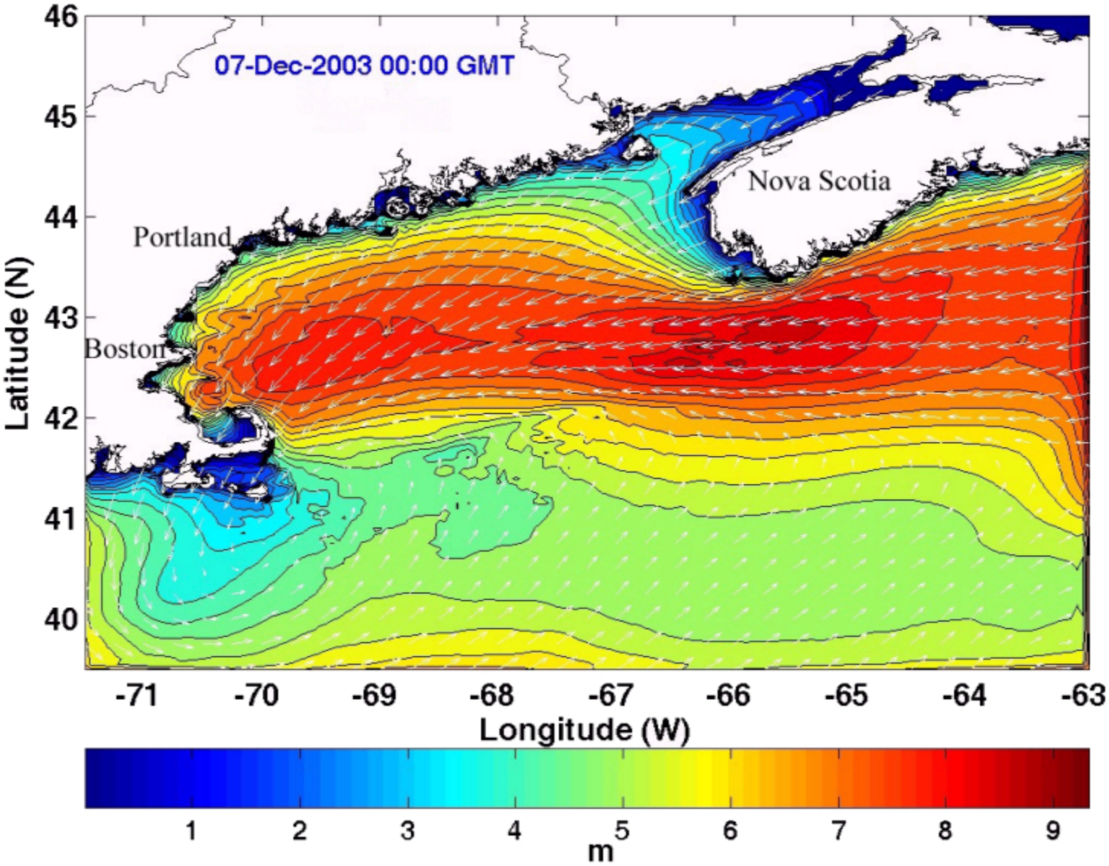
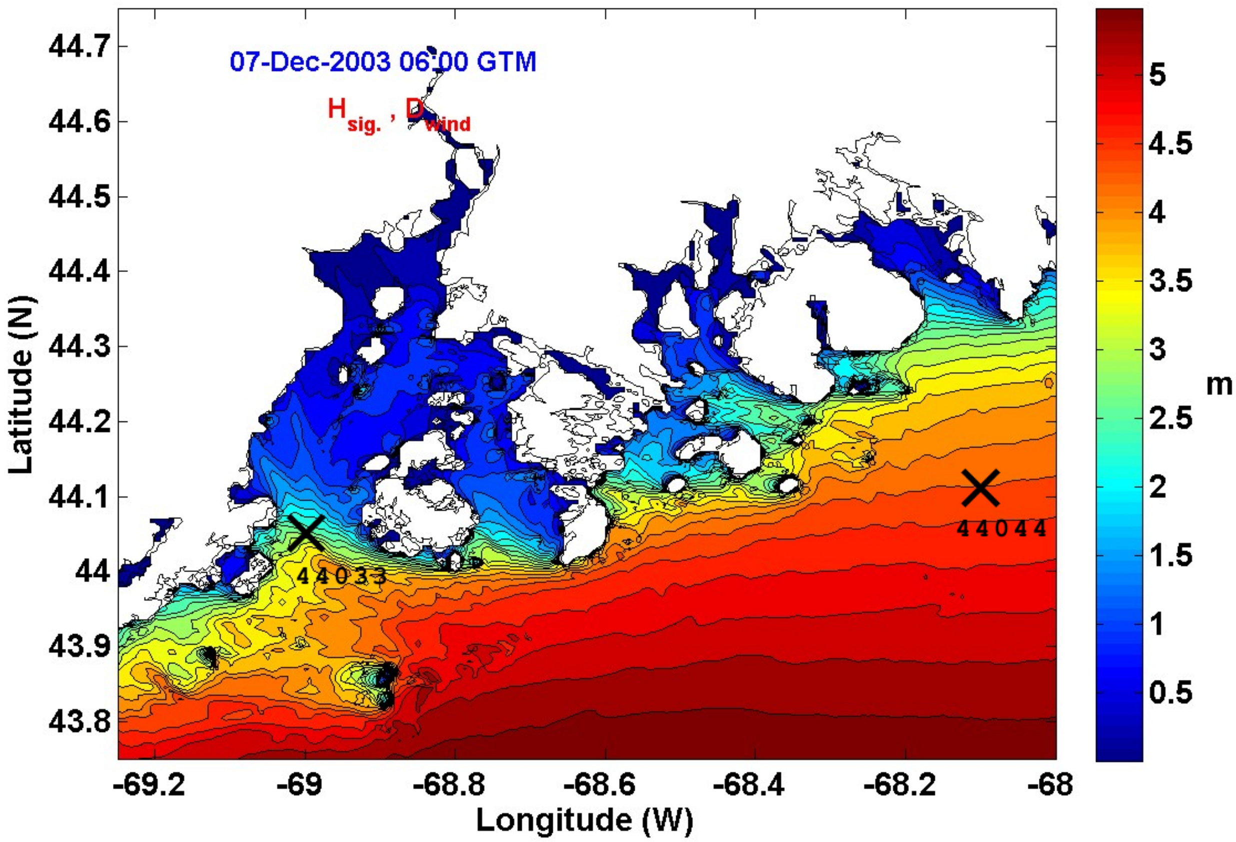


Fig 4. Simulated SWH’s (m) and wind direction for the intermediate domain



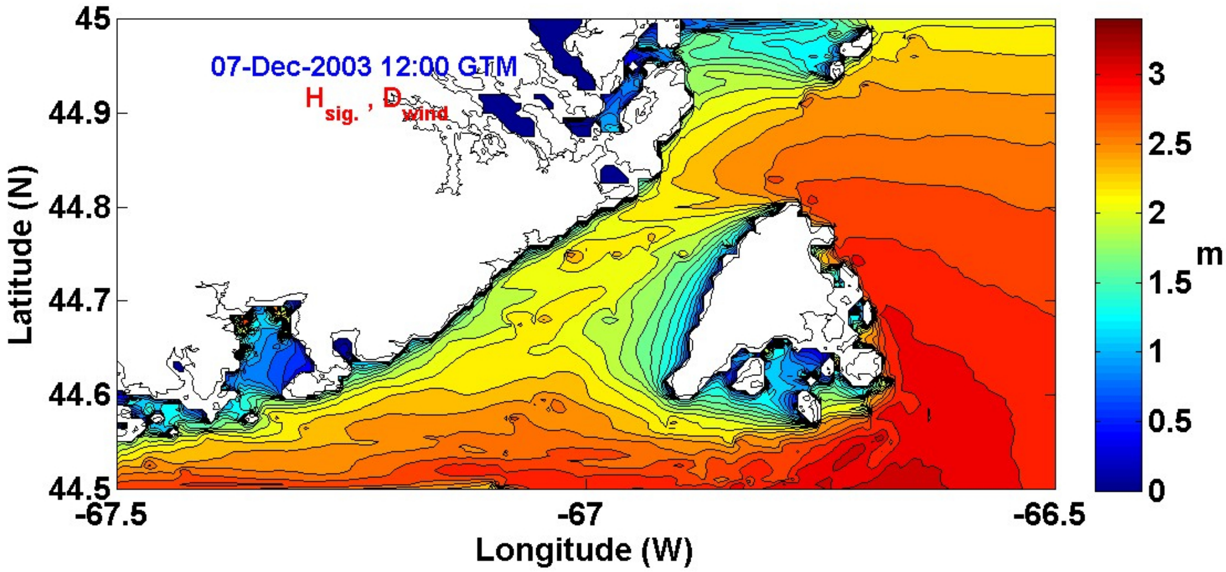


Fig 5. Simulated SWH's(m) and wind direction for Penobscot Bay (top) and Machias Bay (bottom)