ARTICLE IN PRESS

Continental Shelf Research (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Coastal upwelling over the North Aegean Sea: Observations and simulations

Yannis S. Androulidakis[a,b,*], Yannis N. Krestenitis[b], Stella Psarra[c]

[a] Rosenstiel School of Marine and Atmospheric Science, RSMAS/MPO, University of Miami, 4600 Rickenbacker Cswy., Miami, FL 33149, USA
[b] Laboratory of Maritime Engineering and Maritime Works, Aristotle University of Thessaloniki, Greece
[c] Institute of Marine Biology of Crete, Hellenic Centre of Marine Research, Heraklion, Crete, Greece

ARTICLE INFO

Keywords:
North Aegean
Upwelling
Black Sea waters
Numerical simulations

ABSTRACT

Prevailing northerly winds influence the eastern coastal area of the North Aegean (N. Aegean) Sea and form a strong front due to occurring upwelling waters during the summer months. The upwelling processes over the Lesvos coastal region are investigated with the use of *in situ* measurements, numerical simulations, and satellite observations. The interaction of the major lateral buoyant input of Black Sea Waters (BSW) with the upwelling processes and waters is also investigated. The offshore propagation of the up-welled waters over the central N. Aegean region and their interactions with the permanent central cyclonic eddies, the major BSW patterns and the general Aegean cyclonic circulation determine their fate over the Aegean Sea. The upwelling depth is small over the Lesvos coastal region and is restricted in the subsurface ocean (< 40 m). The shallow upwelling depth is also confirmed by the reduction of the Apparent Oxygen Utilization (*AOU*) levels during upwelling events while the pre-existing surface waters, affected by the BSW plume reveal higher *AOU* values. More importantly, the up-welled waters come from above the thermocline nutrient depleted layer and, therefore, no major blooming events may be triggered in the central and eastern Aegean during the summer months. Southerly winds on the other hand, have a double effect. They form upwelling unfavorable conditions and they may facilitate the BSW propagation towards the upwelling region, blocking the eastward Ekman current and strengthening the stratification due to the formation of a surface barrier layer.

1. Introduction

The hydrodynamic and physical characteristics of the North Aegean (N. Aegean) Sea, especially over the upper-ocean, are largely determined by the dominant meteorological conditions (Poulos et al., 1997) in tandem with buoyancy-driven currents induced by the inflow of low-salinity Waters of Black Sea origin (BSW) through the Dardanelles Straits (Zervakis and Georgopoulos, 2002; Kourafalou and Barbopoulos, 2003; Androulidakis et al., 2012b). The SST (Sea Surface Temperature) seasonal mean patterns reveal strong cooling that is associated with upwelling phenomena under northerly summer winds along the eastern boundary of the basin (Albanakis, 1999; Kourafalou and Barbopoulos, 2003; Skliris et al., 2010) and especially over the coastal areas, south of the Dardanelles Straits (Zervoudaki et al., 1999), such as the coastal region of western Lesvos (Fig. 1). Recurring upwelling in the eastern Aegean Sea was first studied by Ünlüata (1986).

The dominant winds during summer, blowing over the whole Aegean Sea, are characterized by strong magnitudes with northerly components (Valioulis and Krestenitis, 1994; Poulos et al., 1997). There is a clear positive SST gradient from east to west, related to the upwelling favorable northerly winds (“Meltemia” or “Etesian Winds”, Kourafalou and Barbopoulos, 2003; Skliris et al., 2010). Generally, these winds are northeasterly over the N. Aegean, northerly over the Central Aegean and turn to northwesterly over the South Aegean (Savvidis et al., 2004). The related upwelling process along the eastern Aegean coastal and shelf areas falls under the generalized case of the continental shelf seawaters, where the wind blows parallel to the coast, with the coastline on the left side of the wind direction in the case of the northern hemisphere. Savvidis et al. (2004), based on simulation results, showed that in the case of the Etesians Winds, applied over the whole Aegean basin with wind speed of 10 m/s, upwelling processes start to develop during a period of a few days. The prevailing northerly winds form a strong front due to occurring upwelling waters over Saros Gulf, south of the Dardanelles Straits and, in the west of Lesvos and Chios islands (Sayın et al., 2011). According to Sayın et al. (2011), the up-welled waters may flow over a larger area offshore from Lesvos Island and up to Chios Basin, affecting the general circulation and forming two cyclonic eddies during summer over the broader east-central region.

* Corresponding author at: Laboratory of Maritime Engineering and Maritime Works, Aristotle University of Thessaloniki, Greece.
E-mail addresses: iandroul@civil.auth.gr (Y.S. Androulidakis), ynkrest@civil.auth.gr (Y.N. Krestenitis), spsarra@hcmr.gr (S. Psarra).

http://dx.doi.org/10.1016/j.csr.2016.12.002
Received 1 February 2016; Received in revised form 28 September 2016; Accepted 2 December 2016
0278-4343/

Please cite this article as: Androulidakis, Y.S., Continental Shelf Research (2016), http://dx.doi.org/10.1016/j.csr.2016.12.002

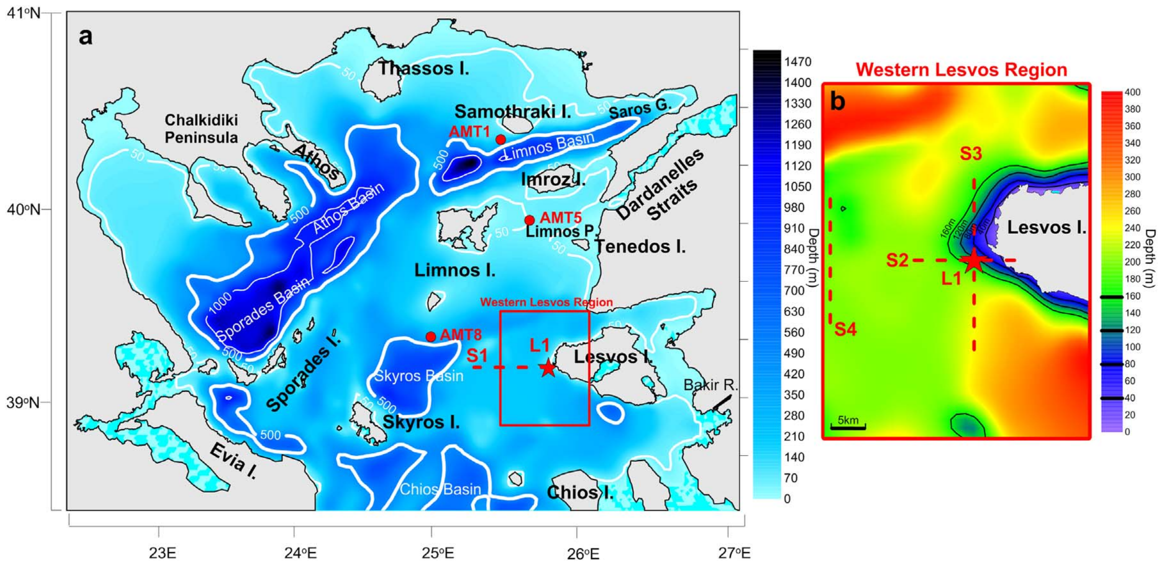

Fig. 1. Bathymetry maps (m) indicating (a) the main features (deep basins, islands and the Dardanelles Straits) of the N. Aegean Sea HYCOM model (NAS-HYCOM) domain and (b) the western Lesvos region. Left (western Aegean) land mass is the Greek mainland; right (eastern Aegean) land mass is the Asia Minor (Turkish) mainland. The solid lines mark the 20 m, 40 m, 50 m, 60 m, 80 m, 120 m, 160 m, 500 m and 1000 m isobaths. The red star indicates the L1 (Poseidon System Buoy) and the red circles indicate the R/V Aegaeo October 2013 cruise stations (AMT1, AMT5, AMT8). Sections S1, S2, S3 and S4 are indicated with dashed red lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The BSW input is the most important buoyant input over the N. Aegean region, affecting the largest part of the upper-ocean, especially during spring and summer, when the discharge through the Dardanelles usually reveals its highest values (Ünlüata et al., 1990). However, recent simulations of the Dardanelles Straits outflow, based on Black Sea water balance (Androulidakis et al., 2012b), showed that strong discharges may also occur in other seasons, such as autumn and winter, due to alterations of river outflows and E-P variability of the Black Sea. Maderich et al. (2015), based on numerical simulations, showed that vertical mixing along the Turkish Strait System determines the flow characteristics of the upper layer towards the Aegean Sea, while the highest upper-layer transport in the Dardanelles exit may occur in spring. The BSW plume induces buoyancy-driven transport pathways that affect the basin-wide N. Aegean dynamics and may influence several Aegean physical dynamics, such as dense water formation (Zervakis et al., 2000; Androulidakis et al., 2012a), mixed layer characteristics and interactions with South Aegean water masses (Theocharis et al., 1999). In summer months, the strong northerly winds in combination with strong BSW discharge rates may bring brackish waters, originated from the Black Sea, directly to the Southwest, towards the Evia Island area (Androulidakis et al., 2012b). The Dardanelles discharge values and furthermore the BSW propagation over the Aegean, used in this study, are based on the simulations by Androulidakis et al. (2012b). Their parameterization of BSW outflow, based on the Black Sea water balance, improved the model performance during summer 2002 in comparison with the use of historical outflow values (their Figs. 6 and 7).

The upwelling waters, on the other hand, may influence the physical and biological characteristics of the near-shore and broader central area. Generally, the upwelling colder waters, enriched with nutrients, move to the surface and may enhance the biological activity, enriching the fish-productivity of the coastal waters (Millan-Nunez et al., 1982). The BSW plume also affects the biological features of N. Aegean basin, such as nutrients, chlorophyll (Kucuksezgin et al., 1995; Ignatiades et al., 2002; Lagaria et al., 2016) and mesozooplankton (Siokou-Frangou et al., 2009) concentrations. BSW through its uninterrupted supply of small quantities of nutrients plays an important role in pelagic production of the N. Aegean Sea (Siokou-Frangou et al., 2002; Souvermezoglou et al., 2014). However, the BSW input through the Dardanelles Straits is enriched in organic rather than inorganic matter (Zeri et al., 2014). To the best of our knowledge, the relation between the upwelling processes over the eastern N. Aegean coastal region and the major BSW plume has not been investigated in the past.

The aim of this study is the investigation of the upwelling processes over the continental shelf of the western Lesvos region, which is one of the most important Aegean upwelling regions. Five upwelling events are detected during the significantly active summer months of 2002 due to long periods with persistent strong northerly winds. The spreading and the relation of the up-welled waters with the broader N. Aegean water masses are also investigated. The impact of the large lateral input from the Black Sea during the upwelling periods is examined. We will show that the major circulation patterns of this brackish water mass over the N. Aegean and especially over the upwelling regions play an important role on the formation and evolution of the upwelling phenomena. We will describe several additional aspects, such as the upwelling depth, the vertical structure of the upwelling area, the differences between the physical characteristics of the up-welled waters and pre-existent and/or surrounding masses, based on *in situ* observations, high resolution numerical simulations, and satellite data. The work is based on the combination of observations with numerical results, produced by the North Aegean Sea Hybrid Coordinate Ocean Model (NAS-HYCOM; Androulidakis and Kourafalou, 2011; Androulidakis et al., 2012a, 2012b).

Following the Introductory section (Section 1), Section 2 includes the methodology of the work, the description of observations and simulations and the evaluation of the NAS-HYCOM during the study period, focused on the upwelling Lesvos region. The detected upwelling events, the respective prevailing atmospheric conditions and the major BSW evolution patterns are presented in Section 3. The surface circulation features, the evolution of the Ekman transport, the vertical structure over the upwelling region and possible implications of upwelling with dissolved oxygen concentrations are discussed in Section 4. A summary of concluding remarks is presented in Section 5.

2. Methods and data

2.1. In situ measurements

The *in situ* measurements used in the study are derived from a buoy of the Poseidon System, implemented and maintained by the Hellenic