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High SST variability south of Martha's Vineyard: Observation and modeling study

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ABSTRACT

High, small-scale SST variability (6 °C over 5–10 km) observed South of Martha's Vineyard during the low-wind component of the Coupled Boundary Layers Air–Sea Transfer (CBLAST-Low) oceanographic field program in August 2003 is investigated using the Navy Coastal Ocean Model (NCOM), with atmospheric forcing provided by the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®).[1] The ocean model includes tidal boundary forcing by the eight major tidal constituents, which is superimposed on the non-tidal lateral boundary conditions obtained from the 1/8° global NCOM real-time hindcast. The simulation is conducted with a high-resolution, 200-m grid, with bathymetry from the NGDC 3-arc-second Coastal Relief Model. The COAMPS fields, tidal forcing and NCOM results are evaluated with the CBLAST-Low observations and previous results. Both the simulation and observation analyses reveal that SST variability south of Martha's Vineyard is significant on August 18 and 25 and is strongly related to the cooling events on August 17 to 18 and August 24 to 25. The northeast winds passing through Muskeget Channel generate sharp horizontal SST gradients on August 18 by accelerating the westward transport of cold water from the cold, tidally-mixed Nantucket Shoals and by wind-induced upwelling and surface-cooling-induced vertical mixing. The mechanism of SST change on August 25 is differentiated from the change on August 18 by the northwest winds being unfavorable to the westward transport of cold water. The SST cooling on August 25 is mainly caused by local vertical mixing induced by heat lost.

1. Introduction

Strong spatial and temporal variability of sea surface temperature (SST) over the waters south of Martha's Vineyard was observed during the CBLAST-Low field program during the summers of 2001, 2002, and 2003 (Edson et al., 2007). The horizontal distribution of SST in this area is highly non-homogeneous, with changes of up to 6 °C at the edges of the cold-water band (Fig. 1). These patterns of high SST variability do not, in general, linger more than a day. However, the high SST variability significantly modulated the air–sea heat exchange, with a dramatic change in the measured latent and sensible heat fluxes (nearly 150 W m^{-2} total) as the observation vessel moved across the narrow oceanic frontal zone (Edson et al., 2007). This substantial modulation has been studied by Vickers and Mahrt (2006) through analysis of aircraft data. They found that the momentum and sensible and latent heat fluxes change greatly when the SST changes exceed 1 °C in amplitude over a distance of about 8 km.

The processes producing this strong SST gradient may involve the tide since the tide is a primary forcing for the regional circulation through tidally-induced vertical mixing and topographic-related tidal residual currents (He and Wilkin, 2006). Tidal mixing is sufficiently strong on the relatively shallow Nantucket Shoals that the water column is well mixed in the vertical throughout the summer, thereby maintaining a perpetually cool SST over Nantucket Shoals and an oceanic front on the west side of Nantucket Shoals despite significant, sustained, surface heating (Wilkin, 2006). One branch of the tidal residual mean current flows westward, advecting the tidally-mixed cold water from Nantucket Shoals to the midshelf south of Martha's Vineyard (He and Wilkin, 2006). However, the cold waters carried by the tidal mean flow are warmed under the influence of surface heating during the summer.

The predominant winds in the study area during the summer are from the SW, with wind speeds typically reaching 2–6 m/s according to the accumulated data from the Martha's Vineyard Coastal Observatory (MVCO) (Edson et al., 2007). The surface waters warm steadily throughout the summer in response to net air–sea heating, with net advection generally playing a modest role in cooling the water column south of Martha's Vineyard and west of Nantucket Shoals (Wilkin, 2006). Strong thermal stratification is a dominant feature in this region.

The high SST variability in Fig. 1 shows that a narrow tongue of cold water breaks the thermal stratification south of Martha's Vineyard and connects with the tidally-mixed water along the flank of Nantucket Shoals. These large, horizontal SST gradients are observed only on

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[1] COAMPS® is a registered trademark of the Naval Research Laboratory.

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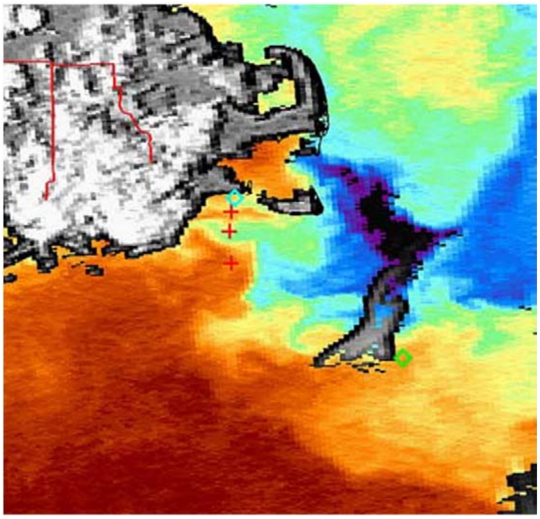

Fig. 1. AVHRR image of the CBLAST experimental area collected at 21:43 UT on August 18, 2003 (courtesy of Thompson et al., 2007).

some days, therefore, the processes involved may not only relate to the horizontal advection of the tidal mean flow but also other possible processes associated with surface forcing, such as local vertical mixing and upwelling by the winds or local surface cooling via air–sea surface heat fluxes.

In this study, we examine the mechanism of the formation of high SST variability south of Martha's Vineyard during August 2003 using the Navy Coastal Ocean Model (NCOM) with high horizontal resolution and observations taken during the CBLAST-Low period. The purpose is to examine the main dynamics and physical processes driving the formation of this small-scale feature and to understand the relative importance of the individual processes involved.

Brief descriptions of NCOM, the atmospheric forcing, and the model configuration are given in Section 2. Tidal analysis of the barotropic tidal residual current and the tidal amplitude and phase are presented in Section 3. The observed high SST variability is reviewed in Section 4. In Section 5, the atmospheric forcing is evaluated with a focus on the periods of high SST variability. In Section 6, the NCOM results are compared with the CBLAST observations. In Section 7, the mechanism of the high SST variability is investigated through the model results. Section 8 contains the summary.

2. Model configuration

2.1. The ocean model NCOM

NCOM is a three-dimensional, primitive-equation, free-surface model using the hydrostatic, Boussinesq, and incompressible approximations (Martin 2000; Morey et al., 2003). NCOM is designed to offer the user a range of numerical choices in terms of parameterizations, numerical differencing, and vertical grid structure. It uses a hybrid vertical coordinate system, which allows for the use of all sigma-levels, all z-levels, or a combination of sigma-levels for the upper ocean and z-levels below a specified depth. The model equations are solved on a staggered Arakawa C-grid. Temporal differencing is leapfrog with an Asselin filter to suppress time splitting. Spatial averages and finite differences are mainly second order, with options for higher-order formulations for some terms. The propagation of surface waves and vertical diffusion are treated implicitly. For this study, the Mellor-Yamada Level 2.5 turbulence scheme is used for vertical mixing and a third-order upwind scheme is used for advection. NCOM forcing can include surface atmospheric fluxes, lateral open boundary conditions, tides, and river and runoff discharges.

NCOM has been applied to a number of regions, including the Adriatic Sea (Pullen et al., 2003; Martin et al., 2006) and Monterey Bay (Hong et al., 2009; Shulman et al., 2007) to study the evolution of fine-scale oceanic features under atmospheric forcing, and the Gulf of Lion to study the effects of time variation of the surface buoyancy flux on the formation of deep-water convection during the winter season (Hong et al., 2007). In a coastal application of ocean data assimilation, NCOM is used in the Navy Coupled Ocean Data Assimilation (NCODA) system (NCODA, Cummings, 2005) as a forward model for a sequential update cycle (Hong et al., 2009). A recent application is the development of NCOM ensemble forecasting (Hong and Bishop, 2005) using the ensemble transform technique (Bishop and Toth, 1999) and adaptive sampling for coastal observations (Hong and Bishop, 2006) using the ensemble transform Kalman filter method (Bishop et al., 2001).

2.2. Atmospheric forcing

The surface atmospheric forcing is from a real-time forecast using the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Hodur et al., 2002) for the CBLAST-Low field program from July to August 2003. COAMPS was run twice daily using 3 nested grids with horizontal grid increments of 3, 9, and 27 km, respectively. The surface forecast fields from the innermost grid were output at hourly intervals and used to force NCOM.

The atmospheric forcing for NCOM consists of the surface air pressure, wind stress, air–sea heat flux, and effective surface salt flux for the momentum, temperature, and salinity equations. The surface latent and sensible heat fluxes can use the COAMPS-computed values (used in this study) or be computed interactively from the COAMPS wind speed, air temperature, and relative humidity and the NCOM-predicted SST using standard bulk formulas and the drag coefficient of Kondo (1975) (Martin and Hodur, 2003). The surface salt flux for NCOM is calculated from the latent heat flux and the COAMPS precipitation. The extinction of solar radiation in seawater as classified by Jerlov (1976) is used to define the subsurface penetration of the COAMPS solar radiation.

2.3. Model configuration

The ocean model was run on a domain matching the size of the COAMPS innermost grid (grid 3) with 1351 × 1351 grid points in the horizontal at a resolution of 200 m (Fig. 2). The vertical grid is logarithmically stretched from the surface downward with an upper-layer thickness of 1 m and a maximum depth of 1365 m. There are a total of 32 layers with a switchover from sigma to z-level vertical coordinates at about 115-m depth. The vertical grid in most of the model domain is sigma coordinate since the depths are mostly less than 100 m. The model bathymetry (Fig. 1) was obtained by a cubic spline interpolation of data from the 3-arc-second Coastal Relief Model developed by NOAA's National Geophysical Data Center (NGDC) (Divins and Metzger, 2008). The bathymetry is fairly complex, with many sand ridges in the area of Nantucket Shoals. The water depths are generally less than 40 m on the shoals. To the east of Nantucket Shoals is a 60-m deep channel called the Great South Channel, to the northeast is the Gulf of Maine (GOM) with depths greater than 200 m, and to the west is the Middle Atlantic Bight (MAB) with relatively smooth bathymetry. The model domain includes a portion of the shelf break near the south boundary so that interaction between the cool continental shelf water and the more saline continental slope water can occur.

The ocean model uses the 1/8° global NCOM real-time hindcast fields with sea surface elevation, temperature, salinity, and currents for initial and lateral boundary conditions (Barron et al., 2006). Tidal forcing includes both elevation and transports for four diurnal (K_1, O_1, P_1, and Q_1) and four semidiurnal (K_2, M_2, N_2, and S_2) constituents from