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Diurnal internal tides detected in the Adriatic

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Abstract. Strong diurnal oscillations, documented by temperature data that were collected along a submarine cliff on the Lastovo Island (southern Adriatic), are studied and compared with sea level and wind measurements at Dubrovnik and Komiža (island of Vis). Three thermistors were deployed at the depths of 15, 22 and 36 m between March 2001 and March 2002. Pronounced diurnal temperature oscillations were detected at 15 and 22 m during the stratified season. The correlation between the sea surface and thermocline displacements was highest in June 2001, when diurnal wind changes were not significant, while diurnal sea level oscillations achieved annual maxima. Thermocline oscillations were in phase with sea level changes. The range of diurnal sea surface variability was close to 19 cm, while the range of corresponding thermocline variability was about 5.4 m. The findings summarize the outcome of the first dedicated study of internal tides in the Adriatic.

Keywords. Oceanography: general (Continental shelf processes; Diurnal, seasonal, and annual cycles) – Oceanography: physical (Internal and inertial waves)

1 Introduction

Internal tides are generated by the barotropic tidal flow over a steep topography variation when the sea is stratified (e.g. Simpson, 1998). They predominantly have a semidiurnal character poleward of the inertial latitude (∼30°), with amplitudes ranging from several meters to more than a hundred meters (e.g. Wunsch, 1975; Huthnance, 1989). Since the inertial period poleward of the inertial latitude is shorter than 24 h, internal oscillations with a diurnal period exist only as waves trapped over topography (Wunsch, 1975). Such waves were, for the first time, observed close to Iceland (Krauss, 1961). Sea currents recorded in Suruga and Sagami Bays (Japan) showed that a diurnal signal is predominant in Suruga Bay, while currents in Sagami Bay exhibit a prevailing semidiurnal nature. This difference arises from diverse types of internal tides existing in these two bays (Inaba, 1981; Ohwaki et al., 1991). Internal tides represent a dynamical process that has not been systematically studied in the Adriatic Sea so far. It was believed that the barotropic tidal currents are too weak there to cause perceptible baroclinic waves. However, U.S. Space Shuttle photographs of the southeastern Adriatic showed bright streaks due to tidal currents, as well as wave packets that could be surface expressions of internal tides (Cushman-Roisin et al., 2001). Diurnal temperature oscillations were noted in the analysis of short-term temperature and current measurements, which were carried out near the island of Lastovo in the summer of 1990 (Leder, 2002). Yet previously available time series were not long enough to enable a detailed study of the internal tides in the Adriatic.

In the period between March 2001 and March 2002 three thermistors were installed on the underwater cliff at Cape Struga on the island of Lastovo (southern Adriatic – Fig. 1). They provided a yearlong temperature series with 16-min resolution at the depths of 15, 22 and 36 m. Previous open-Adriatic temperature measurements did not extend beyond a few weeks, due to heavy fishing activity in the area. The present experiment was designed to study the diversity and distribution of bryozoa along underwater cliffs in the Adriatic Sea (Novosel et al., 2004). Emphasis was placed on the thermal regime in the area of research. Somewhat surprisingly, strong diurnal temperature oscillations were observed at 15- and 22-m depths during the stratified season.

This paper presents the results of the observation and analysis of diurnal thermocline oscillations in the southern Adriatic shelf region. It thus augments the rather limited information available on diurnal internal tides poleward of the inertial latitude. The analysis is based on temperature measurements performed at Cape Struga, as well as on sea level data originating from the closest station available (Dubrovnik) and on wind data from a coastal station (Dubrovnik) and an offshore

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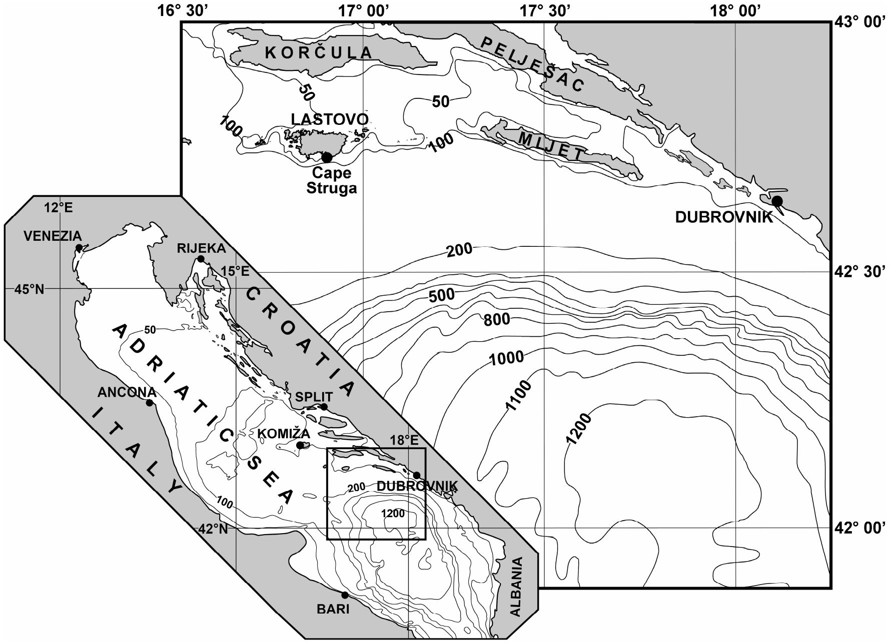

Fig. 1. Bathymetry and position of the southeastern part of the Adriatic Sea. The positions of the thermistors (Cape Struga) and of the meteorological and tide gauge stations (Dubrovnik) are indicated on the large map. The position of the Komiža meteorological station is shown on the small map.

station (Komiža, island of Vis). Wind data were analyzed in order to investigate atmospheric forcing on different scales, including the diurnal one, during the summer period. Diurnal wind changes can spur significant diurnal oscillations of the surface currents (e.g. Hyder et al., 2002). They could act together with varying barotropic tidal flow and influence near-surface temperature variations in the wider shelf break area.

The data are described in the second section, as are the methods used to extract thermocline displacements from temperature series. Background processes controlling temperature variability are presented in the third section. Diurnal internal tides are considered in the fourth section. Finally, the findings are reviewed in the fifth section.

2 Data and methods

The island of Lastovo is located in the southern part of the middle Dalmatia island group (Fig. 1), at the edge of the South Adriatic Pit (depths reaching more than 1200 m). In the shelf break area complex internal wave dynamics have been observed, not only at diurnal but at higher frequencies, as well (Leder, 2002). The topography between Lastovo and the South Adriatic Pit is characterized by a gradual slope between 100 and 200 m isobaths, and a more abrupt change further on.

Between March 2001 and March 2002 three TidbiT type thermistors were placed at 15, 22 and 36 m on the underwater cliff at Cape Struga (sea depth at the base of the cliff is around 80 m). The instruments recorded the sea temperature with 16-min resolution and an accuracy of ±0.2°C. By applying a two-dimensional (time-depth) kriging procedure on the temperature data, the time series of vertical profiles were determined, whereupon a step function was fitted to each profile in order to obtain the time series of the thermocline displacements (Krajcar, 1993). The thermocline depths were well defined only when the thermocline was positioned between 15 and 36 m, i.e. when the most pronounced oscillations occurred at 22-m depth. During July and August 2001, when the largest temperature variability was observed at 15-m depth, thermocline displacements could not be determined since the near-surface temperature was unknown. Hence, the analysis of the thermocline oscillations presented here is based on temperature measurements from June 2001, when the thermocline was positioned between 15 and 36 m, as confirmed by contemporary CTD measurements at a nearby station. The method was evaluated by analyzing a temperature profile recorded by the CTD probe on 25 June 2001 at a station located 53 km to the WSW from Lastovo Island. The difference between the thermocline depth obtained by CTD profiling and that determined by thermistors was about 3 m. This discrepancy depended mostly on the fine details in vertical structure obtained by the CTD probe, thus having a rather small influence on the strong diurnal changes. When a random displacement series with values ranging from –3 m to +3 m was presumed and added to the original thermocline displacement series, the most important conclusions on diurnal oscillations remained the same.

Sea level data used for the comparison of thermocline oscillations with barotropic tides have been recorded at Dubrovnik (located at a distance of 95 km to the east of Lastovo) by an analog tide gauge, with a resolution of 1 h and an accuracy of ±1 cm. Dubrovnik and Komiža were the closest meteorological stations with wind data available during 2001, since anemometers at Lastovo and Mljet were not operational at the time. Dubrovnik is a coastal meteorological station, dominated during summer by the coupling of the Etesian winds (blowing from the northwest) with the sea-land breeze system (Penzar et al., 2001). On the other hand, the Komiža anemometer is positioned on Mount Hum, the highest point of the island of Vis (587 m). Komiža is an offshore station, influenced even more than Dubrovnik by the Etesian winds in summer and – to a lesser extent – by their interaction with the sea-land breeze system. Although it is placed on high grounds, the station is very useful for the distinction between diurnal NW wind variations in the open Adriatic and the well-defined diurnal NE wind changes along the shore, which are pronounced during the summer period. The anemometers recorded wind gusts, as well as wind speed and direction, averaged over 10 min intervals, the latter with an accuracy of ±0.2 m/s and ±5°, respectively.

Classical (stationary) spectral analysis has been used as the first step in the analysis of time series (e.g. Jenkins and Watts, 1968). Since the analyzed series contained a wide range of dominant frequencies, with respective amplitudes varying in time, non-stationary wavelet analysis was also performed (Torrence and Compo, 1998). The fundamental idea behind wavelets is to analyze the time series according to scale. The procedure requires a selection of a suitable analyzing wavelet, the so-called "mother wavelet". By using a convolution-like integral, a kind of comparison between the data and the scaled-and-shifted version of the mother wavelet is carried out. The resulting wavelet amplitude gives a time vs. scale representation of the original data, with the time-frequency window of constant area (e.g. Chui, 1997).

In this paper the Morlet wavelet was used, consisting of a plane wave modulated by a Gaussian:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}, \qquad (1)$$

where η denotes the nondimensional "time" parameter and ω_0 is the nondimensional frequency. The Morlet wavelet is delimited both in time and frequency and characterized by a sinusoidal shape and declining envelope. This makes it particularly suitable for detecting the periodicities in a time series, as well as the time evolution of these periodicities. The necessary wavelet admissibility condition requires that the frequency parameter ω_0 be sufficiently large. The choice of ω_0 equalling 6 results in a good time-frequency localization and a convenient approximate equality between wavelet scale and respective Fourier frequency (period).

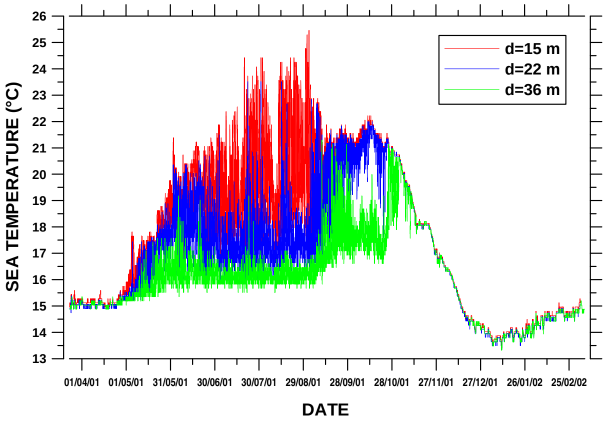

Fig. 2. Original temperature series recorded at the depths of 15, 22 and 36 m at Cape Struga, from March 2001 to March 2002.

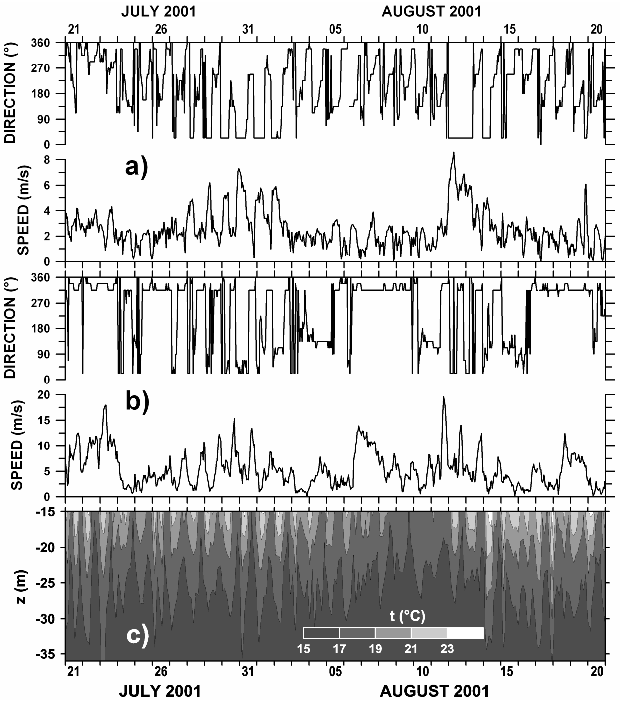

Fig. 3. **(a)** Wind speed and wind direction at Dubrovnik meteorological station, for the interval extending from 21 July to 20 August 2001. **(b)** The same as in (a), except for the Komiža meteorological station. **(c)** Vertical temperature distribution between 15 and 36 m at Cape Struga for the same period.

Finally, the time series were subjected to a band-pass filter (e.g. Emery and Thomson, 1997), in order to extract the most prominent oscillations.

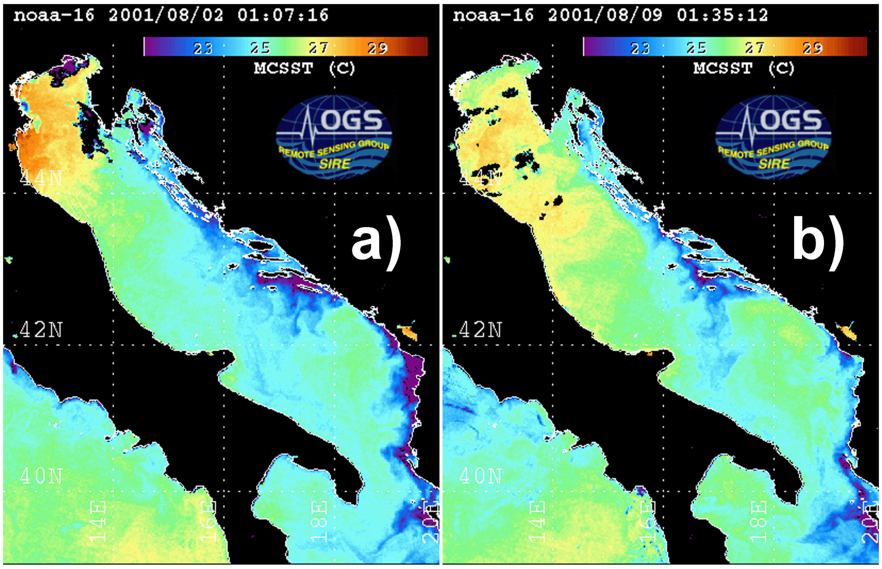

Fig. 4. (a) Sea Surface Temperature (SST) satellite image of the Adriatic at 01:07 UTC on 2 August 2001. **(b)** The same as in (a) except for 01:35 UTC on 9 August 2001. Courtesy of the OGS Remote Sensing Group.

3 Background processes

Sea temperatures recorded between March 2001 and March 2002 at three depths on the underwater cliff at Cape Struga are depicted in Fig. 2. The curves show high-frequency temperature oscillations superimposed on the annual temperature variation. The oscillations occurred during the stratified season (late spring, summer and early autumn), whereas the winter season was characterized by homogeneity along the vertical. The stratification started at the end of April, after the sea had begun to receive heat from the atmosphere. During the summer season a strong thermocline developed. The most interesting features observed at 22-m depth in June and 15-m depth during July–August were intense diurnal temperature oscillations which lasted for several days. At the same time weak fluctuations of temperature were recorded at 36 m, thus pointing to a rather stable water temperature at about 15.8°C below the thermocline. At the end of August the thermocline began to sink into deeper layers and, consequently, temperatures at 22 and 36 m peaked in October (as also documented by the low-pass filtered series of Novosel et al., 2004). In mid-November a rapid cooling took place over the whole water column, marking the end of the stratification period.

The influence of synoptic and mesoscale atmospheric processes is also evident in temperature data. At the end of July and the beginning of August 2001 wind changes were mostly under the influence of the coupling of the Etesian winds with the sea-land breeze system. Northeasterly diurnal wind pulses were dominant along the coast (Fig. 3a), whereas northwesterly diurnal wind maxima occurred offshore (Fig. 3b), preceding coastal extremes by 8–10 h. The NW wind prevailing offshore during this period resulted in a pronounced upwelling in the Hvar-Korčula-Pelješac region and a consequent horizontal sea surface temperature gradient between this area and Lastovo Island (Fig. 4a). When the diurnal NW wind pulses were dominant, localized upwelling and horizontal advection occurred at Lastovo, bringing colder water to the area. When the wind ceased, relaxation and possibly horizontal advection caused a sinking of the thermocline and restoration of warmer water to the surface layer. These temperature changes could be modified by internal tides, and the combined oscillations were found to have a range of about 7°C at the 15-m depth (Fig. 3c).

Diurnal wind oscillations came to an end on 3 August 2001 and temperature variability at 15 m decreased. On 6 August the synoptic situation changed, resulting in the northeasterly Bora pulse in the northern Adriatic (Meteorological and Hydrological Service of Croatia, 2001) and a strong NW wind in the offshore middle and southern Adriatic, lasting from 6 to 10 August (Fig. 3b). The most distinct temperature decrease was recorded at 15 m in the interval extending from 7 to 11 August (Fig. 3c). The episode was so pronounced that it checked seasonal warming and reduced diurnal temperature oscillations. The drop in temperature was caused by a strong upwelling along the southeastern Adriatic coast (as also pointed out by Novosel et al., 2004). This upwelling episode was captured by an SST satellite image taken on 9 August (Fig. 4b), showing lower sea surface temperature along the Hvar and Korčula islands and Pelješac peninsula. Since the wind extended over a long period, the relaxation and horizontal advection processes were slower, resulting in low temperatures prevailing at 15 m over a 3–4 day period.

At the end of 11 August 2001 strong Bora was reported along the eastern Adriatic coast (Meteorological and Hydrological Service of Croatia, 2001). At the same time, well-defined NW wind pulses were measured in the open Adriatic (Fig. 3b). The Bora episode detected at Dubrovnik was also modulated by the sea-land breeze effect and three diurnal wind pulses were observed (Fig. 3a). They probably caused upwelling at Cape Struga when pronounced NW wind maxima occurred offshore, followed by a subsequent temperature increase when the wind subsided (Fig. 3c).

The analysis presented here illustrates the importance of diurnal wind variability for corresponding temperature oscillations in the southern Adriatic. Pronounced diurnal temperature oscillations may, however, also occur at a time of rather insignificant wind forcing, as documented by data collected in June 2001, when diurnal sea level changes achieved annual maxima.

4 Diurnal internal tides

The most important feature of the temperature data were diurnal oscillations observed when the seasonal thermocline was well developed. Inertial oscillations with a period of about 17.6 h were also present during September and October 2001, especially at the depth of 36 m. The power spectra determined for the stratified season (interval extending from 24 April to 14 November 2001) revealed two marked peaks, indicated by arrows in Fig. 5: one at diurnal period and the other close to inertial period. Both of these peaks were significant at all three depths. Inertial oscillations are a well-known feature of the Adriatic under stratified conditions (e.g. Orlić, 1987). Diurnal temperature oscillations at Cape Struga were intermittent, which is a significant aspect of internal tides (Wunsch, 1975). This is probably caused by a variable stratification in the generation region (Baines, 1986). Therefore, non-stationary spectral analysis was also applied, since it is efficient in the time-frequency localization of significant oscillations. Wavelet spectra of sea temperature showed that the strongest diurnal oscillations were recorded in June at 22-m depth and during July–August at 15-m depth (Fig. 6). Similar results were obtained by filtering the data around a 24-h period, giving the highest diurnal sea temperature variability of about 5.5°C at 15 m, at the end of July, 2.8°C at 22 m and 1°C at 36 m in June.

Throughout the July–August 2001 interval the diurnal changes in the sea temperature were correlated with sea level and with diurnal wind oscillations (not shown). Therefore, these diurnal temperature oscillations cannot be attributed solely to internal tides. They result in significant energy being concentrated at the diurnal frequency, and more exhaustive measurements and analyses are needed to separate wind forcing from tidal forcing on such occasions.

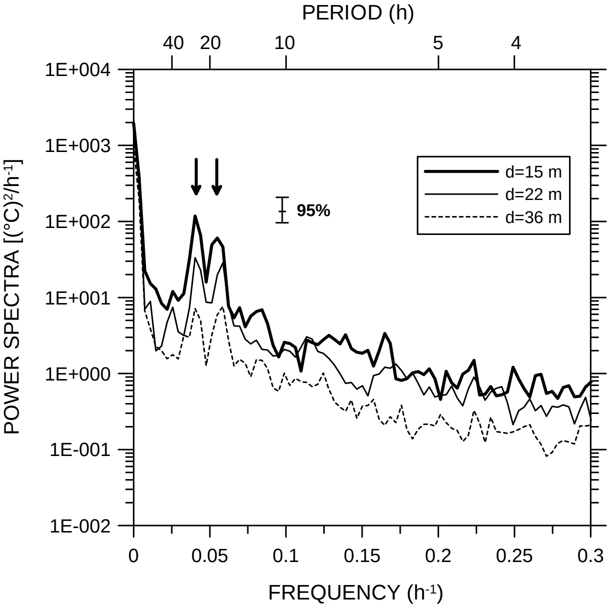

Fig. 5. Fourier power spectra of sea temperature measured at Cape Struga at the depths of 15, 22 and 36 m, for the interval extending from 24 April to 14 November 2001. The corresponding 95% confidence interval is also shown. Left arrow indicates the K1 tidal period, right one denotes the inertial period.

The strongest connection between the sea surface height and thermocline displacement was, however, observed in June 2001, when diurnal wind changes were not significant, neither in Dubrovnik (Fig. 7a) nor at Mount Hum (not shown). At the same time diurnal sea level oscillations achieved the annual maximum in the wavelet spectrum. During June two energetic episodes were present in the sea-level spectrum at diurnal period, as shown in the time series of the normalized wavelet spectra at the K1 tidal frequency (Fig. 7a). This modulation is related to the different phases of the diurnal tidal constituents. The most important diurnal constituent in Dubrovnik is K1, with a significant influence of O1 and P1 constituents being present. Their amplitudes and phases at the Dubrovnik tide gauge are given in Table 1 (Hydrographic Institute of the Republic of Croatia, 1973). In order to investigate the modulation induced by interference of nearby diurnal constituents, predicted tidal heights for 2001 (generated by using seven major tidal constituents in the Adriatic) were subjected to wavelet spectral analysis at the K1 tidal period (not shown). The modulation of the K1 tidal constituent was clearly evident and it influenced the thermocline oscillations, which had two maxima in June (Fig. 7a). The analysis of the predicted tidal heights could be very useful in the future research of internal tides in this region, since it can reveal intervals over which significant internal tides are expected during the stratified season.

Cross-wavelet spectral analysis confirmed that thermocline oscillations were correlated and in phase with sea-level

Table 1. Amplitudes and phases of the most significant diurnal tidal constituents at Dubrovnik tide gauge (Hydrographic Institute of the Republic of Croatia, 1973).

Tidal constituent	Period (h)	Amplitude (cm)	Phase (°)
K1 (Luni-Solar diurnal)	23.93	5.19	62.4
O1 (principal Lunar diurnal)	25.82	1.90	47.3
P1 (principal Solar diurnal)	24.07	1.69	60.2

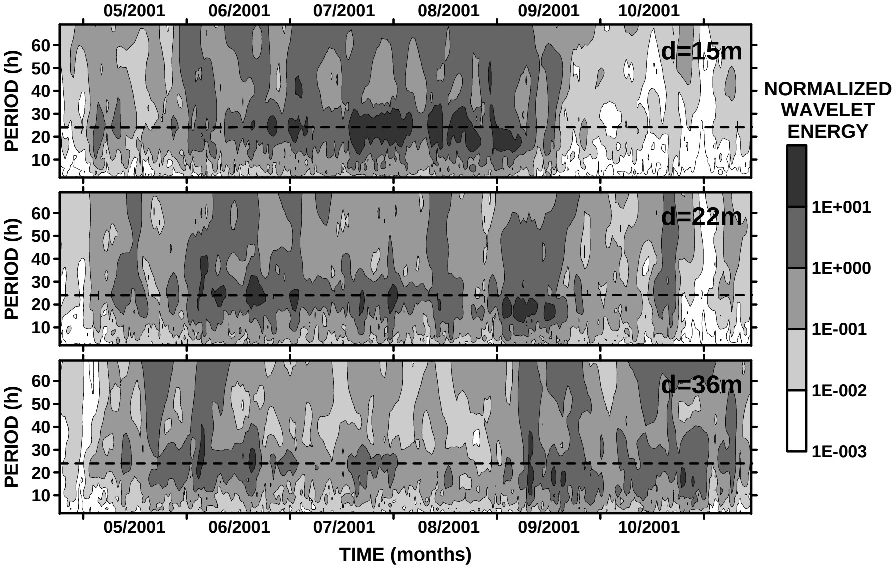

Fig. 6. Wavelet spectra of sea temperature measured at Cape Struga at the depths of 15, 22 and 36 m, for the interval extending from 24 April to 14 November 2001. The spectra are normalized by the respective variances. Dashed lines denote the K1 tidal period.

changes during June 2001 (Fig. 7b). The range of diurnal sea surface variability in that month was close to 19 cm, and the range of corresponding thermocline variability was about 5.4 m, giving an amplitude ratio of about 29 (Fig. 8). Tidal analysis showed that in June the amplitude of the K1 barotropic tidal constituent was around 7 cm, while the corresponding internal tidal constituent had an amplitude of about 149 cm. The phase difference was close to 10°, with internal oscillations preceding surface variations.

A conspicuous feature of the temperature records originating from Cape Struga is the presence of a diurnal signal combined with the absence of a semidiurnal one, which is probably related to the character of barotropic tides in the region. Early researchers interpreted the Adriatic diurnal surface tides in terms of near-resonant excitation of the fundamental Adriatic seiche by the Mediterranean tides (Defant, 1961), thus explaining the relatively large amplitudes of the diurnal tides in the Adriatic if compared with the Mediterranean. More recently, Malačič et al. (2000) showed that diurnal tidal constituents can be ascribed to a topographic wave progressing across the Adriatic, from the eastern to the western coast. As for the Adriatic semidiurnal surface tides, originally they were related to the second Adriatic mode co-oscillating with the Mediterranean (Defant, 1961). Later on, Hendershott and Speranza (1971) explained semidiurnal tides by the superposition of two oppositely travelling coastal Kelvin waves: an incident wave progresses along the eastern coast in the NW direction and a partially reflected wave propagates along the western coast in the SE direction. Different dynamics underlying diurnal and semidiurnal surface tides correspond with the differences in the barotropic tidal currents, with the diurnal currents being rather strong and the semidiurnal currents being weak in the Adriatic shelf break area (as also confirmed by numerical modelling – see Cushman-Roisin and Naimie, 2002). This may help to explain the presence of diurnal oscillations and the absence of semidiurnal ones in temperature data collected at Cape Struga. Alternatively, the semidiurnal internal tide could be radiating away from the generation area, whilst the diurnal internal tide could be trapped in the area.

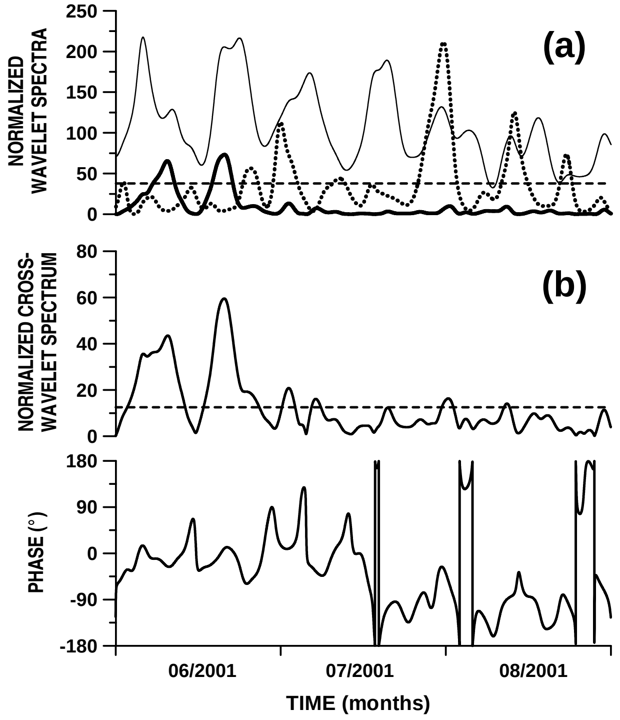

Fig. 7. **(a)** Wavelet spectra of thermocline displacement at Cape Struga (thick full line), sea level at Dubrovnik (thin full line) and NE wind component at Dubrovnik (dotted line), for the interval between June and August 2001, at the K1 tidal frequency. **(b)** Corresponding cross-wavelet spectrum of the sea level at Dubrovnik and thermocline displacement at Cape Struga. The spectra are normalized by the respective variances. Dashed lines denote 95% significance levels.

5 Conclusions

Albeit of modest vertical resolution, long temperature series recorded at Cape Struga on the island of Lastovo enabled the buoyancy- and wind-driven temperature variability to be documented and the first dedicated study of internal tides in the Adriatic to be performed. The wind analysis resulted in a distinction between a month dominated by internal tidal oscillations (June 2001) and the months during which both the wind and tidal diurnal forcing were present (July-August 2001). Several important conclusions can be drawn from this research:

1. Barotropic tidal flow is strong enough to generate internal tides in the Adriatic when interacting with a topography change in a stratified sea.

2. Internal tides in the southeastern Adriatic shelf area have a diurnal period. The diurnal constituent is probably more pronounced than the semidiurnal one because semidiurnal tidal currents are weak in this area. Another possible explanation is that the semidiurnal internal tide radiates away, while the diurnal one is trapped in the generation region.

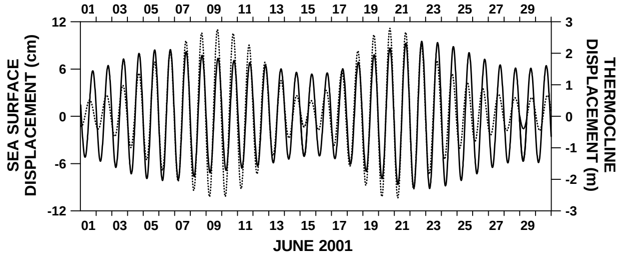

Fig. 8. Sea surface displacement at Dubrovnik (full line) and thermocline displacement at Cape Struga (dotted line), filtered by a band-pass digital filter around diurnal period (June 2001).

3. The most significant diurnal thermocline oscillations at Cape Struga were detected in June 2001, when diurnal wind changes were not significant and thermocline oscillations were in phase with sea-level variations. The range of diurnal sea-level oscillations was close to 19 cm, whereas the range of resulting thermocline variability was about 5.4 m.

The analysis presented here was based solely on data collected by three thermistors and could not rely on current measurements to support the findings further. However, it resulted in a first glimpse of diurnal internal tides in the Adriatic, thus also expanding the limited evidence of such tides poleward of the inertial latitude, in general. The dynamics is considered to be important for an understanding of the different physical and biological processes in the Adriatic, including energy transfer from barotropic to baroclinic tides and the generation of turbulence in the area. Future research on internal tides at the Adriatic shelf break should be based on more complete measurements and should enable propagation of internal tides, as well as the relationship between diurnal thermocline oscillations and barotropic tidal currents to be documented.

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