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Seasonal variability of phytoplankton fluorescence in relation to the Straits of Messina (Sicily) tidal upwelling

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Abstract

In the Straits of Messina the large gradients of tidal displacements as well as the topographic constrictions determine the upwelling of deeper waters in the surface layer. This work describes the seasonal variability of surface distribution of phytoplankton biomass depending on upwelling phenomena. Temperature, salinity, nitrates and phytoplankton fluorescence were measured in 1994 and 1995 by continuous underway surface real-time measurements on board dedicated research boats. Each survey was performed following the dynamic phases of flooding and ebbing tides. Tidal currents are essentially southward during the high tide and northward during the low tide.

During the low water slack, large spatial gradients of physical-chemical and biological parameters were mainly found, while in the high water slack a diffused phytoplankton fluorescence was observed only in autumn, in coincidence of a seasonal thermocline. Salinity, nitrate and chlorophyll-*a* fluorescence data revealed a significant positive intercorrelation, whereas they are inversely correlated with temperature. Generally, during winter, the upwelling distribution was limited to narrow zones, while in summer it involved the middle of the Straits and southern zones. During spring in the southern zone of the Straits, maximum of chlorophyll-*a* fluorescence was detected (May 1995, 0.32 μg-Chla l^{-1}); in summer, when back and forth tidal movements become intense between the Tyrrhenian and the Ionian seas, values was everywhere lower.

The data set from continuous and repeatable acquisition has allowed the study of different time-space scales in the Straits of Messina, a very strong dynamic environment.

The Straits system can be compared to an "intermittent pump" which, during the different seasons, before enriched itself and then it provides nutrients to the surrounding basins.

1 Introduction

Hydrodynamical processes affect the spatial distribution and temporal development of phytoplankton biomass on the world's oceans and seas. Among the hydrological events the divergent current bring nutrients into the upper layer of the water column and modulate the chlorophyll-*a* distribution (Koike et al., 1982; Echevarría et al., 2002; Gomez et al., 2004; Kontoyiannis et al., 2005). Upwelling is a hydrological phenomenon with strong impact on marine ecosystem. In fact, upwelling systems are one of the most productive marine environments, and they are characterised by a "biological richness" in all levels of the trophic chain. Low water temperature is one of the indicators of upwelling, and sea-surface temperature difference between upwelling zone and the surrounding waters is a parameter for defining upwelling intensity (Levasseur et al., 1987; Lee et al., 1997; Tang et al., 2004; Reul et al., 2005). In these environments the phytoplankton growth is mainly regulated by the allochthon nutrients availability, mainly nitrates, which stimulate the new production (Ruiz et al., 2001; Chen et al., 2004).

1.1 Description of the study area

The Straits of Messina, at the centre of the Mediterranean Sea (Fig. 1a), is an area where strong currents determine fast changes of the oceanographic conditions. This system, separating the Italian peninsula from the Sicily island, is a natural connection between the Tyrrhenian in the north-west and the Ionian seas in the south-east (Fig. 1b). Morphologically, the Strait resembles a funnel-shaped geometry with north-south length of 40 km and west-east width ranges from 3 km, near the Tyrrhenian edge, to about 25 km, at the Ionian open boundary. The narrowest section (Ganzirri-Punta Pezzo), which coincides with the sill region, has a depth of ~80 m and divides the area into a northern and a southern sectors. The sea bottom slopes down very steeply to a depth of 1000 m at 19 km south the sill. The northern sector has a more gentle slope, and the 400 m isobath is located 15 km north of the sill toward the Tyrrhenian

Sea. The Straits exhibits strong tidal currents driven by both barotropic and baroclinic processes, due to strong bathymetric constraints exerted by the sill and coastal morphology (Hopkins et al., 1984; Farmer et al., 1995, 2002; Vargas-Yáñez et al., 2002). Large gradients of tidal displacements are encountered in the Straits of Messina, because the predominantly semi-diurnal tides north and south are approximately in phase opposition. Due to both phase opposition and topographic constrictions, the current velocities can attain values as high as 3.0 m s^{-1} in the sill region and are related to the position of the sun, phase of the moon, wind speed and direction and air pressure distribution (Vercelli, 1925; Defant, 1961). The surface waters turbulence in the Straits is mainly influenced by two types of circulation, a steady surface current and a turbulent mixing; both generate discontinuity of the thermo-haline distribution in the surface layer (Fig. 2). The steady current has a maximum speed of 2 m s^{-1} and prevalently N→S direction at the surface (0–30 m). Water turbulence is caused both by internal waves as well as tidal currents (Alpers and Salusti, 1983; Griffa et al., 1986; Di Sarra et al., 1987; Sapia and Salusti, 1987; Bignami and Salusti, 1990; Nicolò and Salusti, 1991; Alpers et al., 1996; Brandt et al., 1997, 1999). The former is caused by differences in water mass density of the two basins that mix up in the Straits. The latter is caused by the opposite tidal oscillation of the two basins (max 27 cm) with almost the same amplitude and period (about 6 1/4 h). These conditions leads to the upwelling of deeper water of Levantine Intermediate Water origin (Cortese and De Domenico, 1990), which are colder, more salty and nutrient-rich with respect to the Tyrrhenian Surface Waters (Atlantic Water origin). Harmonic oscillations of the current flowing from the Tyrrhenian Sea waters into the Ionian Sea (high tide current), and vice versa, from the Ionian water into the Tyrrhenian Sea (low tide current) are encountered, with a brief slack water interval (balancing flow).

Because of these particular environmental features the Straits have been subjected of studies by many researchers, in order to define forcing factors which determine its current regimen (cf., Vercelli, 1925; Vercelli and Picotti, 1926; Defant, 1940; Del Ricco, 1982; Tomasin and Tomasino, 1983; Böhm et al., 1987; Mosetti, 1988; Androsov et al., 1994, 2002). Many hydrobiological studies were conducted during last decades to describe the influence of high hydrodynamic on biological compartments (De Domenico, 1987; Bruni et al., 1988; Genovese et al., 1984; De Domenico et al., 1988; Magazzù et al., 1987, 1989, 1995; Guglielmo et al., 1995; Decembrini et al., 1998, 1999; Azzaro et al., 2004a, b).

1.2 Background and approaches

Most previous hydrological research has been conducted along the principal north-south axis using traditional oceanographic methods, that, due to the time limitations of sampling, have produced incomplete picture to characterise the horizontal extent and timing of the variability of the Straits of Messina. In the last years oceanographic investigations, using innovative strategies and techniques, have permitted to observe the upwelling of deeper waters, not only in restricted zones (sill), but in the wider areas of the system. However, these recent contributions to a better understanding of the system (Azzaro et al., 1995, 2000; Cescon et al., 1997), despite the develop of new approach study, prove to be limited in time. Conceivably, the concomitant ubiquitousness of water currents of different density in the Straits, not miscible between them and exalted from the tide forces, provokes natural vertical instability and rise of deeper waters (upwelling). An hydrological conventional 48-h survey (1-h sampling interval) in a fixed sill station is representative of the frequent upwelling occurrence, as indicated by the detected density inversion (see the example of Fig. 3). It is then assumed below that the timing of these overturns are highly coincident with the slack water interval when the rearrangement of the stable water column occurs as a result of an instability. Near the end of the advective unsteadiness and during the onset of water slack, natural vertical vorticity and turbulent tidal current occurs. Flow continuity requires an upward flow from deeper waters to the south to maintain the divergence. As the vorticity and the associated cyclonic meander dissipate, upwelling should cease. Subsequent tidal stream could sweep the cold anomaly out of the Straits, and cause the temperature to rise again, setting the stage for the next tidal event.

A data set from continuous and repeatable acquisition of information on water temperature and chlorophyll-*a* fluorescence has allowed the study of different time-space scales in the Straits of Messina. Discrete water samples (nutrients, chlorophyll-*a*, etc.) based on conventional methods obtained simultaneously during the surveys, combined with measurements based on new methodology (Azzaro et al., 2001) facilitated the interpretation and evaluation of the potential origins of the chlorophyll-*a* fluorescence. To date, however, a limited number of samples for biological measurements have been carried out, setting limits to the interpretation of these sets of data.

Due to high hydrodynamic system variability, the surface tracking was performed during the slack water, when the advective current can be considered negligible and the turbulent moving water is replaced by upwelling water. Not surprisingly, temperature records indicate that this is the onset of massive upwelling of cold water from depths. In fact, the more evident chemical-physical and biological characteristics were observed during the rise of deeper waters.

The aim of the present study was to assess the seasonal influence of the strong tidal variability on the surface phytoplankton distribution (estimated as chlorophyll-*a* fluorescence) in the water upwelling into the Straits of Messina system. The results covered an annual cycle with monthly frequencies, narrowly focused on providing a first-order description of the observed seasonal variability of the physico-chemical and biological parameters.

2 Materials and methods

Spatial and temporal distribution patterns of physico-chemical (temperature, salinity, and nutrient concentrations) and biological (chlorophyll-*a* measured by in situ fluorescence emission) parameters were monitored for 25 months in the frame of a local research project, and are presently available for the central-northern side of the Straits of Messina. Automatic real-time data were obtained by surface monthly tracking, from December 1993 to December 1995, in the area comprises between Capo Peloro (Sicily) at north and Reggio Calabria at south. This area was covered on board R/B "Delfo" by zig-zag cruise tracks between the Calabrian and Sicilian coasts, following the same propagating tidal wave direction as closely as possible. The location of the area and the track followed by the boat in each survey is displayed in Fig. 1b. It is well known that the maximum intensity (>3 m/s) of the tidal currents are present in spring tide, corresponding to syzygy lunar phases. Measurements were carried out in spring tide period but when the water slackens, to individuate the upwelling of deeper waters. Before measuring the current forecast from "Tide tables of the Istituto Idrografico della Marina, Genova" were used in order to seize the quasi-stationary situations following the dynamic phases of high (high tide current, 3 h/cruise) and low (low tide current, 3 h/cruise) tides.

The above-mentioned sampling strategy (Fig. 4) was recently repeated, and validated by simultaneously airborne images obtained by MIVIS (Multispectral Infrared Visibile Imaging Spectrometer) as reported in Azzaro et al. (2001).

Seasonal real-time tracking of surface water temperature, salinity and fluorescence by chlorophyll-*a* were automatically measured (30 s frequency) using a CTD probe (Meerestechnik Elektronik) implemented with a fluorometer (Haardt-1101LP). The sensors were positioned inside a steel tank where the water flowed, drawn by a membrane pump at the back of the system; the sensors' outputs were transmitted to a computer for display and storage. In addition to the above parameters, in winter and spring 1994, nitrate-nitrite automatic assay were performed (30 s frequency) in two different surveys on board R/V "Urania" using an Alliance Integral analyser (analytical accuracy of 0.15 μM). CTD-Fl data quality for salinity, fluorescence by chlorophyll-*a* and nitrate were checked by comparison with laboratory analysis (according to Strickland and Parsons, 1972; Innamorati et al., 1990; Grasshoff, 1983). The scatter plot of chlorophyll-*a* fluorescence versus chlorophyll-*a* concentration (Fig. 5) reports as they are related.

3 Results and discussions

As a part of several studies related to the influence of the physical forcing on the first level of the trophic chain, the surface waters hydro-biological behaviours from December 1993 to December 1995 are presented. Seasonal average and standard deviation of measured parameters during the slack water after low tide flow (low water slack) and after high tide flow (high water slack) are reported in Table 1. Nitrate and salinity trends in winter and spring seasons are showed to point out the upwelling process. Among the several cruises, four monthly surveys both in low and in high tides have been chosen in order to represent the seasonal phytoplankton fluorescence and temperature conditions depending on the tidal current pattern.

3.1 Nitrate and salinity distributions

The high frequency real-time measurements of surface nitrates and salinity distributions observed in December 1993 and April 1994 are showed in Fig. 6. In winter season during the low water slack the maximum nitrate concentration was found along the Sicilian (1.51 μM – Pace) and Calabrian coasts (1.36 μM – Punta Pezzo) associated with the maximum salinity (38.24) and the minimum temperature (15.3°C). In the high water slack, the nitrate concentration increase is located near Villa S. Giovanni (1.2 μM of NO_3 and salinity of 38.22). Lower nitrate concentration close to undetectable values associated with salinity of 37.50, were measured in the northern zone of the Straits.

During a spring season surveys higher nitrate concentration and wider upwelling zones were detected with respect to winter. The major NO_3 values during spring (3.67 μM) in the low water slack were associated with maximum salinity (38.39) and located between Capo Peloro and Punta Pezzo, while in high water slack the highest concentration (2.81 μM) was recorded between Pace and Punta Pezzo.

The correlation analyses of nitrate concentration and thermo-haline parameters show direct correlations with salinity ($r=0.52$, $p<0.01$, $n=1560$), and inverse with temperature ($r=0.84$, $p<0.01$, $n=1560$), as reported by table of the values limit of the coefficient of correlation for levels of significance 5% and 1% (Fischer, 1946). Regarding chlorophyll-*a* fluorescence, direct correlation (n=1560 December '93 and April '94) with salinity ($r=0.22$ $p<0.01$) and nitrate ($r=0.12$ $p<0.01$) and inverse one with temperature ($r=0.23$ $p<0.01$) were found. It is likely that tidal pumping is an important contributor to the nutrient supply of this area, and suggest that the NO_3 concentration could be considered as a conservative parameter of the upwelled water in the Straits of Messina (De Domenico et al., 1988). Upwelled water is cooler and saltier than the original surface water, and has much greater concentrations of nutrients such as nitrate, which sustain the biological primary production. The equilibrium between nutrient supply and vertical mixing well elucidate the high values of chlorophyll-*a* fluorescence at the boundary of divergence zone by an increase in the upward flux of nutrients to the euphotic zone, generated by intense tidally-induced vertical mixing.

3.2 Seasonal trend of phytoplankton fluorescence and temperature distributions

The hydro-biological parameters monthly recorded during 1995 both in low and in high water slack are described. Their spatial distribution among the different seasons well evidence the tidally-induced upwelling character of the zone. The contour plots of sea-surface temperature and chlorophyll-*a* fluorescence (SST and Chla-Fl hereinafter) seasonal distribution patterns are displayed in Figs. 7 and 8.

General uniformity of the surface thermo-haline horizontal structures were observed during winter months in slack water; water temperature ranged between 14.35°C and 15.67°C ($\Delta T=1.3$°C), and salinity was comprised from 37.44 to 38.12. In the low water slack, SST was lower (15.30°C January '95 – Fig. 7) in the northern zone bounded by the Ganzirri-Punta Pezzo section. In the high water slack, SST is found to be lower (15.20°C January '95 – Fig. 8) mainly in the central zone along the Sicily coast. During winter phytoplankton fluorescence was low and uniformly distributed in the area (around 0.16 μg-Chla l^{-1}) in both slack waters (Figs. 7 and 8). However, in the low water slack a slight increase of Chla-Fl concentration at the middle of the southern zone and westward in the central zone were found, whereas in high water slack (Fig. 8) in the upwelling zone, between Ganzirri-Punta Pezzo, a decrease of Chla-Fl values was measured (0.14 μg-Chla l^{-1}).

During spring season, the upwelling zone found in winter gradually extended to the south (15.50°C in May '95 – Fig. 7), in both slack waters. In particular, during low water slack (Fig. 7) the maximum phytoplankton fluorescence (0.32 μg-Chla l^{-1}) was recorded in the southern part, whereas in the high water slack, Chla-Fl was extremely low with a slight increase in the southern sector (>0.12 μg-Chla l^{-1}).

The maximum SST range was recorded in summer, in the low water slack after higher currents velocity (>2 m/s): a narrow front in temperature (25.53–18.54°C) (Fig. 7) and salinity (37.80–38.35) was found in the northern zone of the system. In the opposing current phase (high water slack; Fig. 8), SST ranged between 27.93°C and 22.88°C and salinity from 37.50 to 38.30. Moreover, the upwelling zone mainly extended along the Sicilian coast, whilst higher temperature values in the northern zone (27.93°C) were recorded (Fig. 8). During summer, coincided with highest surface thermo-haline discontinuities, lower Chla-Fl values were registered (<0.09 μg-Chla l^{-1}) at slack water after both tidal flows and localized in the south-eastern area.

In autumn, on the SST values still acts the summer heating, so there were higher annual average with lesser variations (20.75±2.47°C). Moreover, in October, the previous described phytoplankton fluorescence conditions become inverted (Fig. 8): in the low water slack high values and homogeneous distribution (0.13 μg-Chla l^{-1}) were found; in the divergence areas higher Chla-Fl values (0.18 μg-Chla l^{-1}) were observed at both slack water. In fact, the distribution of biomass in autumn is affected by the presence of the thermocline, that places it deeper. Brandt et al. (1999) report on high-resolution hydrographical measurements carried out in October 1995, approximately at slack water after both tidal flows, when south of the Straits sill the thermic profile is characterized by the presence of a well-mixed near-surface layer with a thickness of about 40 m. The astronomic conditions implies that advective velocities of the waters are stronger in spring till late summer, which could favour some of the phenomena discussed here (greater shear, more mixing). On the other hand, the simultaneous development of the autumnal thermocline will hinder the pumping of nutrients and other particles to the euphotic zone from the deepest. These counteracting influences would probably regard the biological cycle of the layer over the thermocline itself, and any reliable description of the seasonal cycle, needs the availability of more in situ data. Seasonal temperature and chlorophyll-*a* maps (Figs. 7 and 8) suggests these features during most of the year: the former depicts upwelling cores with cold and very rich in particles surface waters, but biologically poor patches. The latter depict a southward tongue of water rich in chlorophyll-*a* connected to the upwelling zone in such way that high chlorophyll-*a* concentrations be found in calmer waters, far from the place where water upwells.

4 Conclusions

The seasonal variability of phytoplankton fluorescence showed low values in the tidally induced upwelling zone due to the strong vertical mixing, except than during autumn when thermocline is also present in the Straits, and the exchange in the water column is limited (Magazzù et al., 1987).

Data shows the existence of an annual cycle of the upwelling peak in late spring till late summer. During autumn and winter seasons the water upwelling is confined to the central zone of the Straits. In spring, the divergence zones occur both in the central and southern sectors of the system. During summer season, the water upwelling takes place in the middle area of the Straits spreading to the southern one.

As regards the whole area, surface physical-chemical and biological parameters ranges increase after the low tide. The highest chlorophyll-*a* fluorescence values were observed during spring season in the low water slack, whilst during autumn the phytoplankton development is stimulated in the opposite high water slack one.

The effects of seasonal variability recorded in autumn, with the high presence of the phytoplankton biomass in divergence zones, are caused by the formation of a thermocline layer with a lesser intensity of upwelling processes (Brandt et al., 1999). The gradual warming and expansion of the surface layer establishes the stratification and nutrients are recycled in the upper layer (Magazzù et al., 1987). In stratified conditions, when the exchange in the water column is limited, nutrients to the photic level are likely supplied by lateral transport and faster remineralization above the thermoclyne. This particular combination means that phytoplanktonic organisms find optimal conditions for their growth at the surface layer: low vertical mixing, light and nutrient availability. In the summer months, although the input of nutrient-rich deeper waters (Cescon et al., 1997), the low autotrophic biomass is due to high vertical hydrodynamics. Although surface data are not alone enough to discriminate what physical process is forcing the biological response, mixing events at the sill region of the Straits of Messina seem probable mechanisms for the fertilization of the upper layer. The evidences of mixing allows us to define the Straits as a pulsating upwelling area, because the mechanisms regulating the mixing events are tidally induced. As a formal model the Straits of Messina may be compared to an "intermittent pump", which compresses and nutrient-enriches itself during the autumn and winter seasons, while in spring it releases and stimulates phytoplankton in both locally and adjacent zones (De Domenico et al., 1988; Azzaro et al., 1995; Magazzù et al., 1995; Decembrini et al., 1998; Kinder and Bryden, 1990). During summer season the surface water enriched with nutrients is advected towards the surrounding areas, where decrease of nutrients and increase of chlorophyll-*a* occur, namely in the north (Gulf of Gioia Tauro; Innamorati et al., 1996) and along the south-eastern Sicilian coast (Böhm et al., 1987; Decembrini et al., 2004; Raffa and Hopkins, 2004), while in other marine ecosystems low phytoplankton growth is due to nutrient depletion of the euphotic layer.

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Table 1. Seasonal (1994–1995) average and standard deviation (sd) of temperature, salinity, chlorophyll-*a* fluorescence in the slack water after low and high tide currents.

Seasons	Low Water Slack – mean (sd)			High Water Slack – mean (sd)		
1994–1995	Temp.°C	Salinity	μg-Chl*a* l–1	Temp.°C	Salinity	μg-Chl*a* l^{-1}
Winter (Dec-Jan-Feb)	15.30 (0.56)	37.90 (0.51)	0.16 (0.05)	15.50 (0.70)	37.77 (0.47)	0.16 (0.04)
Spring (March-April-May)	15.85 (1.06)	38.05 (0.28)	0.26 (0.24)	16.05 (0.78)	37.80 (0.42)	0.10 (0.08)
Summer (June-July-Aug)	19.80 (5.93)	38.08 (0.39)	0.07 (0.03)	25.40 (3.57)	37.90 (0.56)	0.06 (0.05)
Autumn (Sep-Oct-Nov)	20.75 (2.47)	37.98 (0.47)	0.14 (0.13)	20.16 (2.59)	38.01 (0.28)	0.16 (0.03)

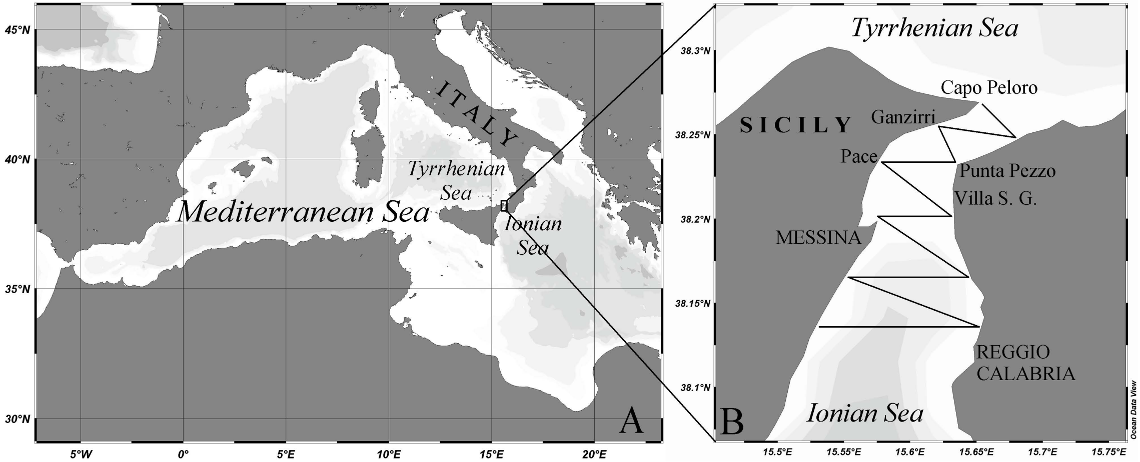

Fig. 1. Geographical location of the Straits of Messina **(A)** and automatic surface tracking **(B)**.

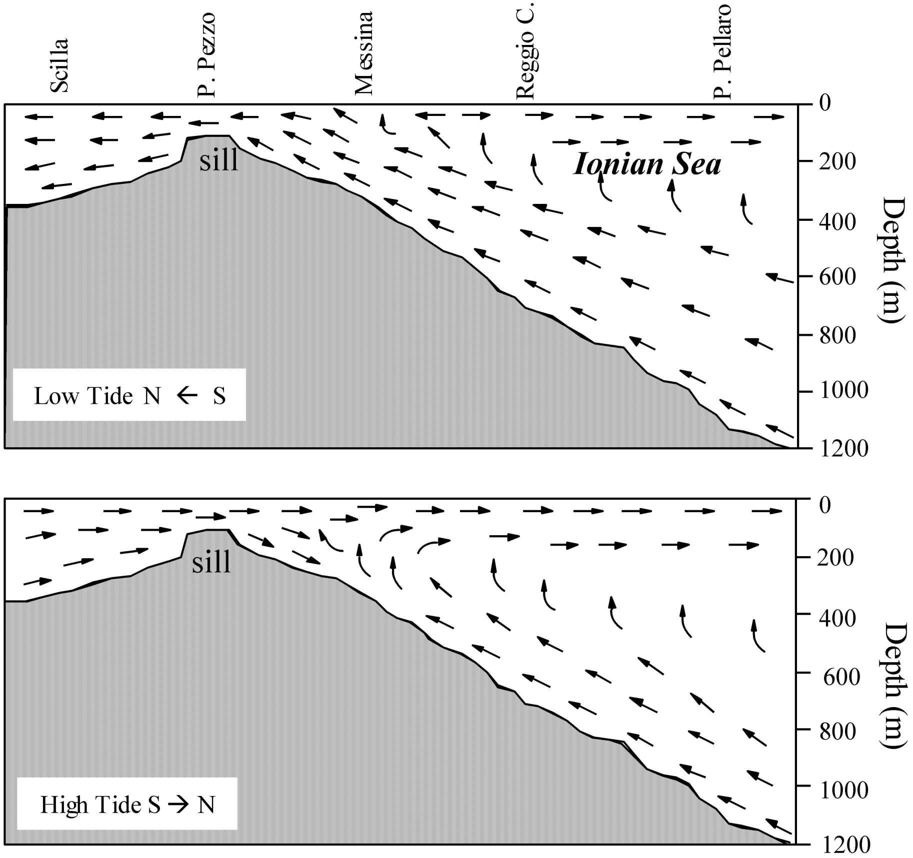

Fig. 2. Straits of Messina: schematic distribution of the tidal currents during the maximum speed in the low and high tide flow (Vercelli, 1925). Sill location refer to Fig. 3.

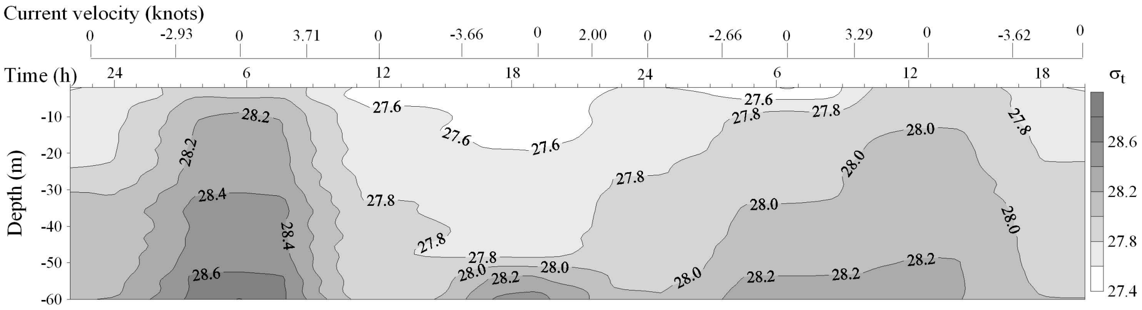

Fig. 3. 48-h behaviour of density at sill station surveyed with a frequency of 1-h at syzygy (December 1993). Estimated current direction (+=S→N; −=N→S) and speed (Knots) from "Tavole di Marea I.I.M.M.". Reference to Fig. 2.

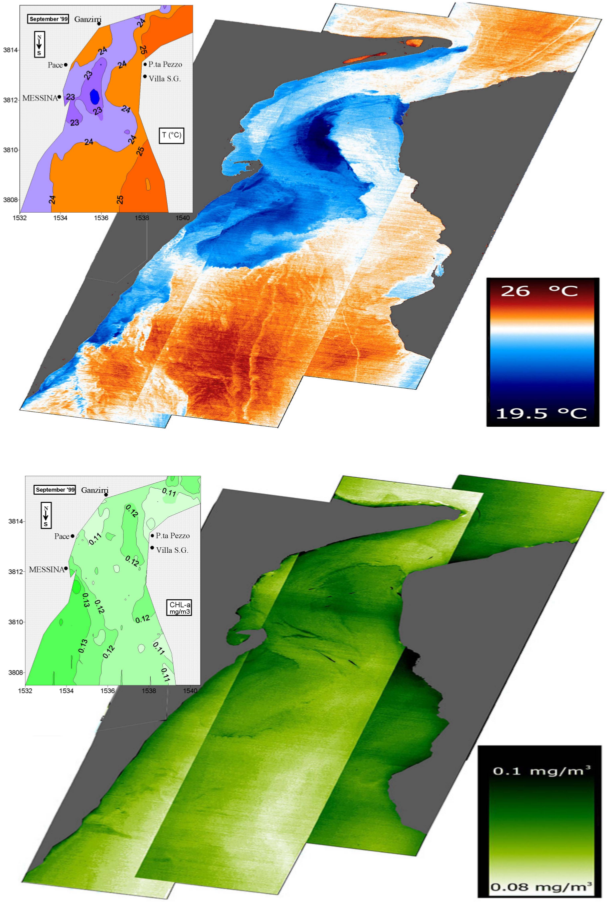

Fig. 4. Map comparison of surface water temperature and chlorophyll-*a* fluorescence produced by data of sailing boat (left) with airborne images (MIVIS, right) data (25 September 1999).

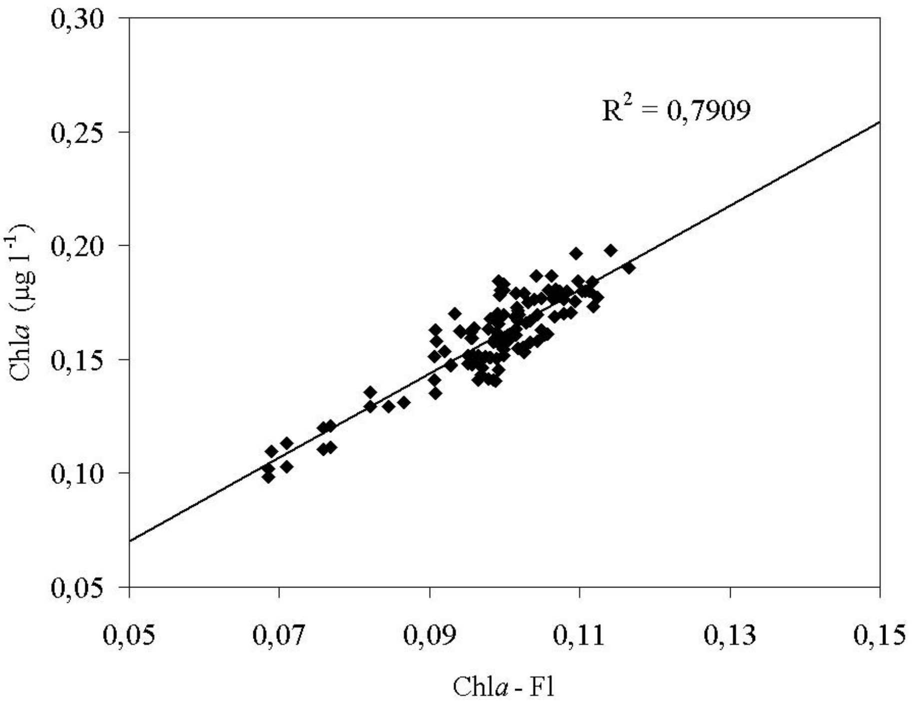

Fig. 5. Plot of chlorophyll-*a* concentration versus chlorophyll-*a* fluorescence.

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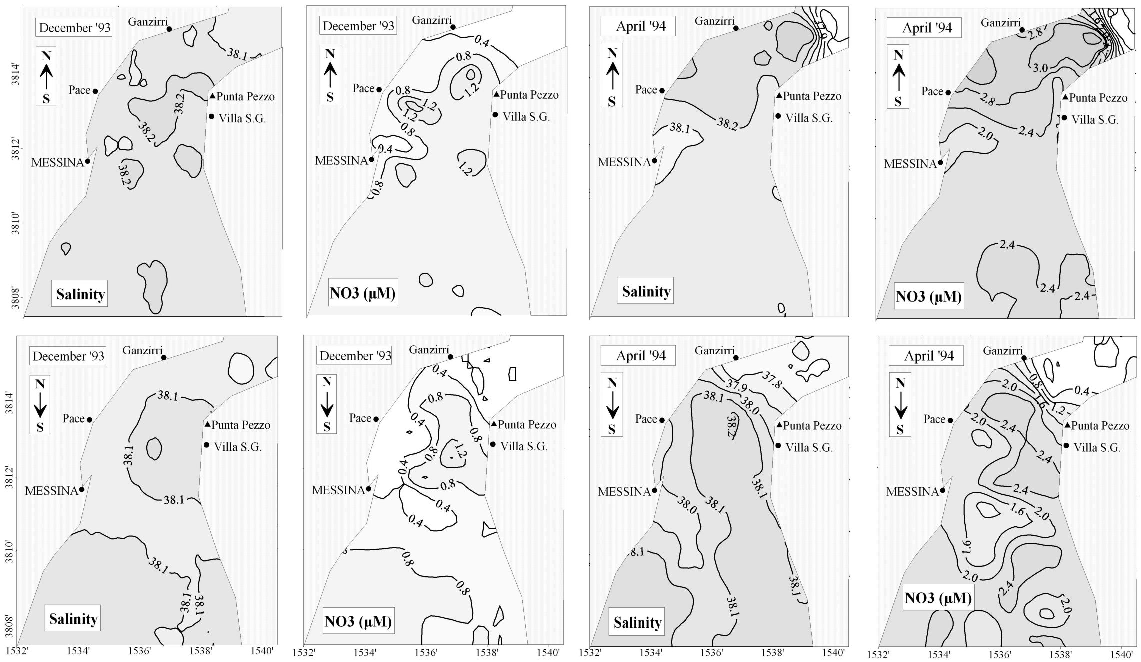

Fig. 6. Effect of diurnal variability of spring-tide on the surface distribution of salinity (left) and nitrate (μM, right) during December 1993 and April 1994 in the slack water after low tide (upper panel) and high tide currents (lower panel).

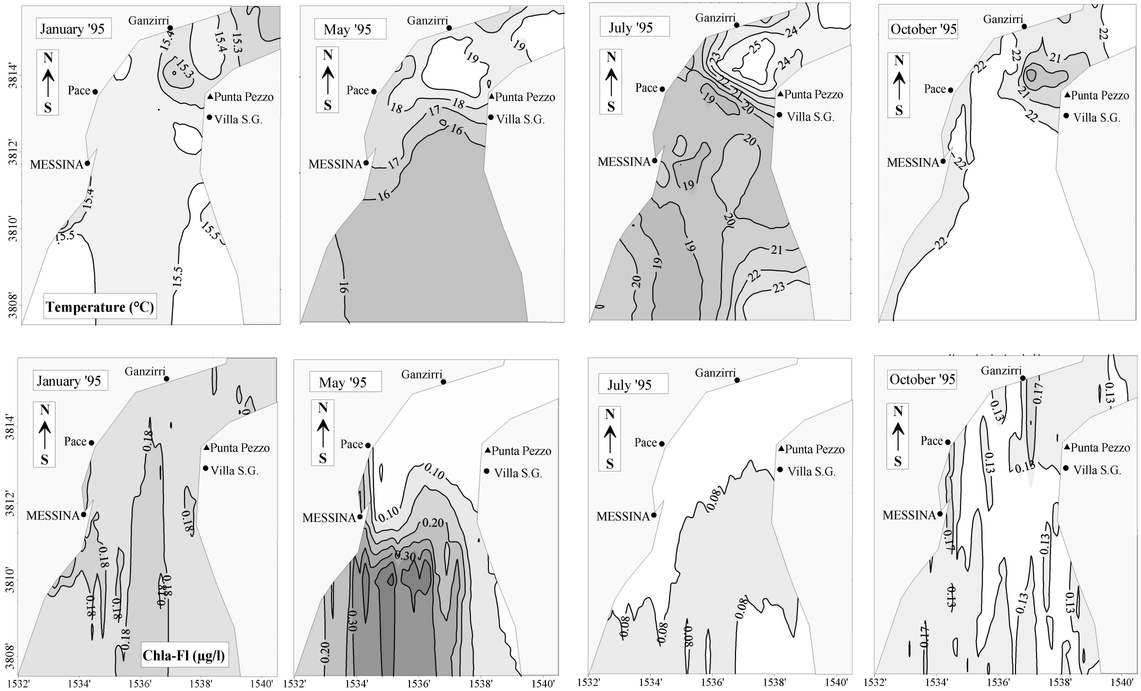

Fig. 7. Effect of diurnal variability of spring-tide on the surface distribution of temperature (°C, upper panel) and chlorophyll-*a* fluorescence (μg-Chl*a* l^{-1}, lower panel) during January, May, July and October 1995 in the slack water after low tide current.

Fluorescence changes in tidal upwelling (Messina Strait)

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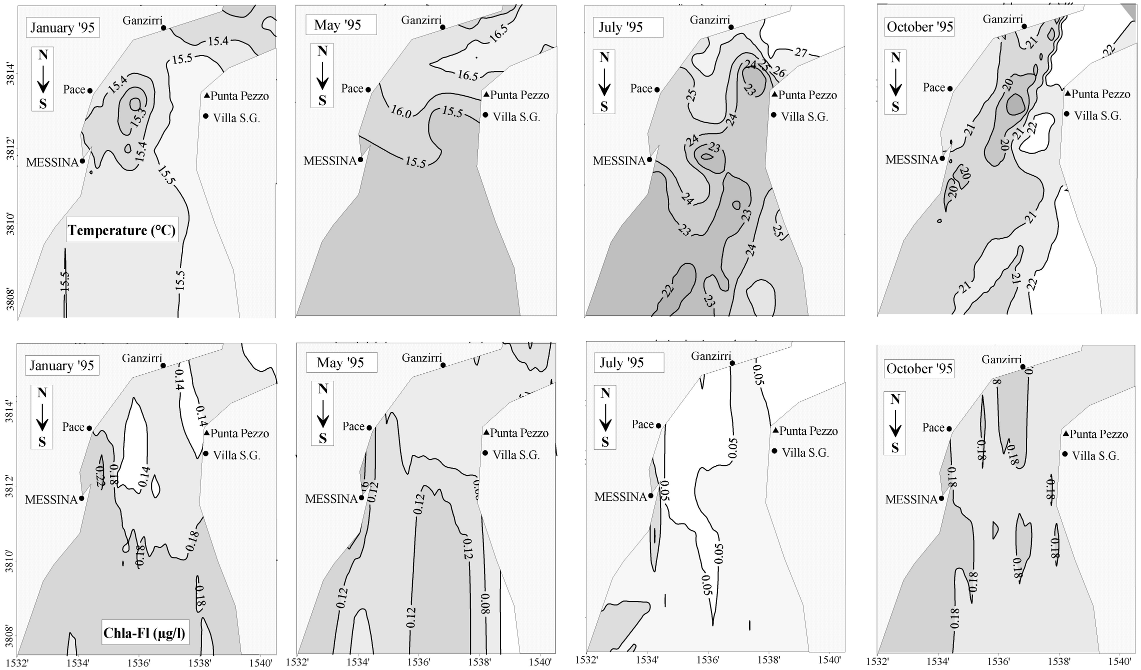

Fig. 8. Effect of diurnal variability of spring-tide on the surface distribution of temperature (˚C, upper panel) and chlorophyll-*a* fluorescence (μg-Chl*a* l^{-1}, lower panel) during January, May, July and October 1995 in the slack water after high tide current.

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