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External forcing of meteorological tsunamis at the coast of the Balearic Islands

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ABSTRACT

High frequency sea level observations at four coastal sites at the Balearic Islands (three in Mallorca and one in Menorca) have been used to examine the external forcing responsible for above normal seiches in certain harbours. Anomalously amplified harbour seiches in this region are known to be mainly associated with the passage of atmospheric pressure perturbations that generate long ocean waves in the open sea that travel northeastward, in the direction from Mallorca to Menorca. In Ciutadella Harbour (Menorca), sea level oscillations regularly reach amplitudes that are potentially dangerous to harbour infrastructure and boats. At other sites, seiches are normally smaller but have similar behaviour, indicating a local response to the external forcing. This external energy formed during the large amplitude events has been estimated based on spectral analysis of coastal measurements and found to have periods predominantly in the range of 5–50 min. Forcing characteristics differ among events but are similar for the same event, even for sites located far apart. Near identical responses are found for two specific sites, Ciutadella (Menorca) and Cala Ratjada (Mallorca). This suggests that sea level measurements at Cala Ratjada could be used to forecast destructive events in Ciutadella Harbour as part of a Mediterranean Tsunami Warning System ICG/NEAMTWS.

1. Introduction

High frequency sea level oscillations in bays and harbours, known as seiches, may reach considerable amplitudes depending on the external forcing in the open sea and the local topographic response. When resonance occurs, such that the period of the external forcing waves coincides with the natural eigen period of oscillations in the embayment, the resulting response may pose severe risks to coastal infrastructure, to commercial and sport fishing activities and to human safety. The external forcing responsible for such amplification consists of long waves, with periods from a few minutes to a few hours. These long waves can originate from different sources: submarine earthquakes, submarine or subaerial landslides and atmospheric activity among others. The latter results from atmospheric gravity waves, fronts, and other meteorological phenomenon have been referred to as "meteotsunamis" (Rabinovich and Monserrat, 1996; Monserrat et al., 2006a).

Meteotsunamis resemble ordinary tsunami waves and can produce similar damage at the coast, although the catastrophic effects related to this type of waves are normally observed only in specific bays and inlets. Large seiches associated with atmospheric forcing have been documented and investigated in many places around the globe. In the Mediterranean, where tides are relatively small, anomalous seiche amplification becomes more evident. Such waves have been reported in Sicily (Candela et al., 1999); in Malta (Drago, 1999), the Adriatic Sea (Orlić, 1980; Vilibić et al., 2004, 2005) and the Aegean Sea (Papadopoulos, 1993). They also occur in the English Channel (Douglas, 1929), the Great Lakes region (Donn and Ewing, 1956), on the northwestern Atlantic coast (Donn and Balachandran, 1969; Mercer et al., 2002), in the Netherlands (De Jong et al., 2003), the Baltic Sea (Metzner et al., 2000), the Argentina coast (Dragani et al., 2002), New Zealand coast (Goring, 2005), and Nagasaki Bay, and other Japanese harbours (Honda et al., 1908; Akamatsu, 1982; Hibiya and Kajiura, 1982).

The site having the largest reported meteotsunami sea level amplitudes is Ciutadella Harbour, a natural elongated and shallow inlet located on the western coast of Menorca Island (Western Mediterranean; Fig. 1). The phenomenon, known locally as "rissaga", occurs normally every year mostly in late spring and summer. Seiches in Ciutadella have a period of approximately 10.5 min and typical amplitudes of a few cm. In contrast, typical rissaga events have trough-to-crest wave heights of about 1 m, but the catastrophic rissagas may reach wave height up to 4–6 m. The last destructive event occurred on 21 June 2006 when sea level oscillations in Ciutadella reached 6 m (Monserrat et al., 2006a,b), causing major damage to the boats moored inside the harbour with economic loss of about 30 million Euros. The early rissaga warning is the key factor to mitigate the catastrophic effects of such events.

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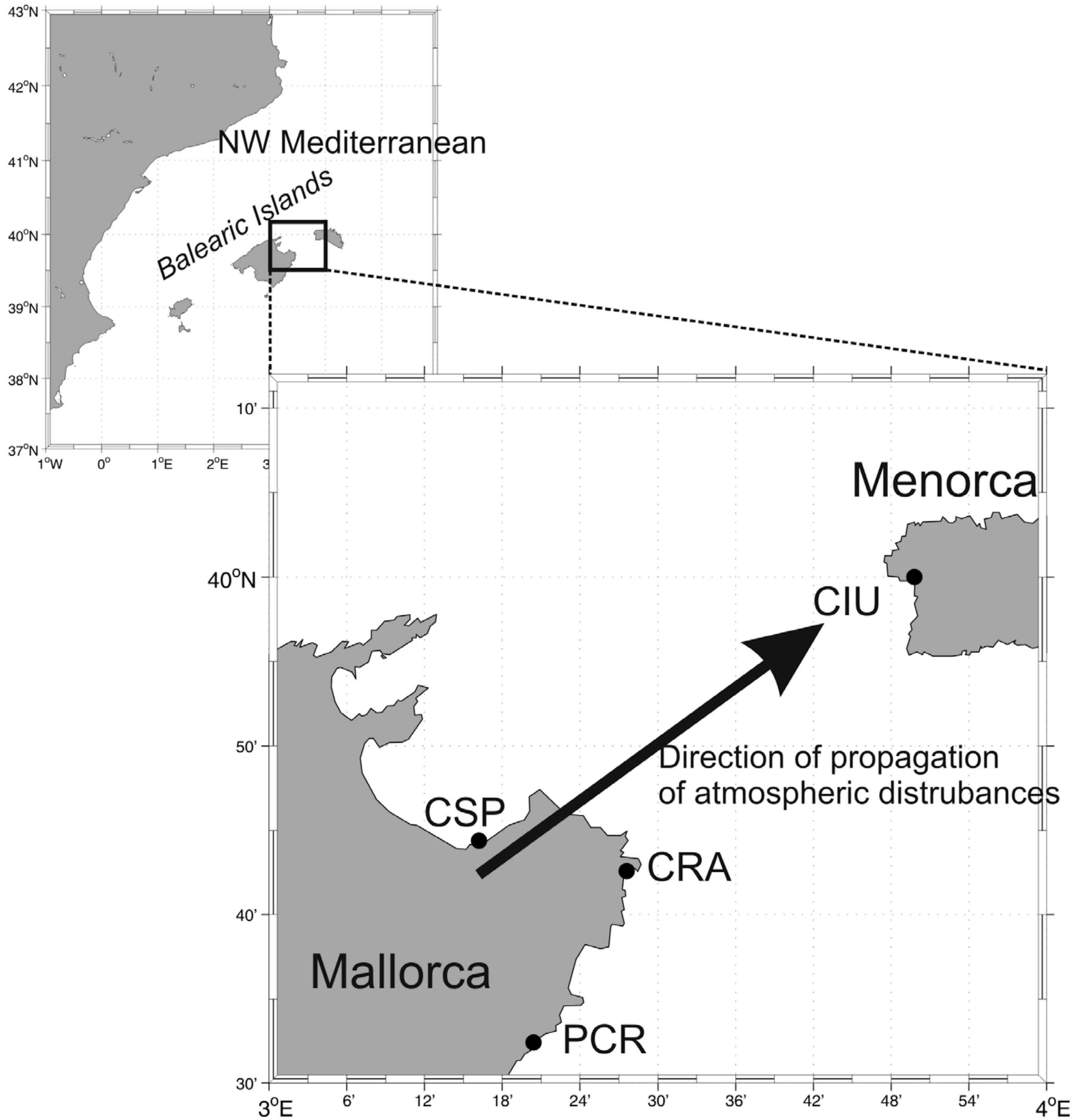

Fig. 1. Map of the area and location of the stations.

The atmospheric origin of rissaga is well established (cf. Tintoré et al., 1988; Monserrat et al., 1991, 1998; Rabinovich and Monserrat, 1996, 1998). During specific synoptic meteorological situations, trains of atmospheric pressure gravity waves travel from SW to NE across the Mediterranean (Monserrat et al., 1991). When these disturbances propagate with a phase speed of about 22–30 m/s, resonant conditions occur on the southeastern shelf of Mallorca Island and kinetic energy is efficiently transferred from the atmosphere into the ocean (Garcies et al., 1996). Arriving at the coast these open ocean long waves may significantly amplify seiche oscillations inside bays and inlets due to harbour resonance. Numerous studies have been addressed to investigate the characteristics and the generation mechanism of these oscillations in Ciutadella Harbour and adjacent inlets. Among the most recent are Liu et al. (2003), Marcos et al. (2004) and Vilibić et al. (2008).

The previous studies of the rissaga phenomenon were mainly based on measurements in Ciutadella Inlet and on the nearby shelf (cf. Gomis et al., 1993; Garcies et al., 1996; Monserrat et al., 1998; Liu et al., 2003). Meanwhile, existing reports, information and data indicate destructive rissaga waves in Ciutadella (Menorca Island) are normally accompanied by above normal seiches on the coast of Mallorca Island (Rabinovich and Monserrat, 1996, 1998). More-over, these seiches commonly begin 1–1.5 h earlier than in Ciutadella hypothetically enabling us to use the former as a predictor for rissaga phenomenon in Ciutadella Harbour. To examine this possibility, a special experiment was provided in 2007–2008 to record simultaneously sea level oscillations on the coasts of Mallorca and Menorca islands. In this paper we analyze this set of data aiming to characterize the external sea level forcing that causes strong seiche events around the Balearic Islands and estimate the possibility to forecast rissaga in Ciutadella Harbour. The data set and the methodology followed are explained in Section 2. Section 3 is devoted to the analysis of sea level oscillations, while Section 4 focuses on the characterization of the sea level forcing. Finally a summary and some conclusions are outlined in Section 5.

2. Data and methods

During 2007 and 2008 an extensive field experiment was carried out in Mallorca and Menorca islands. The experiment was designed to improve the understanding of the rissaga phenomenon observed in Ciutadella Harbour. Specific focus was on the interaction between the atmosphere and the ocean and the propagation of the generated oceanic waves near the Balearic Islands which excite Ciutadella Harbour and lead to rissaga events. We expected that the analysis of the data would provide information on the relationship between the atmospheric waves and the sea level response at different sites and would help to determine the suitability of a possible rissaga warning system.

In this field survey four tide gauges, with collocated atmospheric pressure sensors, were deployed in the region (Fig. 1). Three stations were located on the northeastern coast of Mallorca: Cala Ratjada (CRA), Porto Cristo (PCR) and Colonia de Sant Pere (CSP). Another instrument was deployed in Ciutadella Harbour (CIU), Menorca Island. As indicated in Table 1, not all the instruments worked properly throughout the entire experiment.

Bottom pressure was recorded every 10 s. All time series were quality controlled prior to analysis. The first step was to check each series visually in order to detect errant behaviours (for example, continuous sets of values that were out of range). The obviously wrong data were identified and gaps were introduced. Then, outliers were removed using an iterative standard deviation filter (Emery and Thomson, 2003) and substituted with gaps. The 10-s records were transformed into 1 min time series by averaging every six values. Only minutes with at least four 10-s values were considered; otherwise they are taken as gaps. The percentages of data gaps following the quality control procedure are listed in Table 1 for each station; the actual high-quality data set used for the further analysis is shown in Fig. 2.

Periods with relatively high seiche activity were selected from the 1-min record at Ciutadella tide gauge. Since the forcing mechanism acts over the entire area, seiche oscillations are expected to occur nearly simultaneously at all sites. The Ciutadella record is used as a proxy station because events are larger and therefore easier to identify at this site. Applying the criterium used by Rabinovich and Monserrat (1996) to select a rissaga episode, seven events with sea level oscillations at Ciutadella exceeding 30 cm were identified; at six of them Ciutadella wave heights were more than 1 m. Parameters of these events are listed in Table 2 and the timing of the corresponding events are indicated in Fig. 2. As the duration strongly differs among episodes, in order to allow a better comparison between episodes and stations, a standard length of 2 days has been defined for all events. Example of the data recorded during an event is provided in Fig. 3 which shows sea level oscillations at all sites for the strongest rissaga that occurred in May 2008. Sea level oscillations were much higher in Ciutadella (notice the different scales used in the figure), but they were also present at the other locations. At Ciutadella, the largest wave heights are observed before 06:00 h and after 18:00 h on 25th, with smaller oscillations in between. The same behaviour can be identified at the other stations. At Colonia de Sant Pere, low fre-

Table 1
Recording periods of tide gauges at each site and percentage of data gaps.

Station	Period of operation	Data gaps (%)
CIU	May07–November08	22
CRA	May07–November08	33
CSP	May07–November08	28
PCR	January08–November08	36

Table 2
Parameters of rissaga events recorded during the experiment.

Rissaga events	Duration (h)	Max. wave height (cm)			
		CIU	CRA	CSP	PCR
21-May-2007	6	100	50	45	–
18-June-2007	9	110	40	40	–
22-June-2007	15	160	50	35	–
23-June-2007	18	145	55	40	–
26-June-2007	7	85	45	35	–
22-July-2007	3	110	40	30	–
24-May-2008	90	180	65	60	90

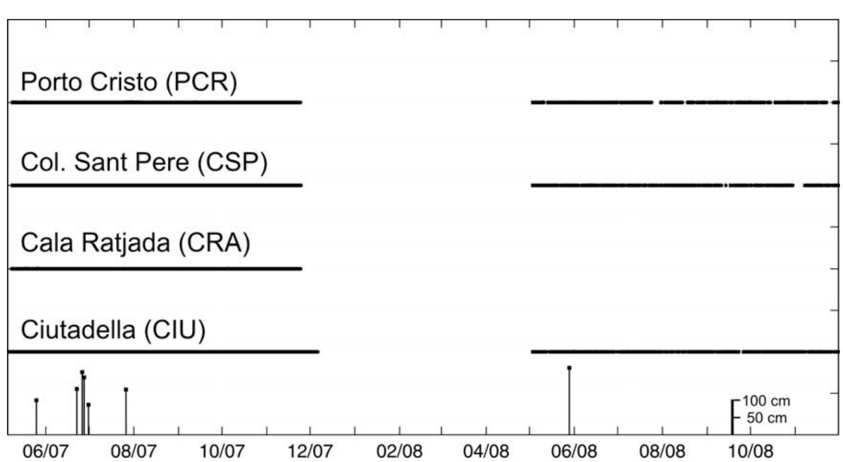

Fig. 2. Periods of operation of tide gauges from the 1-min records. Rissaga events are marked by vertical lines whose lengths indicate the magnitude of the oscillations.

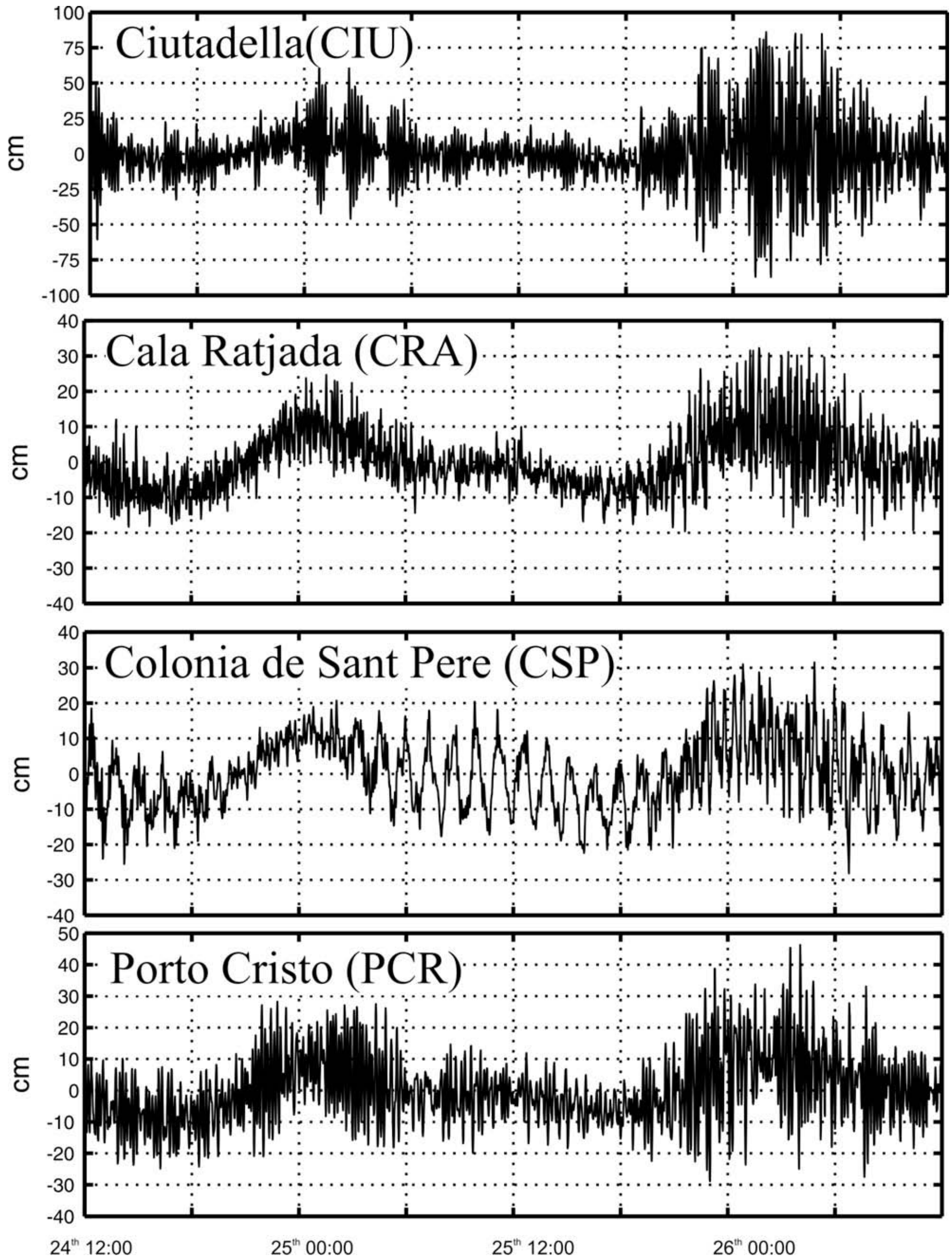

Fig. 3. Sea level oscillations at CIU, CRA, CSP and PCR during the rissaga event of May 2008. Note the different vertical scales for CIU.

quency oscillations are only apparent during this intermediate time as they are masked by larger high frequency oscillations present during the time periods mentioned above.

To examine background oscillations we selected periods with relatively low wave activity.

The energy distribution for seven selected episodes and for background oscillations were estimated by spectral analysis. A Kaiser-Bessel (KB) window (cf. Emery and Thomson, 2003) with half-window overlap was used for all computations.

3. Analysis of sea level oscillations

Coastal sea level oscillations recorded at various sites are determined by the local topography through amplification/attenuation of the external forcing (arriving waves). The effects of local topography alone may be estimated by computing the frequency response of each site during calm periods when sea level oscillations are small. These periods, hereinafter termed background periods, closely represent sea level behaviour in the absence of major external forcing.

To estimate the topographic response at the tide gauge sites, several 4-day background periods have been selected. Spectra have been computed using a KB window of 512 min resulting in 42 degrees of freedom per spectral estimate. Fig. 4 shows the spectra for five different background periods (except for PCR station where only four were defined) under calm conditions (grey lines). PCR tide gauge background periods differ from those of the other three stations because of the lack of data at this station during 2007 and part of 2008. Although the forcing may be small, especially compared with rissaga events, there is always energy coming from the open sea. The mean background spectra have been estimated by averaging spectra at each tide gauge for all available calm periods (black lines in Fig. 4).

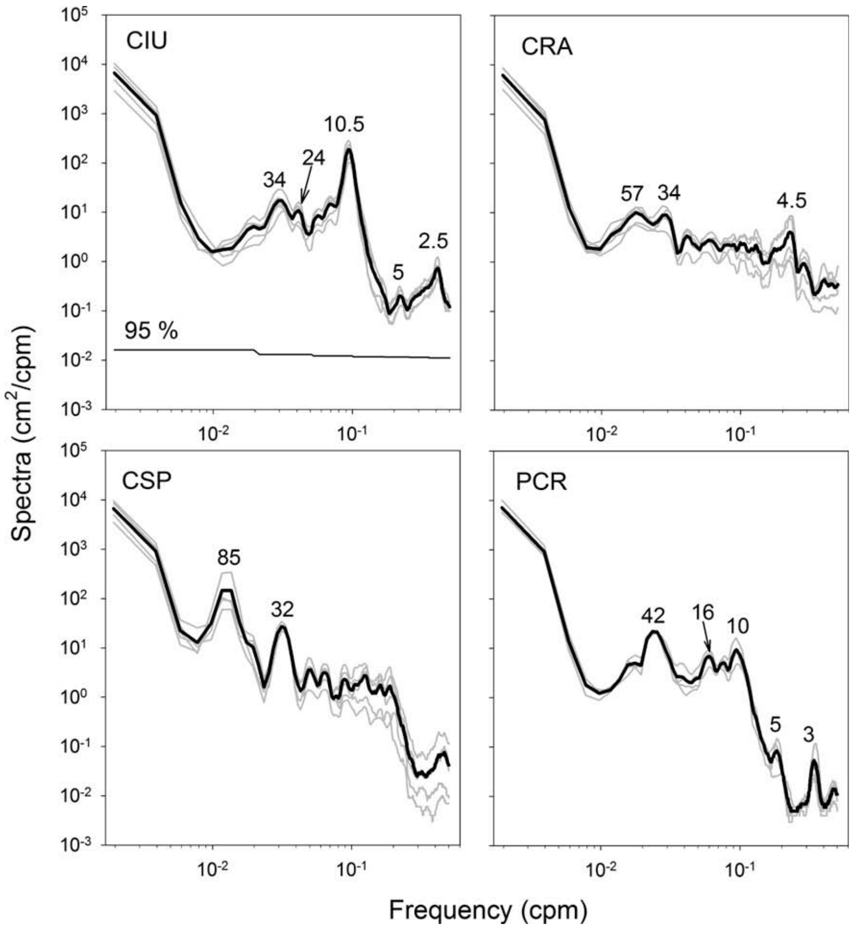

Fig. 4. Spectra of background sea level oscillations during calm periods B1, B2 and B3 (grey lines) and mean spectra for each site (black lines). Periods of main spectral peaks (in min) are indicated. 95% confidence intervals for the spectra are also shown.

The resonant characteristics of each location are clearly defined in the background spectra (Fig. 4). The natural oscillation modes in Ciutadella Inlet have been presented in previous studies based on earlier observations and numerical modelling (cf. Monserrat et al., 1991; Gomis et al., 1993; Garcies et al., 1996; Rabinovich and Monserrat, 1996; Liu et al., 2003) and will only be briefly described here. The main peak at CIU is related to the fundamental (Helmholtz) mode with period of about 10.5 min, while two other peaks (5 and 2.5 min) are associated with higher modes. Two additional low-frequency peaks (24 and 34 min) can also be identified in the spectra; they should be linked to some larger domain. They could be shelf resonant modes or even be associated with some wave mode travelling around the islands. A numerical study including the whole domain could help to better determine the nature of these oscillations. The energy at CRA is significantly smaller than at CIU. The only observed resonant period in the CRA spectra, which can be linked with the inlet geometry is at 4.5 min. At lower frequencies two other modes are seen at 57 and 34 min. The local resonant effects at CSP site are weak and only peaks 85 and 32 min, associated with a domain larger than the inlet geometry, are evident. At PCR the resonant bay modes are at 16, 10, 5 and 3 min periods. There is also a longer period mode at 42 min.

The differences found among the five background spectra for the same instrument are due to different responses to the corresponding forcing signals. Those sites with larger variability in individual spectra (CRA and CSP) are shown to be more sensitive to the characteristics of the forcing conditions, such as the angle of incidence of ocean waves. That is, they oscillate differently under different conditions. On the contrary, the CIU and PCR tide gauges display more constant frequency responses indicating that the topographic constraints are more important. The background spectra, defined as the mean spectra for each station may be considered as the topographic response for each site, being constant in time and thus independent of the external forcing. These topographic responses are constant in time and thus independent of the external forcing.

During rissaga events high frequency sea level oscillations with periods of a few minutes are observed nearly simultaneously at CIU, CRA, CSP and PCR tide gauges (Fig. 3). The largest trough-to-crest wave heights are found at CIU with values up to 180 cm (Table 2), thus masking the tidal signal whose amplitude is only about 10 cm in the Western Mediterranean. Although rissaga events had various durations, a standard length of 2 days has been selected for spectral analysis to allow a better comparison between events. Again a KB window of 512 min has been used to compute the spectra, resulting in 20 degrees of freedom per spectral estimate. The computed spectra at each site for all 7 rissaga episodes are shown in Fig. 5. An energy increase of one to two orders of magnitude relative to the background levels is clearly seen at all sites for periods shorter than 50 min. The most energetic event at all sites occurred on 24 May 2008.

4. Sea level forcing of rissaga events

Assuming that the spectra of the background periods represents the topographic response, the frequency response of the forcing for

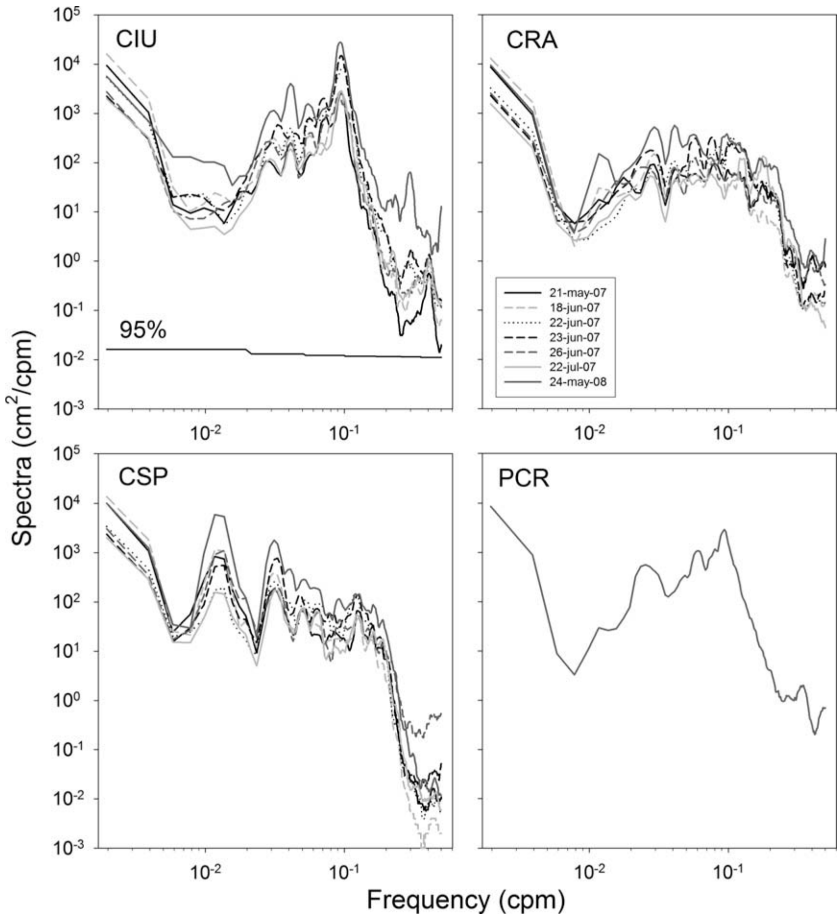

Fig. 5. Spectra of sea level oscillations for the 7 rissaga events. 95% confidence intervals for the spectra are also shown.

each site can be estimated as the ratio between the spectrum of an event and the spectrum of the corresponding background. The observed spectrum during a seiche event (S_{OBS}) as a function of frequency (f) may be considered as the sum of the energy associated with the atmospheric disturbance (S_R) and the energy of the background oscillations (S_{BK}) (Rabinovich, 1997; Monserrat et al., 1998):

$$S_{OBS}(f) = S_R(f) + S_{BK}(f). \tag{1}$$

If we assume linear topographic responses for the inlets, i.e. they only depend on frequencies but not on amplitudes, then:

$$S_R(f) = A(f)E_R(f);$$
$$S_{BK}(f) = A(f)E_{BK}(f), \tag{2}$$

where $A(f)$ represents the amplification due to the local topography, which is considered to be time independent, although strongly variable in space. E_R and E_{BK} are the external forcing during the event and background conditions, respectively. Linear theory is a good approximation except for the very large events, when sea level heights in the harbours are comparable with the water depth. Such effect was considered for Ciutadella Harbour previously (Marcos et al., 2004), but for the 2007–2008 events it is insignificant. The spectral ratio between the spectra for a rissaga event and background oscillations is:

$$R(f) = \frac{S_{OBS}(f)}{S_{BK}(f)} = \frac{E_R(f)}{E_{BK}(f)} + 1. \tag{3}$$

Therefore, the spectral ratio may be considered as the estimation of the energy content of the incoming long waves during the event, provided that E_{BK} is assumed to be an universal function of frequency (Kulikov et al., 1983). See Rabinovich (1997) or Monserrat et al. (1998) for additional details.

Theoretically the spectral ratios for different sites are expected to be identical for the same event. However, in practice, some differences exist between sites, in particular if the sites are located far apart. There are two main reasons of these differences. First of all surface waves arriving at each tide gauge are not necessarily the same since the ocean surface waves generated during an event have certain spatial structure and change their properties during propagation. Secondly, the atmospheric forcing itself also transforms when travelling over the region inducing ocean waves with a little different characteristics. In contrast to ordinary tsunami waves that are generated by a single seismic event, the meteotsunami waves cannot be considered as "free waves" but rather as "forced waves", being continuously generated by the atmospheric passage.

Fig. 6 shows the spectral ratios for each site for three most energetic events. For all episodes, the sea level forcing consists of waves with periods between 5 and 50 min. For the most energetic event of 24 May 2008 an increase of "external" energy is also observed at periods around 100 min. The energy of the external forcing for the different episodes is ordered in the same manner as energy inside the inlets at all sites, thus supporting the assumption of linearity.

Spectral ratios at the same site clearly differ from one episode to another, but certain similarities become apparent when spectral ratios for different sites are compared for the same event.

These similarities become more obvious when the temporal variations in the external forcing at different sites are compared.

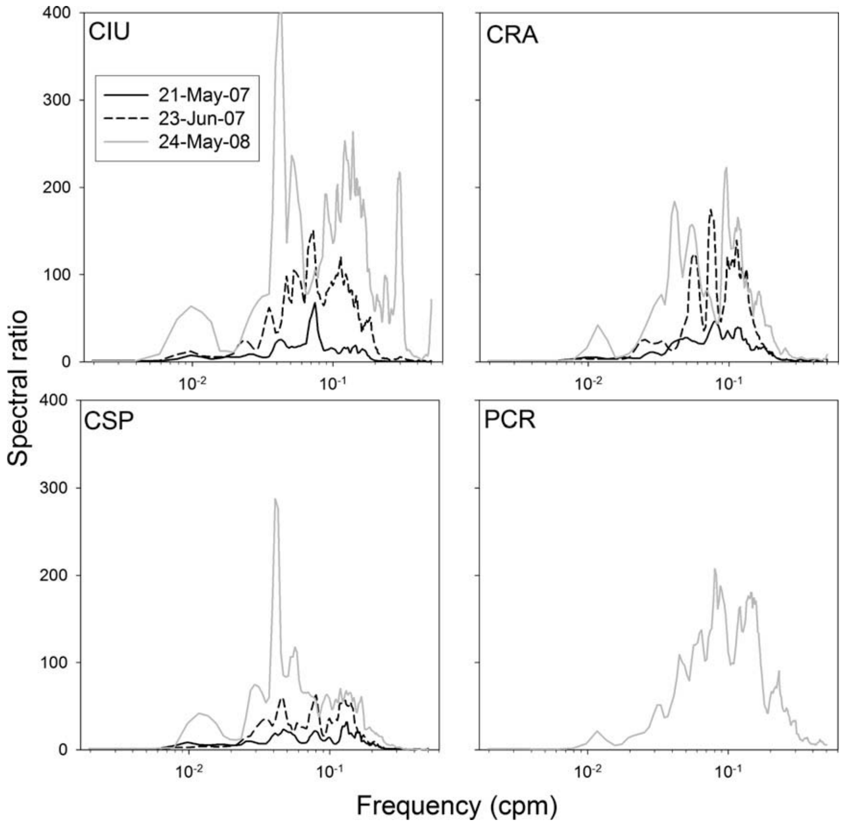

Fig. 6. External forcing of rissaga events at the four tide gauge locations.

The remarkable similarity is observed between Ciutadella and Cala Ratjada ratios. Spectral ratios computed for the three largest events on 22–23 June 2007, 22 May 2007 and 24 May 2008 for daily periods for CIU and CRA are shown in Figs. 7–9. Apparently for periods longer than 30 min the external sea level forcing at CIU and CRA is nearly the same. In contrast, two other stations, CSP and CIU (not shown here for brevity), at these periods have noticeably different spectral ratios, probably because of the reasons mentioned earlier.

For shorter periods, changes in atmospheric disturbances between Mallorca to Menorca are expected to play the major role in differences of the ocean response. Despite this particular feature of the region, the frequencies and magnitudes of the main peaks in the spectral ratios are normally quite close. The mean spectral ratios for sites CIU and CRA have been computed (black lines in Figs. 7–9) and can be considered as the spectral content of the sea level forcing causing rissaga events in the channel between Mallorca and Menorca.

Monserrat et al. (1998) also found obvious similarity in spectral ratios for Ciutadella and the adjacent inlet of Platja Gran, but these two inlets are located nearby. The present study has revealed clear similarity for the harbours located at much larger distances from each other. This result suggests that forcing characteristics, at least for longer periods, remain consistent for disturbances travelling from Mallorca to Menorca.

5. Summary and conclusions

Rapidly sampled sea level observations have been used to examine large amplitude seiche oscillations at four sites on the coasts of the Balearic Islands. The external sea level forcing responsible for the seiche amplification has been estimated using coastal tide gauge measurements. Each site has local resonant characteristics defined by the topography and bathymetry of the corresponding bay and the adjoining shelf. Their natural seiche modes, in the range of several minutes, have been described based on the results of the spectral analysis. The effects of local topography have been isolated by computing the background spectra of sea level oscillations during calm atmospheric periods when seiches were small inside the inlets. Under these calm conditions, two sites, CIU and PCR, were found to have very consistent responses (CIU and PCR), while the other two, CSP and CRA, display slightly variable responses for different periods of time. However, in general these differences are insignificant and background spectra may be considered as good proxies for the local resonant responses of a given site.

The background spectra, together with the spectra of seiche events, allow characterization of the external sea level forcing for each event and location. The frequency response of the forcing for each episode can be computed as the spectral ratio of the energy content of a seiche event and the background spectra. The more uniform is the background spectrum at the site, the more viable and accurate is the characterization of the external forcing. For all rissaga episodes, the energy content for the external forcing is found to be concentrated in periods between 5 and 50 min at all sites. Different forcings at specific sites for particular events are due not only to the differences in amplitudes of the incoming waves but also to the differences in the directions of propagating atmospheric waves relative to the inlet orientation and other topographic parameters.

It was demonstrated that external sea level forcing (source functions) at CIU and CRA are very similar, although the responses of the respective inlets (observed spectra during the rissaga episodes) differ significantly. Strong amplification of arriving waves in Ciutadella Inlet (at CIU site) is due to the elongated shape and shallowness of the inlet. The actual sea level oscillations at CRA are much smaller. The forcing is almost the same for signals with

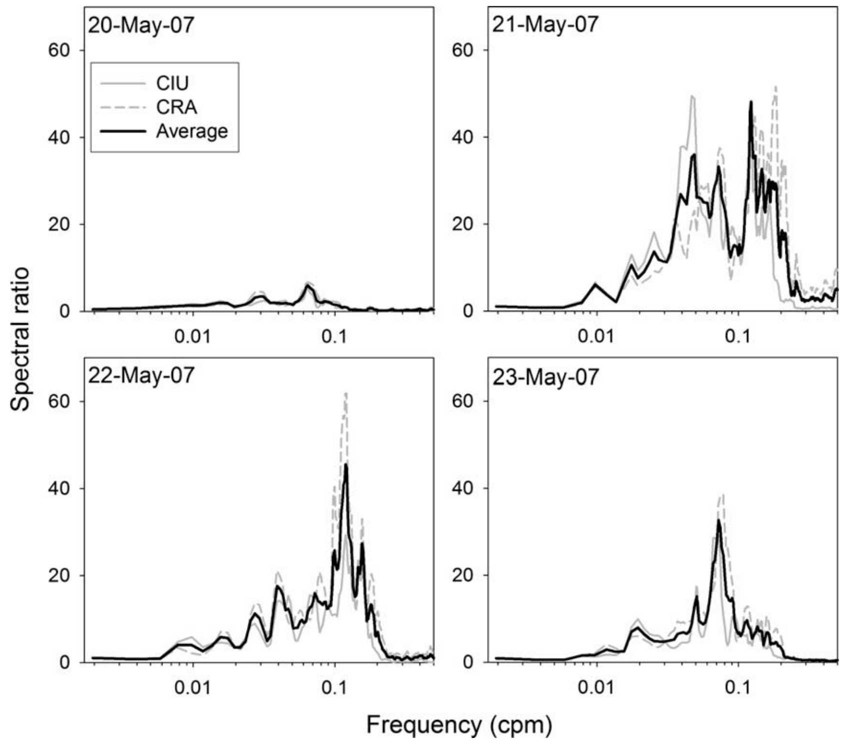

Fig. 7. Spectral ratios ("source functions") of daily spectra for rissaga event of 20–23 May 2007. Black line is the average of the spectral ratio at CIU and CRA. The spectral analysis results in 8 degrees of freedom.

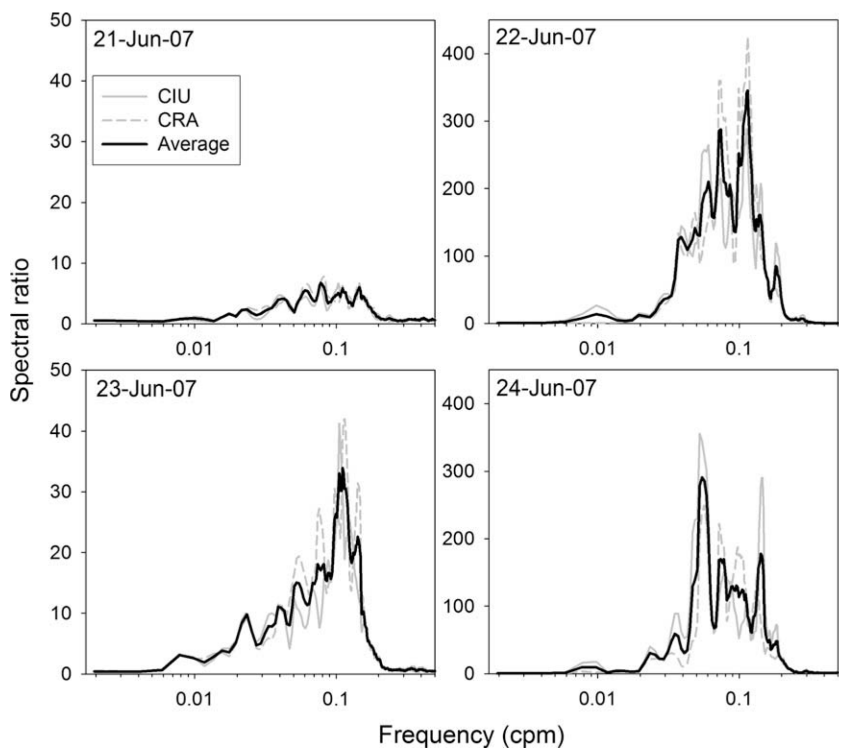

Fig. 8. As in Fig. 6 but for the episode on 21–24 June 2007.

frequencies lower than 30 $\min^{-1}$, and still very similar up to 10–8 $\min^{-1}$. For higher frequencies, changes in the atmospheric pressure signal as it travels from Mallorca to Menorca seem to play a major role and the generated sea level oscillations become very different.

Previous studies have demonstrated that rissaga events in Ciutadella Harbour are forced by atmospheric gravity waves travelling from the SW to NE with a phase speed of about 25 m/s. This means that, assuming that the atmospheric forcing properties do not change during the event and that generated ocean long waves

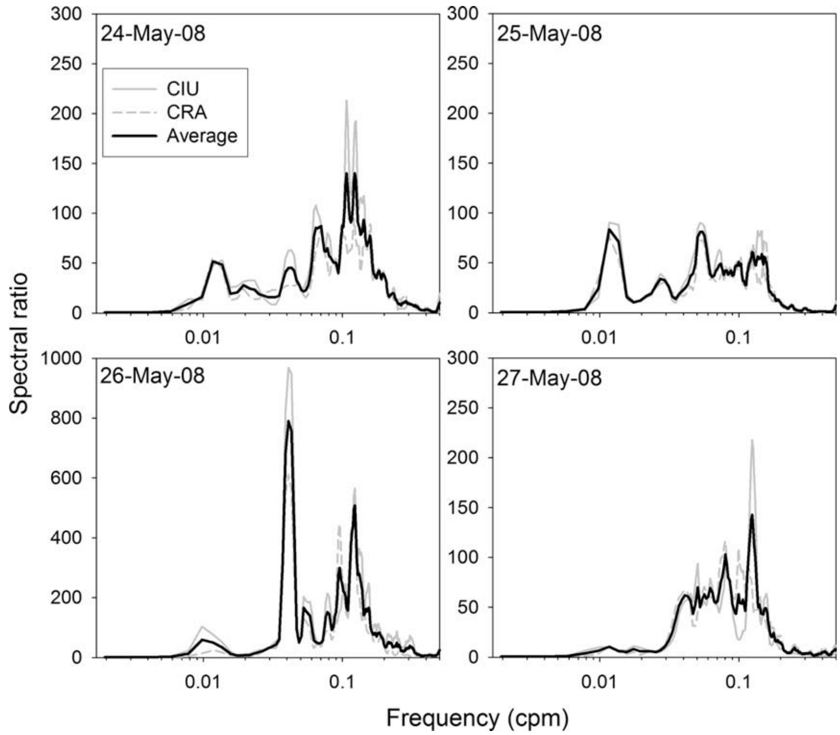

Fig. 9. As in Fig. 6 but for the episode on 24–27 May 2008.

are non-dispersive, the forcing waves would reach the CRA site approximately 40 min before reaching the mouth of CIU. Therefore, it could be possible to use sea level oscillations observed at CRA to predict incoming rissaga events in Ciutadella Harbour. These predictions could form part of a rissaga warning system designed to mitigate the damages inside the harbour. Similar approach probably could be used for some other regions of the Mediterranean where meteotsunamis occur, in particular for the eastern Adriatic: certain 'beacon' sites can play the role of predictors for ports and harbours with probable destructive seiches. The respective instruments may become a part of the elaborating North Atlantic and Mediterranean Tsunami Warning System (NEAMTWS).

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