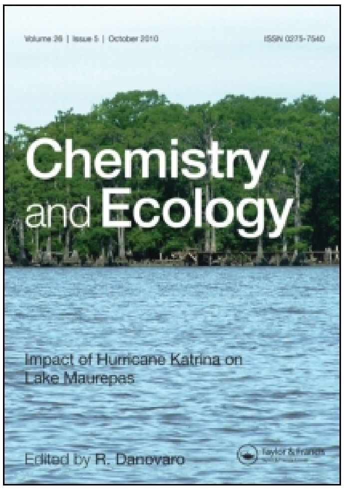

Chemistry and Ecology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713455114

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To cite this Article Raffa, F. and Hopkins, T. S.(2004) 'Circulation and water mass structure over a narrow shelf, Augusta Gulf (sicily)', Chemistry and Ecology, 20: 3, 249 — 266
To link to this Article: DOI: 10.1080/02757540410001699857
URL: http://dx.doi.org/10.1080/02757540410001699857

Chemistry and Ecology
June 2004, Vol. 20 (Supplement 1), pp. S249–S266

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CIRCULATION AND WATER MASS STRUCTURE OVER A NARROW SHELF, AUGUSTA GULF (SICILY)

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The circulation and water-mass structure in the Gulf of Augusta are described with respect to their influence on the deep-chlorophyll maximum (DCM). The Messina Mixed Water (MMW) mass is created in the Strait of Messina and transported southward along the shelf break. The MMW is defined by a lower salinity and higher nutrient values, and it defines the pynocline and DCM environment. It is demonstrated that variations in the direction of this current generate convergences or divergences over the shelf and result in a complex circulation. For the case of an offshelf veering of the current, a divergence is generated over the shelf that creates a circulation pattern in which the advection of MMW onshore, and therefore biological production, is favoured. The shear in the pycnocline also has an influence on the biology such that particles sinking through the pycnocline are exposed to changes in horizontal speed and direction.

Keywords: Water mass; Circulation; Mediterranean; Pycnocline; Messina Mixed Water

1 INTRODUCTION

The Gulf of Augusta is situated about midway along the eastern coast of Sicily (Fig. 1). The area has attracted attention due to the intense petrochemical industry located near the city of Augusta and its port. Some observations have indicated that the industrial outputs may be affecting the coastal waters (Decembrini *et al.*, 1993). On a larger scale, historical and anecdotal evidence studies indicate that the biological production of the shelf waters along the eastern Sicilian shelf is influenced by an enriched water mass formed in the Messina Strait (Cescon *et al.*, 1997; Decembrini *et al.*, 1998; Azzaro *et al.*, 2000), which will be referred to as the Messina Mixed Water (MMW). These facts inspired the first oceanographic survey under a new institutional research program entitled ‘Systems approach to Mediterranean Coastal Areas’. Thus, a preliminary cruise was conducted in the Gulf of Augusta during October 2001 for which the technical details are reported in Decembrini (2003) and Budillon (2003). The primary objectives were: to describe the circulation and water-mass structure in the Gulf (present work), to investigate the time-dependent variability of the DCM at its intersection with the shelf bathymetry, to describe the microbial processes within the environment of the DCM, and to investigate the geomorphology and sediments of the shelf and upper

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ISSN 0275-7540 print; ISSN 1029-0370 online
DOI: 10.1080/02757540410001699857

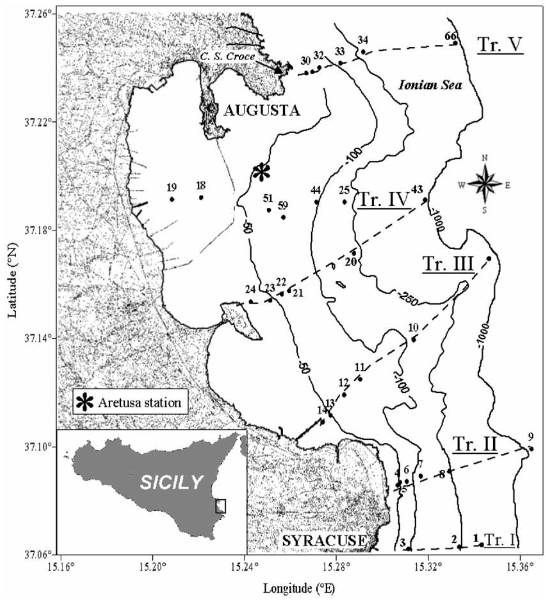

FIGURE 1 Gulf of Augusta: location, bathymetry and location of hydrographic stations during cruise SAMCA of the R/V *Thetys*, October 2001. Most of the stations of the Aretusa time-series station (asterisk) were too close together to be included.

slope. The last three objectives are reported separately in Decembrini *et al.* (2004) and Zaccone *et al.* (2004). All these works were intended to be mutually supportive in the context of describing the ecosystem. The focus of this work is to describe the source and distribution of the nutrient-enriched MMW over the shelf as its presence and its circulation influence the variability and sustenance of the DCM.

1.1 Background

The Gulf of Augusta is located along the eastern coast of Sicily and is formed by the concave coastline between the two Capes of S. Croce and Syracuse both prominent along the eastern Sicilian Coast (Fig. 1) at latitudes 37° 24′ N and 37° 03′ N, respectively, and a longitude of ~15° 28′ E. The shelf is quite narrow, with the shelf break of ~100 m located <4 km offshore from the Capes and <8 km offshore from the central area. It is terraced by an escarpment at ~25–45 m and exhibits some elevations associated with the slope ridge that extend north-eastward from the Capes. The upper slope is very steep, dropping to 1000 m within ~7 km and extending past 2000 m to the Ionian basin interior. Thus, coastal waters are quite exposed to the open Ionian except for those within the Port of Augusta, which are nearly enclosed by artificial barriers.

The Ionian Surface Water (ISW) is influenced by the inputs form the Adriatic via the northern Ionian, from the Atlantic inflow via the Strait of Sicily, from the Tyrrhenian via the Strait of Messina, and from the larger-scale Ionian circulation exchanging with the Levantine Basin (cf. Hopkins, 1978; Lermusiaux and Robinson, 2001; Manca *et al.*, 2002). The ISW is also strongly influenced by local atmospheric exchange, which is most evident in a seasonal thermal signal. The seasonal signal in salinity is damped due to the compensatory effects of advective freshening and net evaporation. Consequently, the surface distribution is more evident in temperature than in salinity. Generally, the subsurface water structure is dominated by the presence of the Ionian Intermediate Water (IIW), which is produced locally during winter convection, and the Levantine Intermediate Water (LIW), which is produced in the Levantine Basin.

Hydrological aspects of the eastern Sicilian shelf region have been described by Grancini and Magazzù (1973). Waters with salinities $S \sim 38.3-38.4$ are found in the Messina Strait at locations where strong vertical mixing occurs between the surface Tyrrhenian and subsurface Ionian waters (Azzaro *et al.*, 1995). The kinetic energy for the mixing derives mostly from the strong tidal currents (up to 200 cm s^{-1}), which are at a maximum in the region of the sill where the Strait's cross-sectional area is at a minimum (Hopkins *et al.*, 1984; Mosetti, 1995). The effect of internal and bottom friction on these large oscillating currents is sufficient to break down the vertical stratification and mix the surface Tyrrhenian and subsurface Ionian waters, producing another water mass characterized by a salinity minimum ($S \sim 38.45$). For the purposes of this paper, we define this water mass as the Messina Mixed Water (MMW), *i.e.* to indicate its geographic location and means of formation. It has been observed to flow consistently southward along the eastern Sicilian coast with velocities of ~20–40 cm s^{-1} (Böhm *et al.*, 1987; Adragna and Salusti, 1990). Thus, the generation of the MMW must have some tidal variability superimposed, but the extent to which this variability is translated along shore is unknown. The formation of the current may be analogous to that of coastal-river plumes in which the variable effluent accumulates until a sufficient hydraulic head is generated to feed a geostrophic boundary current locally (cf. Hopkins, 2002); but it must accumulate on the western side sufficiently in order to continuously feed a core of this water type.

2 METHODS

2.1 Observations

The SAMCA cruise was conducted with the R/V *Thetys* from 6 to 11 October 2001 in the Gulf of Augusta. A conductivity temperature and depth (CTD) probe Sea-Bird 911 equipped with a Turner Scufa fluorometer and a polarographic electrode were used to record conductivity, temperature, pressure, fluorescence and oxygen content for 66 hydrographic stations. The NATO SACLANT Centre, La Spezia, Italy, conducted both pre- and post-cruise calibrations and, in addition, salinity water samples were drawn for laboratory control using a Guildline Autosal. CTD casts were taken to within ~1 m of the bottom using a Tritech altimeter for depth control. The wind, air temperature and pressure were measured at each hydrographic station. The hydrographic survey (6–9 October) primarily involved a sequence of cross-shelf transects to determine the shelf circulation and water mass structure, and a set of stations (9–11 October) in the vicinity of the Aretusa time-series station, to determine the surrounding advective transport field. For clarity, most of the Aretusa stations (35–65) are not shown in Fig. 1. Because of the vessel limitations, the sampling was limited to daylight hours and resulted in some loss of spatial synopticity space between transects and in time during the nights of the time series. Throughout the cruise, the winds were light (<5 m s^{-1}) but with some diurnal variability.

2.2 Steric-Height Method

The circulation, transports, and adjusted sea level (ASL) over the Gulf shelf and for the time series station Aretusa, were computed with the steric-height method (Hopkins, 1996).

The ASL is the value of the steric height at $z = 0$ and represents the difference in total pressure between the observed station and a water column filled with a reference density. When the difference between any two stations is taken, the integrated reference density vanishes, and the resulting steric-height difference (cm) represents the total horizontal pressure difference between the two stations. In practice, the steric heights of water columns are computed by integrating the density from the surface to the bottom and then along bathymetric fall lines (to insure isostacy) to the deepest common point. The surface steric-height gradients are then available for conversion to geostrophic flow and calculation of transports normal to the transect. The accuracy of the method requires sampling along bathymetric fall lines, sampling to within a few meters of the bottom, and maximum synopticity in sampling. The reference point was taken to the 4000 m contour on the fall line from the Gulf of Augusta, and the reference density was taken to be 1.02905 g cm^{-3}. An advantage of integrating to the deep basin reference is that local ASL values can be compared with those from other Ionian locations

Because the *Thetys* could only sample with the CTD winch to 1000 m where the fall lines down the slope were not yet convergent, we used historical data from the POEM data sets (*e.g.*, POEM Group, 1992; Malanotte Rizzoli *et al.*, 1997, 1999) to enable density integrations to a common point at 4000 m in the Western Ionian (coordinates: 35° 35′ N, 17° 15′ E). Assuming the historical data are good, this additional integration improves the accuracy and utility of the method over the assumption that the pressure is isobaric along the 1000 m isobath. For example, the steric-height difference between the northern St. 66 and southern St. 9 was −2.68 cm relative to 1000 m. Using this value would have been equivalent to assuming that there were no compensating pressure gradients in the waters between 1000 and 4000 m. Instead, using the historical data set, the steric height difference was −2.51 cm relative to 4000 m, and thus we improved the estimate by 0.17 cm. In any case, an error in density integration along the bottom, which occurs deeper than two stations along a fall line, would not cause an error in the velocity or transport between them. An error below the deepest common point between two transects would likewise not create an error for the diabathic flow between the transects. The variability in the ASL at Aretusa station gives an idea of the steric height variability occurring at sub-diurnal scales without any possible error due to integration along the bottom, *e.g.*, the mean ALS was 172.32 ± 0.422 cm.

Since geostrophic flow follows bottom contours and since the shoreline and bottom contours are often not parallel, we use a terminology based on the local bathymetry, such that the parabath represents the direction tangential to the bathymetry and the diabath the direction normal to the bathymetry. Thus, the geostrophic flow follows the parabath. At the time of sampling, the detailed bathymetry was not available (a cruise objective), and the transects were designed to follow approximately the fall lines off the shelf and slope and were neither oriented directly offshore nor exactly in line. Whereas the velocities between stations are normal to the line between the stations, the transports integrated along the transect are computed using only the velocity component normal to the linear fit of the stations.

3 RESULTS

3.1 Messina Mixed Water

The composite temperature–salinity (T–S) diagram for this study (Fig. 2) shows an S-shaped water-mass structure that exhibits a broad salinity minimum at $S \sim 38.45$ within the potential temperature range $\theta \sim 17$–21 °C and within the depth range of ~25–50 m. This water type characterizes the MMW. To illustrate how the coastal-water structure differs with the

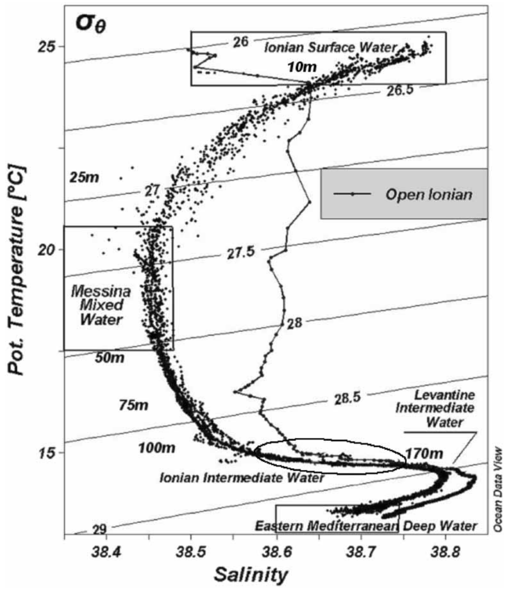

FIGURE 2 *T–S* diagram for the stations in the Gulf of Augusta and of a single station for comparison taken in October 2000 in the deep Ionian ~100 km to the southeast. The approximate locations of water masses mentioned in the text are indicated. A station (KM3: 36° 30′ N, 15° 50′ E) from October 2000 is superimposed on the plot for comparison (data from De Domenico *et al.*, 2003).

deep waters further offshore, we have superimposed a cast, St. KM3, taken in October 2000 at ~100 km to the southeast at ~3400 m depth. The profiles are very different from the surface through to the intermediate depths (~150 m). The difference in the surface water type is not relevant to the discussion and is probably due to a different large-scale circulation that exposed it to a fresher water mass, such as the North Atlantic Water from the Sicily Straits. For the subsurface waters, the impact of the MMW is clear. The shape of the T–S curve for the Augusta stations is indicative of contemporaneous mixing occurring above and below the core water mass. We assume that this mixing occurred during the transit from the Strait to the Gulf of Augusta, but obviously we cannot reconstruct its mixing history, since both the ISW and IIW could have varied in space and time. In this case, the local ISW water type was $\theta \sim 24.5$, $S \sim 38.7$, and the water type of the upper portion of IIW underneath was approximately $\theta \sim 14.7$, $S \sim 38.6$.

The presence of the MMW in the coastal water columns generates several consequences important to our description. First, as is evident in Figure 2, the T–S slope is most normal to the isopycnals within the salinity minimum. Thus, the MMW and the pycnocline are coincident in the vertical. Second, the MMW presence complicates the offshore, horizontal density gradients: that is, the vertical mixing makes the coastal waters above the MMW cooler and fresher, and the waters below it warmer and fresher than those at a similar depths offshore without any MMW. Above the MMW, these differences create a compensating effect on the horizontal density gradient and therefore minimize the baroclinic shear. In contrast, below the MMW, the thermal and haline effects due to the mixing tend to make the inshore waters less dense and therefore increase the horizontal density gradient. This generates a northward shear for the waters under the salinity minimum. Finally, the presence of less dense water underneath the MMW (relative to those offshore) acts to reduce the vertically integrated density making the adjusted sea levels greater along the coastal margin where the MMW is present.

Thus, along the coast where the MMW exists, the upper-layer horizontal pressure-gradient force is eastward and southward (as the MMW diminishes), a necessary condition for driving a geostrophic southward flow along the Sicilian margin. From our limited data set, this flow is most evident and consistent over the upper slope and shelf break, whereas it is more variable over the shelf, as can be seen in the ASL distribution (Fig. 4c). The fact that the stations of Transects II and III were taken on the same day indicates that this cannot be dismissed totally as a lack of synopticity. Our hypothesis here is that even a slight variability in the deep slope boundary current against the coastal shelf/slope bathymetry creates convergences and divergences over the narrow shelf (after Hopkins, 1982). The three salient bathymetric features controlling this process are the very steep upper slope, the Syracuse Ridge coincident with Transect III in Figure 1, and the escarpment between the $\sim$25–50 m isobaths (Budillon *et al.*, 2003).

The mixing processes that make the MMW less dense also produce a water mass richer in nutrients than the ambient Ionian waters at the same depth to the east. This enrichment contributes to the greater organic production observed along the Sicilian coast (Decembrini *et al.*, 1993). However, as the MMW moves southward, it loses nutrients progressively both due to biological uptake within the euphotic zone and through turbulent mixing with the surface waters. In the coastal region of the Gulf of Augusta, our observations showed the depth range of the MMW to be coincident with that occupied by the deep chlorophyll maximum (DCM); in fact, the upper portion of the chlorophyll peak corresponds with the salinity minimum regardless of the depth of light penetration (Decembrini *et al.*, 2004).

While the MMW was present in all of the hydrographic stations, the minimum salinity, its depth and the thickness of the layer all varied in space. The isohaline of 38.5 encloses a layer with a thickness varying between 30 and 75 m, being thinner at its coastal and its offshore limits and having a maximum approximately over the upper slope. An example of the water structure for the transect IV is shown in Figure 3, which illustrates well the changes in vertical structure over the coastal zone relative to that offshore caused by the presence of the MMW. Also illustrated is the thickening of the MMW water type over the shelf break and upper slope, and its thinning in the nearshore portion of the shelf.

The surface water properties were quite homogeneous, with the surface temperature varying between 23.9 and 25.2 °C and the salinity between 38.6 and 38.8 (Fig. 4a and b). Even so, an important signal emerges in the zone marked by lower temperatures and salinities, which to some degree could be an artefact of the interpolation software, but which also corresponds with the onshore flow portion of the sea-level trough evident in Figs. 4a–c. We note that the waters of the southern transect appeared to be of a different origin, with fresher salinities than those within the Gulf of Augusta, which we attribute to the influence of freshwater effluents from the Syracuse harbour.

3.2 Circulation

The adjusted sea level values (Fig. 4c) varied from $\sim$168 to $\sim$174 cm over the observed area. The offshelf comparison from the preceding year (St. KM3 in Fig. 2) had an ASL of 166 cm. Consequently, the variability over the shelf at a length scale of 10 km was of the same order as that between the shelf and a point over the Ionian deep basin at 100 km offshore. The ASL contours intersect the coast more steeply than might be expected, for several reasons: the lack of data at the coast (the surface temperatures and salinities were taken to be equal to that of the shallowest station), the non-synopticity of sampling and possible non-geostrophic effects nearshore. The ASL distribution is dominated by ridges and troughs in the alongshore, with the two main features being a high-pressure area proceeding offshore from the Port of Augusta and a low-pressure area along the bathymetric ridge. In terms of surface circulation,

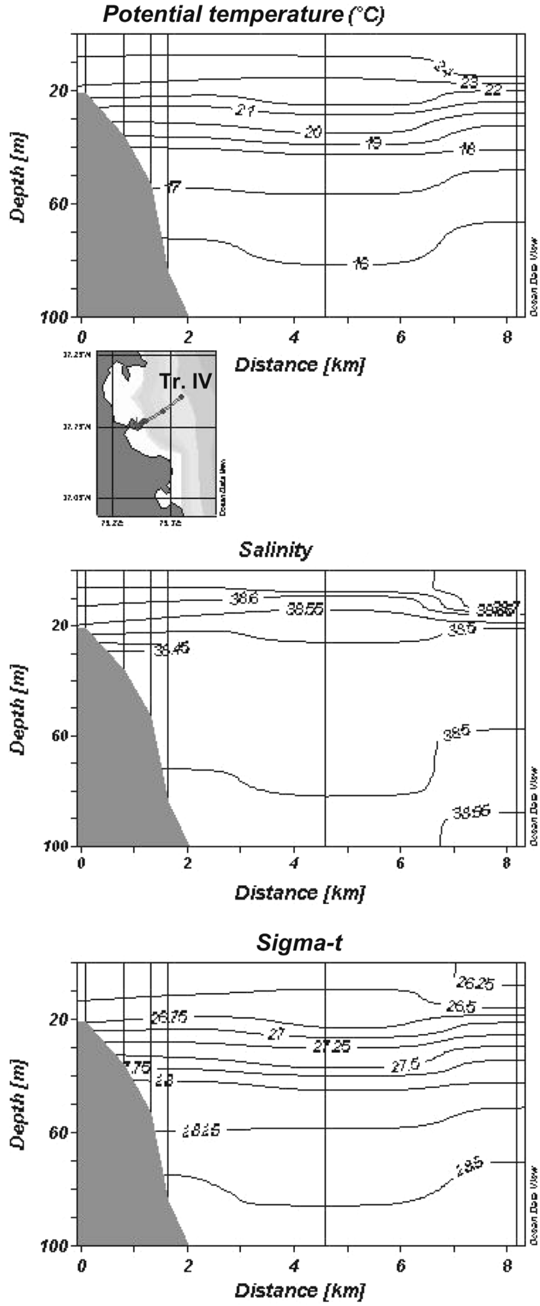

FIGURE 3 Temperature, salinity and density cross-sectional contour plots from Transect IV in the Gulf of Augusta (see Fig. 1).

this implies offshore flow between Transects V and IV, onshore between Transects IV and III, and offshore between Transects III and II. Generally, the higher ASL values are associated with convergent (downwelling) movements, and the lower values with divergent (upwelling) movements. Exceptions to this are the values inside the Port, where the circulation is restricted, and water temperatures were uniformly higher with depth. We caution that

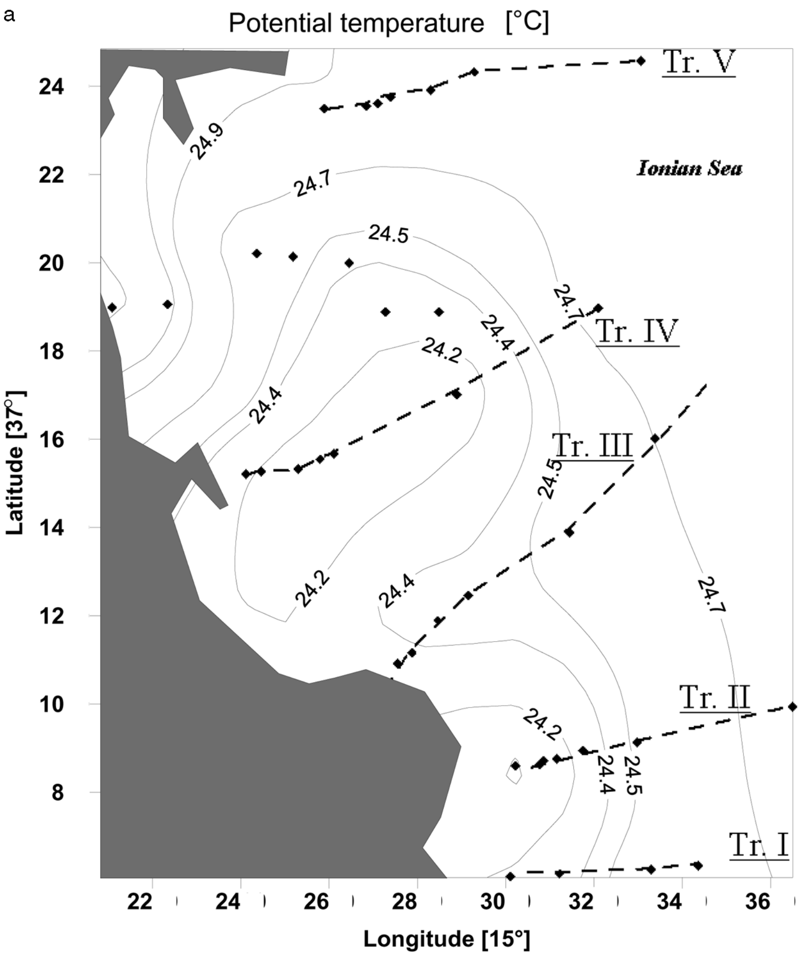

FIGURE 4 Surface distribution of: (a) temperature (°C), (b) salinity and (c) adjusted sea level (cm) from the data set, excluding the time-series data.

because strong baroclinic pressure gradients exist, the ASL contours should not be interpreted as representing transport streamlines.

The adjusted sea levels and the geostrophic velocity components normal to the transect are shown (Fig. 5a–c) for the three transects at the north and south ends and middle of the Gulf. We note that the seaward station (St. 66) of Transect V was taken 3 d later than the shelf stations. At Cape S. Croce, the shelf is very narrow, and the southward inflow of MMW is concentrated over the upper slope at speeds exceeding 50 cm s^{-1}. Transect IV depicts the alongshore flow within the centre of the Gulf. In this case, the ASL has a maximum approximately over the shelf break, which divides the shelf flow regime between a strongly barotropic southward flow over the upper slope, a weak northward barotropic flow over the outer shelf and a southward over mid-shelf with a strong baroclinic shear inflection within the pycnocline. Several aspects concerning the transport of the MMW are clear by comparing the distributions of flow and salinity (Fig. 3). The MMW extends to ~6.5 km offshore, and therefore a portion is being transported along the shelf break and upper slope, another portion is being recycled to the north over the outershelf, and another fresher portion ($S < 38.45$) is flowing south under the pycnocline over the inner shelf. The surface portion of the inner shelf

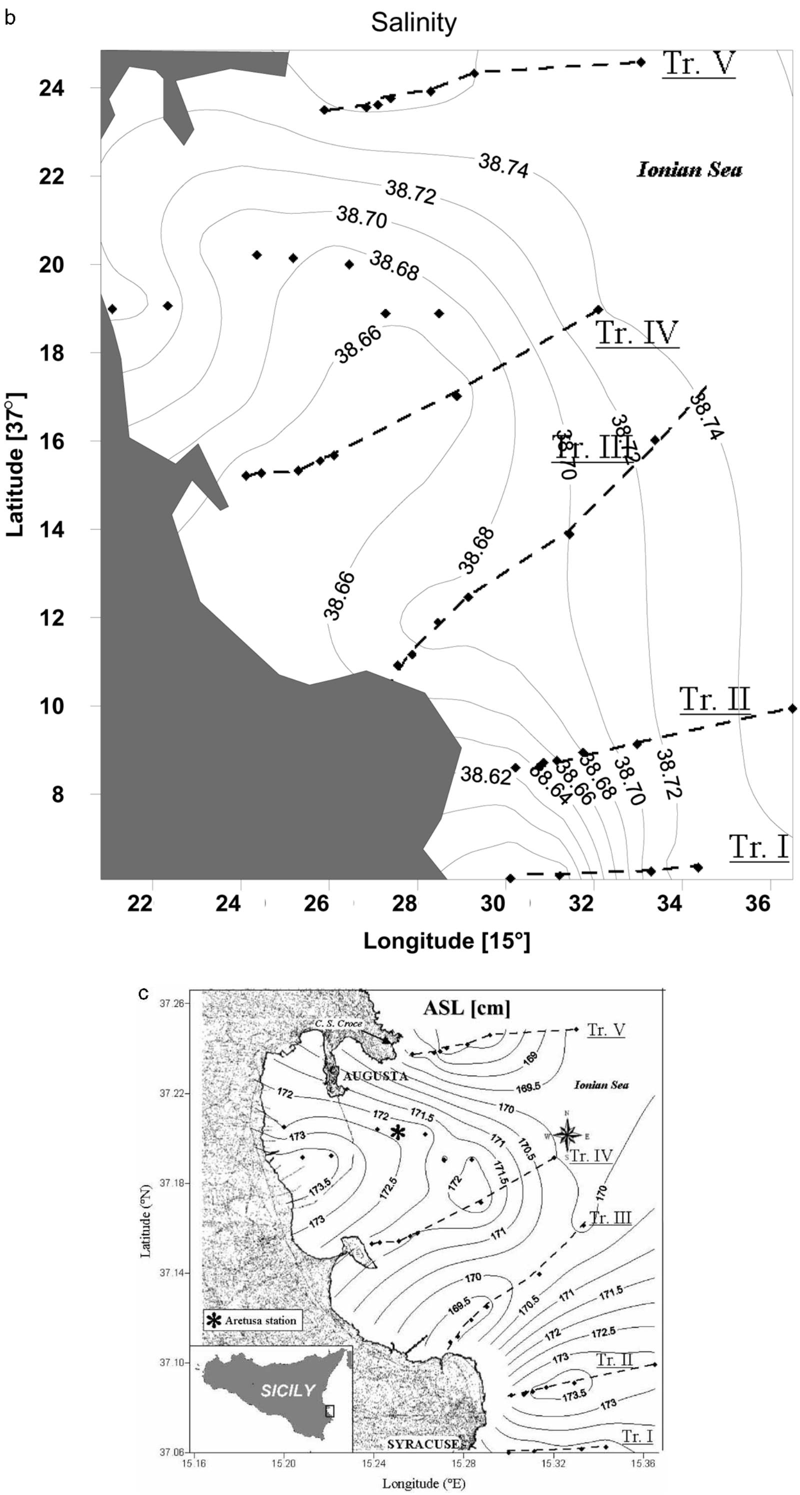

FIGURE 4 Continued.

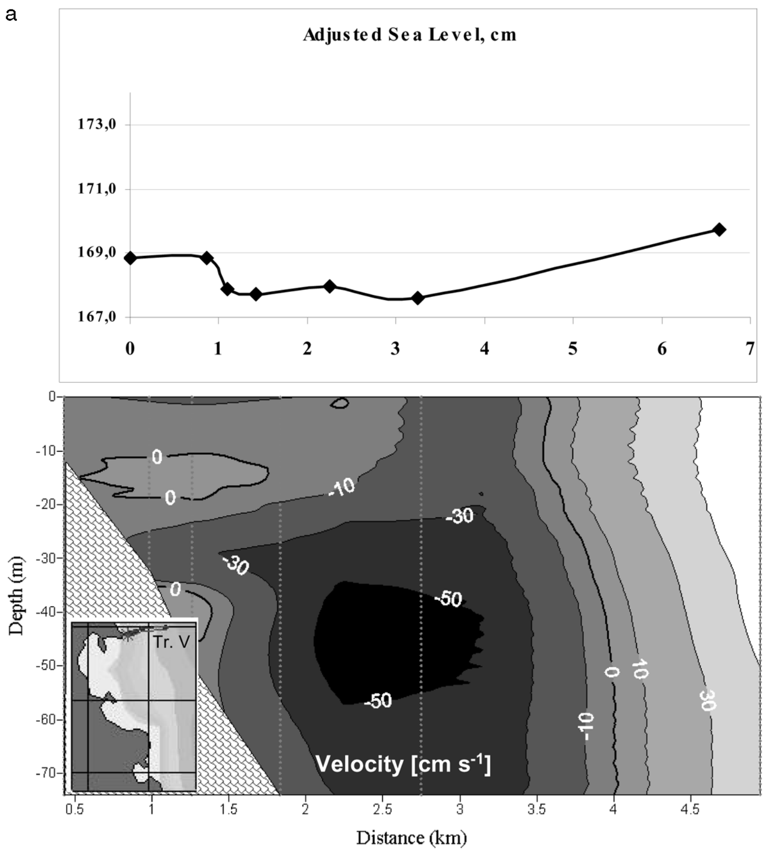

FIGURE 5 Distributions of the adjusted sea level (cm) and of the geostrophic velocity component (cm s^{-1}) normal to the the transect, with positive values indicating a northward direction: (a) for Transect V; (b) for Transect IV; (c) for Transect II. The ASL are calculated at every station, whereas the flow is calculated between every station.

flow is not MMW, and the inflection in the shear is due to a change in isopycnal slope through the pycnocline, discernible in the sigma-t cross-section. Transect II represents the outflow from the Gulf. Figure 5c portrays a modified situation like that found in Transect II, presumably in part due to the intervening bathymetric ridge. The flow over the shelf beak and upper slope has a strong baroclinic shear southward, such that the surface flow is north-, and the flow in the MMW layer is southward. However, the MMW speeds at the depth of the MMW are lower than those of Transects IV and V. Over the narrow shelf, the flow structure is reversed relative to that offshelf with a southward surface flow and northward pycnocline flow.

Because of the limitations for taking stations deep, only three stations were taken along the 1000 m isobath, Sts. 66, 43, 9 north to south, respectively. Consequently, the upper slope region, which turned out to be important to the circulation dynamics of such a narrow shelf, was insufficiently sampled, particularly regarding the role played by the Syracuse Ridge in altering the southward transport of the MMW. The two prominent features of the water-property structure of Figure 6 are a consistently thick layer of the MMW ($S < 38.5$) and a pronounced lowering of the MMW to the south apparently due to a thickening of the surface layer and associated lowering of the pycnocline. This aspect is reflected in the values of the ASL, which decrease from St. 66 to 43 by 0.41 cm and then increase from

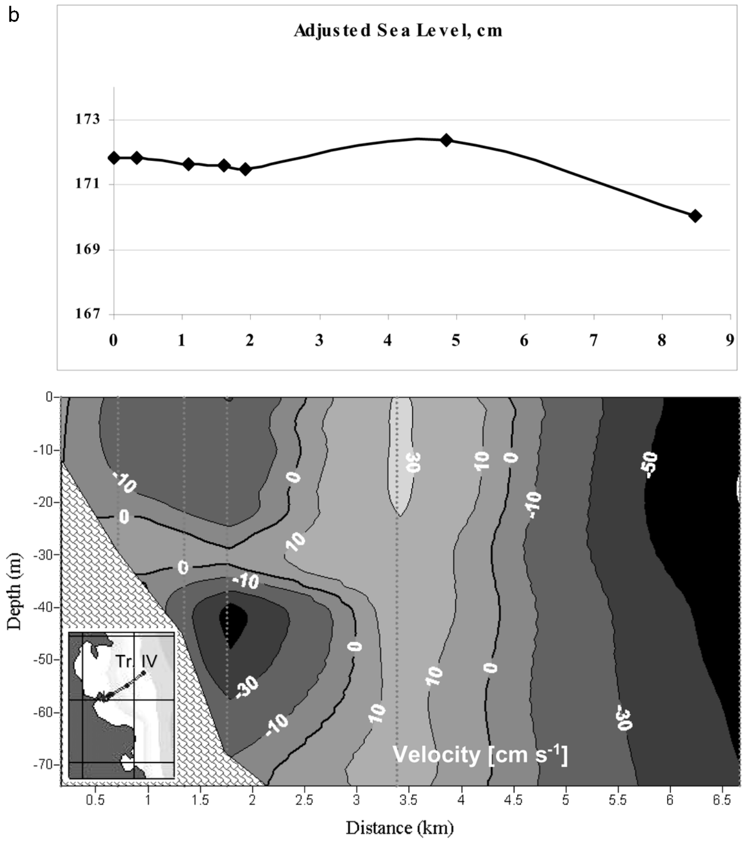

FIGURE 5 Continued.

Sts. 43 to St. 9 by 2.92 cm. The slight southward decrease in the ASL is expected to be compatible with the southward slope current (Hopkins, 1982). The sudden southward increase is not easily explained other than the fact that it is due to a greater amount of less dense water in the surface layer. Although we do not have a sufficient number of stations to define the flow-field over the slope, we do have some additional evidence to help explain this situation.

First, the parabathic flow over the slope just north of the ridge at Transect IV is strongly southward above the shelf break (as in Fig. 5) and decreasingly southward to a depth of ~400 m, well below the top of the ridge directly to the south (Fig. 1). Second, the curvature of the 250 m contour indicative of the upper slope is not so sharp as to prevent such a deep current from geostrophically turning offshore and returning onshore between transects IV and III, *i.e.* around the ridge topography. We expect that the offshore veering would generate a divergence over the shelf, and an onshore veering to the south would generate a shelf convergence. Third, at the 50 m contour, we had five stations from which to calculate the diabathic flow over the mid-shelf (Fig. 7). At 50 m, the diabathic flow is strongly sheared, but not reversing direction at the bottom. The parabathic transects at 80 m and 1000 m were also made with fewer stations, and both confirmed a similar pattern: that of onshelf north of the ridge and stronger offshelf flow south of the ridge. The offshelf flow would require some replacement flow to sustain it either from the north or from underneath, a requirement that is consistent with the results. Horizontal replacement is clearly available with the onshore flow occurring between Transects IV and III, (Figs. 4c and 7). Vertical

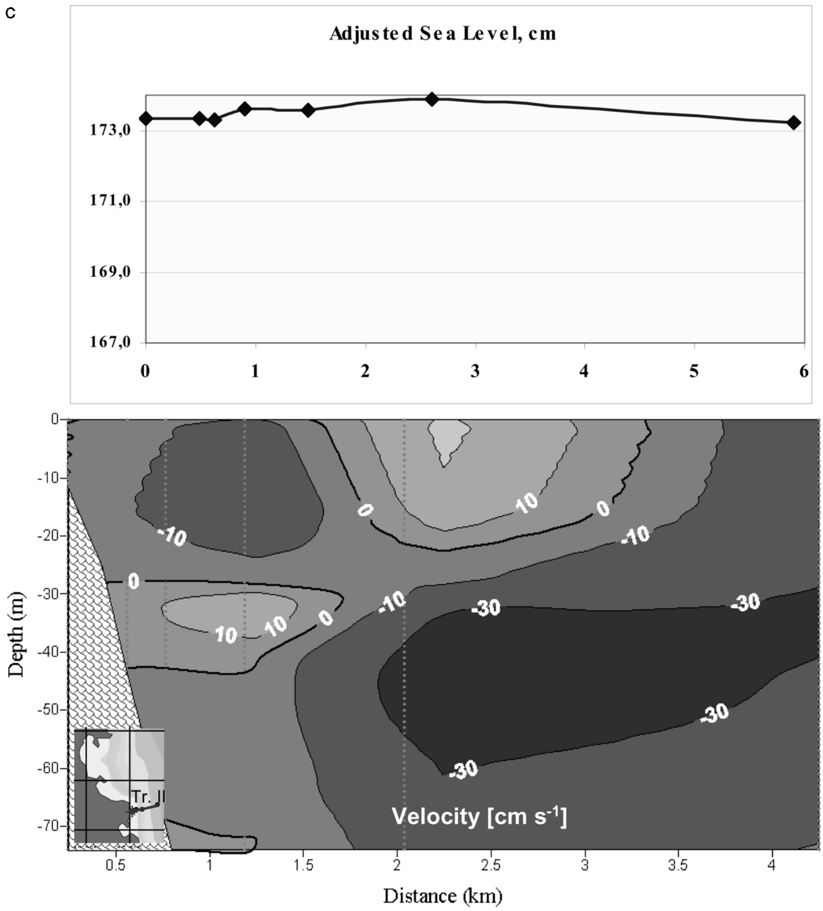

FIGURE 5 Continued.

replacement (upwelling) is also indicated in the 1000 m transect between Sts. 43 and 9 in that the diabathic velocity component reverses to onshore at 100 m, or below the shelf break, *i.e.* the layer above the shelf break is divergent with respect to the coast, and below the shelf break, it is convergent with respect to the slope.

3.3 Time-series Station

The Aretusa biological time series displayed considerable temporal variability (*e.g.*, changes in chlorophyll, nutrients, and phytoplankton composition, etc.) as described in Decembrini *et al.* (2004). Of interest for this work was the role of physical conditions in controlling these changes and their temporal variability. In particular, we attempted to measure the advective flux surrounding the Aretusa St. and to understand the smaller-scale resolution of the MMW distribution. The depth of the Aretusa station was chosen at the point where the DCM begins to intersect the bottom which placed it at $\sim$65 m roughly half way between the shallow escarpment and the shelf break. The centre biological station was sampled 14 times during the 48 h series. During the $\sim$4 h between these casts, additional stations were taken located in the diabath ($\Delta x \sim 3$ km) and in the parabath ($\Delta y \sim 10$ km).

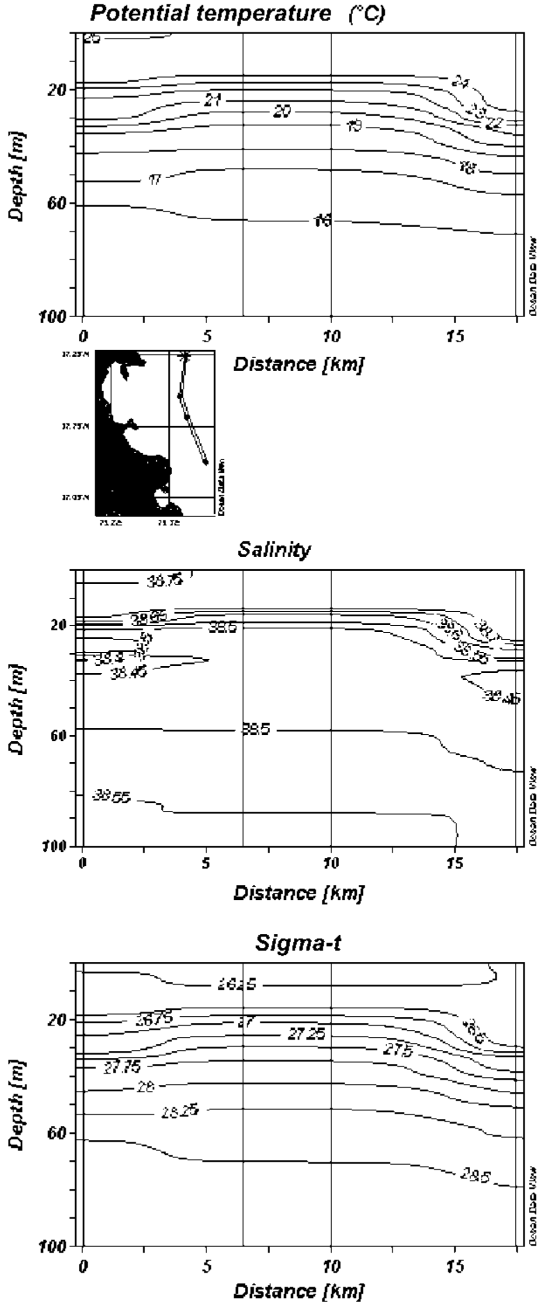

FIGURE 6 Vertical cross-section along 1000 m isobathic of temperature, salinity and density, in the upper 100 m layer. The 1000 m station at the end of Transect III is used in this figure but is a composite of two adjacent stations (*i.e.* weighted 67% in favour of St. 43).

As noted by Decembrini *et al.* (2004), the DCM layer was colocated with the pycnocline, and variations in the thickness of the pycnocline were correlated with higher chlorophyll values within the layer. The thickness was defined by 27.2–28.2 sigma units, and changes in thickness were due primarily to changes in the height of the pycnocline, or the depth of

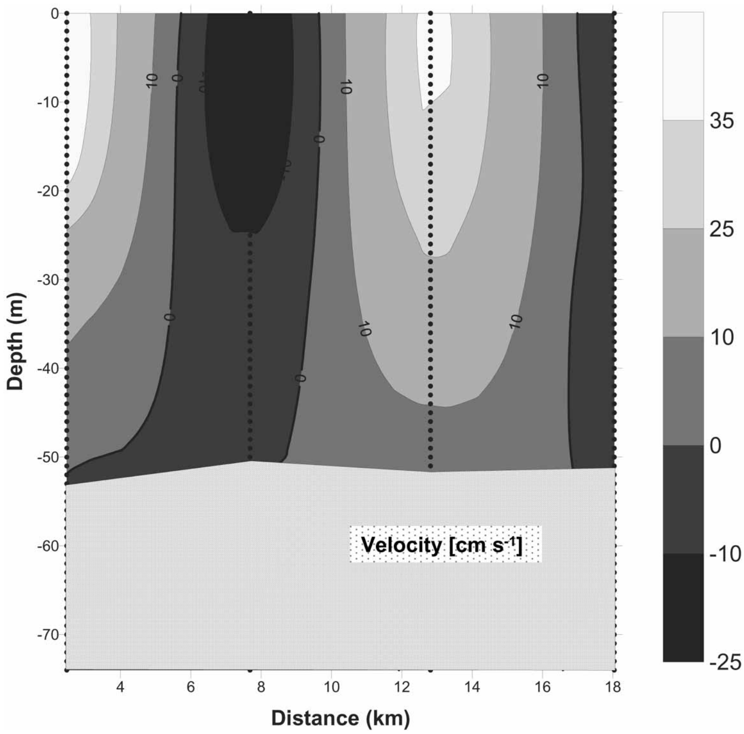

FIGURE 7 Geostrophic component (cm s^{-1}) normal to a transect along the 50 m contour and composed of Stations 32, 37, 22, 12 and 6. The view is to the east with positive values to the east. The vertical dotted lines indicate the mid-points between stations where the velocity components were calculated.

the 1.0272 isopycnal, as opposed to changes in the 1.0282 isopycnal. During the series, the thickness varied from 20 to 60 m, and the pycnocline from depths of 14 to 33 m. Thus, the chlorophyll was also correlated with the depth of the pycnocline, but importantly, this correlation had more to do with the concentration of nitrate than with the intensity of light associated with a shallower pycnocline. Because the presence of the MMW was determinate for the pycnocline, and because the MMW generally contained relatively high nutrients, the amount of MMW present controlled much of the variability in the phytoplankton biomass.

The time series was marked by three chlorophyll events, a maximum at 18.00 h, 9 October, and a minimum at 06.00 h and a secondary maximum at 18.00 h, both on 10 October. These maxima corresponded with maxima in the thickness and minima in the pycnocline depth, while the minimum of chlorophyll was associated with a minimum in the thickness and maximum in the pycnocline depth. While the above mechanism for explaining changes in the pycnoclinal thickness might help explain a greater amount of chlorophyll, *e.g.*, an isopycnal convergence might also create a convergence of phytoplankton, it would not necessarily explain higher dissolved nutrient concentrations. Higher nutrients would be better explained through advection. The most prominent nitrate enrichment occurred at 22.00 h, 9 October, and was coincident with a southern velocity maximum in the depth range of the DCM (Fig. 8b). Another shorter southern flow event occurred at the beginning of the secondary chlorophyll maximum and was associated with a weaker enrichment of nitrate. During the chlorophyll minimum, the flow was northward. Also, during the cases of southern flow, the amount of MMW was slightly greater, and its layer was thicker. These two conditions suggest that southern flow events act to replenish the reservoir of MMW in the shelf area of the Gulf.

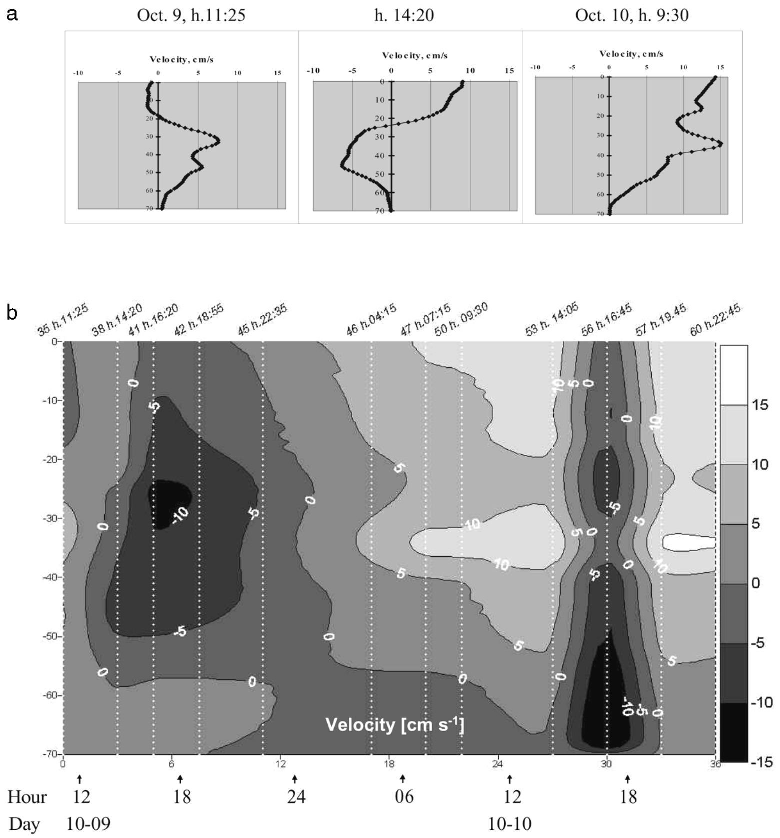

FIGURE 8 (a) Examples of velocity profiles (cm s^{-1}) from the time series at the Aretusa station. (b) Time series of the geostrophic velocity (cm s^{-1}), with positive values indicating northward velocities, at the Aretusa station.

The relatively small volume of such a narrow shelf makes the sea level over the shelf sensitive to diabathic variability in the transport of a slope boundary current (Hopkins, 1982). With the irregular bathymetry and coastline of the Gulf, for example, even small deviations in the mean transport along the upper slope can create a convergence or divergence against the coast. The three salient bathymetric features controlling this process are the very steep upper slope, the Syracuse Ridge coincident with Transect III in Fig. 1, and the escarpment between the ~25–50 m isobaths (cf. Budillon *et al.*, 2003).

Another observed characteristic of the pycnocline is the consistent inflection in the baroclinic shear occurring approximately at the depth of the S_{min}. Examples of velocity profiles are shown from the time series in Figure 8a. The inflection occurs because the isopycnals in the upper part of the pycnocline are not parallel with those in the lower part, as occurs when the pycnocline changes thickness in the horizontal. As a result, the baroclinic shear changes sign somewhere in the middle of the pycnocline, at which point the internal shear stress becomes zero and changes sign. These flow characteristics when occurring at important biological timescales (*e.g.*, diurnal or less) greatly complicate the trajectory of any given sinking particle within the pycnocline. The implication is that the population resident in the DCM has little coherence over time in the vertical.

Putting these facts together, we construct a simple model of how the diabathic modulations of the upper-slope current cause changes in the pycnocline characterisitics over the shelf. An onshore movement of the slope current generates a convergence over the shelf preferentially in the surface layer, which then causes the shelf sea-level to rise, increasingly towards the shore. The filling up of the surface layer causes several responses: a depression and thinning of the pycnocline, a downwelling with increased offshore flow in the pycnoline, the creation of a southward geostrophic flow in the surface and a northward countercurrent in the pycnocline. This situation was observed over the midshelf in Transect II (Fig. 5c) where a convergence situation at the shelf break was occurring. Over the midshelf, the surface flow was southward, and the pycnocline flow was northward. In the case of an offshore movement of the slope current that creates a shelf divergence over the shelf, the opposite response occurs: a sea-level lowering; an upwelling; a thickening and shoaling of the pycnocline; a northward flow at the surface; and an onshore, southward flow in the pycnocline. With respect to the nutrients, the 'shelf divergent' situation with an onshore southward movement in the pycnocline results in more shoreward advection of the MMW. Hence, the observed higher chlorophyll values are correlated with a thicker/shallower pycnocline, southward flow, and higher nutrient concentrations. This scenario is reversed for the 'shelf convergent' situation.

4 DISCUSSION AND CONCLUSIONS

In the shelf area of Augusta, the coastal deep-chlorophyll maximum (DCM) at ~30–60 m is located within the layer of the MMW mass. The MMW is transported southward by a coastal current along the eastern Sicilian margin by the large-scale pressure gradient that is sustained by the very presence of the MMW, which is less dense than the offshelf waters at the same depth. The axis of the current appears to be aligned just seaward of the shelf break or over the upper slope. The larger-scale continuity along the shelf of the MMW from its source in the Strait of Messina is not well known, although satellite imagery strongly points to a consistent distribution along the shelf (Böhm *et al.*, 1987). At the latitude of the Gulf of Augusta, it appears that the presence of the MMW on the shelf derives more from lateral spreading (onshelf) and upwelling from its core over the shelf break than from alongshore advection over the shelf from the north. If the latter were the case, the nutrients of the MMW, being trapped on the shelf for 120 km (~ a week), might be consumed before reaching Augusta.

The shelf circulation, as depicted by the ASL distribution and vertical cross sections, is subject to strong spatial variability on the order of the shelf width (<10 km) in the horizontal and in the order of 20 m in the vertical. Our observations were not extensive enough to differentiate how steady the distributions were. Temporal variability, at the Aretusa station, certainly was strong with flow reversals occurring on a diurnal timescale. However, while the spatial variability in the ASL was in the order of 5 cm, the variability in time (2 d) was in the order of 0.5 cm. Additional variability would be generated by wind forcing and runoff, neither of which was a major factor at the time of the present study.

Our conclusion is that most of the variability on the shelf derives from the slope boundary current due to the effects of its meanders along the steep bathymetry. This would include both steady changes in direction and free oscillations about the axis of the flow. The consequences of these meanders are indicated, for example, in the case of the Syracuse Ridge where the ASL contours and the velocity sections suggest an anticyclonic veering around the Ridge. Because of the small shelf volume, the shelf is particularly sensitive to these diabathic modulations of the slope boundary current. Based on our understanding of this effect, it is possible to suggest the mechanism to explain the pycnoclinal and nutrient variability observed in the DCM.

Essentially, the slope boundary current follows the isobaths of the upper slope (~100–500 m), which are not parallel with the isobaths on the shelf. As the current moves offshelf or onshelf, it creates divergences or convergences over the shelf. These set up two circulation patterns strongly influencing the pycnocline. For the case of a divergence, the shelf sea-level lowers, and a northward geostrophic surface flow develops. Because of strong shear, the flow in the pycnocline is directed onshore and southward. The DCM time-series data showed a strong correlation between chlorophyll and a thick, shallow pycnocline with a southward flow component. Hence, when divergence is established, the pycnocline becomes enriched with a fresher variety of the MWW from the slope current, and biomass and productivity in the DCM are increased. The opposite situation is created for the case of a shoreward convergence. In sum, the biological production in the DCM is controlled indirectly by the variability in the flow direction of the slope current.

The time series also revealed that the pycnoclinal environment was not in a steady state with respect to nutrient advection (above) and differential movements in the vertical. The strong baroclinic shear through the pycnocline was the result of horizontal variability of the pycnocline depth. The shear was also complicated by the fact that the vertical mixing processes above and below the salinity minimum caused the horizontal density gradient to change sign through the pycnocline and thus the velocity shear (Fig. 8a). This happens when both the thickness and depth of the pycnocline change significantly in space. Thus, the upper layers of the DCM are transported differently than the lower layers, *i.e.* at different speeds and different directions. This suggests that the DCM should not be considered as a single habitat in which the population in the lower portion constitutes mostly sinking organisms from the upper portion.

Acknowledgements

This research was supported by MURST, within the SAM project. The authors are grateful for the excellent services provided by the captain and crew of the R/V *Thetys* during the cruise and to Mr Michele Furnari for his technical assistance. Finally, they are grateful for the help on the cruise and discussions provided by their colleagues of the CNR Talassographic Institute of Messina.

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