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West Adriatic coastal water excursions into the East Adriatic

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ABSTRACT

A pool of less saline surface waters was observed in late June 2006 at the northern edge of the South Adriatic Pit (SAP). Three possible sources were considered: (1) Albanian rivers, (2) local Croatian rivers, or (3) relatively fresh West Adriatic Current (WAC) waters. Available CTD and ADCP data, together with satellite images indicate that WAC waters are the most likely source. This requires an excursion of WAC water across the width of the Adriatic and is especially surprising as low winds and stable atmospheric conditions prevailed in mid/late June. However, quite strong NNW winds occurred during the first 12 days of June, with peak winds close to the western shore. These winds were the result of the translation of the Azorean high to the British Isles, producing strong pressure gradients over the Adriatic. The winds enhanced the WAC during early June 2006, preconditioning a cross-basin eddy circulation that appeared during the wind relaxation and calm conditions. As the unusually calm conditions persisted for more than two weeks, the WAC eddies and filaments grew freely and had enough time to reach middle east Adriatic waters. Navy Coastal Ocean Model (NCOM) simulations, using high-resolution Adriatic bathymetry and realistic atmospheric forcing show that such excursions are plausible and can occur when eddies and instabilities push WAC waters across the hyperbolic flow point separating the WAC and Eastern Adriatic Currents near the Palagruža Sill. During the latter half of June 2006, NCOM simulations show that the hyperbolic point was particularly well formed as an anticyclonic WAC, a cyclonic SAP rim flow, an anticyclonic cell southeast of Lastovo Island, and a cyclonic cell over the centre of the Palagruža Sill all bordered on each other. A simplified channel model suggests that the presence of the escarpment is a critical factor for producing cross-basin exchange of the coastal current following the relaxation of strong winds with a cyclonic wind-stress curl. However, the introduction of the Gargano Peninsula in the simulations was critical to the production of mesoscale eddies in the exchange flow, and such eddies qualitatively agree with the convoluted structures observed in satellite images.

1. Introduction

Riverine buoyant inputs to coastal seas often form currents that are bound to the coast and shelf, and propagate along the coast in the direction of a coastally trapped wave (Burrage et al., 2008). This is the case for the Po River plume of the Adriatic as fresh water is trapped along the western (Italian) coastline as a major part of the West Adriatic Current (WAC), a coastal boundary current that extends from the Po River Delta southeastward to the southern Adriatic (Hopkins et al., 1999). Such trapping can be broken by other dynamics and the plume can be advected across the basin as is the case in the northern Adriatic under the influence of strong bora storm winds (Mauri and Poulain, 2001; Kuzmić et al., 2006). However, in general, the Po and WAC influence on the eastern side of the Adriatic is mainly supposed to be indirect through basin-wide thermohaline controls and water mass modification. Therefore, when a large pool of low-salinity water was observed along the eastern edge of the South Adriatic Pit on 26 June 2006, which was seemingly unrelated to river plumes from the eastern coast of the Adriatic, the event motivated this study of cross-basin excursions of fresh waters that are normally coastally trapped. While the observations presented in this paper can only show that the origin of the low-salinity pool is very likely from the WAC, our study of these dynamics in this case study do reveal new insights for mechanisms of cross-basic exchange applicable to the Adriatic and other systems.

The Adriatic Sea is the northernmost Mediterranean embayment, having a shallow (at most 100-m deep) northern part, two depressions (the Jabuka Pit and South Adriatic Pit, SAP, of depths 280 m and 1200 m, respectively), and two sills: the Palagruža Sill separating the

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SAP and the Jabuka Pit, and Otranto Strait between the SAP and the Ionian Sea. A prominent feature of the Adriatic circulation is the cyclonic surface flow, with the East Adriatic Current (EAC) bringing warmer and saline waters from the Ionian Sea and Levantine basin and compensating the volume flux from the fresher WAC waters along the western shelf (Zore, 1956). More specifically, pronounced freshwater inflows that usually occur in spring support development of estuarine-like circulations, with enhanced outflow from the Adriatic in the surface layer being accompanied by increased inflow from the East Mediterranean in the deeper layers (Orlić et al., 2007). On the other hand, wintertime surface cooling of the Adriatic in contrast to warmer conditions over the East Mediterranean result in anti-estuarine circulations, characterized by an intensification of outflow from the Adriatic in the bottom layer and an increase of inflow from the East Mediterranean in the shallower layers (Orlić et al., 2007). The wintertime processes are also characterized by dense-water generation in the northern Adriatic and SAP (Beg Paklar et al., 2001; Vilibić and Orlić, 2001, 2002). The two dense-water masses formed, North Adriatic Dense Water (NAdDW, Vilibić, 2003; Vilibić and Supić, 2005) and South Adriatic Deep Water (SAdDW, Zore-Armanda, 1963; Gačić et al., 2002; Civitarese et al., 2005), impact the entire, deep, Eastern Mediterranean (Malanotte-Rizzoli et al., 1997); yet, they also strongly affect the circulation at Adriatic topographic constraints such as the Palagruža Sill (Vilibić et al., 2004).

As the WAC flows along the western shelf, it may be concentrated in a strong coastal jet or turn offshore during some situations at coastal topographical barriers such as the small Monte Conero Cape, located a few kilometres south of Ancona (Artegiani, 1980; Artegiani et al., 1999). However in mean surface flow maps derived from 9 years of drifter data, Poulain (2001) did not observe WAC cross-basin exchange from west to east anywhere south of the Po River input point, except at Monte Conero Cape during spring and summer. Also, the WAC as defined in that study included both buoyant Po-derived waters and waters that are off the Italian slope but still flowing southeastward, and therefore an offshore excursion of the WAC does not necessarily imply an offshore excursion of the most buoyant riverine waters. During the summertime, the WAC core is usually detached 5–10 km from the coastline, enabling the growth of instabilities and even reversal of currents very close to the shore (Metallo, 1965; Zavatarelli et al., 2002).

By using a numerical model with climatological forcing, Zavatarelli et al. (2002) concluded that the WAC exhibits a strong seasonal change, having more laminar flow during wintertime and meandering around baroclinic gyres on its way to the south Adriatic during summertime. The same has been concluded by Cushman-Roisin et al. (2007) who used a model with fine enough resolution to reproduce baroclinic instabilities (the grid resolution was a few times smaller than the internal Rossby deformation radius). In addition, their results showed that eddies travelling along a smooth shoreline with an

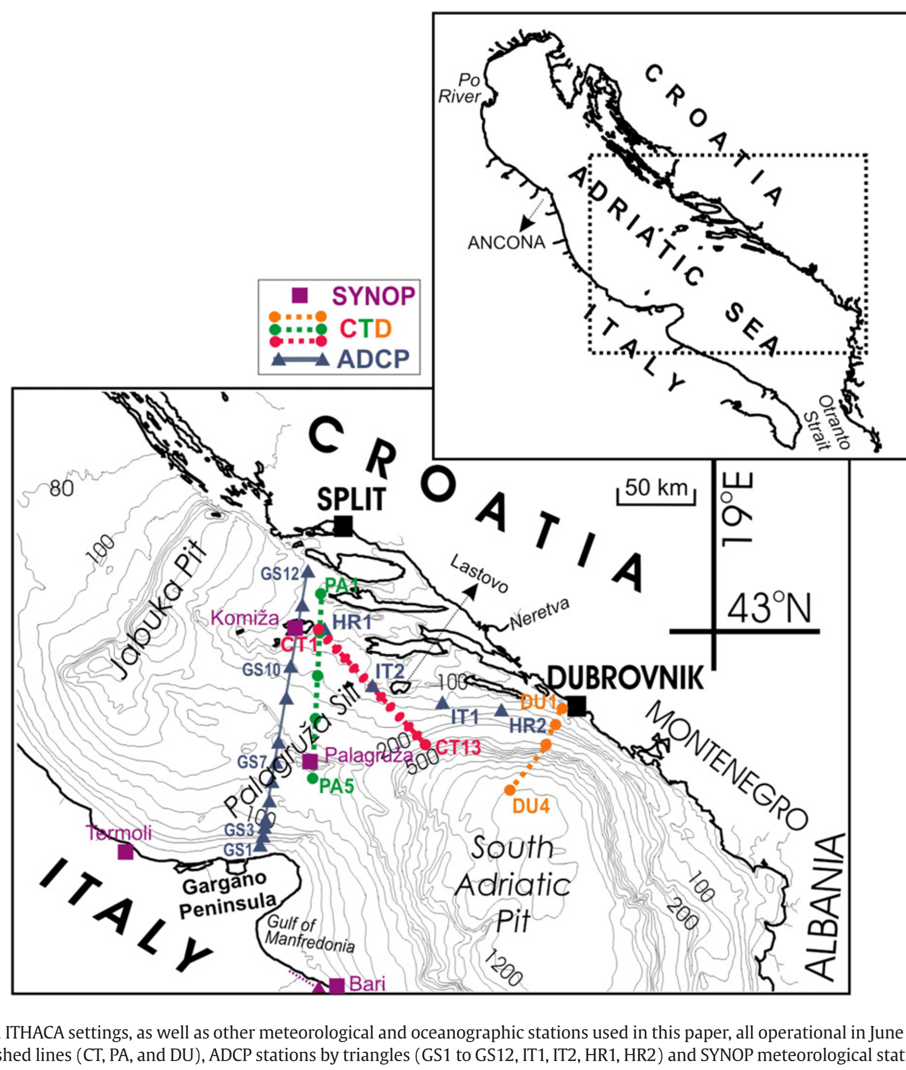

Fig. 1. Experimental DART and ITHACA settings, as well as other meteorological and oceanographic stations used in this paper, all operational in June 2006 in the middle-Adriatic Sea. CTD transects are given by dashed lines (CT, PA, and DU), ADCP stations by triangles (GS1 to GS12, IT1, IT2, HR1, HR2) and SYNOP meteorological stations by rectangles (Termoli, Bari, Palagruža, and Komiža).

offshore bottom slope are strongly affected by the bottom slope itself. This study is supported by observations of 10–20 km diameter eddies travelling alongshore during autumn 1988, found by Paschini et al. (1993) to be controlled by a low Rossby deformation radius (5.4 km for the first mode and 2.8 km for the second mode).

In contrast to the lack of findings of west-to-east flow, as early as the 19th century, Wolf and Luksch (1887) correctly showed east-to-west flows at the Palagruža Sill and in the northern Adriatic. The existence of such cross-basin flows has more recently been confirmed by a large number of authors (e.g., Zore, 1956; Artegiani et al., 1997; Horton et al., 1997). Also, it seems that the Palagruža Sill causes EAC and WAC seasonal meanders (Zore-Armanda and Bone, 1987). As implied by the conservation of potential vorticity and confirmed by the simple analytical theory developed by Carnevale et al. (1999), the EAC is expected to decelerate and become divergent when coming from the deep SAP to the shallow Palagruža Sill, whereas the WAC should accelerate when crossing the Palagruža Sill and entering the deep SAP and be reinforced by flow diverging from the EAC at the northwest edge/slope of the SAP. Thus, steady-state flow is expected to favour cross-basin flow from east to west in all cases. On the other hand, non-steady state simulations with spin-up of a WAC type flow resulted in the development of cyclonic–anticyclonic dipoles and offshore extension (i.e., west to east in the case of the Palagruža Sill/SAP escarpment) of an offshore current (Carnevale et al., 1999). Sharp escarpments (e.g., the transition from the Palagruža Sill to the SAP), supported further offshore extension of the offshore current before its termination as cyclonic–anticyclonic dipoles. However, this theoretical and modelling work addressed barotropic flow over an escarpment and considered only single-sided boundary effects, and therefore excluded many factors which likely play an important role for our case study of the WAC excursion observed in June 2006.

For this case study, we will utilize the large amount of oceanographic data (currents, temperature, salinity and sea level) that were collected in extensive field campaigns carried out through the DART (Dynamics of the Adriatic in Real Time) and ITHACA (Internal Tidal Hydrodynamics and Ambient Characteristics of the Adriatic) projects. Also of importance are meteorological measurements and remotely sensed images and simulations from mesoscale meteorological and oceanographic numerical models. Section 2 gives an overview of these datasets, Section 3 focuses on the oceanographic observations and on the main observational finding (low-salinity waters at the northern SAP edge), Section 4 documents the atmospheric conditions through an analysis of global NCEP (National Centres for Environmental Prediction) surface fields, *in situ* meteorological measurements, and mesoscale modelling results, and Section 5 presents realistic oceanic modelling as well as targeted modelling studies aimed at quantifying the influence of winds and topographical features on the WAC detachment. All of the findings are discussed and summarized in Section 6.

2. Material and methods

Comprehensive ocean observations were made in the middle and south Adriatic in 2005/2006 in the framework of the DART and ITHACA projects. Part of the data from these studies will be utilized in this paper, together with other available meteorological and ocean data. Fig. 1 shows the geographic region and data collection locations used in this study.

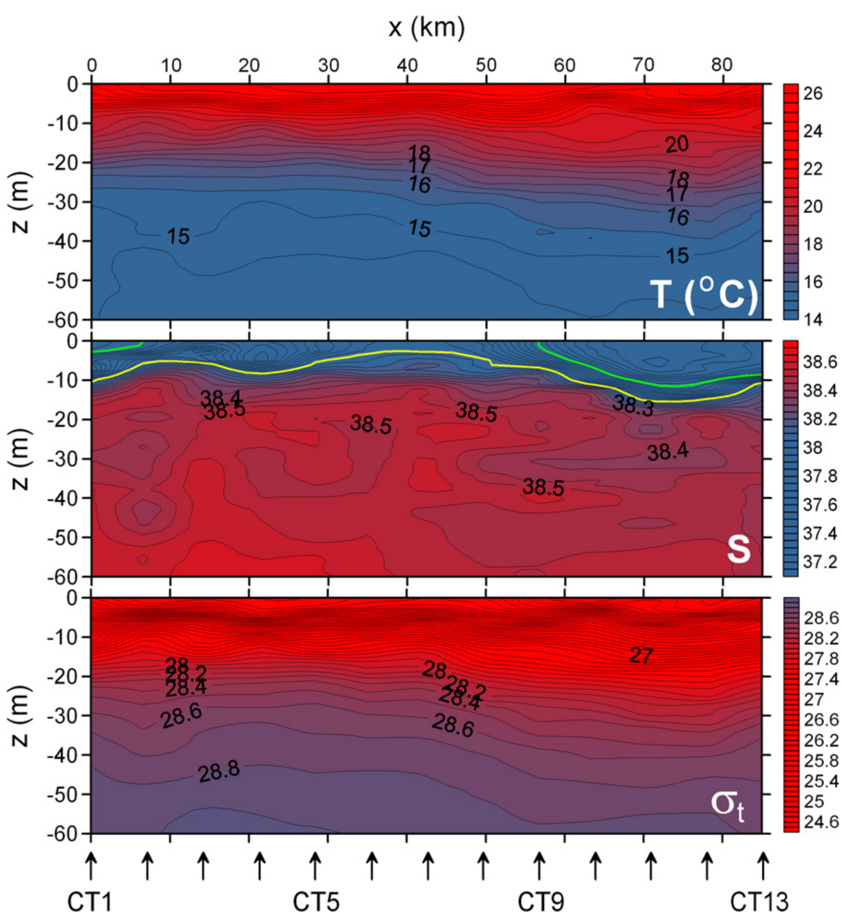

Fig. 2. Temperature, salinity, and sigma-t measured at the CT CTD transect (upper 60 m) on 26 June 2006. Thick lines stand for 37.5 (green) and 38.0 (yellow) isohalines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

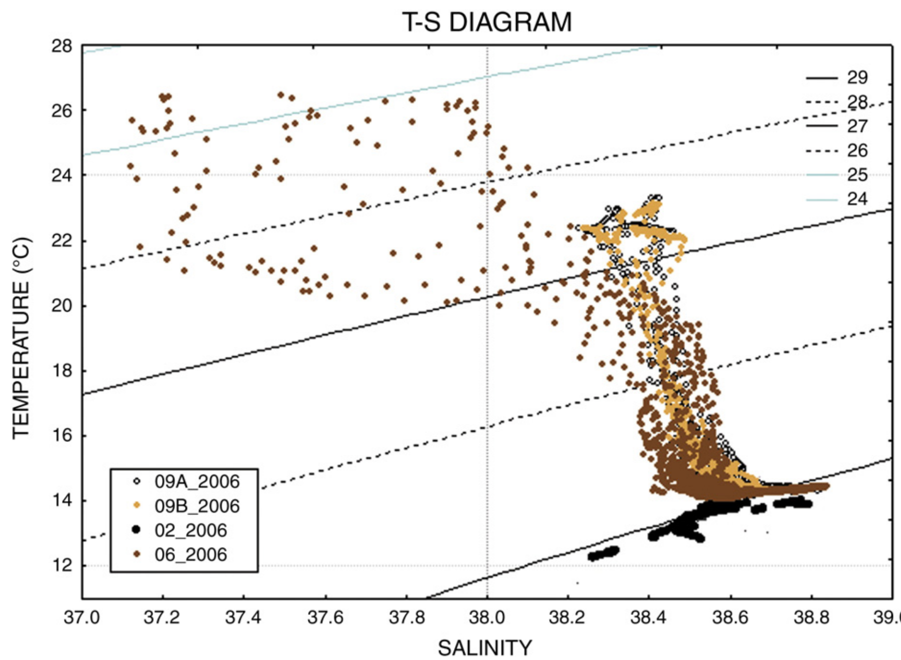

Fig. 3. *T–S* diagram plotted for all the cruises (14 February, 26 June, 28 — A and 29/30 — B September 2006) covering the CT transect.

CTD casts at transect CT were taken at 13 equidistant stations (CT1 to CT13) on 26 June 2006, to attempt to observe internal tides in the area. Surprisingly, a pool of low-salinity water of unknown origin was found at the edge of the SAP. Additional CTD measurements were taken along the PA transect (5 stations) on 15 June (PA1 to PA5), along the DU transect (4 stations) on 22 June (DU1 to DU4) and also along the CT transect on 14 February, 28 September, and 29/30 September. All the CTD casts were collected by Seabird SBE 9 and 25

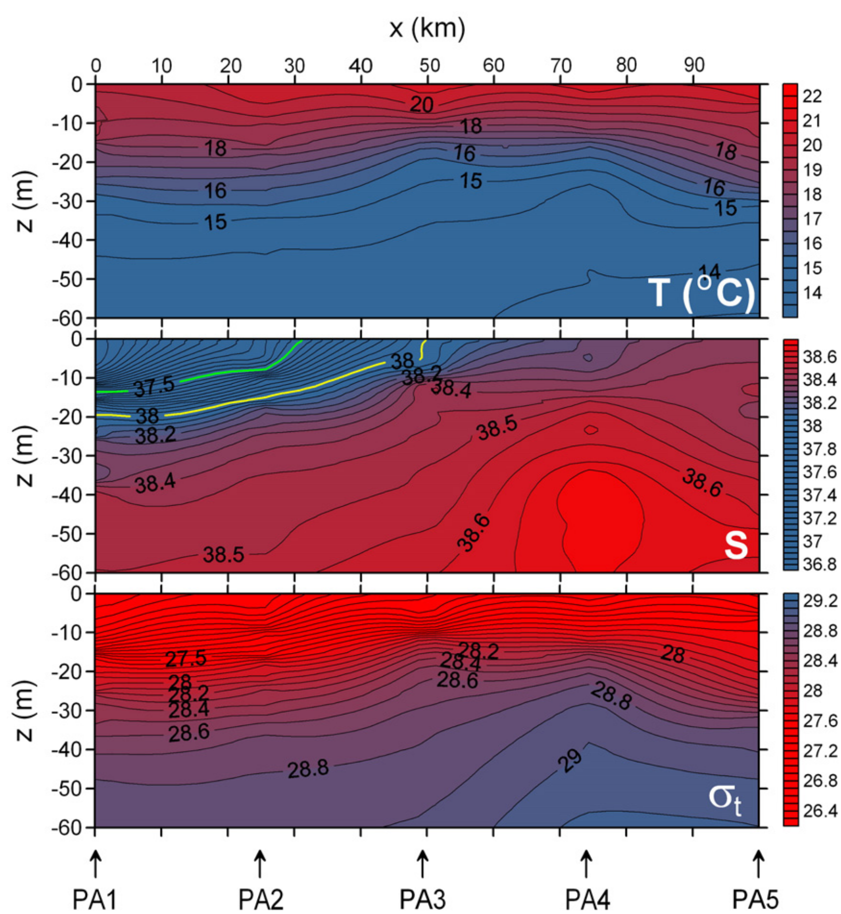

Fig. 4. As in Fig. 2, but for PA CTD transect on 15 June 2006.

multiprobes having an accuracy of ±0.004 °C for temperature and ±0.002 for salinity.

Current data were collected along a line of 12 ADCPs covering the whole Palagruža Sill (GS1 to GS12), as well as along the eastern Adriatic coast (HR1, HR2, IT1, IT2). The measurements were made using RDI Workhorse Sentinel ADCPs operating at 300–1200 kHz, with velocities averaged over 0.5–5 m thick layers and taken at 15-minute time intervals. The ADCPs were placed and protected on the sea bottom within BARNY frames (Perkins et al., 2000).

Meteorological measurements were taken from SYNOP stations in the area. The Croatian national network and Italian and Montenegrin SYNOP stations regularly send the data through the Global Telecommunication System (GTS), including all of the Croatian automatic stations. Croatian SYNOP stations provided data every hour during most of the day, while the data from Italy and Montenegro were received at 3-hour intervals. The automatic stations had a temporal resolution of 10 min. The data have been quality checked through the regular procedures established by the meteorological agencies. As the wind data were the most interesting for our study, we chose to focus on such data collected at stations Termoli, Bari, Palagruža, and Komiža (Island of Vis). In addition to the *in situ* measured data, we found it useful to analyse the global NCEP (National Centres for Environmental Prediction, http://www.ncep.noaa.gov) atmospheric fields for June 2006, focusing on the surface air pressure fields and their anomalies with respect to climatology.

Remote-sensing data were also analysed, focusing on the chlorophyll a (chl) images over the Palagruža Sill during June 2006. These data are very important for our investigations, as the surface WAC (and therefore its eastward excursion) may be easily recognized via these images by the rather high-chl values of these fresh and nutrient-rich waters (Buljan and Zore-Armanda, 1976; Gačić and Artegiani, 2001). We used the images processed by the Gruppo di Oceanografia da Satellite (http://gos.ifa.rm.cnr.it) through the Adricosm project.

Atmospheric fields were obtained from the ALADIN/HR isostatic model of the atmosphere over the Adriatic Sea, which is forced by the ARPEGE global model at its lateral boundaries. For the ocean we used the Naval Coastal Ocean Model (NCOM) with realistic Adriatic bathymetry and forcing by air–sea fluxes from ALADIN/HR, river inflows, and lateral boundary conditions from a global model. Some idealized, process-oriented modelling studies were performed using the Princeton Ocean Model (POM) with simplified bathymetry and forced by idealized wind fields and river discharges. The details of the models' setup, forcing, and other issues are given in Section 4.2 for ALADIN/HR, 5.1 for NCOM, and 5.2 for POM.

3. Ocean observations

3.1. CTD data

As noted in the Introduction, the most intriguing finding, which directed the research presented in this paper, was the low-salinity water at the northern/northwestern edge of the SAP observed on 26 June 2006. This is shown in Fig. 2, where the salinity minimum (<37.2) is found in the outer surface waters of the CT transect (stations CT11–CT13), and not where it appears normally, somewhere between CT1 and CT4. The salinity minimum normally occurs further north and inshore of its 26 June location because of the influence of the largest middle-east Adriatic river, the Neretva (Grbec et al., 2007). A secondary minimum was found

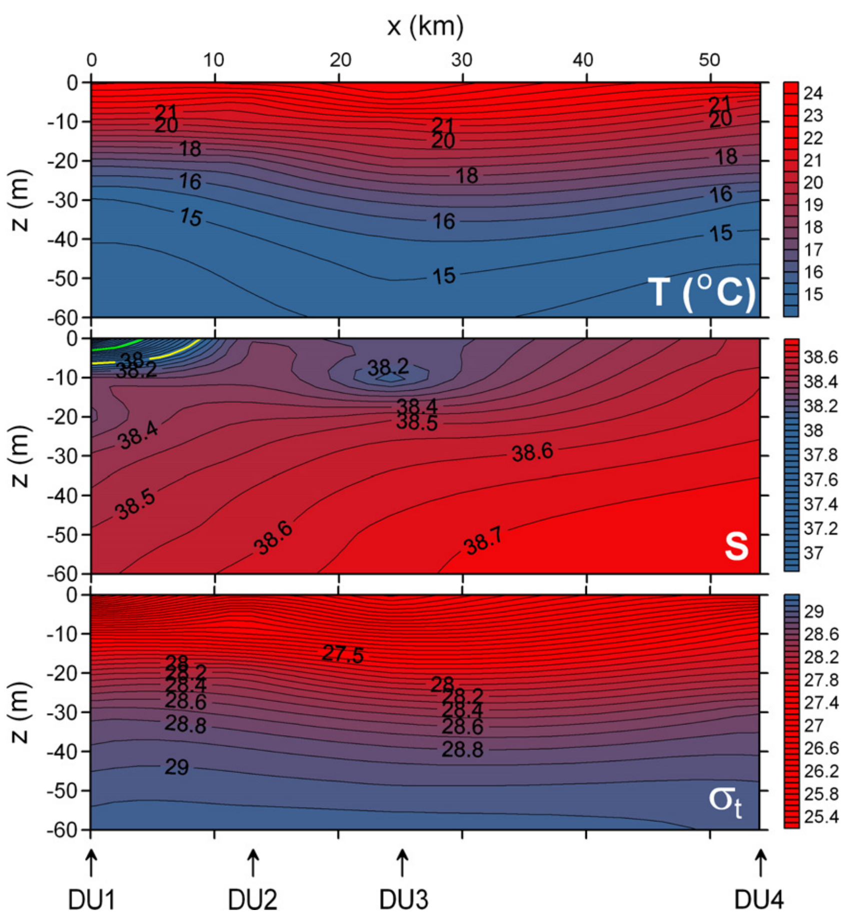

Fig. 5. As in Fig. 2, but for DU CTD transect on 22 June 2006.

at the very surface of CT1, but this was much shallower and less pronounced than the one found in the open Adriatic.

The uniqueness of the 26 June CT CTD cruise strongly emerges when comparing it to the other CT CTD cruises carried out in February and September 2006 (Fig. 3). All of these other cruises measured surface salinity values larger than 38.2, and intermediate and bottom waters that were characteristic for the region. Therefore, we also analysed other data collected in the Palagruža Sill area in June 2006, and found a different situation at the PA transect (Fig. 4) just 11 days earlier (15 June) than on the CT transect (Fig. 2). Highly saline waters (>38.0) were present at the surface of the open Adriatic stations (PA3 to PA5), with a constant increase in surface salinity towards the western Adriatic shelf. Low-salinity surface waters were observed at the inshore stations (PA1 and PA2). At the station closest to the

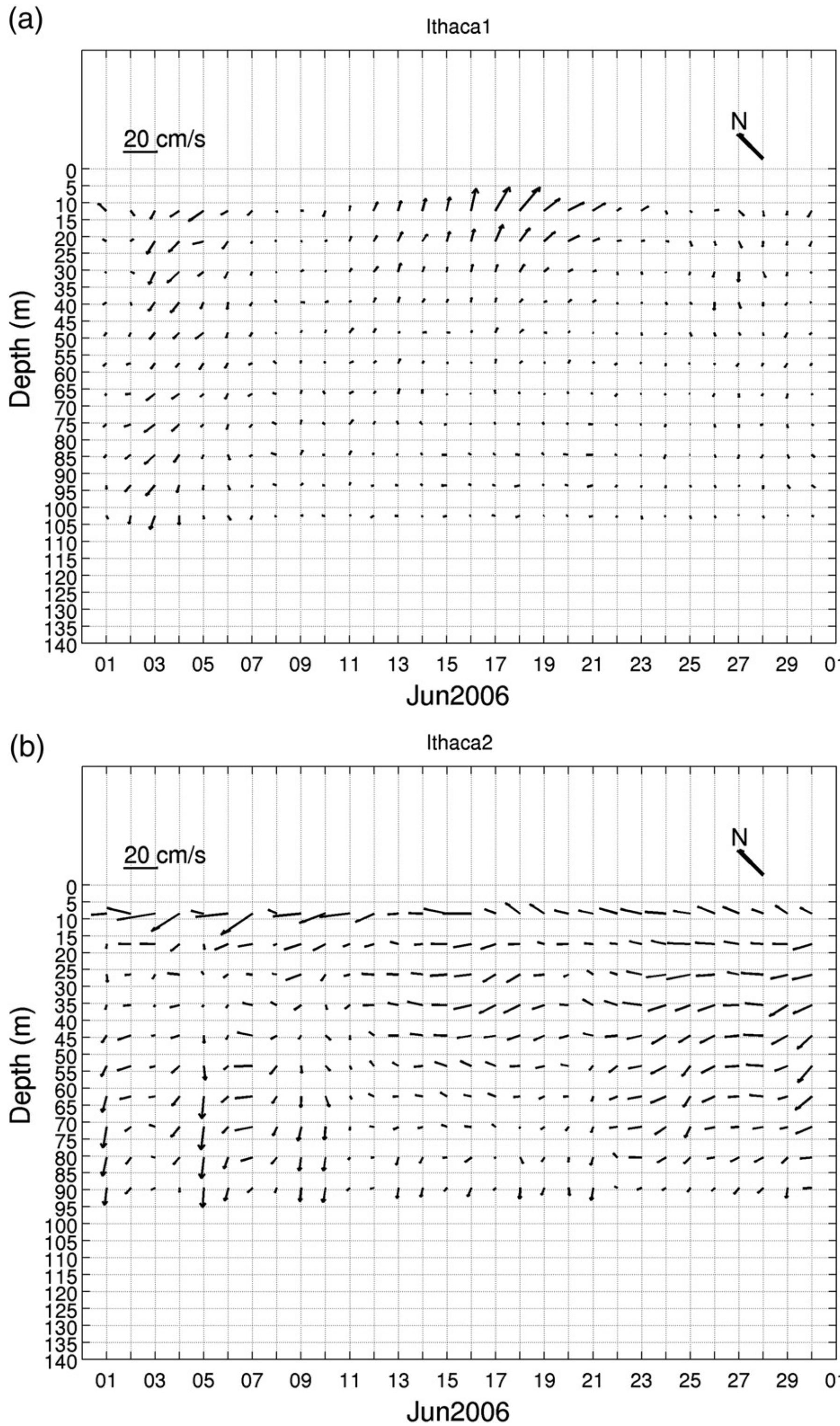

Fig. 6. Daily averaged currents measured at (a) IT1, (b) IT2, (c) GS3, (d) GS7, and (e) GS10 in June 2006.

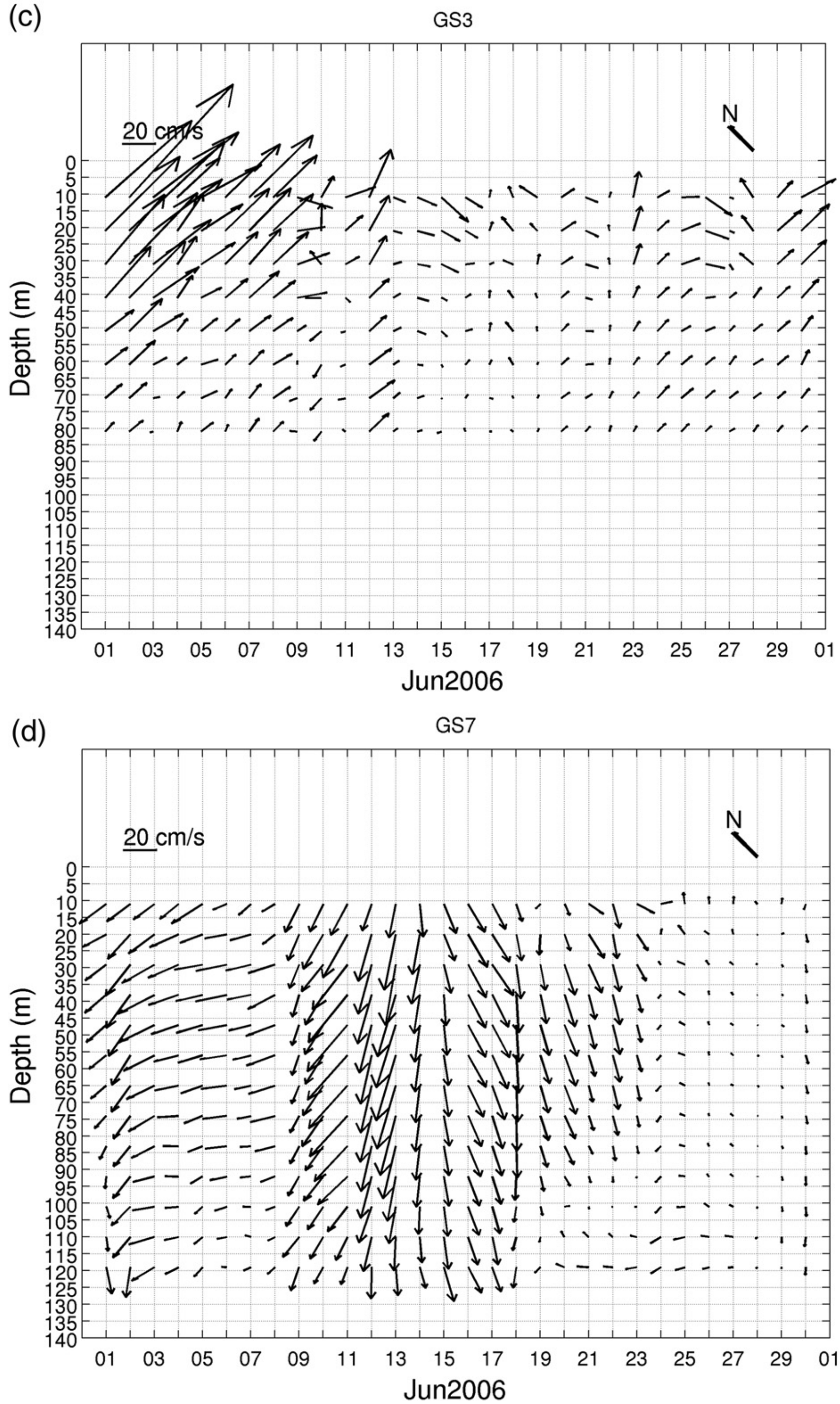

Fig. 6 (*continued*).

western shelf (station PA5), surface salinity reached 38.4. If the low-salinity waters observed at stations CT11–CT13 were of western Adriatic origin and if their arrival was in progress, then the excursion must have occurred (i) southeast from the PA transect, just over the SAP edge, or (ii) anywhere over the Palagruža Sill, but travelling rapidly during these 11 days with an average northeastward velocity of about 15 cm/s. The first option seems to be more realistic, considering the satellite image analysis (Section 3.3).

To investigate the possibility that the low-salinity waters observed at the outer CT transect in late June 2006 had their origin in Albanian waters, we analysed the available data east from the CT transect (Fig. 5). Although some low-salinity waters may be found very close to shore (station DU1 is just a few km from the coast), they are observed at only one station and cover a very thin layer (the 37.5 isohaline occurs at a depth of 3 m). These waters could simply be due to local rivers and submarine karstic springs, which are present in the

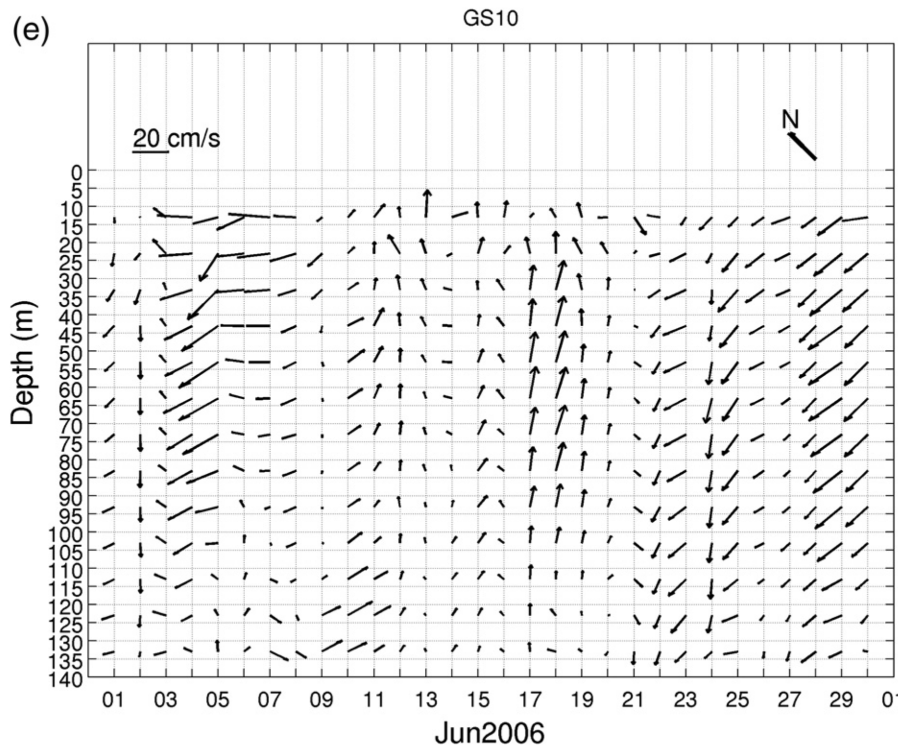

Fig. 6 (*continued*).

Dubrovnik area (e.g., the river of Rijeka Dubrovačka, enters the Adriatic near Dubrovnik and had an average discharge of 17 m^3/s in June 2006; Meteorological and Hydrological Service, unpublished data). The location and low volume of low-salinity waters on the DU transect leads us to conclude that the origin of the low-salinity waters observed in the CT transect is unlikely to be from Albanian rivers. This conclusion is also further supported by the satellite images and current measurements detailed below.

3.2. Currents

Currents were extensively measured in June 2006 at more than 15 stations; however, all of the instruments were upward looking ADCPs, which cannot fully capture the oceanic near-surface layer due to signal contamination from the side lobe echo near the sea surface. The GS stations had their shallowest uncontaminated depth-cell bins between 9 and 15 m, except at the shallow stations close to the Gargano Peninsula (GS1 and GS2) with depth-cells at 2 and 3 m and at GS9 with a shallowest depth-cell at 20 m. Similarly, the bins closest to the surface at the IT1 and IT2 stations were positioned at 11 and 8 m, respectively. Fortunately, the low-salinity water in the CT transect reached almost 20 m, and therefore the flow of this water should reasonably be captured by the current measurements at IT1 and IT2. Indeed, anomalous flow presumably related to the freshwater excursion, occurred between 15 and 21 June at IT1 (Fig. 6a). The surface currents were directed ENE at that time, opposite to the “normal” cyclonic circulation around SAP. Moreover, the cyclonic SAP flow weakened at IT1 and HR2 (not shown) around 8/9 June, and after that stayed quite low and even briefly reversed its direction in the whole water column. Later, after 21 June, the barotropic flow at the northern SAP edge returned to its normal cyclonic pattern with velocities at HR2 peaking at 12 cm/s.

The anomalous surface current episode between 15 and 21 June preceded by a week the observed fresh waters at the outer CT transect. Therefore, we believe that it is evidence of a surface circulation system bringing western Adriatic water from the central to the eastern Adriatic over the SAP edge. The observed eastward surface currents at IT1 during this episode decreased with depth, being hardly noticeable at 30 m. At the same time, surface and intermediate currents at IT2 (Fig. 6b) remained directed towards the NW during all of June; it seems that the fresh waters, once entering the CT transect, bifurcated around Lastovo Island, to the ENE towards IT1 station and to the NW towards IT2 station. There is no evidence from these current measurements of significant surface flow from the inter-island, coastal, middle-Adriatic waters towards the outer stations of the CT transect, indicating that local rivers are an unlikely source for the observed freshwater anomaly.

An interplay between “regular” and “abnormal” circulation regimes in June 2006 on the Palagruža Sill and SAP edge may additionally be visualised through investigation of the GS ADCP stations. Close to the western shore (Gargano Peninsula), strong WAC flow may be observed in the first 11 days of June, with core velocities surpassing 80 cm/s during bursts (Fig. 6c). In contrast, the WAC rapidly weakens in mid-June and currents from GS1 to GS4 become variable, with generally lower daily-averaged currents through the end of June. At stations GS7 (Fig. 6d) and GS8 (not shown) in the middle of the Palagruža Sill, the strong barotropic current directed towards the northern Adriatic changed to flow crossing the Palagruža Sill towards Gargano and remained strong and stable till 22 June. As this flow reached the WAC, it generally turned to join the now weaker eastward flow, creating a pocket of strong, positive vorticity shear north of GS4. South of GS4 the velocity shear was strongly negative for 17–20 June, with flow reversals at GS1-2 and currents turning in a way suggestive of small anti-cyclones between the WAC and the coast.

Further north at station GS10 (Fig. 6e), the currents were lower and more variable but still directed alongshore during the first 8 days of June. Then they switched to cross-shore flow, oriented northwards towards the eastern coast. In summary, it seems that “regular” and “abnormal” circulation regimes may be better described as “alongshore” and “quasi-laminar” versus “cross-shore” and “quasi-turbulent”, with a transition around 11–12 June triggered by a change in the wind forcing (see Section 4).

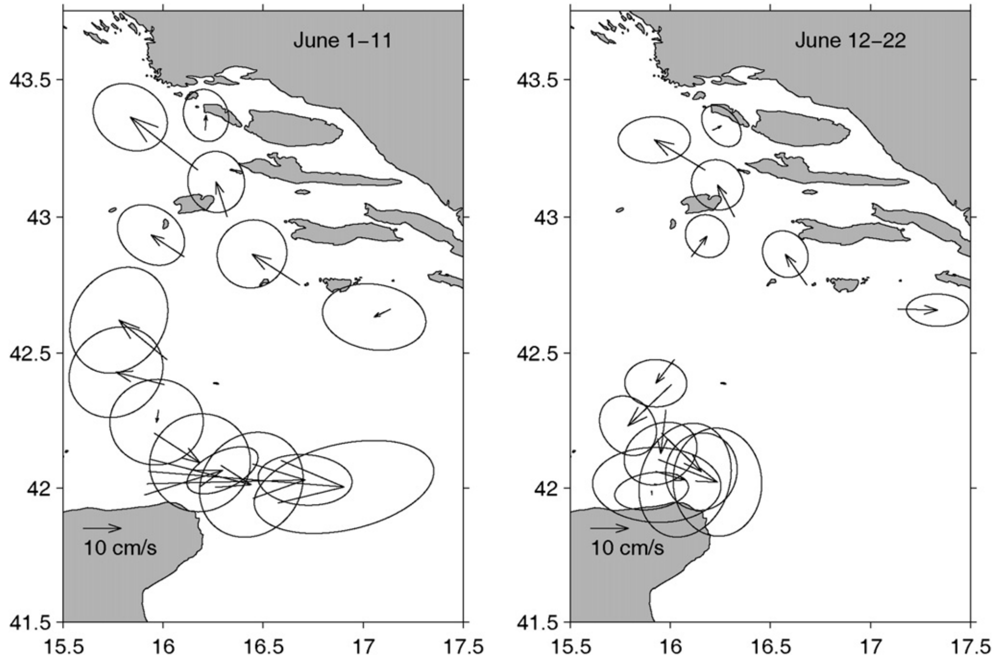

Fig. 7. Mean current vectors and standard deviation ellipses from the near-surface-layer (10 m) de-tided currents between 1–11 and 12–22 June 2006. GS9 is excluded due to 90% measurement failure for near-surface currents on 12–22 June and HR2 not shown as it is located too far to the east of this map.

These two regimes are even better visualised by drawing mean vectors and standard deviation ellipses over the experimental area (Figs. 7 and 8). For the purpose of representing upper-level currents, the depth-cell bin closest to a depth-cell of 10 m was used in Fig. 7. GS9 was excluded from this plot as its top level cell was at 20 m and it had more than 90% failure even at this depth level during the 12–22 June period. GS8 and GS10 also had high levels of measurement failure due the fact that measuring near-surface currents is near the limit of the ADCP capability at these sites, but they were included in Fig. 7 because estimated average speed errors were still below 2 cm/s. The mean WAC core velocity (GS3) in the first period was exceptionally strong (51 cm/s) with lower variability normal to the predominant direction. At the same time, the inflowing EAC is wide and encompasses around 75% of the surface layer of the GS line (or Palagruža Sill). In contrast, the second period is characterized by a weak WAC with larger offshore than alongshore variability. In addition, the WAC was strongest at GS4 due to the inferred inner anticyclonic eddy and instabilities. Also during the second period, the turning of the mean vectors from stations GS4 to

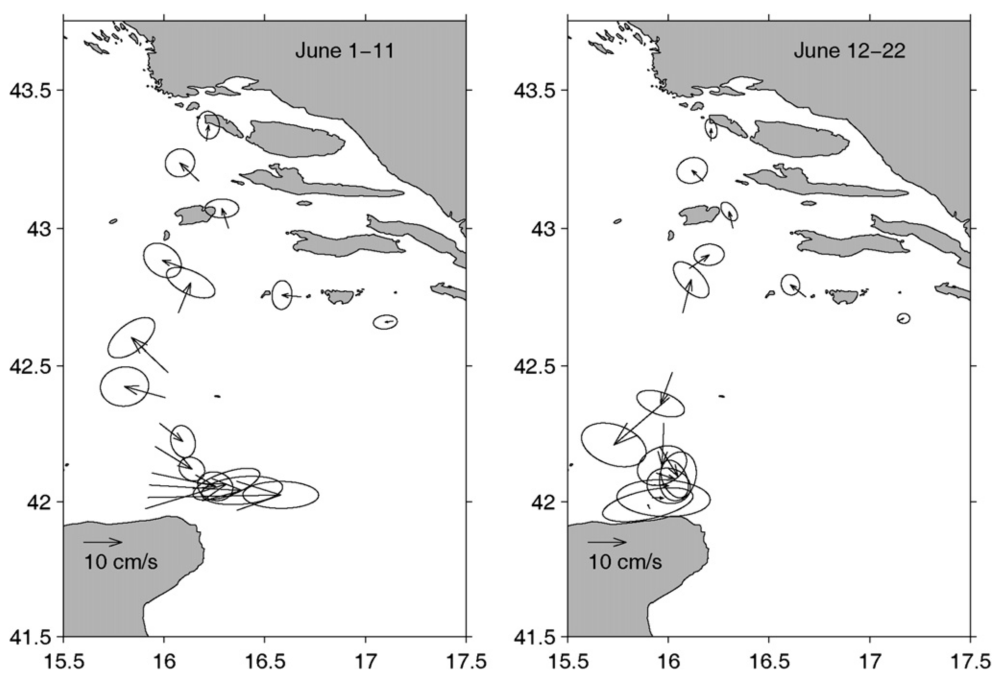

Fig. 8. Mean current vectors and standard deviation ellipses from depth-averaged currents between 1–11 and 12–22 June 2006. HR2 not shown as it is located too far to the east of this map.

GS8 in the large area of positive shear vorticity, suggests the possible existence of an offshore cyclone. Unfortunately, this cannot be confirmed by current measurement as there were no ADCPs over its supposed eastern half. There the implied flow would be towards the north-northeast and could be responsible for advection of west Adriatic waters towards the northern SAP edge and CT transect. However, some evidence for such flows can be found in satellite images as will be discussed in Section 3.3.

Both near-surface (Fig. 7) and averaged (Fig. 8) currents outline the same circulation features, although the near-surface currents are, on average, two times stronger. Therefore, both barotropic and baroclinic dynamics are responsible for the maintenance of these changing circulation regimes. The existence of a significant barotropic component permits use of the numerical exercises of Carnevale et al. (1999) for barotropic flow over an escarpment and idealized POM simulations (Section 5.2) for qualitative interpretation of these observations, and NCOM simulations (Section 5.1) additionally allow examination of the baroclinic component.

3.3. Satellite images

Satellite images of chl concentrations have been found to be useful for studies of freshwater influences in the Adriatic Sea, from Po River studies in the northern Adriatic (e.g., Barale et al., 1984, 1986) to the WAC outflow along the western shelf (e.g., Mauri and Poulain, 2001; Bignami et al., 2007). However, caution is warranted when using chl

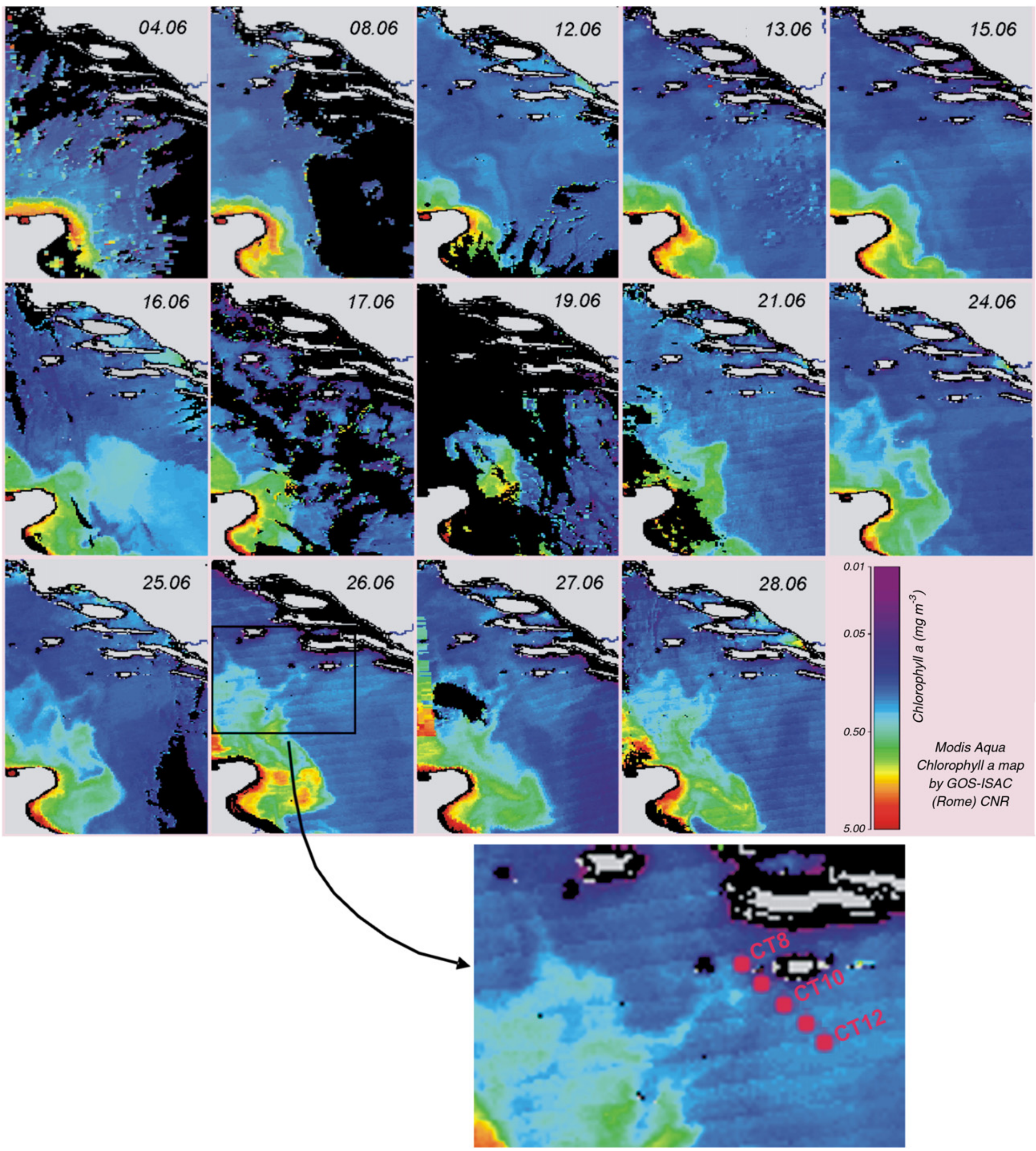

Fig. 9. Time series of chlorophyll a images of the middle Adriatic, taken from 4 to 28 June 2006. The image taken on 26 June is zoomed, with the positions of CT8 to CT12 stations indicated.

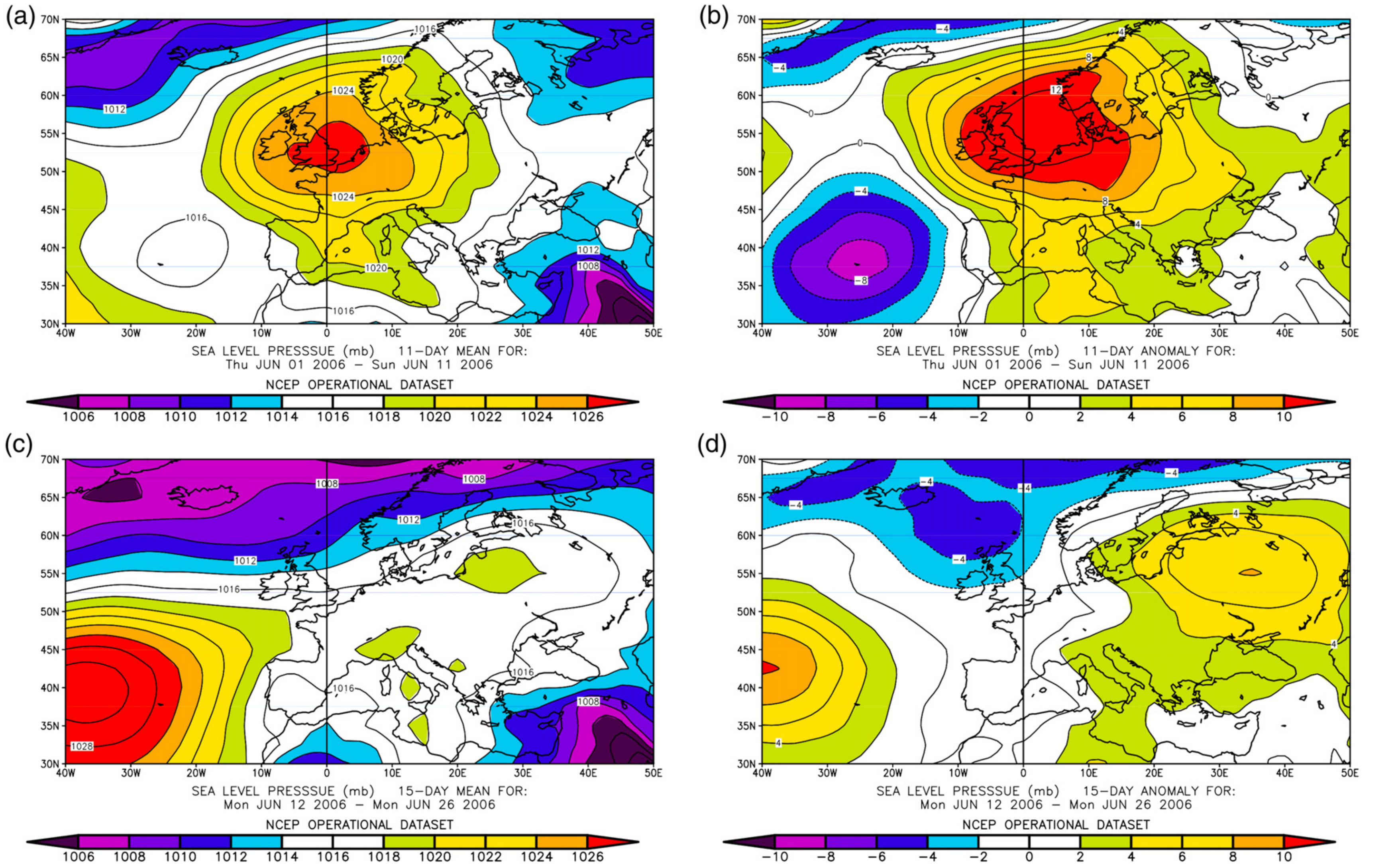

Fig. 10. Mean air pressure and its anomaly (in hPa) over Europe averaged for 1–11 June 2006 (a and b), and for 12–26 June 2006 (c and d).

as a tracer because it is not conservative and is not undoubtedly related to WAC low-salinity waters, especially far from the major nutrient input source (Po River) or near regions where high nutrient waters could be upwelled. With this in mind, we investigated available MODIS images for June 2006 and focused on the Palagruža Sill and NW SAP regions (Fig. 9). On 4 and 8 June, the WAC flow (with high-chl concentrations) is confined close to the Italian coast. Then, the WAC instabilities start to grow, mostly NE of the Gargano Peninsula just east of the GS ADCPs. On 21 June, a broad WAC filament reached the northwestern SAP edge near the centre of the Palagruža Sill. Three days later, a part of this filament can be traced to the outer CT transect. The filament persisted in this region past 26 June and overlapped the period when the low-salinity surface waters were observed in the CTD casts. At the same time, no significant chl concentrations were found along the SAP edge that could be traced as having spread from the east, in agreement with the CTD and current findings that these low-salinity waters were very unlikely to have originated from Albanian river sources.

4. Atmospheric conditions

As a change in wind conditions is the main cause of the current regime transition observed around 12 June in the middle and south Adriatic, herein we will concentrate on the atmospheric conditions that were recorded and modelled in June 2006.

4.1. Synoptic situation

A view of the two different periods in June that correspond to the two circulation regimes is visible in the averaged NCEP air pressure fields. Fig. 10 shows these averages for 1–11 and 12–26 June 2006, together with their anomalies with respect to climatology. In the first period, a rather strong anticyclone persisted over NW Europe, with the centre over the British Isles, while low pressure was situated over the Middle East. The gradients were significant and persistent over the Adriatic Sea, advecting cold air masses from the northeast. The anomaly of the high-pressure system surpassed 12 hPa at its centre (Fig. 10b), while the negative anomaly was positioned over the Azores due to the northeastward shift of the anticyclone.

The situation changed rapidly in the second period, in which the Azores High returned to its “normal” position, but with a secondary maximum over eastern Europe. This moderate anomaly, persisting over the continent, blocked the atmospheric circulation over the Adriatic Sea, where rather weak air pressure gradients were observed, resulting in weak Etesian (NW) winds.

4.2. ALADIN/HR fields

4.2.1. The model

The ALADIN model is a hydrostatic, primitive-equation model developed in the framework of an international cooperation involving fifteen National Meteorological Services. The model evolved from the global ARPEGE (Action de Recherche Petite Echelle Grande Echelle) model of Meteo-France (Courtier et al., 1991), with which it shares most of its physical parameterizations (Cordoneanu and Geleyn, 1998) and which provides it with initial and boundary conditions. The ALADIN model is being run operationally on a daily basis on different domains by the participating countries, and in Croatia the ALADIN/HR model is run by the Meteorological and Hydrological Service as a weather-prediction model (Ivatek Šahdan and Tudor, 2004) on a domain encompassing the Adriatic Sea and adjoining countries. Initial states and time-dependent lateral boundary fields are obtained from the operational outputs of the ARPEGE model, which, thanks to its stretched grid, resolves the mesoscale (30–35 km) over this area. The ALADIN/HR horizontal resolution is 8 km with 37 sigma levels unequally spaced in the vertical, the lowest being about 17 m above sea level.

4.2.2. Model verification and measured winds

During most of June 2006, wind speed and direction were forecast fairly well (Fig. 11), with some departures (over and underestimates) in speed especially during the first ten days. Another period of difficulty for wind speed forecasts was from 22 to 25 June, when measurements show significantly stronger wind than that predicted, but only at certain times of the day and at some stations (not shown). Wind direction was forecast fairly well at all of the Adriatic SYNOP stations, even during the beginning of June. All of this implies the possibility of stronger or weaker ocean transport and mixing than estimates based on the ALADIN fields, but also implies that ALADIN generally has skill in simulating the average fields of June 2006.

Both measured and modelled series uncover the difference between the two periods (1–11 and 12–26 June). For example, during the first period, all the western, middle, and south Adriatic coastal stations were affected by strong and persistent NW winds (Termoli, Fig. 11a), with a maximum speed of 15 m/s measured at Termoli and 8 m/s at Bari. These winds, except for a weakening around 4/5 June, were persistent up to 13 June, and then changed to sea- and land-breeze alternation with velocities lower than 4 m/s. Strong winds were also recorded in the middle of the Adriatic at Palagruža (not shown), where the instruments were located at 100-m height on this cliff-like island. Like at Termoli, the wind speeds also slowed after 13 June. At the Komiža station (Fig. 11b), located at the top of the outer east Adriatic islands (but relatively close to the eastern coastline), the winds were slightly stronger during the first ten days of June than during the rest of June. Yet, they were significantly weaker during the first 10 days than the winds observed on the western coast (Termoli) and in the open Adriatic (Palagruža) during the same period. In addition, the wind direction at Komiža was variable for all of June, indicating that this area was not strongly influenced by the open Adriatic surface atmospheric circulation during June 2006, but was instead dominated by sea- and land-breeze alternation.

4.2.3. June 2006 surface fields

Let us now focus on the surface wind and related fields obtained through ALADIN/HR modelling in June 2006. Fig. 12 displays the averaged surface fields over the two regime periods (1–11 and 12–26 June). During the first period, strong and persistent N and NE winds can be seen over the northern Adriatic, changing their direction towards the NW over the western areas of the open middle and south Adriatic. Over the central and southern Adriatic these winds have a positive curl. The isobars also depict the same surface atmospheric circulation over the open Adriatic, with decreasing gradients over the southern and most northern parts. Turbulent wind stress, which is computed as accumulated turbulent transport of momentum towards the surface, follows the wind pattern, being the strongest over the Jabuka Pit and over most of the western shore.

In contrast, turbulent wind stress decreased by 5 to 10 times in the subsequent period (12–26 June, Fig. 12b), and was uniformly low over the whole Adriatic. No surface pressure changes occurred over the whole Adriatic, maintaining very low wind speed values (<3.4 m/s). The only significant atmospheric forcing event occurring on a daily scale during this period was a strong downward heat flux, which increased the surface ocean temperature. However, this did not have an effect on the processes examined here due to normal lags associated with the Adriatic thermohaline circulation (e.g., Orlić et al., 2007).

5. Ocean modelling

5.1. NCOM realistic simulations

5.1.1. NCOM description

The ocean model used here for the Adriatic simulations, NCOM, is a hydrostatic, primitive-equation, free-surface model as described in Martin (2000), with some improvements as described in Morey et al.

(2003) and Barron et al. (2006). The free surface and vertical mixing are treated implicitly. The vertical grid consists of sigma coordinates in the upper layers and (optionally) level coordinates below a specified depth. The model equations include a source term that can be used for river inflows. Vertical mixing was computed using the Mellor–Yamada Level 2 scheme (Mellor and Yamada, 1974), which is modified for use over the entire water column. The equation of state used is that of Mellor (1991).

The domain used for the Adriatic simulations consists of the entire Adriatic Sea and a small part of the northern Ionian Sea just outside the Strait of Otranto. The horizontal grid resolution is about 1 km. The vertical grid consists of 32 layers, with sigma coordinates used from the surface down to 291 m and level coordinates used below 291 m. A smooth grid stretching was used with a maximum upper-layer thickness of 2 m. Plots of the model domain and additional details of the model setup for the Adriatic can be found in Martin et al. (2009).

The initial and (daily) boundary fields are from a global model, which is run in real time at the Naval Research Laboratory (Barron et al., 2004). Tidal forcing for the eight major tidal constituents was provided at the open boundaries and within the interior via the tidal potential. Atmospheric forcing is from the ALADIN model described in the previous section, and consisted of hourly values of surface atmospheric pressure, wind stress, solar and net longwave radiation, and precipitation. The latent and sensible heat fluxes and evaporation were computed using bulk formulas and the ALADIN wind speed, air temperature, and humidity and the ocean-model-predicted sea-surface temperature. Freshwater river and runoff inflows were taken from the monthly climatology of Raicich (1994), except that daily real-time discharge values were used for the Po River.

5.1.2. NCOM results

NCOM was initialized on 1 January 2005 and run to the end of September 2006. A notable result from the NCOM simulations was the

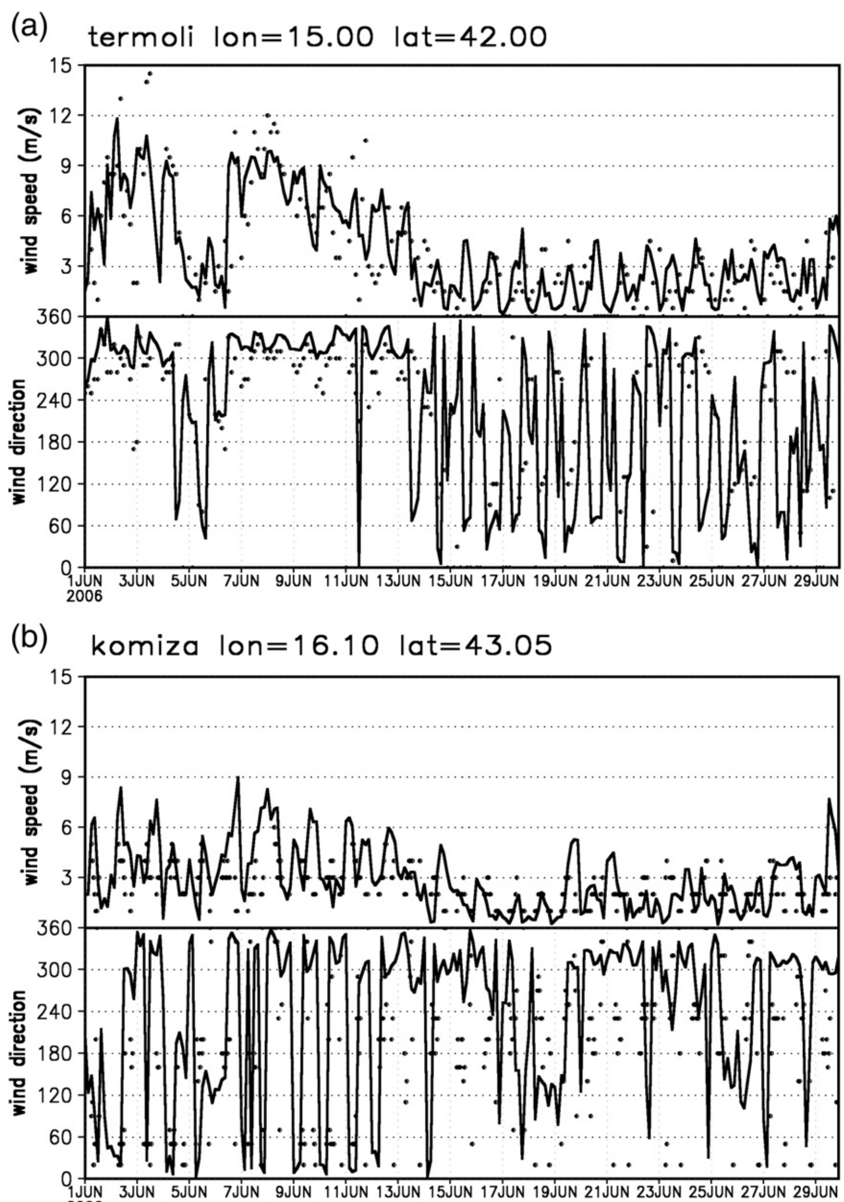

Fig. 11. Wind speed and direction measured and modelled at (a) Termoli and (b) Komiža in June 2006. Full line represents the forecast and dots represent the measurements. Meteorological convention for wind direction is used.

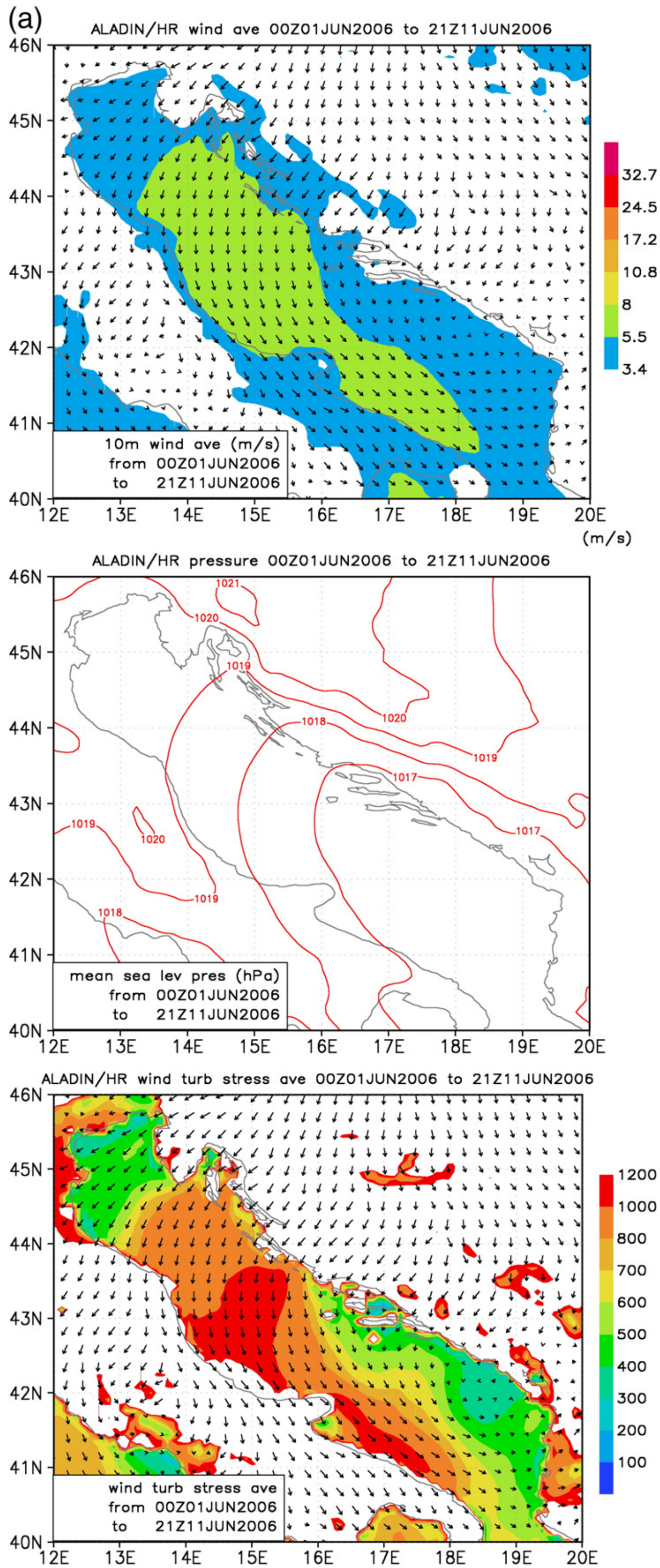

Fig. 12. Mean ALADIN/HR surface wind (in m/s), air pressure (in hPa), and turbulent wind-stress (in J/m^2) fields averaged for (a) 1–11 June 2006 and for (b) 12–26 June 2006.

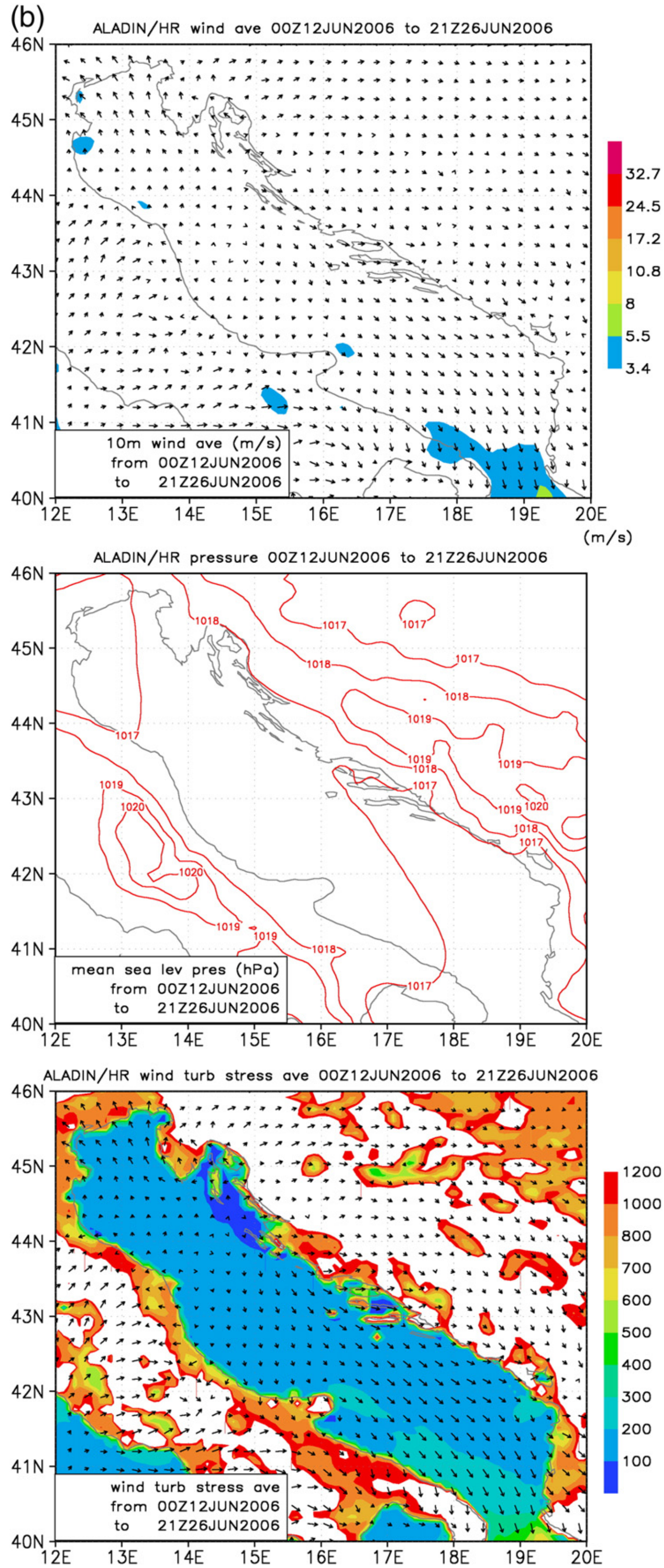

Fig. 12 (*continued*).

response of instabilities in the WAC to the winds (Burrage et al., 2009-this issue). In the central Adriatic, moderate to strong winds from the north and northwest tended to push the WAC against the Italian coast, increase its speed, and suppress instabilities. Cessation of the winds caused relaxation of the WAC, reduced transport, and the development of eddies and instabilities.

A notable WAC instability event during the NCOM simulation occurred in the second half of June 2006. During the first half of June, the strong winds, generally from the northeast to the northwest, kept the WAC in NCOM pinned against the Italian coast. The cessation of the ALADIN winds around 14 June resulted in the rapid development of instabilities in the WAC all along the coast with continued development over the next couple of weeks. Fig. 13a and b shows average surface currents from NCOM in the central Adriatic for the periods 1–11 June and 12–22 June, matching the averaging periods in Figs. 7 and 8. Over the 1–11 June period, the average WAC flow is strong and laminar, but, during the 12–22 June period, the average WAC flow is much weaker and more variable. Note the existence of a small cyclone on the sill, northeast of Gargano, and the existence of a broader anticyclonic cell southeast of Lastovo Island in both periods. In the 1–11 June averages the two cells are farther apart from each other than in the 12–22 June averages.

For further analysis it is constructive to consider the average sea-surface-height (SSH) contours of the two periods as shown in Fig. 13c and d. These contours are the geostrophic streamlines for the surface currents. Of particular importance are the hyperbolic points in the contours just offshore of the WAC to the northeast of Gargano. As shown during the winter experiment of DART by Haza et al. (2007),

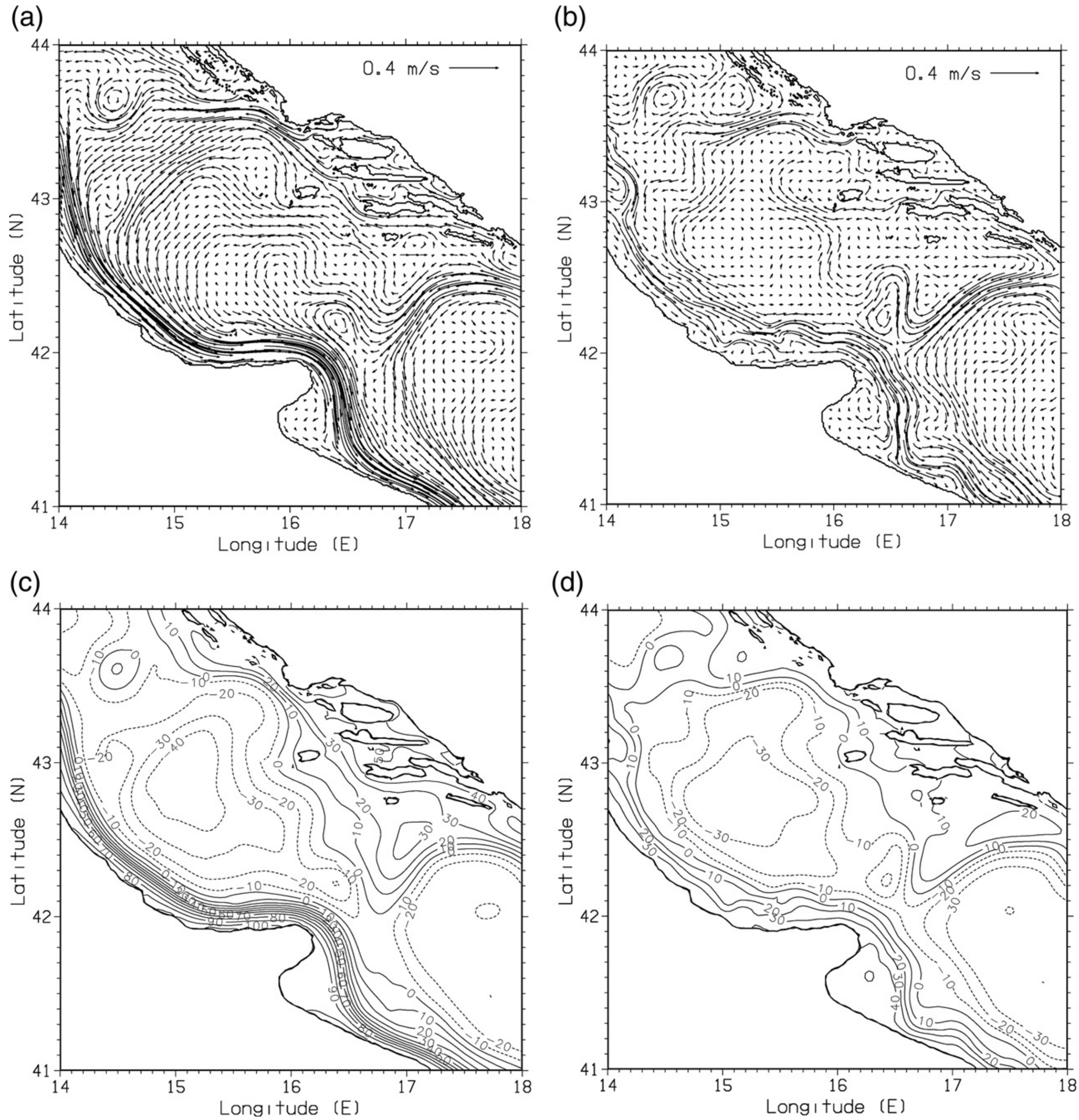

Fig. 13. Surface currents from the NCOM simulation averaged over (a) 1–11 June, and (b) 12–22 June, together with SSH fields (in mm) averaged over (c) 1–11 June, and (d) 12–22 June 2006, and (e) surface salinity for 3 July 2006 (the contour interval for salinity is 0.5), showing WAC offshore flow towards Lastovo Island captured by the 37.5 isohaline.

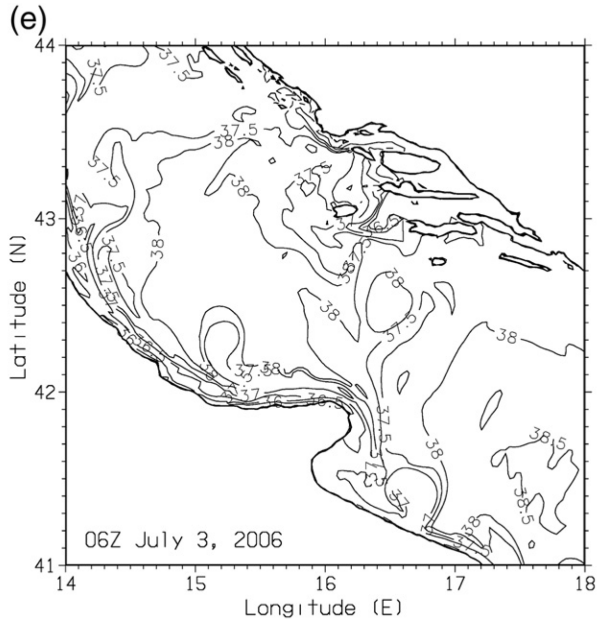

Fig. 13 (*continued*).

this feature can be associated with a point of high dispersion for surface drifters. In the 1–11 June period, the hyperbolic point is less tightly formed and the region between the unconnected 0 mm SSH contours is relatively wide. In contrast, for the 12–22 June period, the hyperbolic point is well formed and the region between the unconnected −10 mm SSH contours is small. Hence, as can be seen in Fig. 13b, only a small anomaly is required at the hyperbolic point to push particles in the outer WAC across the gap and change their pathways from southeastward to northward flow.

Such an excursion clearly takes place twice during the main NCOM simulation. A small excursion occurs on 20 June where a portion of the outer WAC moves offshore at the northwest side of the hyperbolic point into the northeastward flow region between the persistent offshore cyclone/anticyclone pair. A second, larger excursion takes place on 26 June when the WAC flow is arrested and a very strong anticyclonic eddy downstream of Gargano combines with the offshore anticyclonic eddy to form a brief period of continuous, cross-basin, northeastward flow from the Gulf of Manfredonia to Lastovo Island.

Both these events contribute to the formation of a streamer of low-salinity water in NCOM during mid-June to mid-July, extending from the WAC near Gargano Peninsula towards Lastovo Island (Fig. 13e). In NCOM this streamer is formed from both the WAC excursions and from low-salinity water that had earlier been advected from Albanian sources. The pathway of these latter waters followed the rim current of the SAP and then turned to the northeast around the northeast side of the hyperbolic point. However, since NCOM is using climatological values for these rivers, this particular process might be unrealistic for June 2006.

The NCOM simulations show qualitatively the development of conditions conducive to offshore excursions of WAC low-salinity waters in the latter half of June. These conditions include a slowing of the WAC allowing lower-salinity water to spread to the WAC's outer edge, the development of a persistent, clearly-defined hyperbolic point in the flow where WAC and EAC waters come close to each other, and the development of instabilities which can push flow across the gap of the hyperbolic point. Note that particular excursion events are fairly unpredictable, likely due to the role of instabilities in the process. Five different NCOM runs were made for this period with small variations in model simulation input parameters. This ensemble of runs demonstrates this unpredictable character of the events as the events occur at different times and in different ways in the different model runs, and do not occur in all runs.

5.2. Idealized simulations

5.2.1. The model

The Princeton Ocean Model (POM, Blumberg and Mellor, 1997), a three-dimensional, primitive-equation, nonlinear model, was used to elucidate the effects of the topographical features on the wind-induced circulation in the middle and south Adriatic. The equations that capture the model physics are the traditional equations for conservation of mass, momentum, heat, and salt, coupled with the equation of state (Mellor, 1991). Parameterization of vertical mixing of momentum, heat, and salinity is provided by a 'Level 2.5' turbulence closure scheme based upon the evolution of the turbulent kinetic energy and turbulence macroscale (Mellor and Yamada, 1982).

In the process-oriented studies, the Adriatic is approximated by a rectangular basin 800 km long and 200 km wide, with a southern open boundary representing the Otranto Strait (Fig. 14a), where radiation boundary conditions have been applied. The model grid has 5-km horizontal resolution and 21 unequally spaced sigma layers along the vertical. Two idealized bathymetries were used in the simulations: a flat-bottom basin with a depth of 200 m (B) and a stepwise bathymetry (S) approximating the major topographical features of the Adriatic Sea: the shallow northern Adriatic, the Jabuka Pit, the SAP, and the Palagruža Sill (Fig. 14b). A Shapiro filter (Shapiro, 1970) was applied to the stepwise bathymetry in order to avoid numerical errors. In addition, the influence of the Gargano Peninsula on the WAC has been investigated by attaching a rectangular- (C1) or triangular-shaped (C2) peninsula to the western coast (Fig. 14a), having a base of 50 km and being positioned in the middle of the 130-m deep and 150-km wide Palagruža Sill. Various combinations of flat and step-like topographies, with or without a peninsula have been used in the model runs. The initial temperature field was horizontally homogeneous with the vertical structure set to summer climatological values (Artegiani et al., 1997). In the experiments with no river influence, the initial salinity field was set to a constant value of 38, whereas in the experiments with river discharge, the salinity field was initialized by a 10-day run with rivers as the only forcing. In all the simulations with river discharge (R), the river mouths were equally distributed along the Adriatic coast as point sources. The total discharge was set equal to the climatological Adriatic freshwater input for June (Raicich, 1996). The river inflows in POM were parameterized according to Kourafalou et al. (1996).

After the initialization, the model was forced by different wind patterns: (W1) a spatially homogeneous along-basin wind, i.e. NW wind, (W2) a spatially homogeneous wind rotated 22.5° from the along-basin direction, i.e. NNW wind, as such inclination may be found in the ALADIN fields (Fig. 12), and (W3) a NNW wind pattern with a linear decrease of speed in the cross-shore direction from 10 m/s on the western coast to 0 m/s at the opposite eastern shore. The W1 and W2 simulations used wind stresses of 0.06 Pa and the linear decrease in wind in the W3 simulation produced a wind-stress curl of 0.55 Pa/1000 km. These values were based on simulated winds from ALADIN which showed a mean wind stress of 0.042 Pa and a mean wind-stress curl of 0.506 Pa/1000 km for 1–11 June over the central Adriatic. In the numerical experiments the wind was kept constant for 10 days and then the speed was decreased to zero over the next three days by cosine decay (Fig. 14c). After that, the model was run for another 20 days without wind forcing.

5.2.2. The simulations

To begin, we will document the common features obtained in the various model runs with wind forcing. First, no significant qualitative changes were observed in the surface current fields between model runs using W1 and W2 winds (Fig. 14a) either in flat-bottom or in

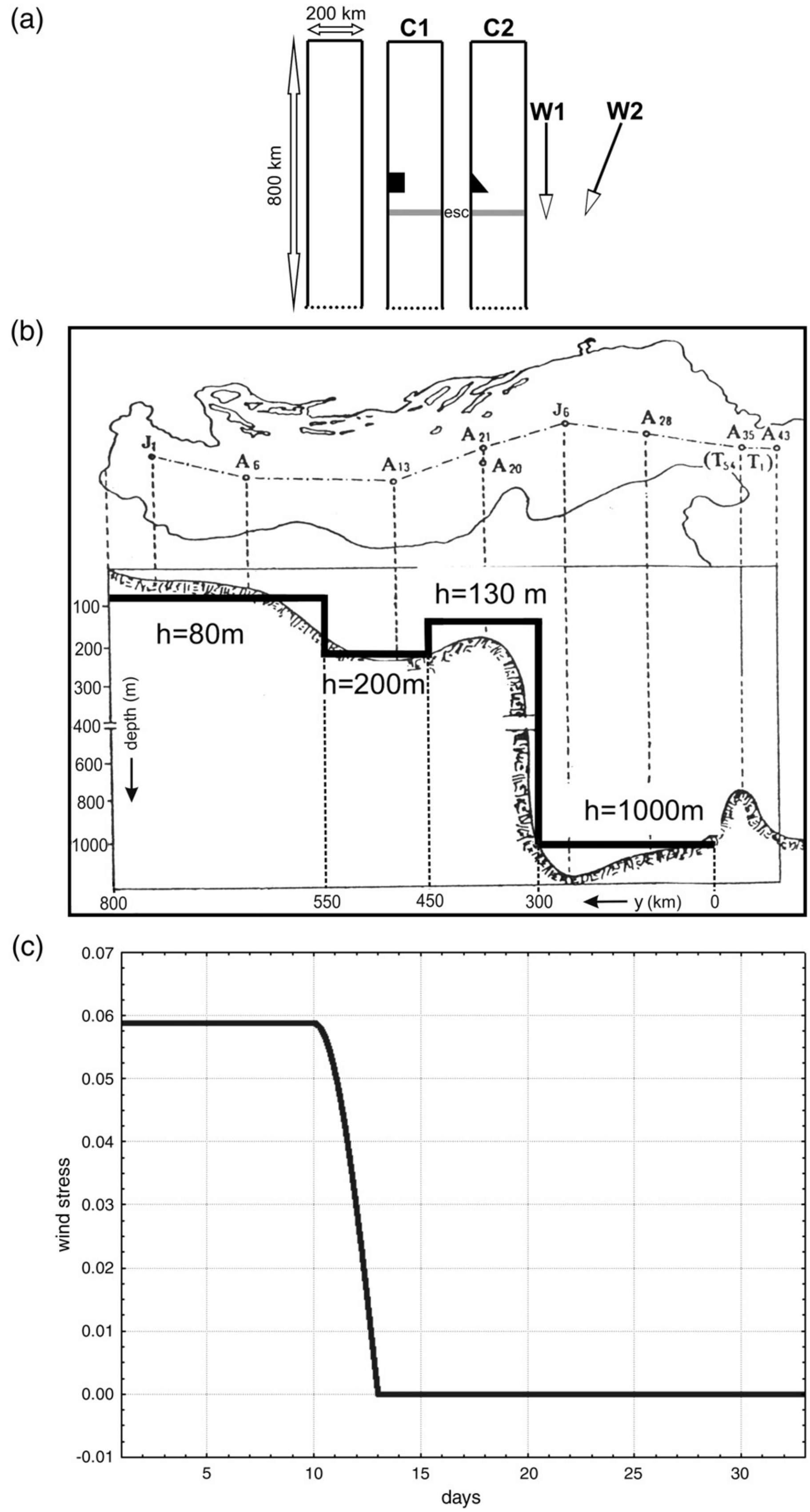

Fig. 14. Idealized bathymetries and wind forcing function used in the process-oriented tabulated simulations: (a) rectangular 800 × 200 km bathymetry, with the rectangular-shaped (C1) and triangular-shaped (C2) peninsula located in the middle of the western shore, the position of the major escarpment indicated (esc), and along-basin (W1) and inclined (W2) wind directions, (b) stepwise along-basin approximation of the Adriatic, and (c) temporal variation of the wind-stress function uniformly distributed over the model domain and blowing from NW (along-basin, W1) or NNW (inclined for 22.5°, W2), or increasing the NNW wind uniformly from 0 m/s at the eastern shore towards 10 m/s at the western shore (W3).

stepwise bathymetry runs. Thus we conclude that a small change in wind direction does not substantially change the sea-surface dynamics. For both spatially homogeneous wind fields, the surface currents are directed downwind while the wind is blowing, whereas they tend to reverse near the coast during wind relaxation.

Introduction of the Gargano Peninsula in the flat-bottom basin, either as a rectangle (not shown) or triangle (Fig. 15), causes anticyclonic downwind flow around the obstacle when spatially homogeneous winds (W1, W2) are blowing. Thereafter, topographically-driven anticyclonic eddies can be found for both simulations; two for the C1 (rectangle) and one for the C2 (triangle) model runs. The anti-cyclones south of the Cape in these simulations agree with observations and NCOM simulations of anticyclonic eddies in the Gulf of Manfredonia which can form in the lee of the WAC flow around Cape Gargano (Burrage et al., 2009-this issue), although the simulated eddies from our study are positioned somewhat differently due to the idealization of the topography. The eddies begin to grow just after the wind relaxation, and then move slowly offshore as the western coastal current decreases in strength and reverses in some areas. In the simulations with a spatially inhomogeneous wind field (W3) over a flat bottom, currents were downwind only along the western coast and upwind along the opposite eastern coast during the whole 33-day experiment (Fig. 15). As expected, positive wind-stress curl was effective at spinning up basin-wide cyclonic circulation. Somewhat more surprising was that this had a lasting effect on the evolution of the anticyclone after the wind had stopped as the persisting cyclonic circulation inhibited eastward movement of the eddy and caused it to remain trapped in the lee of Cape Gargano.

In the presence of stepwise bathymetry only (SW2 runs, Fig. 16), the initial flow was generally downwind with cross-basin flow towards the west, and the initial flow pattern closely matched the initial flow pattern of the equivalent flat-bottom simulation (BW2, not shown). However, after the winds cease and as the coastal currents reverse, weak cross-basin flows towards the east of about 7 cm/s can be noticed at the largest step/escarpment, e.g. between the Palagruža Sill and the SAP, and such flows are absent in the flat bathymetry run. Introduction of the Gargano Peninsula generated two stationary anticyclonic eddies during the wind relaxation period without significant influence on the weak cross-shore current (Fig. 16).

Wind-stress curl above a stepwise bathymetry caused the flow field to depart from the uniform basin-wide cyclonic circulations seen in the flat-bottom runs with wind-stress curl (e.g. lower panels of Fig. 15). With stepwise bathymetry, cyclonic cross-basin flow was intensified at the steps/escarpments and weak elsewhere as can be seen in Fig. 17 for the two escarpments associated with the Palagruža Sill. When the winds cease, two separate cyclonic gyres form, bounded by the Palagruža Sill/SAP escarpment. Thus flow is eastwards north of the escarpment and westwards south of the escarpment and little if any flow from the “WAC” crosses the escarpment. The eastward flows are stronger by a factor of 3 in speed and in width compared to the eastward flows from the runs without wind-stress curl initial conditions. Introduction of the Gargano Peninsula again generates a

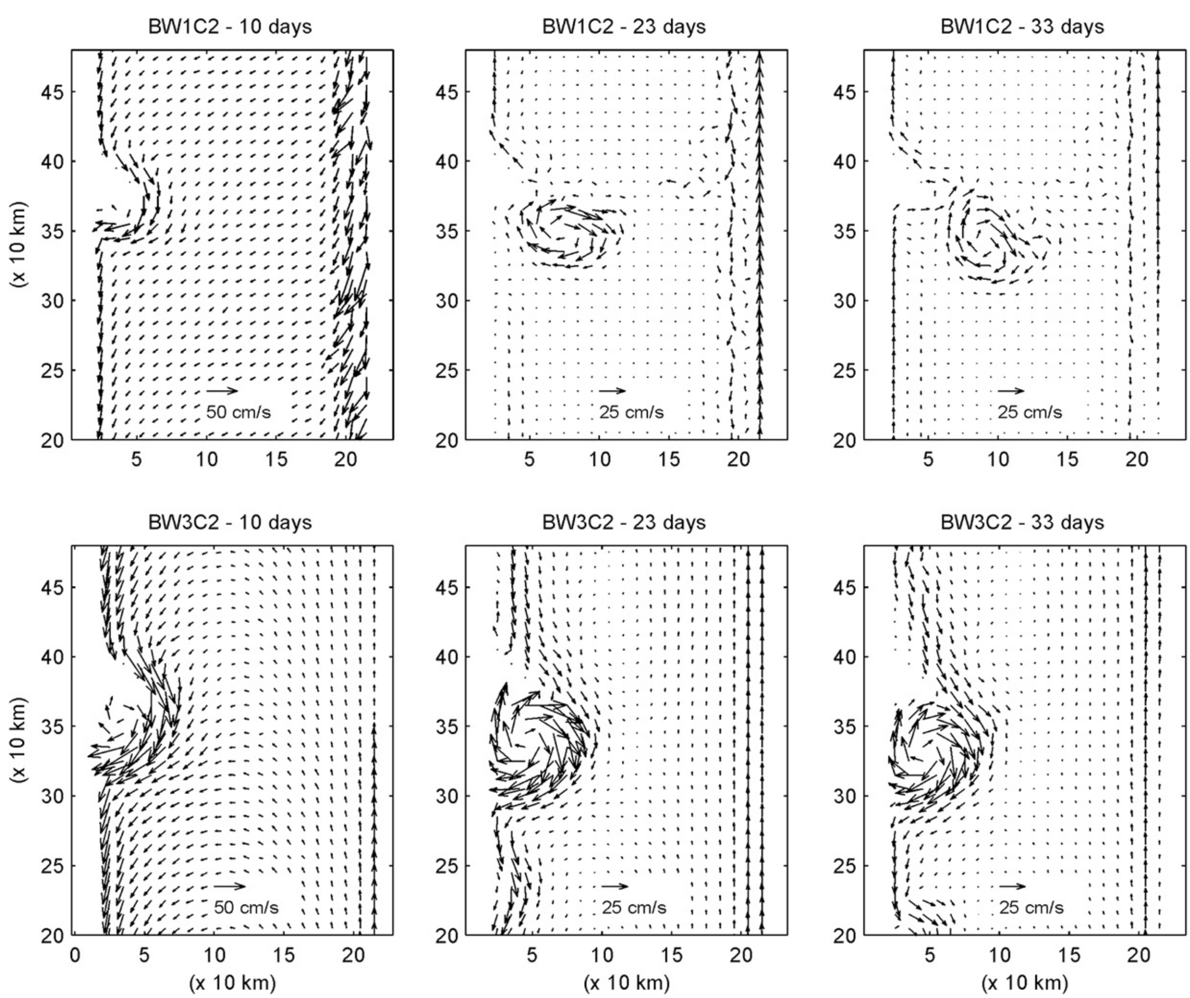

Fig. 15. Snapshot of the surface current field around Palagruža Sill obtained in the BW1C2 and BW3C2 simulation for days 10, 23, and 33 after the wind initiation.

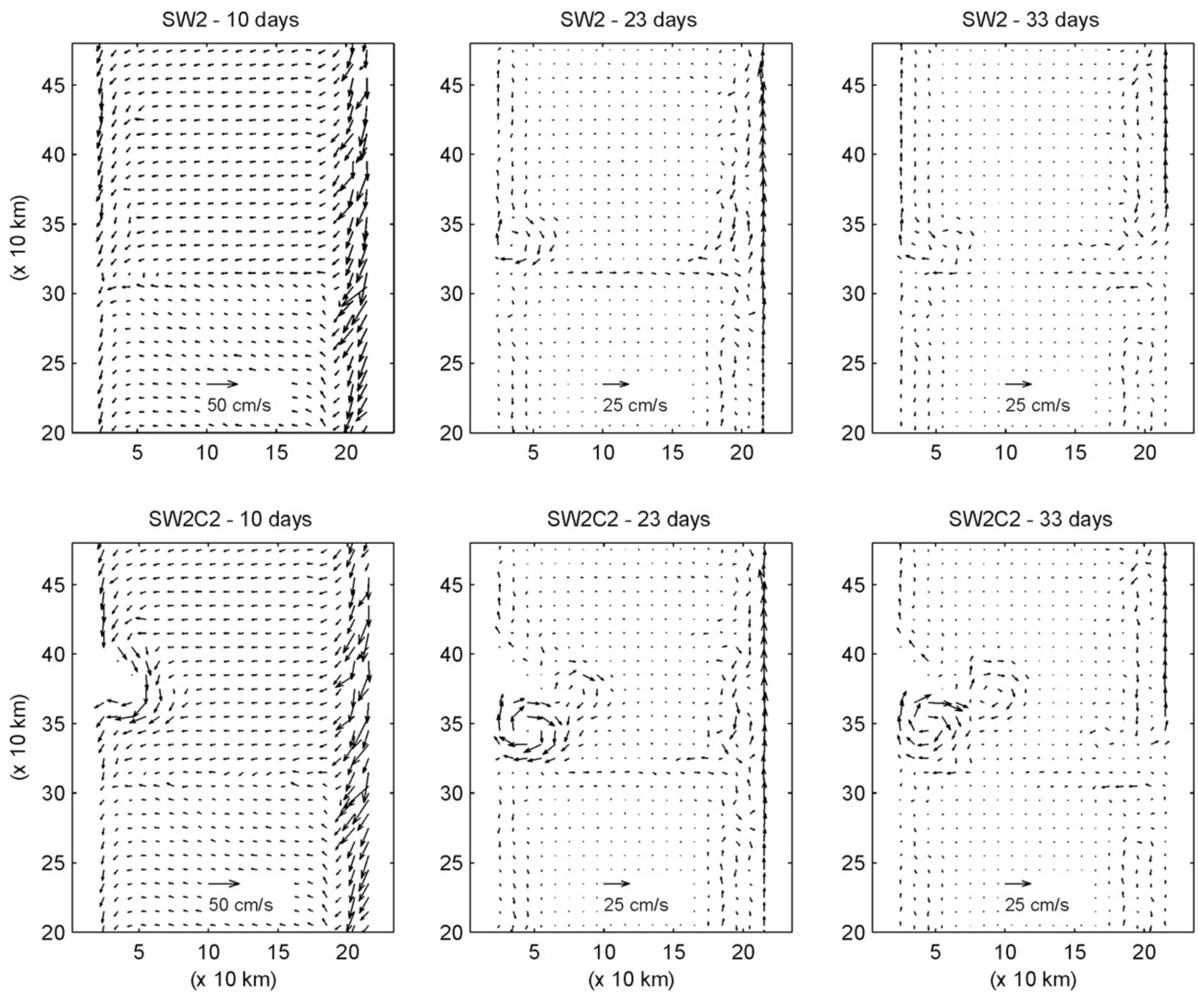

Fig. 16. As in Fig. 15, but for SW2 and SW2C2 simulations.

strong, trapped anticyclonic eddy (similar to the one in the lower panel of Fig. 15), but it also generates mesoscale meanders in the eastward escarpment current (Fig. 17). Generally, the eastward escarpment current is weaker and positioned more to the north than in the SW3 experiment without the peninsula, and it contains eddies and meanders evolving with time. In contrast, the westward escarpment current is relatively unperturbed.

By adding the rivers in the simulations, a basin-wide cyclonic circulation is established prior to the wind blowing, with incoming currents along the eastern coast and outgoing currents along the western side. During the next ten days of constant wind forcing and river inputs, the wind-induced currents become dominant and the surface current fields resemble the corresponding fields from the runs without rivers but with slightly higher intensities due to the increased stratification and decreased mixed-layer depth (Pollard et al., 1973). Surface current fields obtained in the experiments SW3 and RSW3 have almost identical structures (Figs. 17 and 18). However, introduction of the triangular Gargano Peninsula with river flows creates a more complicated flow structure than the comparable simulations without river flows as strong instabilities are generated upstream and to the east of the peninsula when the wind forcing ceases (Fig. 18). The mesoscale instabilities propagate eastward, remaining to the north of a 15 cm/s eastward escarpment current that is stronger than the current in the comparable case without river flow but weaker than the current in the comparable case without a peninsula.

One should be careful when applying these results to WAC flow past the real SAP/Palagruža Sill escarpment. Stepwise bathymetry closes isobaths at the escarpment and does not include isobaths that follow the western Adriatic shelf slope. An important consequence is the elimination of alongshore, potential vorticity conserving pathways for the WAC, thus enhancing the tendency for cross-basin flow in the idealized studies. Also, another effect that cannot be simulated with this bathymetry is the enhancement of cyclonic vorticity input to the sea from such NW and NNW winds blowing over the real Adriatic with a cross-shore bottom slope and shallower depths on the western than on the eastern side. 'Further study of relative importance of these two effects is needed, since they are expected to have opposing impacts for cross-shore flow.'

6. Summary, discussion, and conclusions

In situ data analyses, atmospheric and oceanic realistic numerical modelling, and process-oriented simulations were all used to attempt to explain the source and propagation of anomalous fresh waters observed in the northern part of the SAP during 26 June 2006. Unfortunately, despite the extensive field observations and modelling efforts already in place from the DART and ITHACA projects, the *in situ* and remote-sensing measurements did not fully capture the event. This illustrates the difficulty of resolving mesoscale and smaller scales over broad areas and over the full extent of travelling instability events. Although we cannot present conclusive evidence that the fresh waters were of WAC origin, the existing evidence shows that this is the most likely explanation and the analysis of the data and modelling results reveals new insights into pathways, forces, and the role of

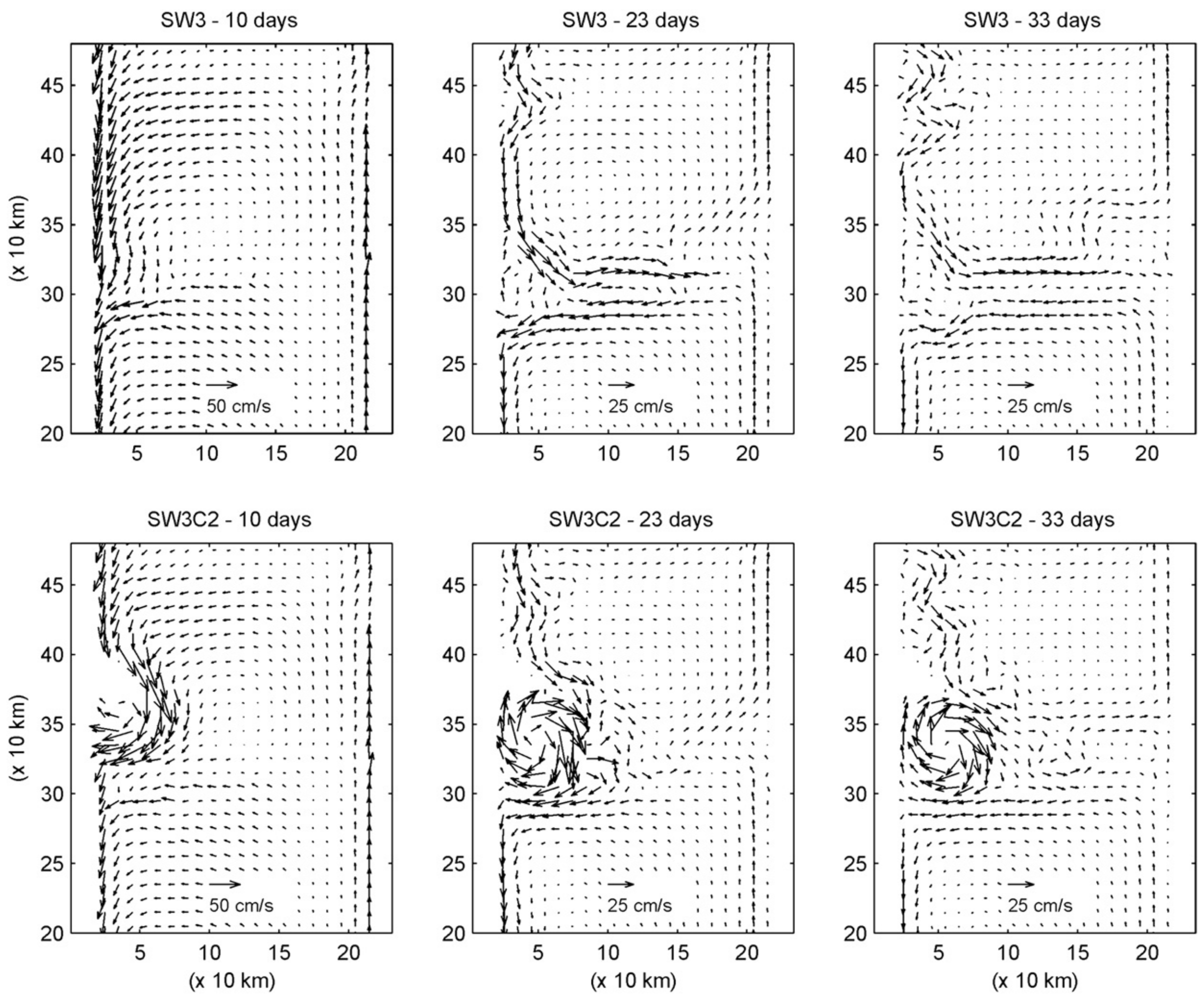

Fig. 17. As in Fig. 15, but for SW3 and SW3C2 simulations.

topography in anomalous cross-basin exchange that should be important for the central Adriatic and other similar settings.

There are three primary sources of fresh water in the central Adriatic region, Albanian rivers, Croatian rivers, and WAC waters. The lack of an offshore extent of the fresh water in CTD data measured east of the observed waters (Fig. 5) indicates that it is unlikely that the waters had their origin in Albanian rivers. However, NCOM runs forced by climatological east Adriatic rivers (which should be larger than real 2006 river discharges) do show waters of Albanian river sources reaching the CT transect region. In NCOM the pathway of these waters is the same as the pathway of WAC waters, i.e., the Albanian-derived waters follow the rim of the SAP and then cross the basin during particular exchange events at a hyperbolic point in the flow northeast of the Gargano Peninsula. Another possible source for the freshened waters was flow from local coastal middle-Adriatic waters, where a large river, the Neretva, enters the Adriatic. Available current data (e.g., Fig. 6b) gave no indication of significant surface current flow in this direction. This does not exclude the possibility that an excursion from coastal middle-Adriatic waters could have been shallow (<10 m) or horizontally thin and thus have been missed by the ADCPs, but such circumstances seem unlikely. The last possibility was that the observed low-salinity waters are of WAC origin, and satellite images provide evidence for this as high-chl waters can be traced from the WAC all the way across the Adriatic to just south of Lastovo Island. Also, both NCOM and idealized model studies show that such an excursion is dynamically feasible under the meteorological conditions of the central Adriatic in June 2006. Therefore, we focus on exploring this possibility as a general study of cross-basin exchange of a normally coastally-bound buoyant current.

Both the NCOM and idealized studies show possible mechanisms for sudden cross-basin excursions of a coastally-bound current. In agreement with what was observed (Fig. 7), all modelling studies point to the importance of a fundamental change in the current conditions related to a relaxation of strong winds that permit cross-basin exchange to occur. NCOM results suggest the importance of a hyperbolic point in the flow where WAC and EAC waters come close together due to the SAP escarpment forcing curvature in the EAC. This is the point in NCOM where the cross-basin exchange occurs in agreement with what is observed in the satellite images (Fig. 9). The hyperbolic point is just to the south of an anticyclonic–cyclonic dipole of the EAC and the structure of the point and dipole is sensitive to wind conditions. During 1–11 June the dipole was positioned closer to the eastern shore (Fig. 13a) and the cyclonic cell was oriented across the sill, thus there wasn't a potential pathway for WAC waters towards the CT line, even if they could jump across the relatively wide hyperbolic flow area. In contrast, during the wind cessation phase from 12–22 June, the dipole moved towards the western shore, and the cyclonic cell changed to a cross-basin orientation (Fig. 13b). Thus, weakening of the WAC and related instabilities allowed fresh water to jump from the outer WAC across the hyperbolic point and cross the basin following the shared edge of the anticyclonic–cyclonic dipole. Once an excursion occurred, some waters could remain in the anticyclonic cell in the

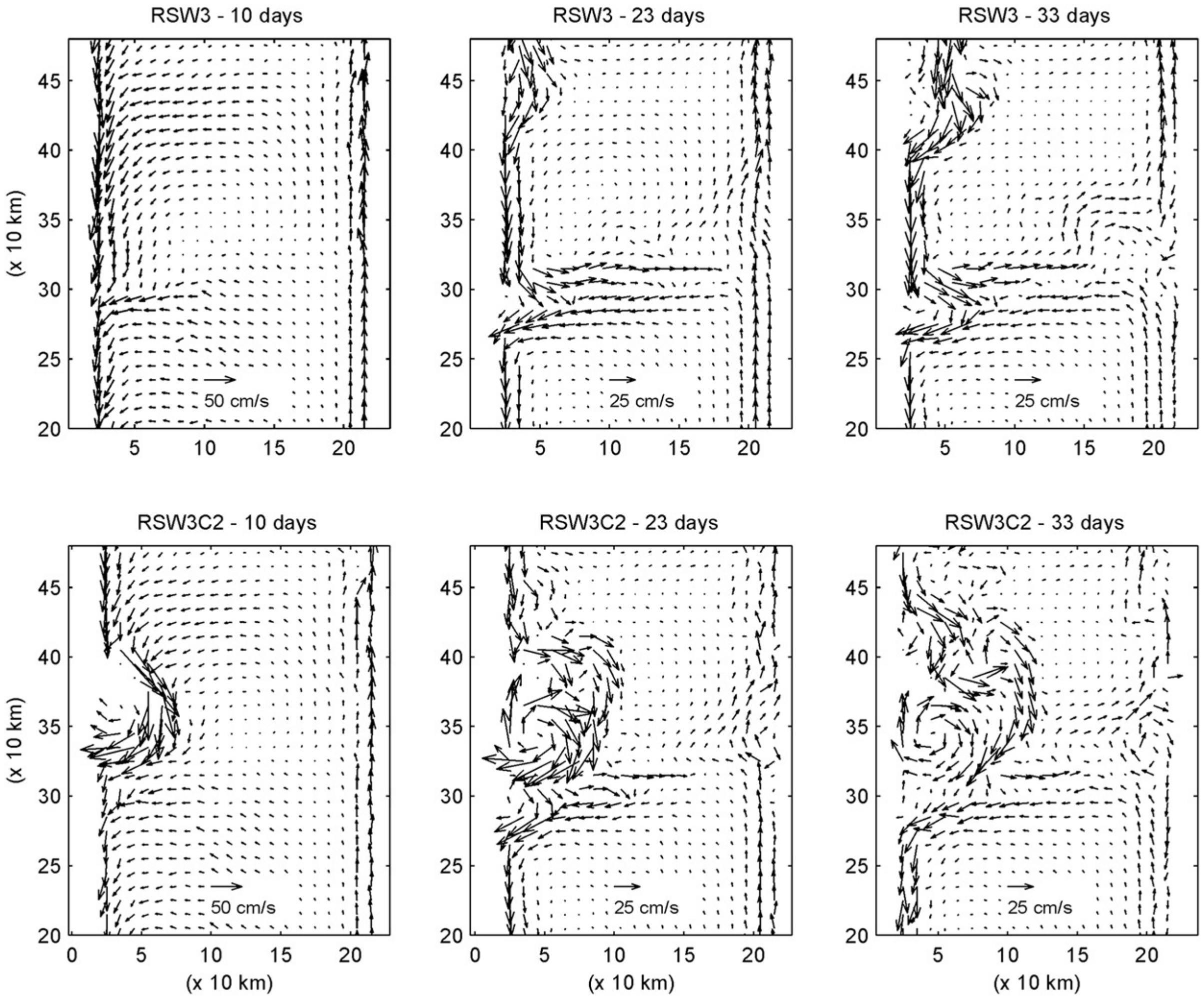

Fig. 18. As in Fig. 15, but for RSW3 and RSW3C2 simulations.

region of the CT transect for extended time periods. The ADCP observations of flow towards Italy during 12–22 June (Fig. 7) are consistent with the flow along the northeastern side of the cyclonic cell observed in NCOM, but in NCOM this flow is further to the east than what was observed.

Idealized simulations allow some separation of the various roles of a wind-stress curl, an escarpment, a peninsula, and a buoyancy current for offshore excursions. The existence of a SAP/Palagruža Sill escarpment and the relaxation of prior NW or NNW wind forcing produce opposing cross-basin flows on either side of the escarpment. This flow is enhanced if the prior wind possessed a cyclonic wind-stress curl. Introduction of a peninsula causes meanders and eddies to occur in the fields and slightly reduces the strength of the cross-basin flow. The introduction of fresh water into the coastal current does not change the simulations much for cases without a peninsula, but the combination of fresh water and a peninsula leads to a maximum of eddy and instability activity. In these simulations, the presence of the escarpment is the critical factor for producing cross-basin exchange of the coastal current. However, the presence of the peninsula plays a critical role in producing instabilities and meanders in the flow, which qualitatively matches the convoluted chl shapes seen in the remote-sensing images during likely cross-basin exchange events.

Both NCOM and the idealized studies with escarpments have points near the sill where currents in opposing circulation cells come in close proximity to each other. In NCOM, this is the hyperbolic point where the WAC turns anticyclonically around the Gargano Peninsula and the EAC bifurcates from the SAP rim flow to flow over the centre of the sill. The hyperbolic point is best formed when this crossing is in the form of an anticyclonic–cyclonic dipole and thus there are four curving circulations coming together in one location: an anticyclonic WAC, a cyclonic SAP rim flow, an anticyclonic cell southeast of Lastovo Island, and a cyclonic cell over the centre of the Palagruža Sill. In contrast, the idealized studies form opposing cross-basin flows along the escarpment. Thus the escarpment delineates the boundary between a closed cyclonic gyre in the SAP and a closed cyclonic gyre over the Palagruža Sill. The eastward flow that closes the Palagruža Sill provides a direct pathway for advection of WAC waters to the east rather than the indirect pathway found in NCOM. This major difference is likely due to the lack of isobaths that cross the escarpment in the idealized study. Further study of these effects is needed.

What is the prevalence and importance of these cross-basin flows for the Adriatic and similar basins? Strong and quasi-permanent NNW winds (bora and tramontana) do not usually blow for almost two weeks (11 days) as was observed in early June 2006. The anomalous atmospheric conditions were caused by the translocation of the Azores High towards the British Isles. The winds were the strongest along the western shore, causing WAC peak velocities to briefly exceed 100 cm/s. These two weeks were followed by two weeks of relatively weak winds, setting up ideal conditions for cross-basin exchange as examined in this paper. Although June 2006 was fairly anomalous in its conditions, there is evidence that cross-basin exchange in the central

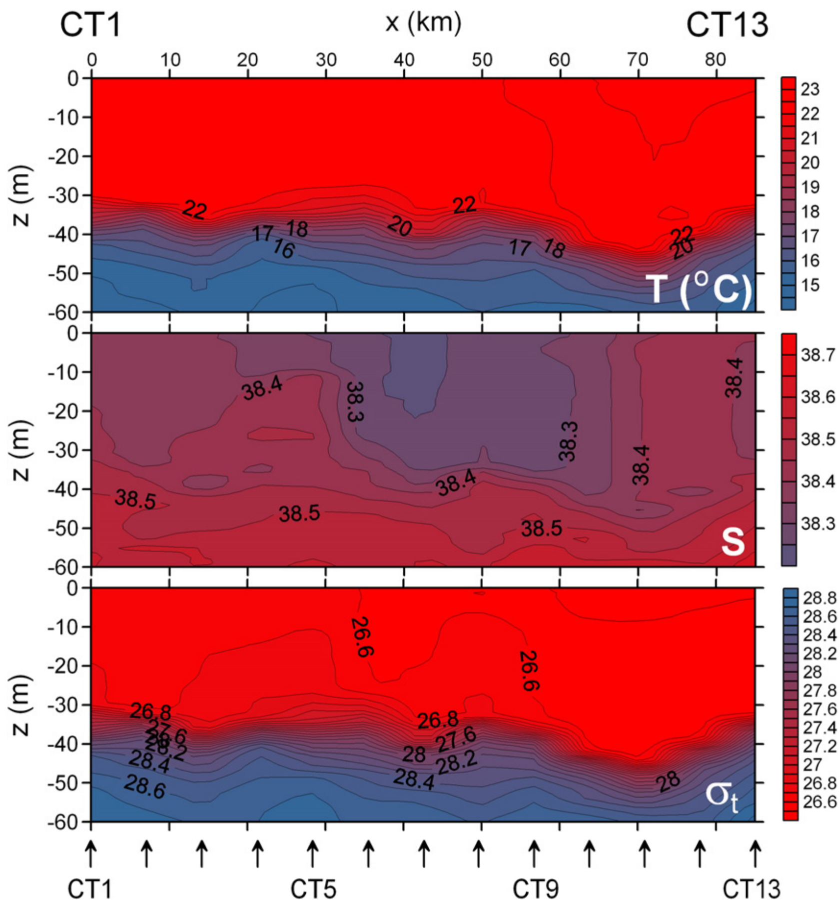

Fig. 19. Temperature, salinity, and sigma-t measured at the CT CTD section on 28 September 2006.

Adriatic following similar mechanisms could be more prevalent. Some evidence may be found in climatological data analysed by Grbec et al. (2007); they found the secondary climatological minimum in surface salinity in July at regularly-surveyed Stončica station (equivalent to station CT1; the primary minimum is in May, when the east Adriatic rivers have maximum discharges), which might be related to west Adriatic waters and a climatologically strong WAC (Zore, 1956). Also, further evidence of the prevalence of this mechanism may be found in late September 2006, again on the CT transect (Fig. 19), as less saline waters (but not as fresh as in late June 2006) were found within the transect and the surface chl distribution (Fig. 20) again suggested the WAC and the Palagruža Sill as the source of these waters. Moreover, evidence exists for eastward excursions of west Adriatic coastal waters during other times. In March 2006, three of the six surface drifters (44925, 44927, and 44930) released near the predicted NCOM hyperbolic points really travelled towards the Croatian coast to the northeast (Haza et al., 2007). Chl satellite images from 5 May 2002 show a cross-basin filament similar to the one shown in Fig. 9 for 24 June 2006. A thorough review of possible past occurrences is beyond the scope of the present study, but it seems that June 2006 is not likely unique and the prevalence of these events is an interesting topic for future research.

Similar eddies can also grow at the Monte Conero promontory south of Ancona, which is substantially smaller than the Gargano Peninsula. Once generated, these eddies and associated filaments can often be observed moving towards the eastern shore, reaching the centre of the Adriatic. Such motion is visible during June 2006; a large cyclonic filament appeared downstream of Monte Conero at the same time as the one observed near the Palagruža Sill cell during the wind relaxation period (see the full image on http://gos.ifa.rm.cnr.it, real-time images, the Adriatic Sea, 24 June). However, offshore flow from Monte Conero can also be due to a direct response to storm wind shear (Fig. 14 of Martin et al., 2006). This again emphasizes the possibility of various conditions generating offshore transport of western coastal waters, and reveals a direction for future investigations.

The role of these offshore transport “bursts” of west Adriatic water towards the east Adriatic could have a large impact on the biogeochemical cycle as a whole. As WAC waters are rich with nutrients, especially with nitrogen-based compounds, their transport to the oligotrophic east Adriatic waters may enlarge and trigger primary production in this area, which is typically characterized by nitrogen-limited conditions (Šolić et al., 2008). Nevertheless, this may not be the case during summertime low-river-runoff periods (Grilli et al., 2005). Also, the WAC carries a high sediment load and its offshore transport could result in larger sedimentation rates over the Palagruža Sill and eastern waters. Finally, mixing of low-density, west Adriatic waters and saline Levantine Intermediate Water could modify the EAC thermohaline characteristics and inflow rates affecting the along-Adriatic water mass exchange.

This study also emphasizes the importance of monitoring and forecasting mesoscale, topographically-driven dynamics for accurate characterization of the Adriatic Sea circulation. An important issue is the use of high-resolution mesoscale atmospheric models (ALADIN in our case) for the description of the atmosphere–ocean interaction. These models predict the local wind dynamics much better than the global models, which do not have well-resolved orography (e.g., Belušić and Bencetić Klaić, 2006; Pasarić et al., 2007). Also, for local coastal prediction, accurate mesoscale information is required in the boundary conditions to account for eddy propagation into the region from the far field. The use of remote-sensing images ahead of routine monitoring cruises may redirect observational ocean efforts,

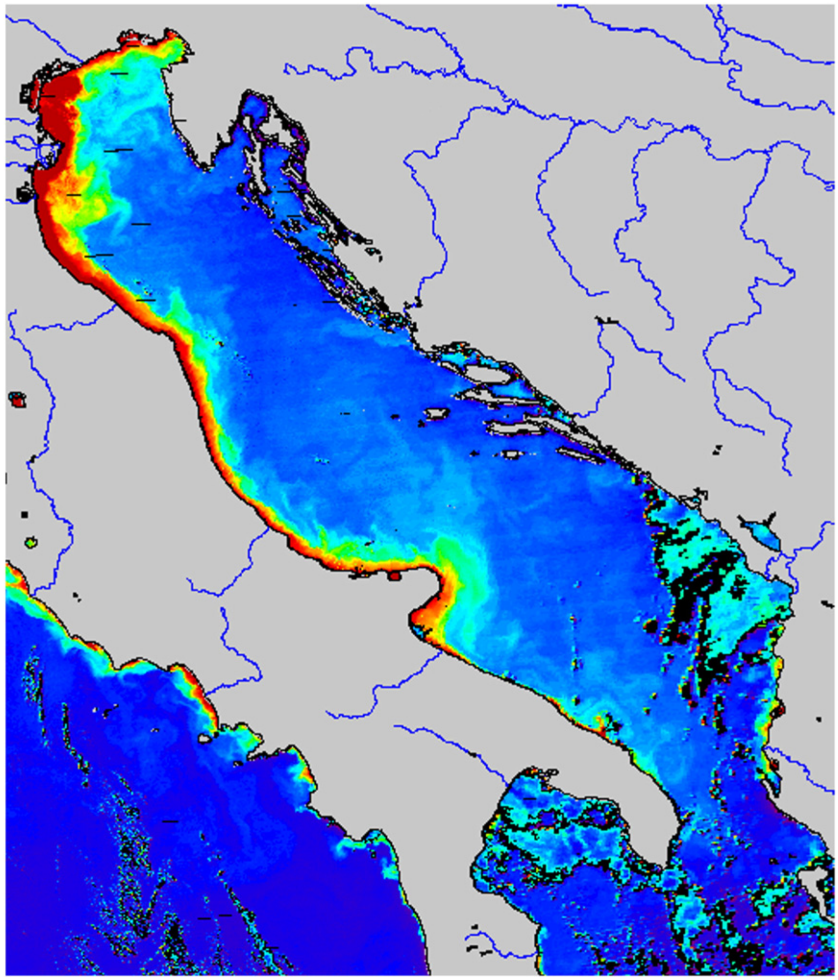

Fig. 20. Chlorophyll a image of the Adriatic Sea, taken on 28 September 2006.

especially when investigating mesoscale ocean dynamics, eddies, and freshwater filaments.

Finally, this study points to the importance of hyperbolic flow points for anomalous cross-basin exchange events in systems with inflowing and outflowing boundary currents. Further investigation of two-sided boundary flows over sills and application to other systems is warranted.

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