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PERIODIC UPWELLING/DOWNWELLING OBSERVED IN THE ADRIATIC SEA

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1. INTRODUCTION

The present abstract focuses on the Adriatic shelf-break area. Previously, it has been found that the along-basin flow there is oppositely directed in the winter and summer seasons (Zore-Armanda, 1968), that seasonally dependent circulation contributes to a strong temporal variability of thermohaline properties (Grbec and Morovic, 1997), and that barotropic-like currents reverse on a few-day scale (Leder et al., 1996). More recently, it has been shown that during the stratified season diurnal internal tides are generated in the area by the interaction of diurnal barotropic tides with topography (Mihanovic et al., 2006). As the previous detection of internal tides was based on a limited data set, the project entitled "Internal Tidal Hydrodynamics and Ambient Characteristics of the Adriatic (ITHACA)" was initiated in order to provide a more complete information. The aim of the project was also to consider the way changes of background stratification and currents modify internal waves, and vice versa – to address a possible influence of internal waves on deductions based on measurements that are scattered in space and time. Whereas the project did provide some answers to the questions originally posed, it also resulted in an unexpected finding: diurnal wind variability was occasionally found to be strong in the area, supporting periodic interchange of large-amplitude upwelling and downwelling. In what follows the project is briefly described and some preliminary findings on the periodic upwelling/downwelling are discussed.

2. DATA

Measurements supported by the ITHACA project were carried out at the stations shown in Fig. 1 from February to September 2006. During the experiment (1) ADCP measurements were performed at three stations using trawl-resistant bottom mounts (called barnys), (2) thermistor data were collected on the islands of Lastovo, Susac and Bisevo utilizing 3 x 10 sensors deployed on steep cliffs opened to the southeast, (3) shipboard CTD surveys were carried out on four occasions at an along-basin transect comprising 13 closely spaced stations, (4) optical surveys were performed at thermistor stations while deploying and recovering them, (5) surface tides were monitored at the permanent Split and Dubrovnik stations and at one of the ADCP stations, and (6) meteorological conditions were documented by permanent stations in the area (Split-Marjan, Dubrovnik, Komiza, Hvar and Palagruza).

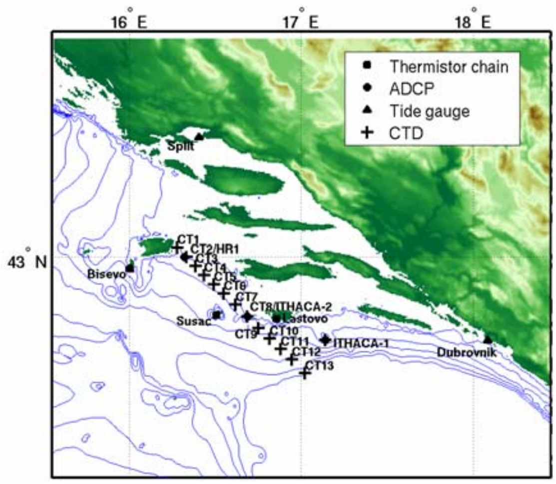

Figure 1. Stations at which various oceanographic data were collected between February and September 2006.

Most measurements followed standard practice in oceanography and meteorology. There was, however, one exception: thermistors were not deployed on the moorings but on the steep island cliffs (Fig. 2). Since fishing activities in the area would not allow the moorings to survive for more than a month or

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two, the approach was necessary in order to enable the data to be collected over more than six months. As it turned out, practical necessity proved to be scientifically beneficial, since the cliff measurements provided information on temperature variability at the coast, where the diurnal upwelling/downwelling interchange is most pronounced, rather than further offshore, where the interchange is attenuated. In the measurements TidbiT type thermistors were used, and the sensors were distributed between the depths of 4 and 40 m with a 4 m vertical resolution – at three sites. The instruments recorded the sea temperature with a 10 min temporal resolution and an accuracy of ±0.2°C at 21°C. The experiment was very successful, with 29 sensors being recovered, and only one lost at the depth of 32 m at the Susac island.

Figure 2. Deployment of TidbiT thermistors on the island of Bisevo in February 2006.

3. RESULTS

Preliminary analysis of the data collected has shown that lower frequencies were strongly controlled by the east-coast inflow to the Adriatic, which, however, underwent a summertime change – recorded in July 2006 at two of the ADCP stations, between May and July 2006 at one station. Higher frequencies were dominated by inertial oscillations on one hand and by diurnal oscillations on the other. Whereas the former were well visible in all the temperature and ADCP time series, the latter were more localized: as shown by stationary spectral analysis (Fig. 3), subsurface temperature oscillations, characterized by the 24, 12 and 8 h periods, were particularly strong at one of the islands (Lastovo, 42.724 N, 16.884 E), and the corresponding baroclinic current variability was largest at a nearby ADCP station (ITHACA 2, 42.751 N, 16.682 E).

There are obviously two possible sources of diurnal variability – tidal and wind forcing. In order to distinguish between the two, wavelet spectral analysis was performed. In the analysis the tidal forcing was represented by sea levels measured at Dubrovnik and by barotropic currents recorded at station ITHACA 2, the wind forcing by data collected at meteorological stations Komiza and Dubrovnik. Temporal variability of the two forcing mechanisms was compared to fluctuations of the 17°C isotherm recorded at Lastovo. Figure 4 (up) shows that the beats of diurnal tides were well visible in both the sea level and current time series and that they closely followed each other. In June 2006, when the tidal forcing was strongest, diurnal isotherm variability was apparently related to it. In the middle of July 2006, however, when diurnal isotherm oscillations were most pronounced, the tidal forcing was at a minimum. Figure 4 (down) reveals that diurnal wind variability culminated at the time, strongly suggesting that the wind forcing was responsible for the maximum diurnal oscillations of isotherm elevation.

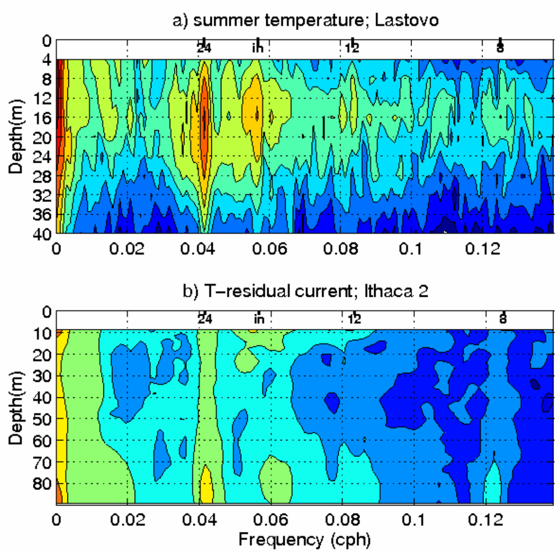

Figure 3. Depth-frequency plots obtained from (a) temperature time series collected at Lastovo and (b) cross-basin currents recorded at station ITHACA 2 and detided by allowing for seven barotropic tidal constituents. Red (blue) color implies high (low) spectral density.

To illustrate in a simple way behavior of the thermocline and to determine temperature of the layers above and below it, a step function was fitted to the thermistor data at each moment they were recorded. The thermocline

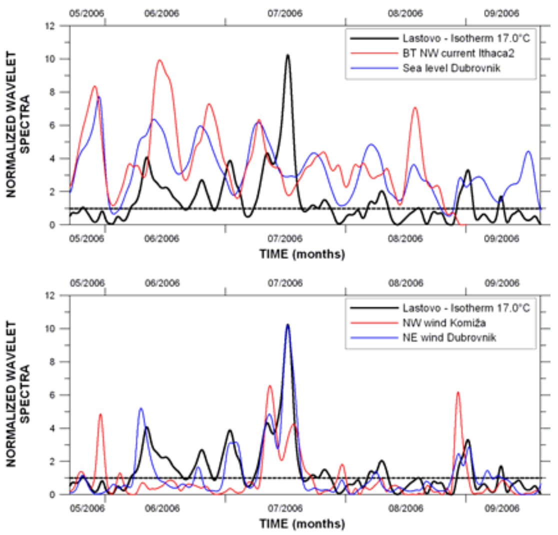

Figure 4. Wavelet spectra at diurnal period for the interval extending from May to September 2006. The upper figure shows results obtained from sea level measured at Dubrovnik, northwestward barotropic current measured at station ITHACA 2 and 17°C isotherm displacement registered at Lastovo, the lower figure displays results obtained from northeastward wind measured at Dubrovnik, northwestward wind recorded at Komiza and, again, 17°C isotherm displacement registered at Lastovo. The spectra were normalized by the respective variances and significance levels, so that the 95% confidence level equals 1. Notice that the current measurements terminated on 1 September 2006, whereas the other time series extended over an additional month.

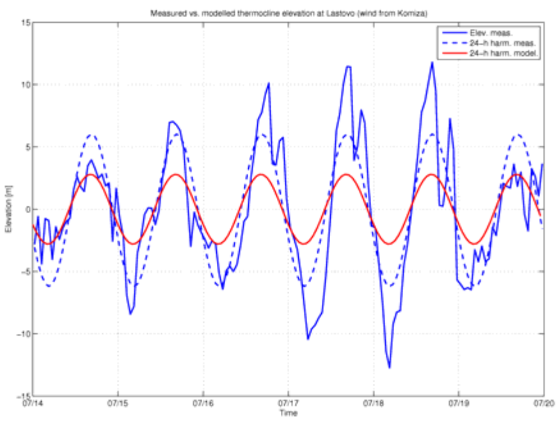

Figure 5. Thermocline elevation measured at Lastovo from 14 to 19 July 2006 (full blue line), 24 h oscillation fitted to the data (dashed blue line), and 24 h oscillation modeled as described in the text (red line).

elevations thus obtained for the interval extending from 14 to 19 July 2006 are shown in Fig. 5. Obviously, the range of diurnal thermocline variability surpassed 20 m. The thermocline was lowest at about 6 am, and was highest at about 4 pm with a secondary maximum occurring at about 10 pm. The diurnal thermocline oscillations were driven by the sea/land breezes, with the relatively weak morning breeze, blowing from the southeast, corresponding to the thermocline reaching the deepest point, the relatively strong (up to 10 m/s) afternoon breeze, blowing from the northwest and locally known as maestro, coinciding with the thermocline being close to the sea surface. In Fig. 5 a pure 24 h signal, fitted to the thermocline time series, is also shown. It explains 65% of variance of the time series, with the rest being due to a number of higher harmonics.

4. DISCUSSION

In order to interpret the experimental findings, a simple analytical model, reproducing response of a reduced-gravity *f*-plane sea bounded by a vertical wall to a rotating wind stress, has been developed. The model is a variant of the models proposed by Wolanski (1986) and Cushman-Roisin (1994), the main differences being that besides the longshore wind stress the offshore wind stress has been considered and that solution has been obtained not only for subinertial but also for superintertial frequencies. The model predicts resonance at inertial frequency, and different behavior at subinertial and superinertial frequencies: whereas in both cases wind directly forces rotating currents, the influence of the coast results in the upwelling/downwelling interchange trapped at coast in the former case and in the inertia-gravity waves radiating from coast in the latter case.

Taking into account the 24 h constituent of wind stress recorded at Komiza and some typical parameters for the area in July (including the average thermocline depth of 20 m and the proportionate density defect equal to 1.5 x 10^{-3}), the model predicts the 24 h thermocline oscillation as shown in Fig. 5. By comparing the modeled and observed signal it may be noticed that the phase is accurately reproduced whereas the amplitude is underestimated by a factor of two. Similar comparison for the other periods shows that the linear model underestimates the observed amplitudes even more at the periods of 8, 6 and 4.8 h, but also that it is surprisingly accurate at the 12 h period. It would thus appear that excitation of the July 2006 upwelling/downwelling events in the Adriatic shelf-break area was near-resonant, and that it was further amplified due to nonlinear interaction of various wind-driven constituents.

5. CONCLUSION

As has been shown, the sea/land breezes may occasionally generate pronounced upwelling/downwelling events in the Adriatic shelf-break area. Whereas previous studies of similar events occurring elsewhere had concentrated on the current variability (Halpern, 1977; Rosenfeld, 1988; Lerczak et al., 2001), the present study has focused on the thermocline oscillations. The approach provided some important insights, but also opened a number of questions that we plan to address by the process-oriented numerical modeling. Thus, for example, the precise nature of nonlinearity demands our attention, with some candidates being the variability of the sea state related to the sea/land breezes and the advection and entrainment varying over the upwelling/downwelling cycle. Another interesting topic is the difference between the subinertial and superinertial phenomena: the other spots, besides Lastovo, at which the periodic upwelling/downwelling occurs in the Adriatic should be detected, and the possibility that they coincide with the points from which the inertia-gravity waves radiate should be checked. Since both the subinertial and superinertial processes may influence productivity of the Adriatic, the former locally, the latter at a distance, their study appears to be of interest to a wider community of oceanographers.

ACKNOWLEDGEMENT

The ITHACA project was financed by the US Office of Naval Research and by the Croatian Ministry of Science, Education and Sports. Additional support was received through the “Dynamics of the Adriatic in Real Time (DART)” project funded by the US Naval Research Laboratory.

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