Natural Hazards **18:** 27–55, 1998.

Generation of Meteorological Tsunamis (Large Amplitude Seiches) Near the Balearic and Kuril Islands

ALEXANDER B. RABINOVICH[1] and SEBASTIAN MONSERRAT[2]
[1]*Tsunami Center, P.P. Shirshov Institute of Oceanology, 36 Nakhimovsky Prosp., Moscow 117851, Russia;* [2]*Departament de Física, Universitat de les Illes Balears and Instituto Mediterráneo de Estudios Avanzados, IMEDEA, CSIC-UIB, Palma de Mallorca E-07071, Spain*

(Received: 24 September 1997; in final form: 18 May 1998)

Abstract. Extreme atmosphere-induced seiche oscillations occasionally occur in specific inlets and bays of the world ocean causing severe damage to coastal areas, ships and port constructions. Ciutadella inlet (Menorca Island, Western Mediterranean) can be singled out as a place where such large seiches, locally known as *rissaga*, are quite common. Similar (although weaker) oscillations are also regularly observed in bays of Shikotan Island (South Kuril Islands, northwestern Pacific). Several spectacular events in these regions, identified in the first part of this study (Rabinovich and Monserrat, 1996), are analysed to determine the atmospheric parameters responsible for the generation of large-amplitude seiches. Their generation mechanism was shown to be quite different from that causing ordinary background oscillations. Coincidence of some external factors and certain resonance effects seem to be necessary to produce the destructive waves. In particular, rissaga waves in Ciutadella inlet were found to be related to significant atmospheric disturbances propagating from the southwest, coinciding with the orientation of the inlet, and having a phase speed of about 30 m/s, which is close to the phase speed of long waves offshore from Menorca. Pronounced resonant properties of the inner basin strongly amplify incoming waves in Ciutadella inlet. In contrast, the bays of the northwestern coast of Shikotan Island are protected from normally incident atmosphere-induced waves by the elongated Kunashir Island, hence the whole situation there is not so favorable for the excitation of large seiches.

Key words: long waves, seiches, wave generation, tsunami, harbour resonance, atmospheric pressure oscillations, bottom pressure measurements, rissaga, Ciutadella, Balearic Islands, Kuril Islands.

1. Introduction

Extremely strong seiche oscillations are regularly observed in specific sea areas around the world, in particular in Nagasaki Bay, Japan (Honda *et al.*, 1908; Hibiya and Kajiura, 1982), Longkou Harbour, China (Wang *et al.*, 1987), near Sicily and in Trieste Bay, Italy (Defant, 1961; Wilson, 1972), in the Adriatic Sea (Hodžić, 1979) and the Aegean Sea (Papadopoulos, 1993), etc. These oscillations have the same temporal and spatial scales as ordinary tsunami waves and affect coasts in a similarly destructive way, but they are related to meteorological rather than to seismic forcing. Nomitsu (1935) and Defant (1961) used the term *'meteorological tsunamis'* for this type of waves.

Ciutadella Harbour (Menorca Island, Spain) is one of the places where such meteorological tsunamis are quite common. They are known by the local name of *'rissaga'* (Ramis and Jansà, 1983; Monserrat *et al.*, 1991). *Rissaga* waves with heights more than 3–4 m, causing severe damage to the coastal area, ships and harbour constructions, have been observed in Ciutadella several times. Similar oscillations also occur in some other harbours and inlets of the Balearic Islands and the Mediterranean coast of the Iberian Peninsula, although they are typically not so strong as in Ciutadella.

A lack of reliable observation data is the main factor limiting the understanding of the generation mechanism of *rissaga* waves (as well as large amplitude seiches in other regions of the world ocean). For that reason, in 1988, La Universitat de les Illes Balears (UIB), Palma de Mallorca, Spain, began field experiments to obtain simultaneous records of long sea surface waves and atmospheric fluctuations in the region of Ciutadella Harbour. A few spectacular cases of strong oscillations recorded during these experiments were examined by Monserrat *et al.* (1991) and Garcies *et al.* (1996).

Similar experiments were made by the Institute of Marine Geology and Geophysics (IMGG), Yuzhno-Sakhalinsk, Russia, in 1987–1988 on the southwestern shelf of Kamchatka (Kovalev *et al.*, 1991) and later in the region of Shikotan Island, the South Kuril Islands (Rabinovich *et al.*, 1993; Djumagaliev and Rabinovich, 1993). The main target of these observations was tsunami monitoring and the investigation of the resonant properties of the local topography. In 1989–1991 Vladimir Djumagaliev (Hydrophysical Observatory 'Shikotan', IMGG) installed three accurate inshore microbarographs and several bottom pressure stations in various bays and inlets of Shikotan Island.

It is interesting to generalize and compare the results of these experiments in two different areas of the world ocean (Balearic and Kuril islands). In the first part of this study (Rabinovich and Monserrat, 1996, referred to in the following text as RM1) the authors presented a review of abnormal seiche oscillations (meteorological tsunamis) observed in various sites of the world ocean with particular attention to the *rissaga* phenomenon and described the experiments and observation data in the areas of the Balearic and Kuril islands. The main purpose of analysing these data was to compare the response of various basins to the same atmospheric disturbance, and the same basin to different disturbances. The general spectral features of ocean waves and atmospheric pressure oscillations, as well as some particular cases of abnormal amplitudes, were studied for both regions. The strongest events were selected and examined and three different types of seiche oscillations were identified (*'impulse'*, *'resonance'*, and *'complex'*). Two key questions arose from this analysis:

- *Why are disastrous seiche oscillations generated only in some specific places in the world ocean, in particular in Ciutadella inlet?*

- *What kind of external factors (conditions) cause these strong events?*

The possible reasons why extreme seiches are observed only in a few inlets and harbours were discussed by Rabinovich (1993, section 3.11). Tintoré *et al.* (1988) and Gomis *et al.* (1993) tried to explain the origin of this phenomenon in Ciutadella; however, a lack of statistical significance prevented them from coming to definite conclusions. More detailed investigations are necessary to find an answer to this question.

The main purpose of the present study is to use the observation data to find an answer to the second question. Comparative analysis of seiche oscillations and atmospheric pressure fluctuations shows an evident correlation between these two processes. At the same time the nature of this correlation is far from straightforward: sometimes relatively weak pressure fluctuations generated significant seiches or, vice versa, strong atmospheric events did not cause noticeable seiche oscillations. Investigation of the inlet/bay response to fluctuations of atmospheric pressure and the external parameters determining the nature of this response is the main topic of the present paper. The atmospheric factors causing the generation of destructive *rissaga* waves in Ciutadella Harbour is the principal question. However, extensive statistical material obtained in other bays/inlets of the Balearic and Kuril Islands enable us to pose a wider problem to look at: *What kind of conditions are generally favorable for effective seiche generation?*

For the region of the Balearic Islands we used two sets of data (Figure 1a):

- 1989 – sea level at stations CS (Ciutadella inlet, Menorca Island), PS (Palma de Mallorca) and SS (Sol de Mallorca), the latter two in Palma Bay on Mallorca Island; atmospheric pressure at two stations, CP (Ciutadella) and PP (Palma);
- 1990 – sea level at station CS and atmospheric pressure at four stations, one in Ciutadella (CP), and three others in the vicinity of Palma de Mallorca (PP1, PP2, PP3) forming a triangle.

The 1989 atmospheric pressure data were not of high quality and there were many gaps in the record. The accuracy of the microbarographs were significantly improved in 1990; however that year was not so ‘rich’ in *rissaga* events as 1989 and there were no other sea level recorders working in 1990 except the Ciutadella station (CS).

For Shikotan Island we used fortnightly simultaneous records of May 1991 of long waves in three neighbouring bays on the northern coast of Shikotan: MS (Malokurilskaya Bay), OS (Otradnaya Bay) and KS (Krabovaya Bay), and atmospheric pressure fluctuations at stations MP (Malokurilsk), KP (Krabozavodsk), and DP (Dimitrova), forming a triangle sited 8–10 km apart (Figure 1b).

The detailed information on observation sites, instruments and data is presented in RM1. The main attention in the present paper is paid to strong events, i.e. to oscillations with trough-to-crest wave heights of more than 40 cm in Ciutadella (8 events in 1989 and 2 events in 1990) and more than 20 cm in Krabovaya Bay (3 events).

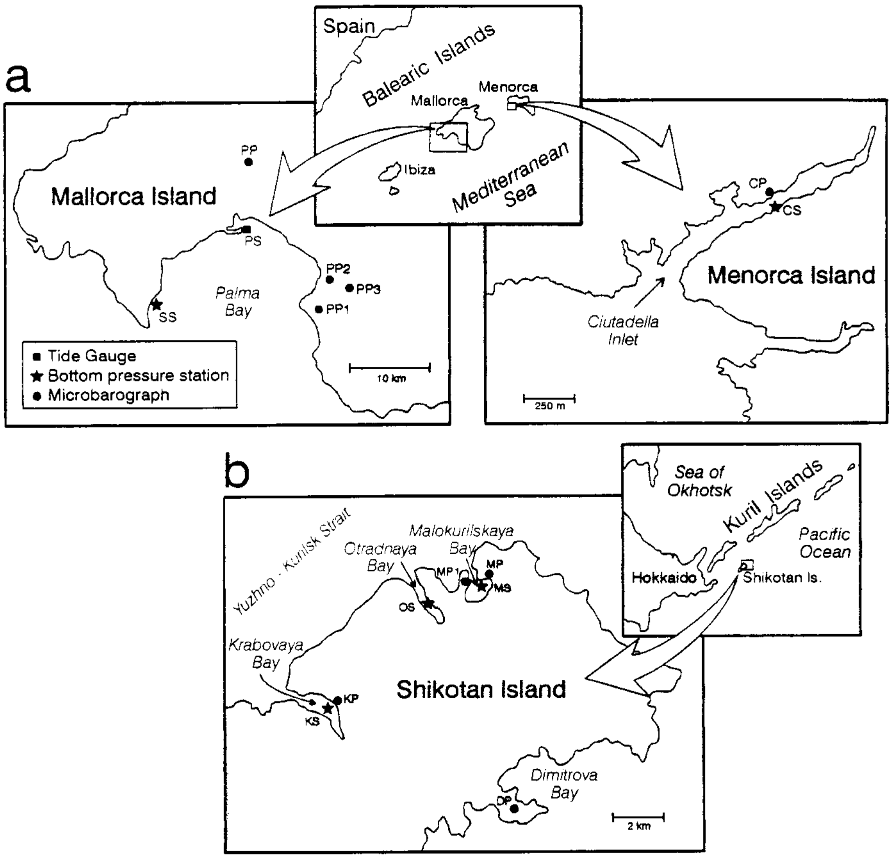

Figure 1. Location of the instruments in the region of the Balearic Islands, Western Mediterranean (a) and Shikotan Island, northwestern Pacific (b).

2. Comparative Analysis of Seiche Oscillations in Different Bays

Spectral analysis of long wave records in bays of the Balearic Islands (Ciutadella and Palma Bay) and Shikotan Island (Krabovaya, Otradnaya and Malokurilskaya) demonstrated that the corresponding spectra at these bays (with the exception only of Otradnaya) have prominent peaks caused by resonant features of the associated basins. In particular, dominant oscillations in Ciutadella inlet (10.6 min), Krabovaya (29.0 min) and Malokurilskaya (18.6 min) bays are related to the fundamental (Helmholtz) modes of these basins. Waves with a period of 24.0 min at Palma Bay are apparently excited by the first 'rocking' bay mode with a nodal line across the bay. The sets of eigenoscillations in different bays are strongly localized and independent of each other. At the same time, if seiches in neighbouring bays are generated by the same external forcing, then the intensity of these oscillations should be correlated and vary in time in a similar way. Comparison of wave heights (or rms) of seiches in different bays is important for the estimation of relative

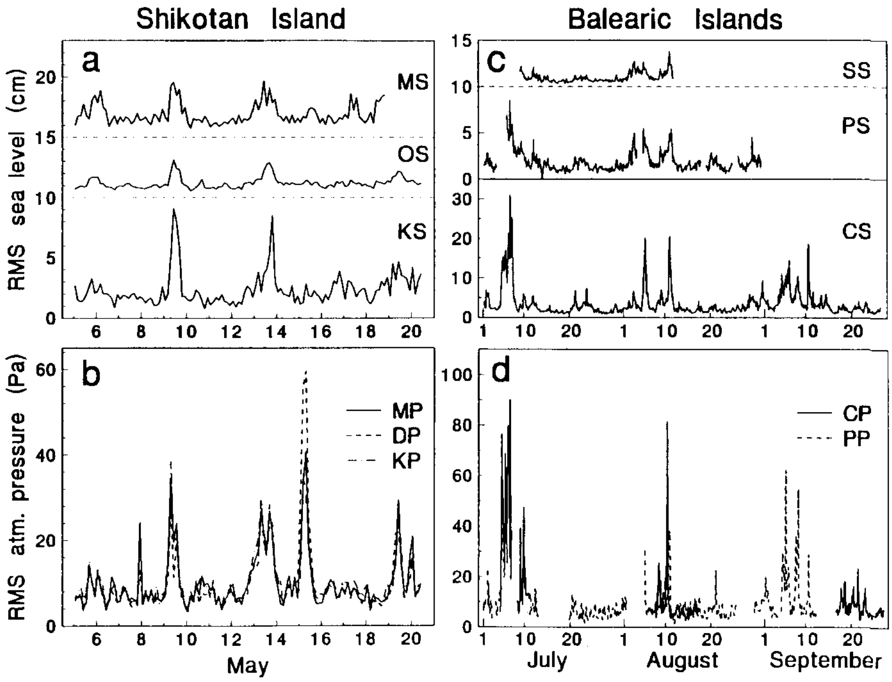

Figure 2. Rms variations of sea level (a) and atmospheric pressure (b) in the region of Shikotan Island during May 1991, and in the vicinity of the Balearic Islands during July–September 1989 (c, d).

topographic resonant features of the bays and for local marine hazard zoning of the corresponding coasts.

The residual (nontidal) series of sea levels (bottom pressure) were subjected to a high-pass Kaiser–Bessel filter (Harris, 1978) with a 3-hour cutoff period to isolate seiche oscillations observed in the bays. The statistical characteristics (variance, rms, maximum, and minimum) of seiches were computed over 6-hour overlapping segments with 3-hour shift. The same analysis was also carried out for atmospheric pressure fluctuations. As an example, rms time variations of sea level and atmospheric pressure in the region of Shikotan Island and in the vicinity of the Balearic Islands (for 1989) are presented in Figure 2. The plots show the simultaneous character of seiche activity in various bays of both regions. At the same time, it is clearly seen that there is a different reaction in different basins to similar forcing, thereby demonstrating the significant influence of local topography.

Scatter plots of 6-hour time-averaged rms sea level oscillations were constructed for various pairs of stations to examine the correlation and regression of seiches in different bays (Figure 3).

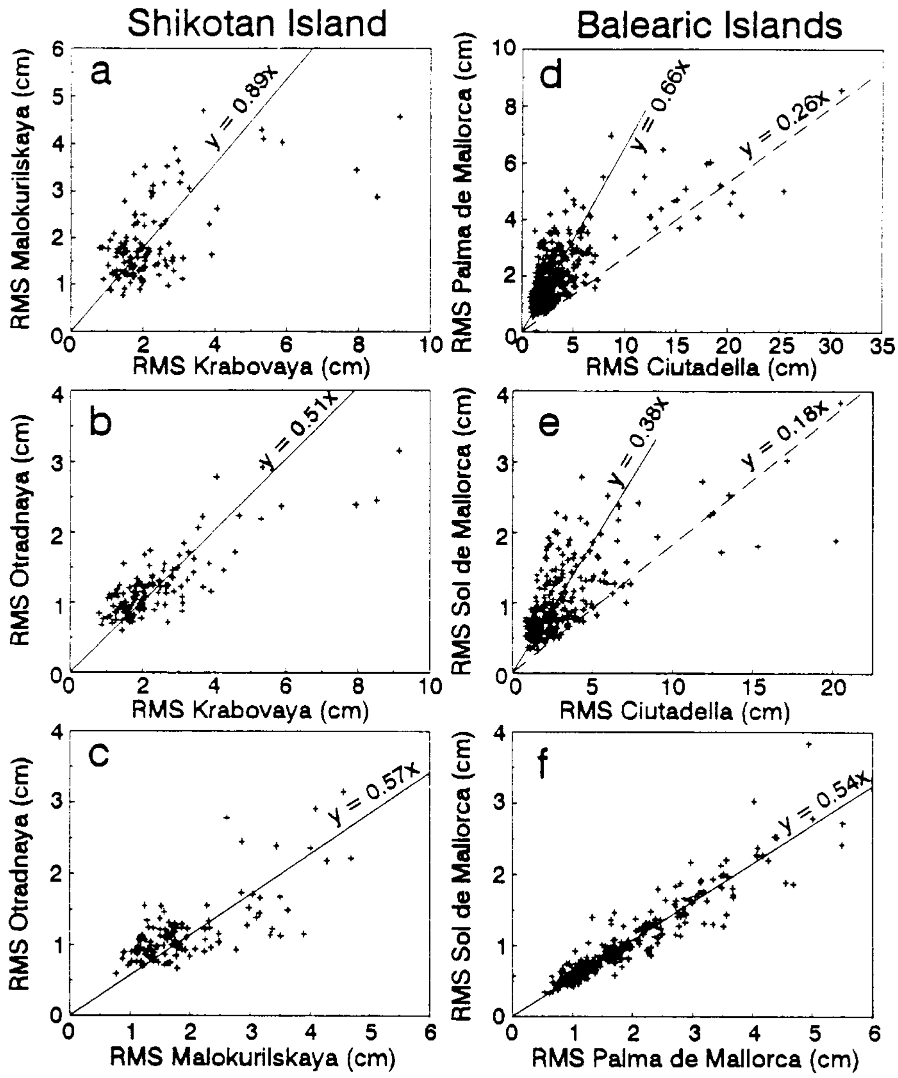

Figure 3. Scatter plots of six-hour time-averaged rms sea level oscillations for various pairs of stations in Shikotan Island (a)–(c) and the Balearic Islands (d)–(f). Regression relationships are indicated by solid lines. Dashed lines in (d) and (e) show the regresion relationships for $\sigma_{CS} > 10$ cm.

For Shikotan Island we obtained the following estimates:

$$\begin{array}{llll} \text{Krabovaya–Malokurilskaya} & \rightarrow & \text{Cor}_{(KS–MS)} = 0.61, & \sigma_{MS} = 0.89\sigma_{KS}, \\ \text{Krabovaya–Otradnaya} & \rightarrow & \text{Cor}_{(KS–OS)} = 0.83, & \sigma_{OS} = 0.51\sigma_{KS}, \\ \text{Malokurilskaya–Otradnaya} & \rightarrow & \text{Cor}_{(MS–OS)} = 0.72, & \sigma_{OS} = 0.57\sigma_{MS}. \end{array} \quad (1)$$

The same kind of analysis was also done using the maximum values and the results were very similar to those for the rms.

The ratios in (1) show a quantitative relationship between background long wave oscillations in three bays of Shikotan Island. The correlation is sufficiently high and the regression coefficients are stable, at least for $\sigma_{KS} < 7$ cm. It is interesting, however, that for a few cases when relatively strong seiches were observed in Krabovaya ($\sigma_{KS} > 7$ cm), seiches in Malokurilskaya and Otradnaya bays were much weaker than the regression coefficients in (1) suggest (Figure 3a, b).

For Ciutadella inlet and Palma Bay (Balearic Islands) the corresponding estimates calculated from simultaneous segments of the records CS, PS, SS were the following:

$$\begin{array}{lll} \text{Ciutadella–Palma} & \rightarrow \ \mathrm{Cor}_{(CS\text{–}PS)} = 0.76, & \sigma_{PS} = 0.34\sigma_{CS}, \\ \text{Ciutadella–Sol de Mallorca} & \rightarrow \ \mathrm{Cor}_{(CS\text{–}SS)} = 0.69, & \sigma_{SS} = 0.21\sigma_{CS}, \\ \text{Palma–Sol de Mallorca} & \rightarrow \ \mathrm{Cor}_{(PS\text{–}SS)} = 0.93, & \sigma_{SS} = 0.54\sigma_{PS}. \end{array} \quad (2)$$

It is not surprising that two stations located in the same bay (PS and SS) had much higher correlation than stations located in different bays. Nevertheless, the latter coefficients ($\mathrm{Cor}_{(CS\text{–}PS)}$, $\mathrm{Cor}_{(CS\text{–}SS)}$) were sufficiently high, demonstrating the mutual source of oscillations in Ciutadella and Palma Bay.

The estimates presented in (2) were obtained using all the accessible data. However, as is clearly seen in Figures 3d, e, the relationships between CS–PS and CS–SS are quite different for small and large values of σ_{CS}. For Ciutadella inlet the same effect as was mentioned above for Krabovaya Bay is present, but much more evidently. Here we have better statistics and can obtain independent estimates for two σ_{CS} ranges:

Background oscillations (for $\sigma_{CS} < 10$ cm)

$$\begin{array}{lll} \sigma_{PS} & = & 0.66\sigma_{CS} \\ \sigma_{SS} & = & 0.38\sigma_{CS}; \end{array} \quad (3)$$

Rissaga waves (for $\sigma_{CS} > 10$ cm)

$$\begin{array}{lll} \sigma_{PS} & = & 0.26\sigma_{CS} \\ \sigma_{SS} & = & 0.18\sigma_{CS}. \end{array} \quad (4)$$

The difference between (3) and (4) is quite significant. Comparison of Figure 2d with a plot of Ciutadella wave heights (Figure 11b in RM1) shows that the mean rms of $\sigma_{CS} = 10$ cm corresponds approximately to an extreme wave height $H_{CS} = 40$ cm chosen in RM1 as a criterion to select rissaga events. The larger background seiche heights in Ciutadella inlet, in comparison with Palma Bay, are probably related to the influence of local topography, i.e., to a specific form (elongated and shallow) and higher Q-factor in Ciutadella inlet (Q-factor is a parameter indicating energy decay at a resonant frequency: the higher Q is, the slower is the decay). It is well known (see, for example, Honda *et al.*, 1908; Nakano and Unoki, 1962) that seiche heights in elongated, narrow-mouthed and shallow inlets, like

Krabovaya or Ciutadella, are normally much larger than in wide open-mouthed bays, like Palma Bay. However, from (3) and (4) we see also that during the rissaga events, *relative amplification* of seiche oscillations in Ciutadella (in comparison with background oscillations) is much stronger than in Palma Bay. This implies that in Ciutadella different mechanisms are responsible for the generation of background seiches and *rissaga* waves. In explaining this effect we will probably also be able to explain why such strong seiches are regularly observed specifically in Ciutadella inlet.

Atmospheric pressure fluctuations measured at different stations, both of Shikotan and the Balearic Islands, were also compared. The 1990 data in Ciutadella and Palma, which were of higher quality than in 1989, were used in a correlation analysis. The results were as follows:

$$\begin{array}{lll} \text{Krabozavodsk–Malokurilsk} \rightarrow \mathrm{Cor}_{(\mathrm{KP–MP})} = 0.95, & L_{ij} = 8.2\,\mathrm{km}, \\ \text{Krabozavodsk–Dimitrova} \rightarrow \mathrm{Cor}_{(\mathrm{KP–DP})} = 0.84, & L_{ij} = 9.2\,\mathrm{km}, \\ \text{Malokurilsk–Dimitrova} \rightarrow \mathrm{Cor}_{(\mathrm{MP–DP})} = 0.88, & L_{ij} = 9.8\,\mathrm{km}; \end{array} \tag{5}$$

$$\begin{array}{ll} \text{Palma 2–Palma 1} \rightarrow \mathrm{Cor}_{(\mathrm{PP2–PP1})} = 0.96, & L_{ij} = 3.7\,\mathrm{km}, \\ \text{Palma 2–Ciutadella} \rightarrow \mathrm{Cor}_{(\mathrm{PP2–CP})} = 0.63, & L_{ij} = 109.5\,\mathrm{km}, \end{array} \tag{6}$$

where L_{ij} means the distance between the stations. The correlation of atmospheric pressure fluctuations measured at the same island was quite high, but that between Palma (Mallorca Island) and Ciutadella (Menorca Island), separated by more than 100 km was also significant. So when CP station was not working, we can use PP station for qualitative comparison with seiche activity in Ciutadella (see Figure 2c, d as an example). The regression coefficients for all pairs of microbarographs were close to 1.0. Hence, these stations have no specific orographic features amplifying or attenuating atmospheric waves.

3. ‘Rissaga’ of 10–11 August 1989 in Ciutadella

Observations during 1989 (July–September period)were rich in strong events. However, several gaps in the atmospheric data (1989 CP record) allowed us to investigate fully only a few cases. Monserrat *et al.* (1991), using the CP and CS records, examined the strongest rissaga event observed in Ciutadella on 4–7 July 1989 and found a good correlation between sea level oscillations and atmospheric pressure. The maximum oscillation was recorded at about 21.20 UT on 6 July with a trough-to-crest wave height of 197 cm occurring just when an abnormal train of atmospheric waves was crossing the region. The degree of matching between the increase of energy at a period band around the resonant period of the inlet for both sea-level and atmospheric pressure suggests that the large oscillations could be explained by local harbour resonance.

The event on 10–11 August 1989 was another and maybe even more interesting example. For this event all instruments were in operation and accurately recorded the corresponding abnormal atmospheric pressure/sea level oscillations in the investigation area (Figure 4). The PP record clearly shows a strong zigzag-like disturbance of atmospheric pressure with a double amplitude of about 200 Pa (2 mbar) which arrived at the Palma instrument about 19.00 UT on 10 August. This disturbance caused a noticeable intensification of seiche oscillations in Palma (PS) and Sol de Mallorca (SS). The same disturbance (but about twice the amplitude) reached the region of Ciutadella approximately one hour later, generating large-amplitude seiches in the inlet with a maximum trough-to-crest wave height of 87 cm slowly decaying with time (see CP and CS records in Figure 4). About 4 hours later, another atmospheric disturbance arrived first at Palma and then at Ciutadella, causing a significant increase in seiche oscillations. Just after this second disturbance a maximum wave height of 103.8 cm was recorded in Ciutadella inlet. There were no strong atmospheric pressure disturbances afterwards and subsequently the seiche oscillations in Ciutadella inlet slowly damped over a period of about 20 hours, apparently because of continuous energy pumping from the open sea and the the high Q-factor of this basin. This type was addressed in RM1 as an ‘impulse’ type and we clearly see that the trains of seiche oscillations were caused mainly by two impulses of atmospheric disturbances.

Some wave parameters can be estimated for this case. Simultaneous 4-hour records of the atmospheric pressure in Palma and Ciutadella (PP, CP) and sea level in Ciutadella (CS) during the initial period of the event are presented in Figure 5. The distance, Δr, between PP and CP stations is about 110 km. The time difference, $\Delta t \simeq 1h$, between wave crests observed at PP and CP stations indicates that atmospheric waves propagated from the area of Palma Bay to Ciutadella inlet with a phase speed $U = \Delta r/\Delta t \approx 30$ m/s. A very similar value of the atmospheric wave speed for this event was obtained by Monserrat *et al.* (1991) from cross-correlation estimates using PP and CP records. Such phase speed is typical for atmospheric buoyancy waves (Gossard and Hooke, 1975). The most energetic period of the corresponding oscillation (Figure 5a) is approximately 1 hr, which means that the atmospheric wave had a length of about 110 km; i.e., the wavelength was about the same as the distance between Palma and Ciutadella.

From Figure 5 we see that the first atmospheric disturbance (ΔP), ranging from 200 Pa (2 mbar) in Palma to 400 Pa (4 mbar) in Ciutadella, generated seiches in the inlet with a maximum height of 87 cm, which was reached during the third oscillation. The wavelength of the atmospheric disturbance was two orders higher than the length of the inlet (about 1 km), so the direct generation of seiches is highly unlikely (this question was discussed by Gomis *et al.*, 1993). The dominant atmospheric period (1 hr) was much greater than the resonant period of Ciutadella Harbour (10.6 min). Thus, the observed strong seiches could not be explained by local resonance in the harbour. We may hypothesize that the atmospheric disturbance generated long waves in the open sea and then these waves approached the western coast of Menorca, exciting the large seiches in Ciutadella.

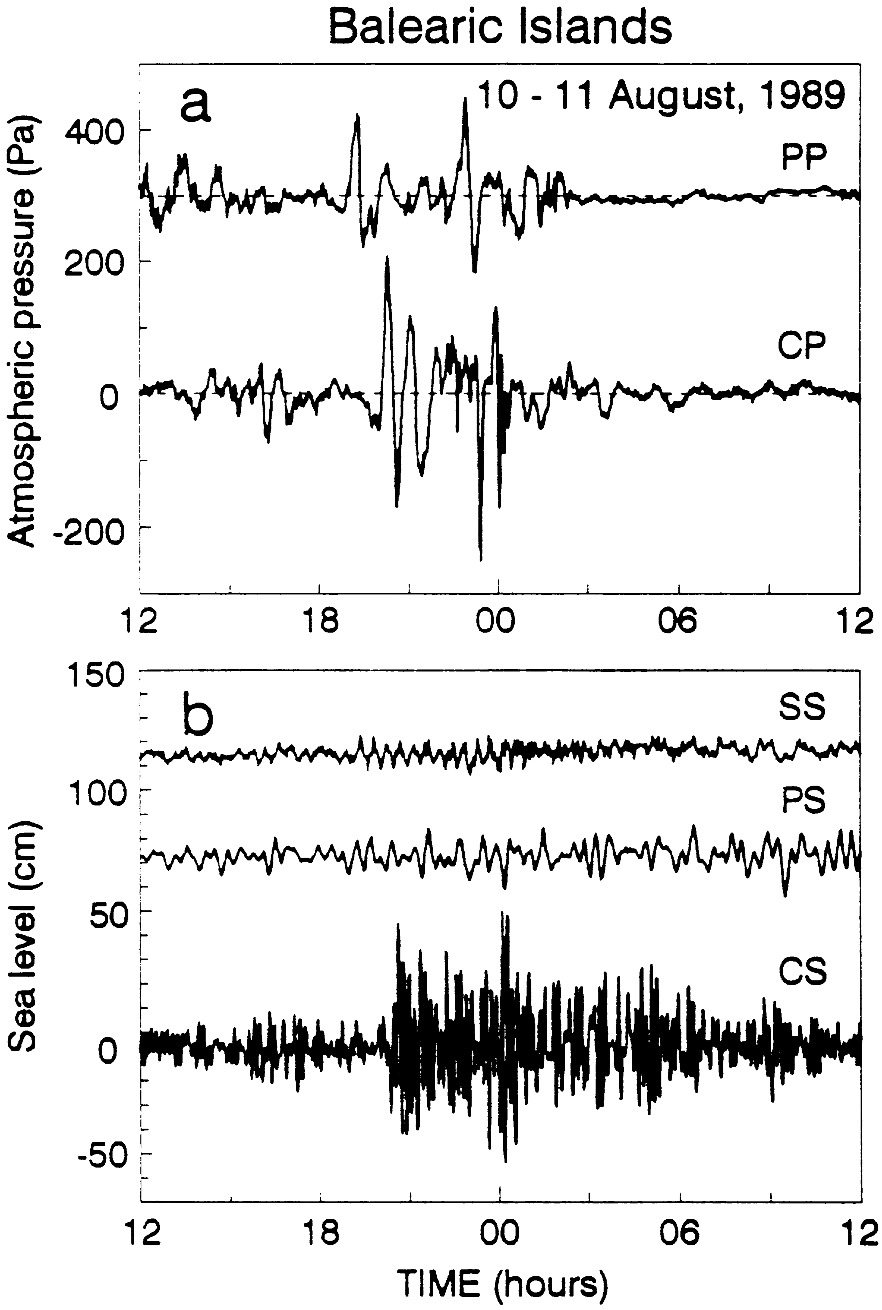

Figure 4. High-pass filtered atmospheric pressure records in Palma (PP) and Ciutadella (CP) (a), and simultaneous residual sea level records in Sol de Mallorca (SS), Palma (PS), and Ciutadella (CS) (b), during the *'rissaga'* event on 10–11 August 1989. Signals have a different offset for better visualization.

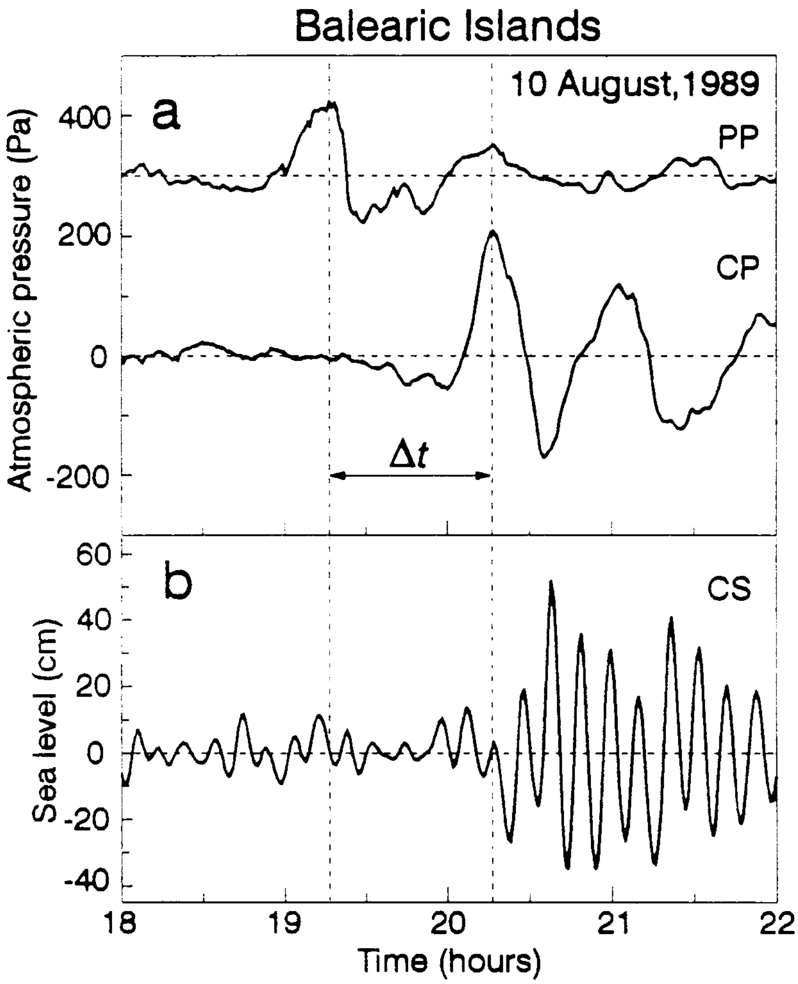

Figure 5. Atmospheric pressure records in Palma (PP) and Ciutadella (CP) and sea level record in Ciutadella (CS) during the initial period of the event shown in Figure 5. The time difference between the initial wave crests observed at PP and CP stations is indicated (Δt).

The barotropic response of sea level to an atmospheric pressure disturbance ΔP can be expressed as (Proudman, 1953)

$$\zeta = \frac{\zeta_0}{1 - U^2/c^2}, \tag{7}$$

where $c = \sqrt{gh}$ is the phase speed of long waves, h is the depth, ρ is the water density, $\zeta_0 = -\Delta P/\rho g$ is the static sea level, and g is the acceleration of gravity. When $U \ll c$ (a typical situation for the open ocean) $\zeta \simeq \zeta_0$, i.e. 1 cm of sea level rise corresponds to 1 mbar of atmospheric pressure fall (*'inverted barometer law'*). In our case $\zeta_0 = 2$–3 cm only. However, the outer shelf between Mallorca and Menorca islands has a depth of approximately 100 m, so the long waves propagating over the shelf have the speed $c \simeq 31$ m/s, very close to the phase speed of the atmospheric disturbances. The practically simultaneous amplification of the atmospheric waves and seiches in the vicinity of Ciutadella Harbour clearly demonstrates the coincidence of these speeds. Thus, the so called *'Proudman resonance'* (Rabinovich, 1993) was very likely to occur during this event, and the observed efficient generation of long waves propagating over the shelf might be expected.

A very similar situation was described by Hibiya and Kajiura (1982), who tried to explain 278 cm *'abiki'* waves recorded on 31 March 1979 in Nagasaki Bay, Kyushu Island. They found that open sea waves were generated by a distant atmospheric pressure disturbance with an amplitude of about 3 mbar. This disturbance propagated over the East China Sea with a speed of 31 m/s, comparable with the long wave speed 22–38 m/s on the wide shelf in the region. Due to the resonant situation, the generated long waves were amplified to about 15 cm by the time they reached the entrance of Nagasaki Bay. Additional amplification of these waves in the bay was related to local resonant features of the inner basin.

Hibiya and Kajiura (1982) pointed out that (7) is not suitable for the resonant situation, when $U \simeq c$. Instead, the problem should be treated as an initial value problem; the generated wave height in this case increases linearly with time and can be estimated as

$$\zeta = \frac{\zeta_0}{L_P}\frac{\chi_w}{2}, \tag{8}$$

where χ_w is the distance over the sea travelled by the atmospheric disturbance, $L_P = U\Delta t_P$ is the spatial scale of the frontal side of the disturbance (a distance between the disturbance maximum and and undisturbed surface), Δt_P is the corresponding temporal scale. The ratio ζ_0/L_P in (8) is in fact the gradient of atmospheric pressure. Expression (8) shows that sea level response to atmospheric activity increases with an increase of pressure gradient and travel distance. In our case $U = 30$ m/s, $\Delta t_P = 15$ min, $\zeta_0 = -\Delta P/\rho g$ = 2–3 cm. Thus, if we assume that $\chi_w = 200$ km, ζ would increase by a factor of approximately 3 and reach 8–12 cm. The further growth of this wave in Ciutadella inlet up to 87 cm was apparently related to resonant amplification inside the inlet. This example demonstrates the evident similarity of generation of extreme seiches in two different regions and the important role of Proudman resonance in this process (see also Ewing *et al.*, 1954; Donn and Balachandran, 1969).

4. Correlation of Atmospheric Activity and Seiche Oscillations

As follows from expressions (7) and (8) the response of sea level to an atmospheric disturbance is linearly proportional to the magnitude of the disturbance. So it is worth considering the correlation of atmospheric pressure fluctuations and seiches in bays and inlets of the Balearic and Kuril Islands.

These disturbances can be quite different. In particular, consider the following examples (Wilson, 1972; Rabinovich, 1993):

- barometric fluctuations, atmospheric internal gravity waves, trapped atmospheric waves;
- atmospheric fronts (especially cold fronts), pressure jumps, squall lines, wind gusts, and gales;
- deep cyclones, typhoons, hurricanes and related atmospheric pressure oscillations.

It is natural to assume that various types of disturbances affect the sea surface in a different way, probably explaining the different types of observed seiches.

Defant (1961) emphasized that in mid-latitudes these disturbances move approximately eastward, therefore larger and more frequent seiches are normally observed in bays and inlets with westward-facing entrances. This is just the case of Ciutadella inlet (Figure 1a), in contrast, for example, to Mahon, another narrow elongated inlet located on the eastern side of Menorca Island, where very strong seiches have never been reported (see RM1). Three Shikotan bays (Malokurilskaya, Otradnaya, and Krabovaya) are situated on the northwestern side of Shikotan Island (Figure 1b), i.e. are also affected by prevailing eastward-moving atmospheric processes.

Unquestionable correlation of atmospheric activity and seiches is clearly seen for the regions of the Kuril and Balearic islands. All cases of seiche amplifications in Shikotan bays occurred during an increase of intensity of atmospheric pressure fluctuations (Figure 2a, b). The same picture was observed also in 1989–1990 in Ciutadella inlet: intensification and weakening of seiche oscillations corresponded well to changes of atmospheric pressure (Figures 2c, d, and 6a). Ramis and Jansà (1983) also reported that rissaga events in the vicinity of the Balearic Islands occur under particular atmospheric conditions and that significant atmospheric pressure oscillations were recorded by barographs during such events. Three cases of extraordinary sea level oscillations in the eastern Adriatic, described by Hodžić (1979), were also associated with trains of intense atmospheric waves.

Thus, the increase of seiche intensity normally corresponds to atmospheric activity with the exception of seiches generated by tsunamis (cf. Murty, 1977) or internal sea waves (cf. Chapman and Giese, 1990).

However, the opposite is not true: sometimes even very strong atmospheric events do not excite seiches. For example, a train of significant atmospheric waves propagated over Shikotan Island on 15 May 1991 but did not cause any seiche oscillations at Malokurilskaya, Krabovaya, and Otradnaya bays (Figure 2a, b). The same situation was observed in the region of Ciutadella on 31 August, 9 and 13 September 1990 when atmospheric pressure disturbances did not generate noteworthy seiches in the inlet (Figure 6a). We also see that the disturbances of very similar intensity on 24 and 25 September 1990 both generated large seiches, but of different magnitude, in the latter case they were much stronger than in the former (Figure 6a).

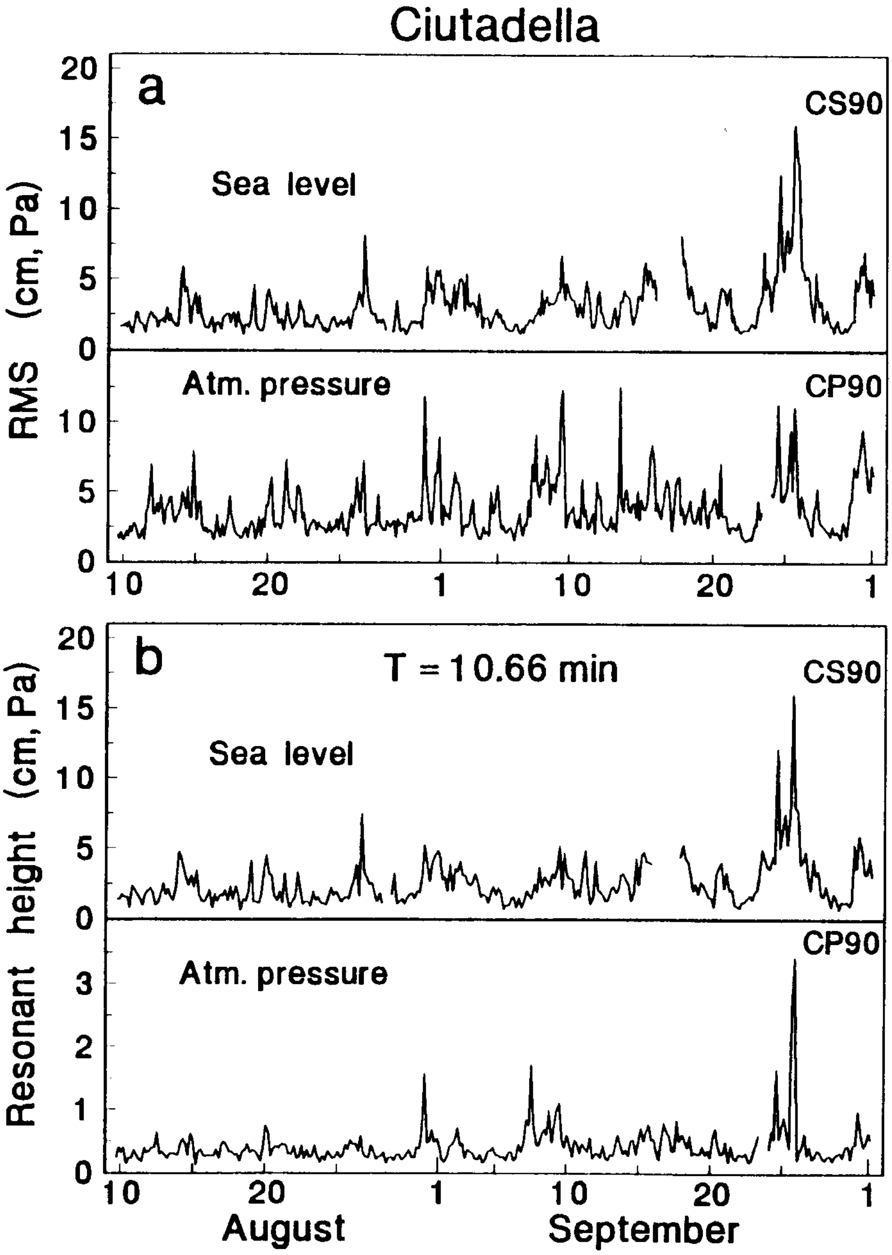

Figure 6. Rms variations of sea level and atmospheric pressure in Ciutadella inlet for August–September 1990 (a), and the same for resonant deviations (T = 10.66 min) (b).

The complicated character of the correlation between atmospheric pressure fluctuations and seiches is clearly seen in Figure 7a (scatter plots for Krabovaya and Malokurilskaya bays, not shown here, are similar). The scatter points of rms sea level and atmospheric pressure (estimated using 6-hour segments of filtered data with an overlapping of 3 hours) are mainly located within specific ranges:

$$\begin{aligned} 0.28\sigma_{CP} \leq\ & \sigma_{CS} \leq\ 2.49\sigma_{CP}, \\ 0.07\sigma_{KP} \leq\ & \sigma_{KS} \leq\ 0.57\sigma_{KP}, \\ 0.10\sigma_{MP} \leq\ & \sigma_{MS} \leq\ 0.67\sigma_{MP}, \end{aligned} \tag{9}$$

where sea level is in cm and atmospheric pressure is in Pa

These points were used to estimate correlation and regression of the corresponding oscillations:

$$\begin{aligned} &\text{Ciutadella, 1990} \rightarrow \text{Cor}_{(CP\text{--}CS)} = 0.54, \quad \sigma_{CS} = 0.79\sigma_{CP}, \\ &\text{Krabovaya} \rightarrow \text{Cor}_{(KP\text{--}KS)} = 0.46, \quad \sigma_{KS} = 0.19\sigma_{KP}, \\ &\text{Malokurilskaya} \rightarrow \text{Cor}_{(MP\text{--}MS)} = 0.37, \quad \sigma_{MS} = 0.15\sigma_{MP}, \end{aligned} \tag{10}$$

The atmospheric pressure fluctuations were weaker in Ciutadella (in 1990) than in the region of Shikotan. However, the sea level oscillations were significantly stronger in Ciutadella. The corresponding regression coefficients for Ciutadella are approximately 5 times larger than for Shikotan. This means that the extreme seiches observed in Ciutadella are related specifically to certain resonant features of the inlet itself but not to extraordinary atmospheric events occurring in the region.

The correlation between atmospheric pressure and sea level is significant but not high. So, we can conclude that there are some other important parameters of atmospheric processes (besides intensity) which determine heights of the generated seiches. In particular, the effectiveness of seiche generation probably depends on the amount of atmospheric energy at *resonant frequencies* rather than on the total energy of the atmospheric disturbances.

A multiple filter technique (Dziewonski *et al.* (1969); Kulikov *et al.*, 1996) was used to study changes of the wave amplitude $A(f, t)$ for specific extreme events as function of the frequency f and time t. The constructed '$f - t$ diagrams' (Figure 8) show that the frequencies of dominant oscillations during the events remain steady in time and correspond to the fundamental resonant frequencies of the basins (10.6, 29.0, and 18.6 min for Ciutadella inlet, Krabovaya and Malokurilskaya bays, respectively). At the same time there are several trains of oscillations probably related to a 'pumping' of atmospheric energy (directly or through the waves generated over the shelf) into seiches. Assuming that oscillations in a bay present a linear response of the system to external forcing, we expect a higher correlation between seiche intensity and atmospheric energy specifically at the resonant frequencies of the corresponding bays.

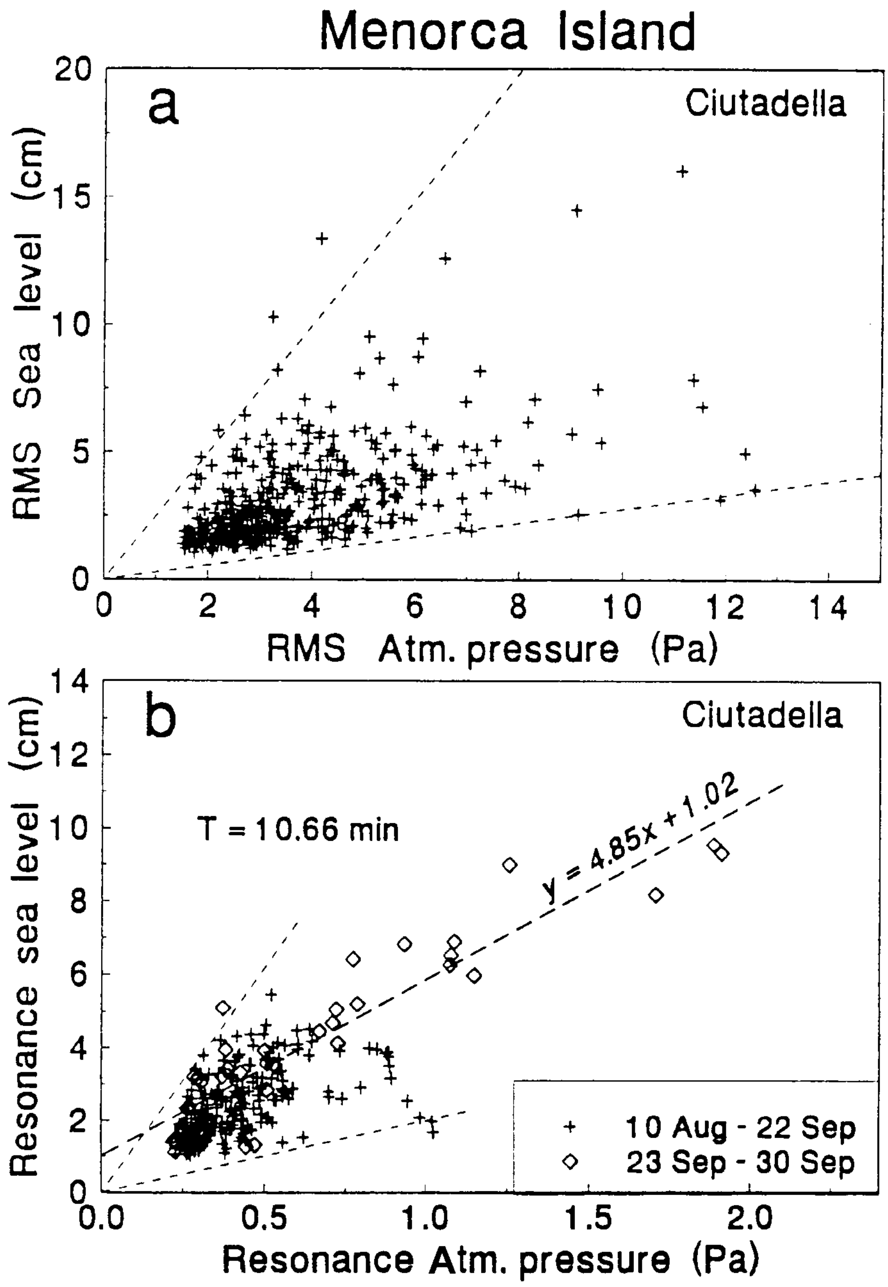

Figure 7. Scatter plot of six-hour time-averaged rms for sea level and atmospheric pressure in Ciutadella (a), and the same for the resonant deviations (b). The dashed line indicates linear regression for the active period (23–30 September 1990).

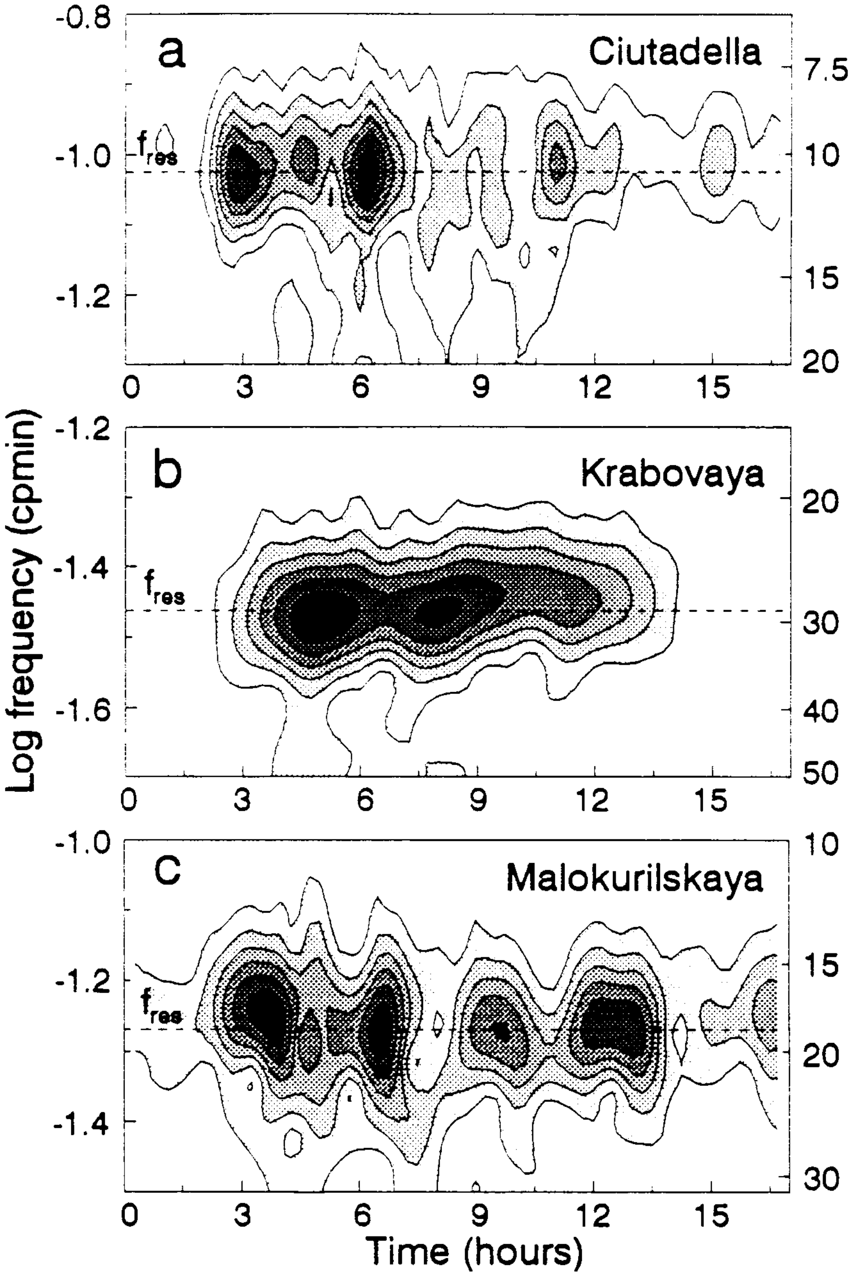

Figure 8. Spectral amplitude evolution ($f - t$ diagrams) for Ciutadella (a), Krabovaya (b) and Malokurilskaya (c) for 20 hours around selected events. The fundamental resonance frequency of each inlet is marked.

Standard deviations at resonance frequencies ('resonant deviations' hereafter) both for sea level and atmospheric fluctuations were estimated as

$$\hat{\sigma} = \left[\Delta f \sum_{j=k-1}^{j=k+1} S(f_j) \right]^{1/2}, \tag{11}$$

where $S(f_j)$ is the spectral density at the frequency f_j, f_k is the frequency nearest to the resonance and Δf is the frequency resolution of the corresponding spectrum. We used Δf = 0.00782 cpm for Ciutadella and Δf = 0.00391 cpm for Krabovaya and Malokurilskaya bays. The parameter k was chosen to be: k = 12 for Ciutadella ($T_k = 1/f_k$ = 10.66 min), k = 9 for Krabovaya (T_k = 28.4 min) and k = 14 for Malokurilskaya (T_k = 18.3 min).

Figure 6b presents simultaneous evolution of resonant deviations of sea level and atmospheric fluctuations in Ciutadella computed using independent time segments of 256 min. Agreement between these two graphs is much better than between the general rms deviations (Figure 6a). In particular, the amplification of atmospheric activity observed on 31 August, 9 and 13 September 1990 were not accompanied by intensification of seiches. However, the corresponding atmospheric maxima disappeared in Figure 6b. Apparently, they were associated with atmospheric waves having periods very different from the resonance period 10.6 min of Ciutadella inlet and this is the reason why they did not generate significant seiches.

It becomes also clear why atmospheric disturbances of similar intensity on 24 and 25 September 1990 generated seiches of quite different height (Figure 6a): the latter disturbance had much more energy at frequencies close to the resonance frequency of the inlet (Figure 6b).

A scatter plot for resonance deviations similar to the one computed for general rms deviations (Figure 7a) is shown in Figure 7b. The results were found to be quite different for the relatively quiet period between 10 August and 22 September 1990 and for the active period at the end of September. For the quiet period the general picture was similar to that observed for general rms deviations (Figure 7a), the correlation value was practically the same and the scatter points were also located within the particular range:

$$\text{Ciutadella (calm)} \rightarrow \text{Cor}_{(\text{CP--CS})} = 0.53, \quad 1.97\hat{\sigma}_{\text{CP}} \leq \hat{\sigma}_{\text{CS}} \leq 12.4\hat{\sigma}_{\text{CP}}. \tag{12}$$

However, for the active period between 23 and 30 September 1990 the correlation between resonant atmospheric and sea level deviations was very high:

$$\text{Ciutadella (active)} \rightarrow \text{Cor}_{(\text{CP--CS})} = 0.92, \quad \hat{\sigma}_{\text{CS}} = 4.85\hat{\sigma}_{\text{CP}} + 1.02. \tag{13}$$

Such a character of the correlation apparently has an important physical meaning. Atmospheric oscillations in the vicinity of Ciutadella are probably the most important but not the only source for the seiches in the inlet. These seiches could also be caused by wind waves, internal waves, or external long waves generated by wind or atmospheric pressure far away from Menorca Island. The constant term in the linear fit expression (13) just shows that seiches in Ciutadella exist even when there are no atmospheric oscillations at all. In a quiet period these secondary factors plays a role comparative with the role of atmospheric oscillations. However, in an active period the role of the latter increase significantly. As a consequence, the relative percentage of the correlated resonant energy is much higher for active than for quiet periods.

Results of a similar analysis applied to the region of Shikotan Island are presented in Figure 9. The correlation coefficients between resonant atmospheric and sea level deviations increased in comparison with the values presented in (10), but they were still not high; the scatter points were located in particular ranges:

$$\begin{array}{lll} \text{Krabovaya} \rightarrow \mathrm{Cor}_{(\mathrm{KP-KS})} = 0.53, & 0.17\hat{\sigma}_{\mathrm{KP}} \le \hat{\sigma}_{\mathrm{KS}} \le 1.60\hat{\sigma}_{\mathrm{KP}}, \\ \text{Malokurilskaya} \rightarrow \mathrm{Cor}_{(\mathrm{MP-MS})} = 0.56, & 0.45\hat{\sigma}_{\mathrm{MP}} \le \hat{\sigma}_{\mathrm{MS}} \le 3.53\hat{\sigma}_{\mathrm{MP}}. \end{array} \qquad (14)$$

All attempts to further improve the results by varying the averaging intervals failed. Apparently very similar correlation values for Krabovaya, Malokurilskaya and Ciutadella inlet (quiet period) presented in (14) and (12) are not just accidental, but reflect the similar sources and generation mechanisms of background seiche oscillations in all three basins. In contrast, two abnormal events in Ciutadella on 24 and 25 August 1990 evidently had a different nature and accordingly much higher correlation coefficient.

The main unsolved problem for the region of Shikotan Island remained the same: why the train of remarkable atmospheric waves on 15 May 1991 did not generate seiches in Krabovaya and Malokurilskaya bays? As is clearly seen in Figure 9, the atmospheric deviations at resonance periods 28.4 and 18.3 min on 15 May were not weaker than on 9 and 13 May when significant seiches were recorded in these two bays. We assume that the reason is related to the direction and phase speed of the corresponding atmospheric waves. This question is examined in the next section.

There is one more item which should be noted. It was shown in RM1 that the spectra of atmospheric pressure fluctuations both in the region of the Balearic and Kuril islands are normally smooth and monotonic and decrease with increasing frequency according to an $\omega^{-2.3}$ power law in good agreement with observations in other regions (cf. Kovalev *et al.*, 1991). So, we expect that the relative role of atmospheric pressure in seiche generation also decreases with an increase in the resonance frequency of the corresponding bays. However, the strong seiches in Ciutadella, having the shortest period of the three bays, demonstrates once again the importance of peculiar topographic features of the inlet in seiche generation. At the same time the results show also that the generation of strong seiches by resonance with external forcing is only one of the possible forcing mechanisms. As was demonstrated in Section 3, *rissaga* waves on 10–11 August 1989 in Ciutadella inlet with wave height more than 1 m were generated when the most energetic

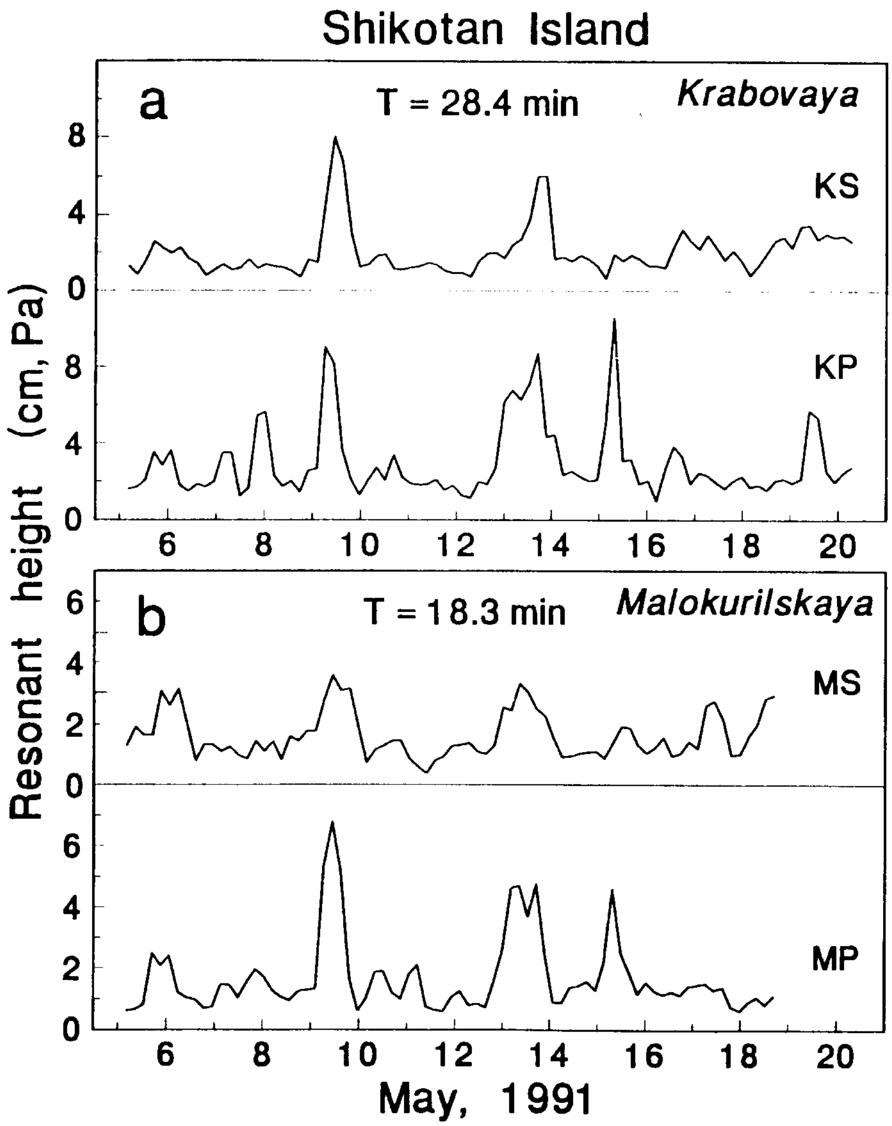

Figure 9. As in Figure 6b but for Krabovaya and Malokurilskaya bays.

atmospheric waves had a typical period of about 1 hr, i.e. approximately 6 times larger than the resonance period of the inlet.

5. Influence of Atmospheric Wave Parameters on Seiche Generation

In the two previous sections we examine the correlation between atmospheric activity and the intensity of seiche oscillations in three bays. However, the direct generation of seiches by atmospheric disturbances in such small basins is scarcely effective. In fact, as was discussed in Section 3, these seiches would be induced by the atmosphere through *a two-step generation mechanism*: (1) Generation of long waves in the external area by direct atmospheric forcing; (2) generation of seiches in the inner basin by the long waves coming through the bay mouth. Consequently, high correlation of seiches and atmospheric fluctuations is expected only if this long wave generation occur in the vicinity of the bay or if the characteristics of the atmospheric waves become stable over large distances. From this point of view examination of spatial coherence of atmospheric fluctuations is a question of high importance. The parameters and efficiency of long wave generation over the shelf strongly depend on the direction (relative to the coastline) and phase speed of the propagating atmospheric waves. Estimation of these atmospheric wave properties are the topics of this section.

5.1. SPATIAL COHERENCE OF ATMOSPHERIC FLUCTUATIONS

We may assume that the spatial scale of the atmospheric forcing of sea level does not exceed the scales of the coherent atmospheric processes with similar periods. Different pairs of microbarographs in the region of the Balearic and Kuril Islands allowed the comparison of these scales for both areas. For this analysis we used four pairs of stations, two pairs for the Balearic Islands: PP2–PP1 (distance 3.7 km) and PP2–CP (109.5 km); and two pairs for the Kuril Islands: MP–KP (8.2 km), and MP–MP1 (1.0 km). The coherence estimated for the latter pair was taken from Rabinovich (1993). The microbarograph MP1 was temporarily deployed at the Hydrometeorological station Malokurilsk on the opposite side of Malokurilskaya Bay from the Hydrophysical Observatory in Shikotan (see Figure 1). So, having four pairs separated by different distances, we were able to examine variations of coherence as a function of period and distance.

The presented estimates (Figure 10) show that in the general case the atmospheric pressure has negligible coherence for oscillations with periods less than 1 hour at distances greater than 10 km. For waves with periods $T < 10$ min the radius, L, of coherence $\gamma^2 > 0.2$ was only about 3 km. In one of the few papers related to this question, Herron *et al.* (1969) observed a similar coherence structure but with a little slower decay (L = 30 km for T = 1 hour, L = 7 km for T = 10 min).

Weak spatial coherence of high-frequency background atmospheric processes demonstrates that they cannot be an effective mechanism of the generation of sea level oscillations. The whole picture changes dramatically during strong atmospheric events. Monserrat and Thorpe (1992) found a train of significant atmospheric waves propagating over the region of the Balearic Islands on 24–26 September 1990. The estimates of spatial coherence for the most energetic 12 hours of this event show a considerable increase of coherence (Figure 10c) and a corresponding decrease of the minimum periods of significant coherence. Such a situation is clearly much more favorable for the generation of long waves in the

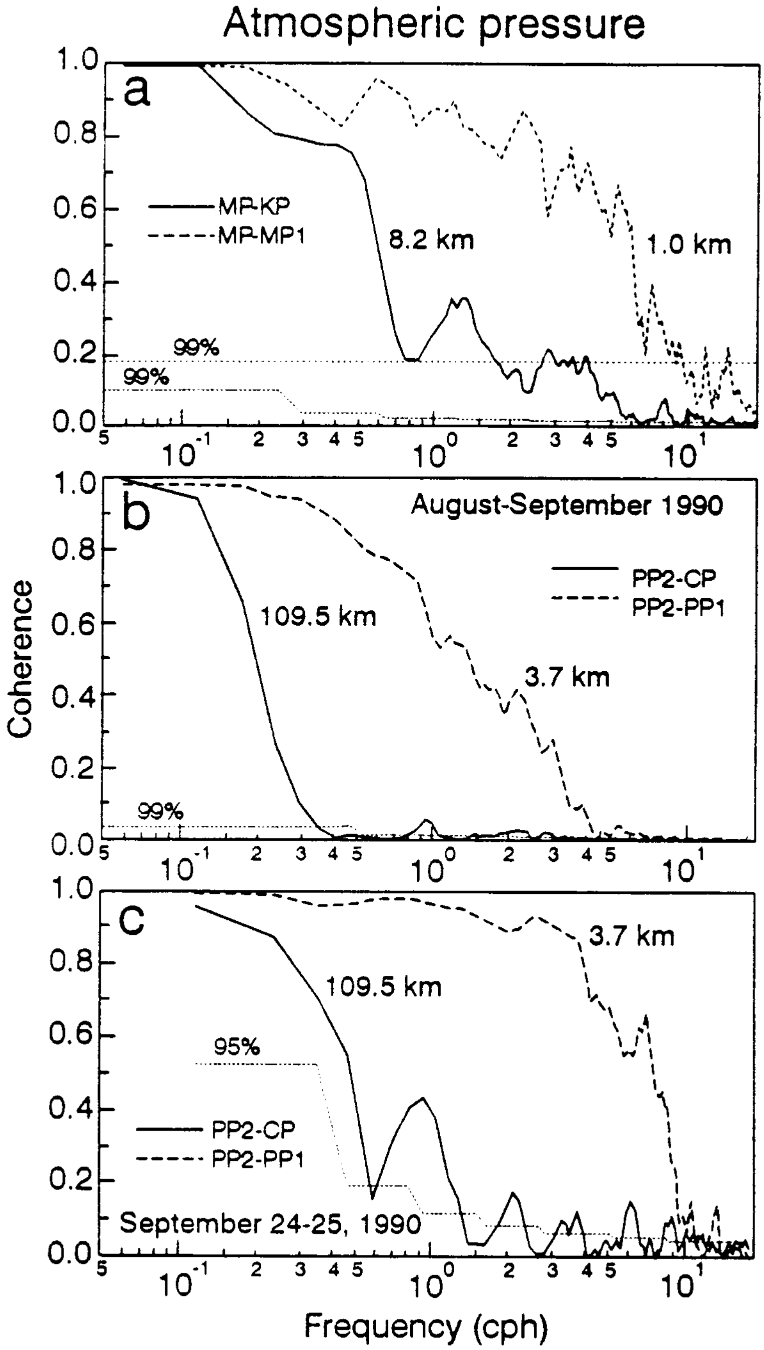

Figure 10. Coherence of atmospheric pressure between pairs of stations separated by different distances: MP–MP1 (1.0 km), and MP–KP (8.2 km), both located in Shikotan Island (a); PP2–CP (109.5 km) and PP2–PP1 (3.7 km), located in the Balearic Islands (b); the same as (b) but for a short period of high atmospheric activity (c).

sea. The two strongest rissaga events in 1990 (on 24 and 25 September) occurred just in this period.

A similar result was found for the region of the Kuril Islands. The spatial coherence has been estimated for three time-intervals of 17 hours corresponding to the moments when major atmospheric activity was recorded in this region. A remarkable increase of coherence has been found in each of these cases. For example, the minimum periods with a coherence greater than 0.4 for the MP–KP pair (8.2 km) was 12 min (for the event on 9 May), 18 min (for 13–14 May) and 13.5 min (for 19 May). The corresponding period estimated for the whole record (i.e. for both, active and quiet periods) was 90 min.

So for spatial atmospheric coherence we also found significant difference for relatively quiet periods and periods of high activity. This may be one additional factor influencing the different generation mechanism of ordinary seiches and destructive oscillations (meteotsunamis).

5.2. ESTIMATION OF PHASE SPEED AND DIRECTION OF ATMOSPHERIC WAVES

Monserrat and Thorpe (1992) performed a correlation analysis of several cases of significant atmospheric waves over Mallorca Island during August–September 1990, the strongest one of which was observed on 24–26 September. Using three microbarographs (PP1, PP2, and PP3) deployed in the vicinity of Palma (Figure 1a) they estimated certain parameters (wavelength, phase speed, and direction of propagation) of the corresponding wave train observed in the area and found that it travelled from the southwest with a phase speed of about 29 m/s. Such direction of propagation coincides with the orientation of the southeastern coast of Mallorca Island (Figure 1a), so the atmospherically induced long waves would propagate along the adjusted shelf specifically in the direction of Ciutadella (see Figure 1). In addition, this direction coincides with the orientation of Ciutadella inlet itself. Moreover, the estimated atmospheric wave speed U = 29 m/s is very close to the phase speed of long waves $c = \sqrt{gh} \simeq 31$ m/s (see Section 3). Thus, the parameters of atmospheric waves were apparently quite favorable for seiche generation in Ciutadella inlet and two rissaga events occurred in this particular period.

Unfortunately, lack of necessary atmospheric data in the immediate vicinity of Ciutadella prevents a more detailed analysis of this case or the cases related to the 1989 rissaga events. However, we were able to examine the parameters of atmospheric waves for the region of Shikotan Island where three microbarographs (MP, KP, and DP) were working simultaneously with bottom pressure stations (MS, OS, and KS).

In contrast to Monserrat and Thorpe (1992), we used results of spectral analysis instead of correlation analysis to estimate the corresponding parameters. The method was described by Likhacheva *et al.* (1985). For any fixed frequency, ω_n, a phase angle φ_{ij} between stations i and j determined by cross-spectral analysis of the respective series can be presented as

$$\varphi_{ij}(\omega_n) = \mathbf{k}(\omega_n) \cdot \mathbf{r}_{ij} + \eta(\omega_n) = k(\omega_n)x_{ij} + l(\omega_n)y_{ij} + \eta(\omega_n), \tag{15}$$

where k, l are the components of the wave vector $\mathbf{k}$, $\mathbf{r}_{ij}$ is the radius-vector with the components x_{ij} and y_{ij} connecting two stations, and η is the random noise. For an arbitrary number of stations $N \geq 3$ the components k_n and l_n can be found using the least squares method by minimizing the following expression:

$$\sigma^2 = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} w_{ij}(\omega_n) \left[\varphi_{ij}(\omega_n) - k_n x_{ij} - l_n y_{ij}\right]^2, \tag{16}$$

where w_{ij} is the weighting factor that depends on the relative significance of the respective pair of stations.

The accuracy of the estimates of φ_{ij} depends on the coherence, γ^2 (Bendat and Piersol, 1986). So we used specifically the coherence as the weighting factor $w_{ij}(\omega) = \gamma_{ij}^2(\omega)$.

To eliminate unreliable values of $\varphi_{ij}(\omega_n)$ used for the computation of the wave numbers, we applied the following criteria:

$$\varphi_{ij}(\omega_n) \geq \epsilon_{ij}(\omega_n), \tag{17}$$

$$\varphi_{ij}(\omega_n) \geq \omega_n \Delta t, \tag{18}$$

$$\gamma_{ij}^2(\omega_n) \geq 0.35, \tag{19}$$

where Δt = 1 min is the sampling interval. If any of these criteria were not fulfilled the corresponding pair was excluded from computations. Because of these criteria we could analyse processes only in a relatively narrow frequency band where coherences and phase differences were sufficiently high.

We focussed our attention on three events when large seiches were observed in the bays of Shikotan Island and the event on 15 May 1991 when a strong atmospheric disturbance propagated over the island, but no noticeable seiches were induced. For all these cases the coherence between three microbarographs for periods more than 15–20 min was sufficiently high and we could do this examination. For the computations, used time segments of 1024 points (about 17 hr) in association with the corresponding events (see Figure 2a), providing spectral resolution Δf = 0.00782 cpm and degrees of freedom ν = 30.

The results of the computations are presented in Table I. They look a little surprising if we do not take into account specific geometry of this region. In the two cases when the strongest seiches were recorded in Krabovaya and Malokurilskaya bays (on 9 and 13 May, 1991), the associated atmospheric waves propagated from the west or southwest, i.e. in the *longshore* direction for the corresponding coast of

Table I. Parameters of the atmospheric waves for a few strong events in the area of Shikotan Island

Period	Events											
(min)	9 May			13 May			15 May			19 May		
	λ (km)	U (m/s)	ϕ (°)	λ (km)	U (m/s)	ϕ (°)	λ (km)	U (m/s)	ϕ (°)	λ (km)	U (m/s)	ϕ (°)
42.7	43.6	17	262	53.7	21	208	71.9	28.1	49	64.3	25.1	130
32	32.4	16.9	259	65.7	34.2	190	39.8	20.7	52	51.7	26.9	122
25.6	22.5	14.7	265	47.2	30.7	200	31.7	20.7	62	42	27.3	125
21.3	21.5	16.8	258	34.3	26.8	199	27.3	21.3	70	37.1	29	131
18.3	–	–	–	–	–	–	21.9	20	66	–	–	–

Shikotan Island (see Figure 2b). In contrast, the wave train of 15 May propagated *onshore*, which normally is the most favorable direction for seiche generation (as for example, in Ciutadella inlet). However, for Shikotan Island this direction is *almost closed* by the elongated Kunashir Island (see inset in Figure 2b), so atmosphere induced long waves formed in the southern part of the Sea of Okhotsk cannot come into the area of Shikotan and generate seiches there. From this point of view even opposite (offshore) direction is more favorable because long waves generated in the Pacific can go around Shikotan Island and cause seiche oscillations in bays of the northwestern coast. This is the way that earthquake generated tsunamis usually come into the area (Rabinovich *et al.*, 1993). Specifically this is the situation for the third event (of 19 May 1991) when the atmospheric waves approaching the coast of Shikotan Island from the southeast caused noticeable seiches.

So the results of this analysis demonstrate that the direction (and partly also speed) of propagating atmospheric disturbances near the resonant frequency of the bay play a very important role in the formation of seiches in coastal regions. Taking these parameters into account allowed us to explain certain peculiarities of seiche character that could not be explained before.

6. Discussion and Conclusions

We analysed what kind of external conditions are favorable to produce large seiches (meteotsunamis) in Ciutadella inlet on Menorca Island (Balearic Islands, Western Mediterranean) and Shikotan Island (South Kuril Islands, northwestern Pacific) and found essential similarities in seiche generation in both regions. Altogether there were 10 strong events in the observation period of 1989–1990 in Ciutadella inlet and 3 events in the area of Shikotan Island (May, 1991). All these 13 events were well correlated with significant disturbances of atmospheric pressure observed simultaneously.

The general tendency of the correlation between atmospheric pressure and sea level is clear: stronger atmospheric disturbances normally generate larger seiche oscillations. However, the detailed character of this correlation is not so simple: there are several exceptions to this general tendency; now and then even quite powerful disturbances do not excite noticeable seiches.

So it is natural to suppose that there are certain additional factors influencing the response of sea level to atmospheric forcing. We tried to identify and examine these factors. All three bays investigated (Ciutadella inlet on Menorca Island; Krabovaya and Malokurilskaya bays, both on Shikotan Island) have very definite resonance structures of eigen-oscillations strongly dominated by the fundamental (Helmholtz) mode with periods 10.6, 29.0 and 18.6 min, respectively. Hence, we attempted to compare the intensity of seiche oscillations with atmospheric wave activity specifically for the frequency bands corresponding to the bay resonances. This approach improved the results and increased the estimated correlation. A high correlation between resonant deviations of atmospheric pressure and sea level (Cor = 0.92) was found for Ciutadella inlet for the ‘active’ period of the last week of September 1990, when two significant rissaga events occurred. However, for the ‘quiet’ period in this region, as well as for the whole observation period in the region of Shikotan Island, this correlation was much smaller (Cor $\simeq$ 0.50), apparently because background seiches are generated by several different factors (e.g. by wind or wind waves).

Also, it was found that the phase speed of atmospheric waves in some spectacular cases of significant rissaga waves was about 30 m/s, i.e. very close to the phase speed of long waves on the shelf of Mallorca. Moreover, for long waves generated by atmospheric disturbances propagated over the Balearic Islands from the southwest, the southeastern shelf of Mallorca Island acts as a wave guide. The associated wave trains crossing Menorca Channel between Mallorca and Menorca islands would head specifically for the area of Ciutadella, this probably being the reason for the abnormally large seiches generated there. The orientation of Ciutadella inlet itself, in this particular direction, is a key factor amplifying the corresponding effect.

It is well known that the wave heights of seiches generated in various bays and inlets depend strongly on the resonant characteristics of the inner basin and the adjusted shelf (cf. Wilson, 1972; Murty, 1977). The different responses of different bays to the same forcing demonstrate the significant influence of local topography.

Gomis *et al.* (1993) showed theoretically that Ciutadella inlet has very prominent resonant properties providing significant amplification of incoming waves. Similar atmospheric forcing generates much larger seiches in Ciutadella than in the other bays and inlets of the region such as Palma Bay, for example. However, there are many other basins worldwide with pronounced resonant properties where atmosphere-generated seiches are much weaker than in Ciutadella. We do not specifically address this question in the present paper, but it is worth emphasizing that seiches are in fact the product of resonant properties of the local topography and external forcing. The former is an inherent feature of the corresponding region and independent of time, the latter essentially depends on time but only slightly on the region. Apparently disastrous meteotsunamis are observed only where and when specific resonance interaction between topography and atmospheric forcing occurs.

Analysing the data from two different regions we distinguished several factors favorable for seiche generation: (1) strong atmospheric disturbances travelling over the area; (2) essential amounts of energy at the frequency bands close to the resonant frequencies of the corresponding basins; (3) onshore atmospheric wave direction coinciding with the orientation of the inlet; (4) phase speed of atmospheric waves matching the phase speed of long waves on the shelf. The coincidence of all these factors is quite rare, as is therefore the formation of extreme seiches. Rissaga events with wave heights 1.0–1.5 m are normally observed in Ciutadella inlet 1–2 times a year, but really destructive oscillations with trough-to-crest heights more than 3 m occur here only once every few years. However, in many other regions such coincidence is never possible. For example, Kunashir Island protects Shikotan Island from long waves coming from the northwest, which would be the most effective direction to generate seiches in Krabovaya and Malokurilskaya bays. Seiches in these bays can be induced only by waves propagating along the northwestern coast of Shikotan Island or around the island. This is probably one of the reasons why atmosphere generated seiches there are much weaker than in Ciutadella.

Another interesting result was the different character of formation of background seiches, continuously existing in the basins, and extraordinary events occurring only occasionally. One of the reasons for this difference is that the background oscillations are formed by many various mixed sources, including tides, internal waves, wind, wind waves, long waves coming from remote regions, etc. Generation of particular events (significant seiches) is determined by the specific dominant forcing, mainly by the atmospheric disturbances moving in the vicinity of the observation regions. Another reason is that, as was found, the spatial scales of coherence of atmospheric processes (and therefore the forcing area) increase significantly during strong atmospheric events. However, probably the most important reason is that these specific events are the result of the *resonance response* of the sea surface to the atmospheric forcing, so that relative amplification of such seiches is much stronger than usual.

Acknowledgements

This research has been partially sponsored by the CICYT of Spain under the contracts MAR95-1863 and AMB95-1251-E and by RFBR-INTAS project 1000I-96. The authors would like to thank Robert L. Haney and R. Falconer Henry for their critical comments on the text, Vladimir A. Djumagaliev for providing the atmospheric pressure and bottom pressure data in the region of Shikotan Island, and José Luis López Jurado and Francisco Arredondo for providing certain sea-level records in Ciutadella inlet and Palma Bay. Finally, the authors would like to thank Patricia Kimber for drafting some of the figures and Mark Blazek for his help with the English.

References

Bendat, J. S. and Piersol, A. G.: 1986, *Random Data Analysis and Measurements Procedures*, Wiley, New York.

Chapman, D. C. and Giese, G. S.: 1990, A model for the generation of coastal seiches by deep-sea internal waves, *J. Phys. Oceanogr.* **20**, 1459–1467.

Defant, A.: 1961, *Physical Oceanography*, Vol. 2, Pergamon Press, Oxford.

Djumagaliev, V. A. and Rabinovich, A. B.: 1993, Long wave investigations at the shelf and in the bays of the South Kuril Islands, *J. Korean Soc. Coastal Ocean Eng.* **5**, 318–328.

Donn, W. L. and Balachandran, N. K.: 1969, Coupling between a moving air-pressure disturbance and the sea surface, *Tellus* **21**, 701–706.

Dziewonski, A., Bloch, S., and Landisman, M.: 1969, Technique for the analysis of transient seismic signals, *Bull. Seismol. Soc. Am.* **59**, 427–444.

Ewing, M., Press, F., and Donn, W. L.: 1954, An explanation of the Lake Michigan wave of 26 June 1954, *Science* **120**, 684–686.

Garcies, M., Gomis, D., and Monserrat, S.: 1996, Pressure-forced seiches of large amplitude in inlets of the Balearic Islands. 2. Observational study, *J. Geophys. Res.* **101**, 6453–6467.

Gomis, D., Monserrat, S., and Tintoré, J.: 1993, Pressure-forced seiches of large amplitude in inlets of the Balearic Islands, *J. Geophys. Res.* **98**, 14437–14445.

Gossard, E. E. and Hooke, W. H.: 1975, *Waves in the Atmosphere*, Elsevier, Amsterdam.

Harris, F. J.: 1978, On the use of windows for harmonic analysis with the discrete Fourier Transform, *Proc. IEEE* **66**, 51–83 (also in S. B. Kesler (ed.), *Modern Spectrum Analysis, II*, IEEE Press, New York, 1986, pp. 172–204).

Herron, T. J., Tolstoy, I., and Kraft, D. W.: 1969, Atmospheric pressure background fluctuations in the mesoscale range, *J. Geophys. Res.* **74**, 1321–1329.

Hibiya, T. and Kajiura, K.: 1982, Origin of 'Abiki' phenomenon (a kind of seiches) in Nagasaki Bay, *J. Oceanogr. Soc. Japan* **38**, 172–182.

Hodžić, M.: 1979, Exceptional oscillations in the Bay of Vela Luka and meteorological situation on the Adriatic, *International School of Meteorology of the Mediterranean, 1 Course*, Erice, Italy.

Honda, K., Terada, T., Yoshida, Y., and Isitani, D.: 1908, An investigation on the secondary undulations of oceanic tides, *J. College Sci.*, Imp. Univ. Tokyo, 108 pp.

Kovalev, P. D., Rabinovich, A. B., and Shevchenko, G. V.: 1991, Investigation of long waves in the tsunami frequency band on the southwestern shelf of Kamchatka, *Natural Hazards* **4**, 141–159.

Kulikov, E. A., Rabinovich, A. B., Thomson, R. E., and Bornhold, B. D.: 1996, The landslide tsunami of November 3, 1994, Skagway Harbor, Alaska, *J. Geophys. Res.* **101**, 6609–6615.

Likhacheva, O. N., Rabinovich, A. B., and Fine, A. V.: 1985, Analysis of the atmospheric pressure field over the Sea of Okhotsk and the northeastern Pacific Ocean, in *Theoretical and Experimental Investigations of the Long Wave Processes*, USSR Academy of Sciences, Vladivostok, pp. 144–157 (in Russian).

Monserrat, S., Ibbetson, A., and Thorpe, A. J.: 1991, Atmospheric gravity waves and the 'rissaga' phenomenon, *Q. J. Roy. Meteorol. Soc.* **117**, 553–570.

Monserrat, S. and Thorpe, A. J.: 1992, Gravity wave observations using an array of microbarographs in the Balearic Islands, *Q. J. Roy. Meteor. Soc.* **118**, 259–282.

Murty, T. S.: 1977, Seismic sea waves – tsunamis, *Bull. Fish. Res. Board Canada 198*, Ottawa.

Nakano, M. and Unoki, S.: 1962, On the seiches (the secondary undulations of tides) along the coast of Japan, *Records Oceanogr. Works in Japan*, Spec. No. 6, 169–214.

Nomitsu, T.: 1935, A theory of tsunamis and seiches produced by wind and barometric gradient. *Mem. Coll. Sci. Imp. Univ. Kyoto A* **18**(4), 201–214.

Papadopoulos, G. A.: 1993, Some exceptional seismic (?) sea-waves in the Greek Archipelago, *Science of Tsunami Hazards* **11**, 25–34.

Proudman, J.: 1953, *Dynamical Oceanography*, Methuen and Co., London.

Rabinovich, A. B.: 1993, *Long Ocean Gravity Waves: Trapping, Resonance and Leaking*, Gidrometeoizdat, St. Petersburg (in Russian).

Rabinovich, A. B., Djumagaliev, V. A., Fine, I. V., and Kulikov, Ye. A.: 1993, Analysis of weak tsunamis in the region of the Kuril Islands and resonance influence of topography, *Proc. IUGG/IOC International Tsunami Symposium*, Wakayama, Japan, pp. 95–105.

Rabinovich, A. B. and Monserrat, S.: 1996, Meteorological tsunamis near the Balearic and Kuril Islands: Descriptive and statistical analysis, *Natural Hazards* **13**, 55–90.

Ramis, C. and Jansà, A.: 1983, Condiciones meteorologicas simultaneas a la aparicion de oscilaciones del nivel del mar de amplitud extraordinaria en el Mediterraneo occidental, *Rev. Geofisica* **39**, 35–42 (in Spanish).

Tintoré, J., Gomis, D., Alonso, S., and Wang, D. P.: 1988, A theoretical study of large sea level oscillations in the Western Mediterranean, *J. Geophys. Res.* **93**, 10797–10803.

Wang, X., Li, K., Yu, Z., and Wu, J.: 1987, Statistical characteristics of seiches in Longkou Harbour, *J. Phys. Oceanogr.* **17**, 1063–1065.

Wilson, B.: 1972, Seiches, *Adv. Hydrosci.* **8**, 1–94.