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Meteorological Tsunamis Near the Balearic and Kuril Islands: Descriptive and Statistical Analysis

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Abstract. Large-amplitude sea level oscillations in the tsunami frequency range have been occasionally observed in some coastal zones of the World Ocean when no seismic activity was recorded. These waves are mainly related to local atmospheric disturbances and, following Defant, are going to be referred to as 'meteorological tsunamis'. As well as ordinary tsunamis, meteorological tsunamis can also be a cause of loss of life and catastrophic destruction in coastal areas. A review of such waves is presented with particular attention to the disastrous oscillations in Ciutadella inlet, the Balearic Islands, locally known as 'rissaga'. Sea level/bottom pressure measurements in the regions of the Balearic (Western Mediterranean) and Kuril (Northwest Pacific) Islands were processed together with simultaneous atmospheric pressure records in the same areas to study the nature of meteorological tsunamis.

The results are used to present a descriptive and statistical analysis of strong events in these regions, to examine the response of the same inlet to different atmospheric events, and the different bay/inlets to the same event. It is found that seiches in various inlets strengthen at the same time just when atmospheric activity increases, although every inlet responds to a similar atmospheric forcing with different intensity, probably due to the influence of the local topography and geometry. Three types of strong events are identified apparently responding to different generation mechanisms.

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

1. Introduction: Meteorological Tsunamis in Various Regions of the World Ocean

Disastrous powerful long waves are observed now and then in some coastal areas of the World Ocean. These waves have similar periods to ordinary tsunami waves (from a few minutes to 2–3 hours) and affect the coasts in a similar destructive way, but are related not to underwater earthquakes but to meteorological forces. It is difficult sometimes to distinguish between meteorological long waves and tsunamis. For example, the wave train of 11 May 1981 with a height of about 60 cm observed near the coast of South Africa and first described in '*Tsunami Newsletter*' (September, 1981) as a tsunami, was afterwards identified as atmosphere-induced long waves (Shillington, 1984). These waves are well known in Japan; (Honda *et al.* 1908) indicated that they are usually caused by passages of typhoons or strong cyclones. They have been also related to frontal zones, atmospheric pressure jumps and trains of atmospheric gravity waves (Defant, 1961; Nakano and Unoki, 1962; Wilson, 1972; Murty, 1984). In particular, large long waves generated by atmospheric jumps and squalls caused significant destruction and casualties in the region of the Great Lakes (Ewing *et al.*, 1954; Donn and Ewing, 1956; Donn, 1959; Donn and Balachandran, 1969).

The name *'meteorological tsunami'* was initially proposed for these waves by Japanese authors (Nomitsu, 1935) and then widely used by Defant (1961). The terms 'secondary undulations of tides', 'harbour oscillations', 'large seiches', or 'forced seiches' are also used (Nakano and Unoki, 1962; Wiegel, 1964; Wilson, 1972; Murty, 1984) but none of them are satisfactory for *hazardous* atmosphere-induced long waves. Some local names (e.g., *'abiki'*, *'yota'*, *'rissaga'*, *'Seebär'* etc.) in fact are different denotations of the same (or very similar) physical phenomenon. The general term 'meteorological tsunami' seems to be appropriate for these waves. There are no differences between 'seismic' and 'meteorological' tsunamis as regards their transformation in the coastal area or the amplification of incoming waves in bays or harbours; the techniques used to study both phenomena are similar. Just as not every large underwater earthquake excites a tsunami (Murty, 1977), so even strong typhoons or atmospheric pressure jumps do not always generate destructive long waves. Both ordinary tsunamis and meteorological tsunamis are relatively infrequent events. Some specific resonance conditions are apparently necessary to generate noticeable meteorological tsunamis.

Long waves coming from the open ocean are amplified in inner inlets, bays and harbours and generate seiches. However, the amplitude of this amplification is very different for different basins. Honda *et al.* (1908) and later Nakano and Unoki (1962) investigated more than one hundred gulfs, bays and inlets of the Japanese coast and found that large seiches are observed only in a few of them. Significant sea-level oscillations in bays, known in Japan as *'yota'* (Honda *et al.*, 1908), are mainly recorded in elongated, shallow and narrow-mouthed inlets. Extremely strong oscillations, so called *'abiki'* waves, are excited periodically in Nagasaki Bay (Honda *et al.*, 1908; Hibiya and Kajiura, 1982).

According to (Akamatsu, 1982) 18 *abiki* events with wave heights of more than 1 m occurred in the period 1961–1979; the strongest one was on 31 March 1979, when a tide gauge located in the middle part of the bay recorded oscillations with period 35 min and height up to 278 cm, while at the northern end of the bay they reached 478 cm. Considerable damage was caused by this event and three women were drowned (Hibiya and Kajiura, 1982). Another destructive example of *abiki* was observed on 16 March 1988 also with the same 35 min period (Figure 1a).

Near the coast of Korea relatively large oscillations are regularly recorded only in one place, in Pohang Harbour (Park *et al.*, 1986).

Very strong oscillations are common also in Longkou Harbour, West China (Wang *et al.*, 1987); seiches with ranges exceeding 1 m were recorded there 13 times in 23 years (1957–1980) with a reported maximum of 2.93 m. The whole form of the latter case, with a large first wave and rapid decay (Figure 1b), is very similar to the well-known case of significant oscillations in the Gulf of Trieste on

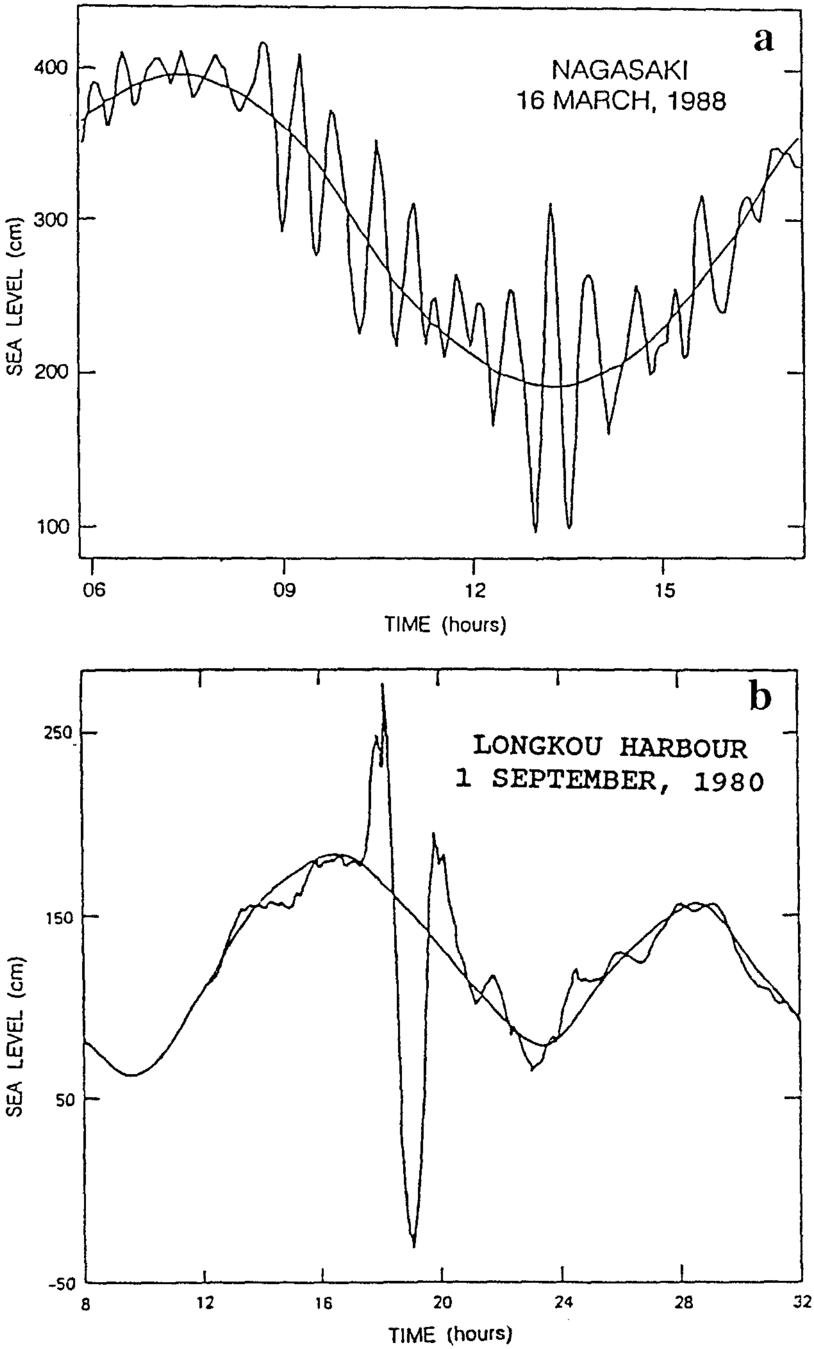

Fig. 1. Strong seiche oscillations recorded in Nagasaki Bay, Japan (courtesy of Japan Meteorological Agency) (a) and in Longkou Harbour, China (from Wang *et al.*, 1987) (b).

13 October 1933 (Figure 95 in Defant, 1961; Figure 12 in Wilson, 1972) generated, as it was proved, by Proudman resonance of the atmospheric waves, propagating over the northern Adriatic, and long sea waves.

Other known places with extraordinary strong long wave oscillations are the west coast of Sicily where this phenomenon is referred to as *'marubbio'* and the Gulf of Fiume noted by the strong currents related to seiches called here *'stigazzi'*. A phenomenon quite similar to tsunamis occurs episodically on the coast of the Baltic Sea, which is known there as *'Seebär'*. *Seebär-waves* with a height of 1–2 m come unexpectedly when the water is calm, even smooth, and appear a wave-train implies 'rhythmic intervals' (Defant, 1961; Wilson, 1972).

Large amplitude seiches are common in some inlets and harbours of the Mediterranean coast of Spain and the Balearic Islands where the phenomenon is locally known as *rissaga* (Fontseré, 1934; Ramis and Jansà, 1983; Jansà, 1986). Sea-level oscillations are occasionally extremely large in Ciutadella Harbour, Menorca Island (Monserrat *et al.*, 1991) causing significant damage to ships, fishing boats and harbour structures.

The Mediterranean Sea is the region where meteorological tsunamis occurred most frequently. Hodžić (1979) described three cases (21 August 1977; 19 September 1977; 21 June 1978) of extraordinary oscillations with heights 1–2.5 m and periods of about 15 min recorded in the Bay of Vela Luka, a long and narrow inlet located in the eastern Adriatic. Papadopoulos *et al.* (1992) examined *'exceptional sea-waves'* with periods of about 12 min recorded on 7 May 1991 at several places on the coast of Greece and found that these waves were certainly not related to seismic activity although they looked just like tsunami waves.

It is remarkable that all these hazardous waves are repeated regularly in the same specific places and usually with the same periods. *Abiki* and *yota* in Japan, *Seebär* in Baltics, *marubbio* at Sicily coast, *rissaga* in Spain, oscillations in Pohang Harbour, Korea, and Longkou Harbour, China, as well as catastrophic waves in the Great Lakes are examples of disastrous coastal waves which apparently have the same atmospheric origin and similar resonance nature related to the characteristics of the atmospheric disturbances and topography of the corresponding regions. However, the generation mechanisms of the events and the reasons why they are manifested so strongly in just these places are unclear.

Although in the region of the South Kuril Islands the atmosphere-induced waves are not so strong, seiche oscillations with wave heights of several tens of centimetres generated by meteorological forcing are quite frequent. During the tsunami monitoring measurements in this area, several tsunami-like long wave trains were recorded, and only after special investigation it was found that they were caused by atmospheric activity and not by seismic events.

The necessity to distinguish between seismic and meteorological tsunamis, to examine the generation mechanism of the latter, to inspect resonance properties of various inlets and bays, as well as the direct threat of hazardous phenomena to the coasts, prompted Universitat de les Illes Balears (UIB), Palma de Mallorca, Spain, and Institute of Marine Geology and Geophysics (IMGG), Yuzhno-Sakhalinsk, Russia, to organize similar independent experiments in 1989–1992 in the region of the Balearic (Spain) and South Kuril (Russia) Islands. Simultaneous observations of sea level and atmospheric pressure were made in both regions (Monserrat *et al.*, 1991; Monserrat and Thorpe, 1992; Djumagaliev and Rabinovich, 1993). Some comparative results of these experiments are presented in this paper as an attempt to estimate the influence of local topography and atmospheric characteristics on seiche generation in general, and especially on the excitation of destructive waves.

A short historical review on the *rissaga* phenomenon and its manifestation in Ciutadella Harbour is given in Section 2. Some comments on the experiments and the available data are made in Section 3. Section 4 is devoted to a preliminary analysis and the preparation of the data. The general spectral properties of atmospheric pressure and sea-level waves in the region of the Balearic and Kuril Islands are presented in Section 5. The statistical characteristics of strong seiche events and a simple analysis comparing atmospheric activity and the occurrence of these events are presented in Section 6. Section 7 is dedicated to the discussion of some open questions related to the generation of these strong seiches. The results are summarized in Section 8.

A more detailed analysis of the relations between atmospheric pressure and sea-level oscillations and an examination of possible generation mechanisms of these strong seiches are the topics of the second part of this study (Rabinovich and Monserrat, 1995).

2. Manifestation of Rissaga Waves Near the Balearic Islands

Short period sea-level oscillations of abnormally large amplitude are periodically observed in some bays and inlets of the Western Mediterranean. Their periods range between 5 and 30 min and trough-to-crest heights can reach values of several metres. Tides in the Mediterranean are relatively weak, usually less than 15–20 cm, and therefore coastal/harbour structures are not normally designed to accommodate significant sea-level changes. This is why such oscillations may cause severe floods in coastal areas. The negative effect of sea-level variations is significantly amplified by the accompanying currents which may be extremely strong in some inlets due to the short periods of the natural oscillations.

References on the hazardous consequences of such variations have been found in letters written in the XV century; major damage produced by sudden non-astronomical changes of sea level were reported in some inlets and harbours of the Balearic Islands*. Riudavets (1885) in his book *History of Menorca Island* described a spectacular phenomenon in Ciutadella (Menorca, Balearic Islands), where extreme sea-level oscillations occurred in the inlet, mostly in summer time, causing terrible destruction to the boats and harbour structures. Riudavets used the

* Arxiu del Regne de Mallorca. Col.lecció Pasqual. Papers No 872 (in Catalan).

local name *'rissaga'*, the Catalan equivalent of the Spanish term *'resaca'* for these strong short-period harbour oscillations.

From then onwards, many episodes noted because of their damage in the coastal area, have been reported in local newspapers. Significant long wave oscillations were observed in many inlets and harbours of the Catalan and Valencian coasts of the Iberian Peninsula, and at the Balearic Islands, but just in Ciutadella they were more frequent and usually stronger than in any other place.

In the first scientific paper related to this phenomenon, Fontseré (1934) presented a statistical study of what he called *'seiches'* on the Catalan coast. He mentioned that these *seiches* always occur in the period between June and September. Fontseré attempted to relate this phenomenon to the seismic activity in the Mediterranean but did not find any correlation. On the other hand, he found that barograph oscillations were always recorded during the events and supposed that the phenomenon had an atmospheric origin.

Ramis and Jansà (1983) focused on the oscillations observed in the Balearic Islands. They, as well as Fontseré (1934), turned their attention to the presence of the intense pressure fluctuations preceding the appearance of *rissaga* waves. In addition they identified similar synoptic situations and weather aspects during the events. Dust rains typically attended a *rissaga* and a covered sky with a peculiar humid ambience was observed usually in hours previous to the largest sea-level variations. They also noticed all known cases of the events occurred in June-September. Surely, it is not just a coincidence that three cases of extraordinary seiches in the Bay of Vela Luka, Dalmatia, described by Hodžić (1979), were observed in the same months and in analogous synoptic situations.

Ramis and Jansà (1983) collected information from local witnesses for one particular event, 2 July 1981, and found that extraordinary seiche oscillations were observed simultaneously in most of the bays and inlets of the Balearic Islands. Wave heights ranged from 0.5 to 2 m and predominant periods were from 5 to 10 min, except in Palma de Mallorca, where seiches with periods 14 and 28 min were recorded.

Although these oscillations are reported in many locations of the Western Mediterranean, only in some of them are they strong enough to provoke hazardous manifestations in the coastal zone. Table I presents the main characteristics of seiches during *rissaga* events on the Catalan coast of Spain and the Balearic Islands, based on information from Ramis and Jansà (1983), Jansà (1986), and Massaguer and Net (1986). As it is seen from this table, the place where this phenomenon seems to occur most often and present the most dramatic consequences is Ciutadella, a narrow and shallow inlet located on the western coast of Menorca (Figure 3b).

Seiche oscillations of duration ranging from a few hours to a few days with wave heights exceeding 0.5 m recur in Ciutadella practically every summer. However, large-amplitude waves (*rissaga*), with dramatic consequences for the harbour, usually take place only once in 5–6 years. The recent extreme events in Ciutadella occurred in September 1975, July 1981, June 1984 and July 1989. Strong currents generated in the inlet during *rissaga* cause most of the damage in the area, breaking harbour structures and ropes tying the boats to the harbour walls. The June 1984 event deserves special mention, when one of the oscillations had a height more than 3 m, leaving the end of the inlet empty of water. A photo presented in Figure 2a was taken in Ciutadella at the moment of a low level. Five minutes later the sea level here was 3 m higher, this giving an idea of the strength of the currents involved. For comparison, Figure 2b shows the inlet at the same place in a normal situation.

In spite of the significant risk of the *rissaga* events for Ciutadella and some other bays of the region, no instrumental measurements of sea level here were taken until recent times. Moreover, there was only one tide gauge in the whole region of the Balearic Islands, viz. in Palma de Mallorca, but even that one was not working regularly. Thus, practically all information about *rissaga* wave parameters, in particular, that presented in Table I, was based on visual observations and probably was inaccurate*.

Experimental sea-level data in Ciutadella became available since 1988 when UIB deployed a bottom pressure station in the inlet to quantify the phenomenon. A tide gauge was also installed there in 1989 by the Institute Español de Oceanografía of Palma de Mallorca and has been working intermittently since that time. The measurements of atmospheric pressure fluctuations in the region of Ciutadella were initiated by UIB at about the same time. These simultaneous high quality measurements of sea level and pressure has given support to the hypothesis of an atmospheric origin for these abnormal seiches. In particular, it was found that a significant increase in spectral energy occurred both in atmospheric pressure and sea level during the strong event recorded in Ciutadella on 7 July 1989 (Monserrat *et al.*, 1991).

However, the exact mechanism of *rissaga* generation is still unclear. Tintoré *et al.* (1988) proposed that a triple resonance interaction of atmospheric waves, edge waves propagating over the shelf of Menorca, and eigenoscillations of the inlet could play a key role in excitation of abnormal seiches in Ciutadella. Gomis *et al.* (1993) afterwards showed that a direct forcing of the inlet by the atmospheric pressure is unlikely but instead, that open ocean waves, generated by atmospheric waves, could act as an intermediate mechanism, and force *rissaga* oscillations in the inlet by resonance. They also suggested that the particular shape of Ciutadella harbour (elongated and shallow) causes extremely strong amplification of incoming waves, explaining the large seiche amplitudes.

Tide-generated internal waves supposedly play a key role in the generation of significant sea-level oscillations near the coast of the Philippines and Puerto Rico (Giese and Hollander, 1987; Chapman and Giese, 1990; Giese *et al.*, 1990).

* For example, periods of seiche oscillations in Ciutadella, indicated in Table I, are mainly 5–6 min. In fact, as was shown by further instrumental recording, they are 10–11 min. It is quite possible that observers were talking about half-cycle.

a

b

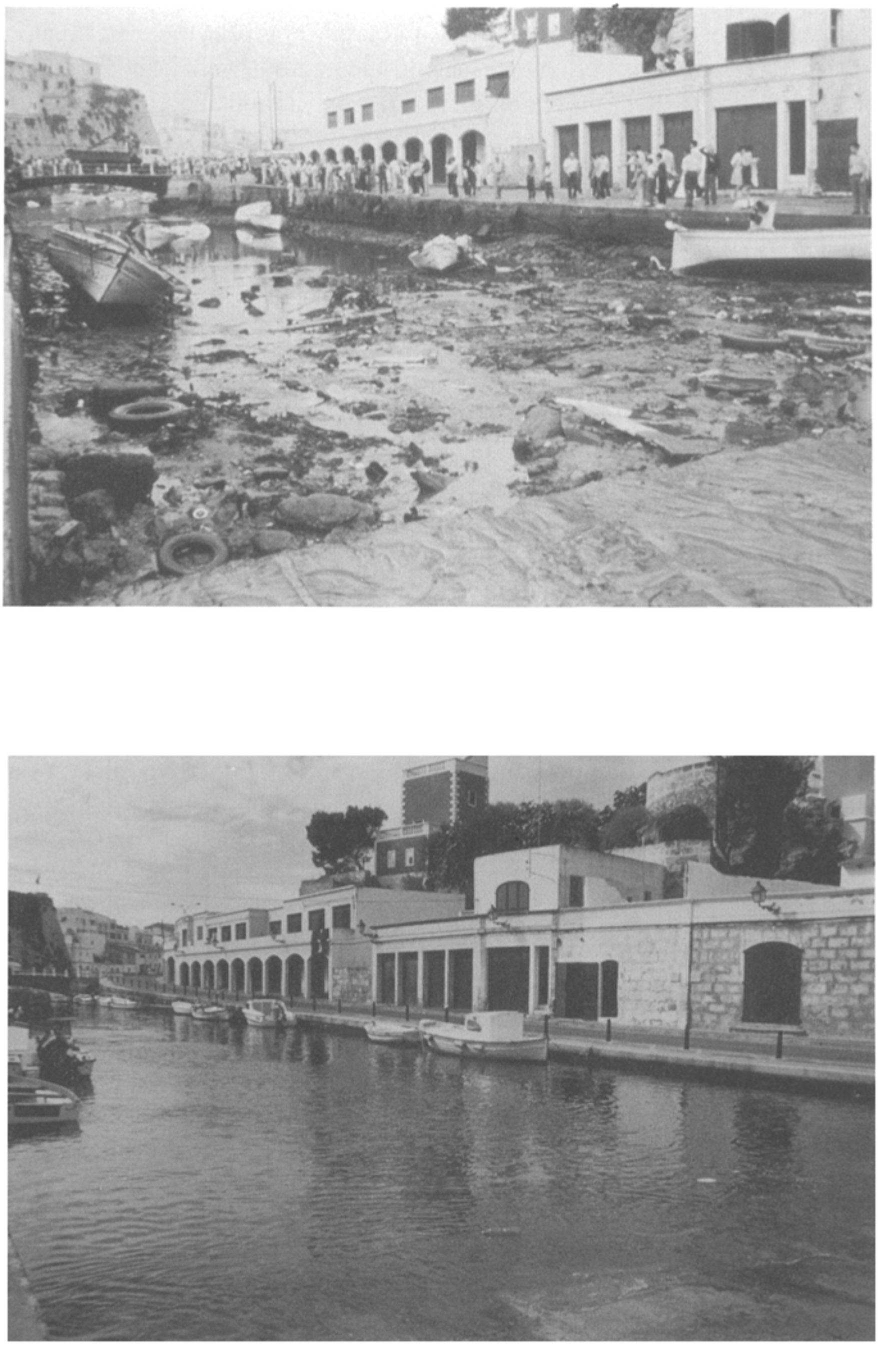

Fig. 2. Ciutadella harbour view taken during the June 1984 *rissaga* (courtesy of Josep Gomes) (a) and a similar view 9 years later during a normal situation in the inlet (b).

TABLE I. Characteristics of large seiche oscillations observed on the coasts of Catalonia and the Balearic Islands

Date	Station		Wave height (cm)	Period (min)	Duration (hours)
11 July 1972	Tarragona	(Catalonia)	300	–	–
16 September 1975	Barcelona	(Catalonia)	60	8–10	12
16 September 1975	Ciutadella	(Menorca Is.)	200	–	48
14 July 1977	Ciutadella	(Menorca Is.)	50	–	–
2 July 1981	Barcelona	(Catalonia)	100	–	–
2 July 1981	Costa Brava	(Catalonia)	300	3–4	–
2 July 1981	Andratx	(Mallorca Is.)	100	5–6	–
2 July 1981	Palma	(Mallorca Is.)	40	14, 28	–
2 July 1981	Pollensa	(Mallorca Is.)	80	10	–
2 July 1981	Porto Colom	(Mallorca Is.)	100	6	–
2 July 1981	Sa Rapita	(Mallorca Is.)	100	5	–
2 July 1981	Sta Ponça	(Mallorca Is.)	200	5	–
2 July 1981	Ibiza	(Ibiza Is.)	100	–	–
2 July 1981	Ciutadella	(Menorca Is.)	200	8–10	15
2 July 1981	Caserio Cabrera	(Cabrera Is.)	80	–	–
18 July 1981	Ciutadella	(Menorca Is.)	100	–	–
29 July 1982	Ciutadella	(Menorca Is.)	–	–	48
21 June 1984	Ciutadella	(Menorca Is.)	300	–	–
14 June 1985	Porto Colom	(Mallorca Is.)	40	–	–
14 June 1985	Ciutadella	(Menorca Is.)	90	3.5–4	7
19 June 1985	Porto Colom	(Mallorca Is.)	60	–	–
19 June 1985	Ciutadella	(Menorca Is.)	90–100	5	10
3 July 1985	Porto Colom	(Mallorca Is.)	100	–	2
3 July 1985	Ciutadella	(Menorca Is.)	90	5–7	8
31 July 1985	Ciutadella	(Menorca Is.)	80	–	4

Recently, the possible influence of internal waves on *rissaga* has also been investigated (Giese *et al.*, 1994) but no definitive coherence has yet been found. Wind waves frequently play an important role in the generation of harbour oscillations, especially high-order seiche modes (Wilson, 1972; Bowers, 1977; Okihiro *et al.*, 1993), although no investigation related to this possible source mechanism has been carried out in this region.

To the present time it has been difficult to draw definite conclusions on the nature of *rissaga* phenomenon due to the lack of statistics. One of the main purposes of the present study is to obtain these statistics, examining the reaction of the same inlet to different atmospheric events, and of different bay/inlets to the same event.

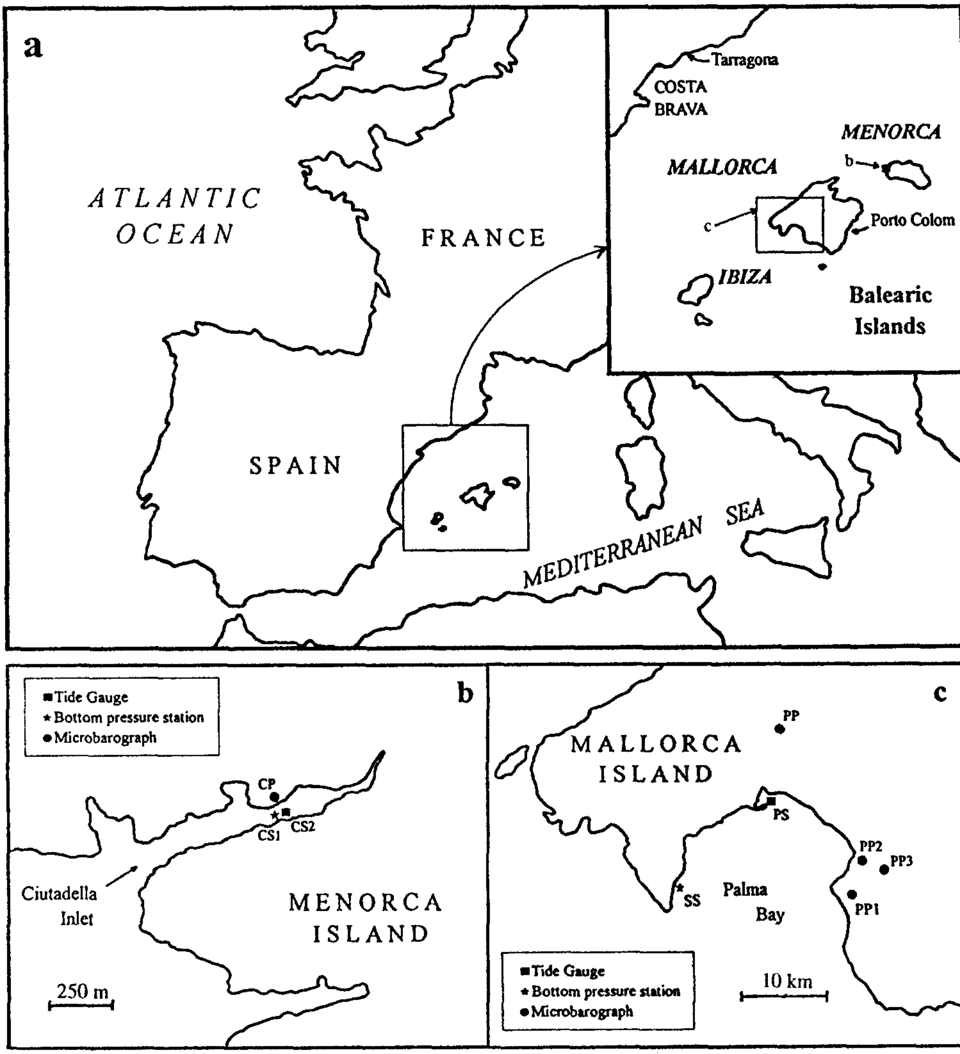

Fig. 3. Location of the instruments in the region of the Balearic Is., Western Mediterranean.

3. Instruments and Observations

3.1. BALEARIC ISLANDS

Sea-level oscillations and surface atmospheric pressure fluctuations were recorded in the Balearic Islands during 1989–90 to investigate the characteristics of large amplitude seiches in this region and their relation to the atmospheric processes.

Sea-level data for 1989 were available from four instruments located in the area. Two of them (CS1 and CS2) were situated practically at the same place inside of the Ciutadella inlet, Menorca Is. (Figure 3b). Two others were deployed in Palma Bay, Mallorca Is.: in the region of the Palma de Mallorca main port (PS), and in the southwestern part of the bay near to Sol de Mallorca (SS) (Figure 3c). The instruments CS2 and PS were tide gauges installed by the Instituto Español de Oceanografía (IEO), CS1 and SS were bottom pressure stations deployed by the UIB (CS1) and INCIMA Company (SS). Unfortunately, in 1990 only one of these instruments (CS1) was working regularly and could be used in the present analysis.

Two microbarographs were also placed by the UIB in 1989: one in Ciutadella (CP), and another one at the University, Palma de Mallorca (PP). The position of the last one was changed in 1990 (PP1) and two more microbarographs (PP2, PP3) were installed in Mallorca to form a triangular array sited about 3–4 km apart (Figure 3c). This triangle allowed determination of the atmospheric wave parameters, in particular phase speed and the direction of wave propagation (Monserrat and Thorpe, 1992).

The microbarographs used in 1989 were based on differential pressure transducers (Furness Controls, Type FCO 16). The reference-pressure vacuum flask had short-term temperature stability (for periods < 30 min) better than $0.03°C$, the corresponding reference-pressure changes were about 0.1 hPa. However, long-term (diurnal) temperature changes caused significant instrumental drift of the observed pressure.

An improved version of the microbarographs was used in 1990. Each barometer consisted in an insulated thermostatically-controlled oven operating at $50°C$ and housing an absolute pressure sensor (commercially available) which was calibrated in the laboratory. This new design avoided the use of a reference-pressure vacuum flask, improving the quality of the data.

The IEO buoy tide gauges (CS2 and PS) were ALLGOMATIC field stations made by CMOS technology. The resolution of sea-level variations was 1 cm.

A more detailed description of the microbarographs and tide gauges can be found in Monserrat *et al.* (1991) and Monserrat and Thorpe (1992).

The bottom pressure station located in Ciutadella (CS) was an M100 model developed by Tom Wilson (Brightwaters Instruments). The pressure sensor has a resolution of 0.11 mbar with a maximum value of 6896.5 mbar (100 psia). The bottom pressure station located in Palma Bay (SS) was an ENDECO type 1029 SSM sea-level recorder. The pressure sensor has a resolution of 0.3 cm and an accuracy of about 0.15 cm over the full scale range.

A sampling interval of 1 min was used for all instruments in 1989 except SS, recording bottom pressure every 2 min. No averaging was done during the sampling interval for microbarographs and tide gauges, so the given values corresponded to instantaneous measurements of atmospheric pressure and sea level. The bottom pressure stations integrated the readings over the filtering interval, which was set equal to 30 s for the Ciutadella instrument (CS) and 1 min for the instrument placed in Palma (PS).

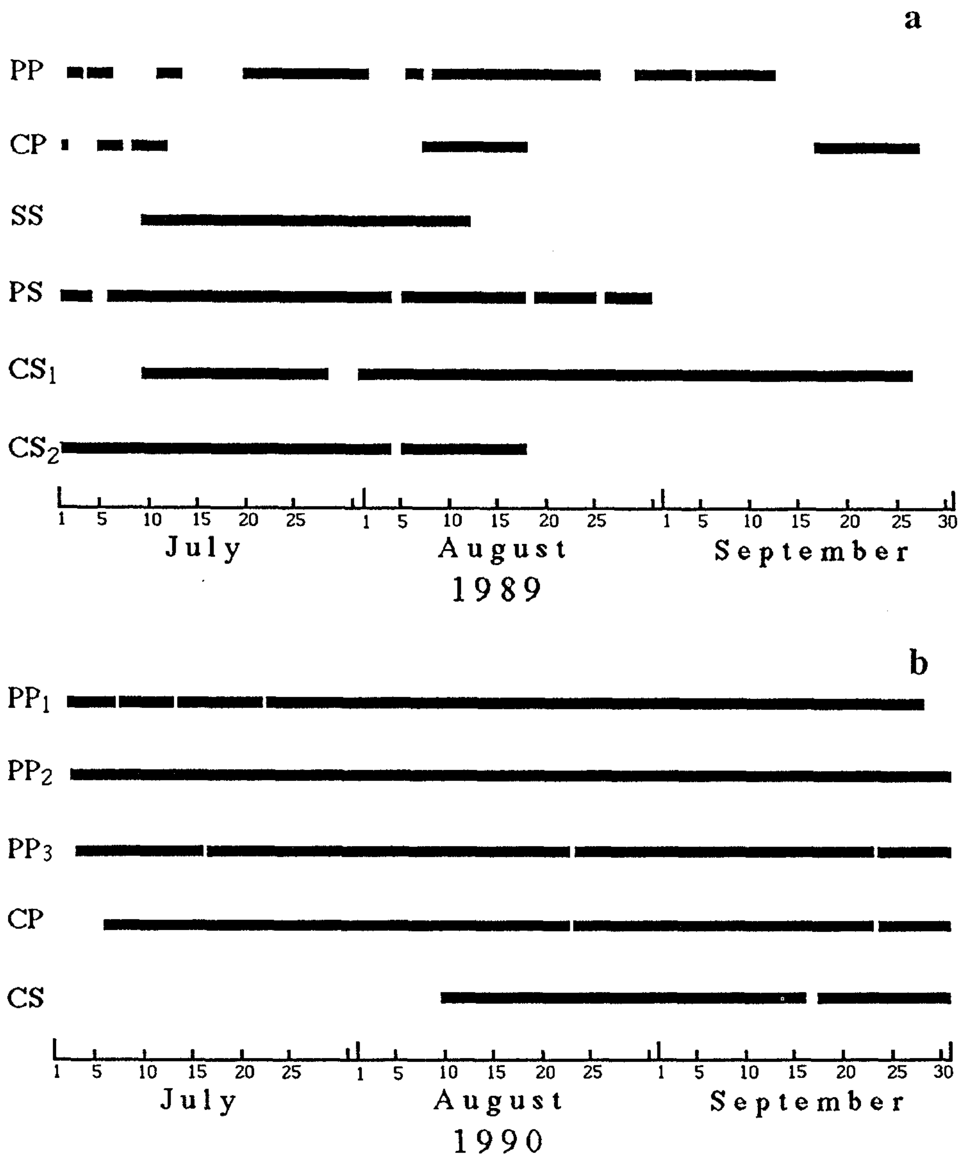

Fig. 4. Diagram of the available sea-level and atmospheric pressure data in the region of the Balearic Islands in 1989 (a) and 1990 (b).

Due to power cuts and other technical problems there were several gaps in the data records. A summary of the 1989 data used in this study is presented in Figure 4a.

The time interval used in 1990 was 30 seconds for all the instruments: microbarographs (CP, PP1, PP2, PP3) and the bottom pressure station CS1 in Ciutadella inlet. The quality of the data, especially atmospheric pressure, was much higher this year than in 1989, and there were only a few small gaps in the records (Figure 4b). However, 1990 did not produce as many *rissagas* as the previous year, and no sea-level data were available for Palma Bay.

3.2. SHIKOTAN, SOUTH KURIL ISLANDS

A series of long wave field measurements was made by V.A. Djumagaliev in the region of Shikotan Island during the IMGG experiments in 1989–92 (Djumagaliev and Rabinovich, 1993). Several cable and autonomous bottom pressure gauges were installed in different bays and inlets of the island for monitoring of marine hazardous phenomena and investigation of the resonance properties of the corresponding basins; three precision quartz microbarographs were used for simultaneous measurements of atmospheric pressure fluctuations. Several months of quality data were obtained at these stations and, in fact, two weak tsunamis were recorded (Djumagaliev *et al.*, 1993; Rabinovich *et al.*, 1993).

Three microbarographs were placed: (1) at the Hydrophysical Observatory (HPO) 'Shikotan', Malokurilsk (MP), (2) in Krabozavodsk (KP), and (3) near Dimitrova Bay (DP) (Figure 5). The same microbarographs were used earlier in KAMSHEL experiments 1987–89 at the southwestern coast of Kamchatka (Kovalev *et al.*, 1991). The main purposes of the atmospheric measurements at Shikotan Island were: investigation of the pressure-induced long ocean waves and examination of the atmospheric gravity wave field in the surface layer itself.

The sampling interval (integrating time) both for bottom pressure stations and microbarographs was chosen to be 1 min yielding a Nyquist frequency of 0.5 cpm.

In the present paper attention is focused on the analysis of simultaneous half-month records (5–21 May 1991) of sea-level oscillations at the stations MS, OS and KS installed in three bays (Malokurilskaya, Otradnaya, and Krabovaya) of the northern coast of Shikotan, and microfluctuations of atmospheric pressure at the stations MP, KP, and DP forming a triangle with sides 8–10 km (Figure 5). A deep cyclone passed over the South Kuriles during this period; a few other events of high atmospheric activity also occurred, in particular the passage of a thunderstorm on 9 May followed by a train of significant pressure oscillations (Djumagaliev and Rabinovich, 1993). These data enable us to study the reaction of three nearby but different inlets to the same external atmospheric forcing and the same basins on different forcing. The corresponding results are compared with similar results for the region of the Balearic Islands.

All these series, except MS, had length 22 574 values (i.e. min) in the mentioned period; the record of MS was a little shorter (20 187 values) because of some technical problems with a shore recorder.

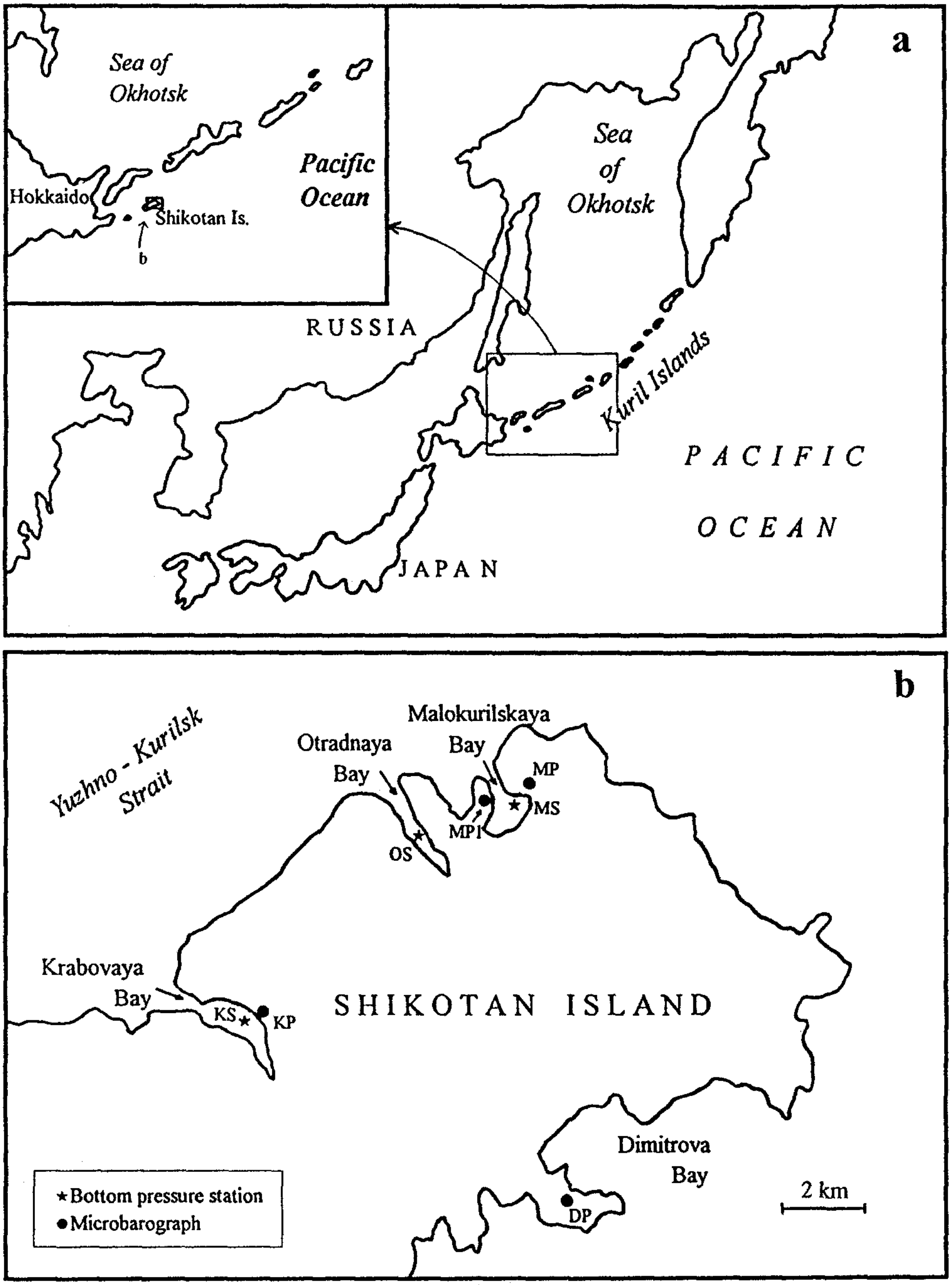

Fig. 5. Location of the instruments in the region of Shikotan Island, South Kurils.

4. Data Preparation and Preliminary Analysis

The whole data set was read into a computer and carefully verified. Obvious errors, due to power jumps, glitches in data transmission and recording, were corrected. Some small gaps in the data (less than 2 hours) were filled by linear interpolation. The least-square method was applied to estimate tidal constituents in sea-level/bottom pressure records; then the predicted tides were subtracted from the initial records and the residual series were used for further analysis.

Prepared in this way, time series for Shikotan Island are presented in Figure 6. A deep cyclone, with a pressure fall of about 35 hPa, passing over the region on 13–16 May is probably the most obvious feature of the Shikotan atmospheric pressure records (Figure 6a). Some high-frequency oscillations may also be noticed in these records. High-passed Kaiser–Bessel filter (Harris, 1978) with 3 h cutoff period was applied to isolate these components (Figure 6b). Low-frequency motions are much weaker in bottom pressure records; the high-frequency components, related mainly to the seiches in the corresponding basins, are the predominant type of oscillations in the residual series (Figure 6c).

Atmospheric pressure and sea-level (bottom pressure) records in the region of the Balearic Islands have a similar character. As an example, a few simultaneous sections of records for the period 5–17 August 1989 are presented in Figure 7. The initial series of atmospheric pressure for 1989 (before high-passed filtration) are not shown because they were contaminated by daily temperature variations. It is clearly seen that sea-level oscillations in Ciutadella inlet are much stronger than in Palma Bay (Figure 7b) and also that these oscillations correlate with atmospheric activity.

The observations at the stations CS1 and CS2 in Ciutadella inlet look very alike (Figure 7b) despite the fact that the first instrument was a bottom pressure recorder and the second one was a sea-level tide gauge. A detailed investigation of the correlation between these two instruments was made by means of cross-spectral analysis. A Kaiser–Bessel spectral window (Harris, 1978) of length $n = 1024$ and halfwindow overlapping was performed to improve the spectral estimates. Additional frequency averaging with variable window (Luther, 1982) was done to smooth high-frequency oscillations and to increase the degree of freedom (ν). Two simultaneous sections of the CS1 and CS2 records were chosen for analysis: (1) 9–28 July 1989; (2) 5–17 August 1989. For the first section $\nu = 104$ for low frequencies and $\nu = 520$ for a key period 10.6 min; the corresponding values for the second section are 70 and 350. The results of computations are presented in Figure 8.

The main differences between CS1 and CS2 spectra are at very low frequencies ($f < 0.016$ cpm) and at high frequencies ($f > 0.13 - 0.16$ cpm) (Figures 8a,b). The low-frequency differences are related to the influence of static atmosphere-induced oscillations; such oscillations caused by the 'inverted barometer' effect are not recorded by bottom pressure stations (see, for example, Rabinovich, 1993), which is why the sea-level spectrum CS2 is higher at these frequencies than the

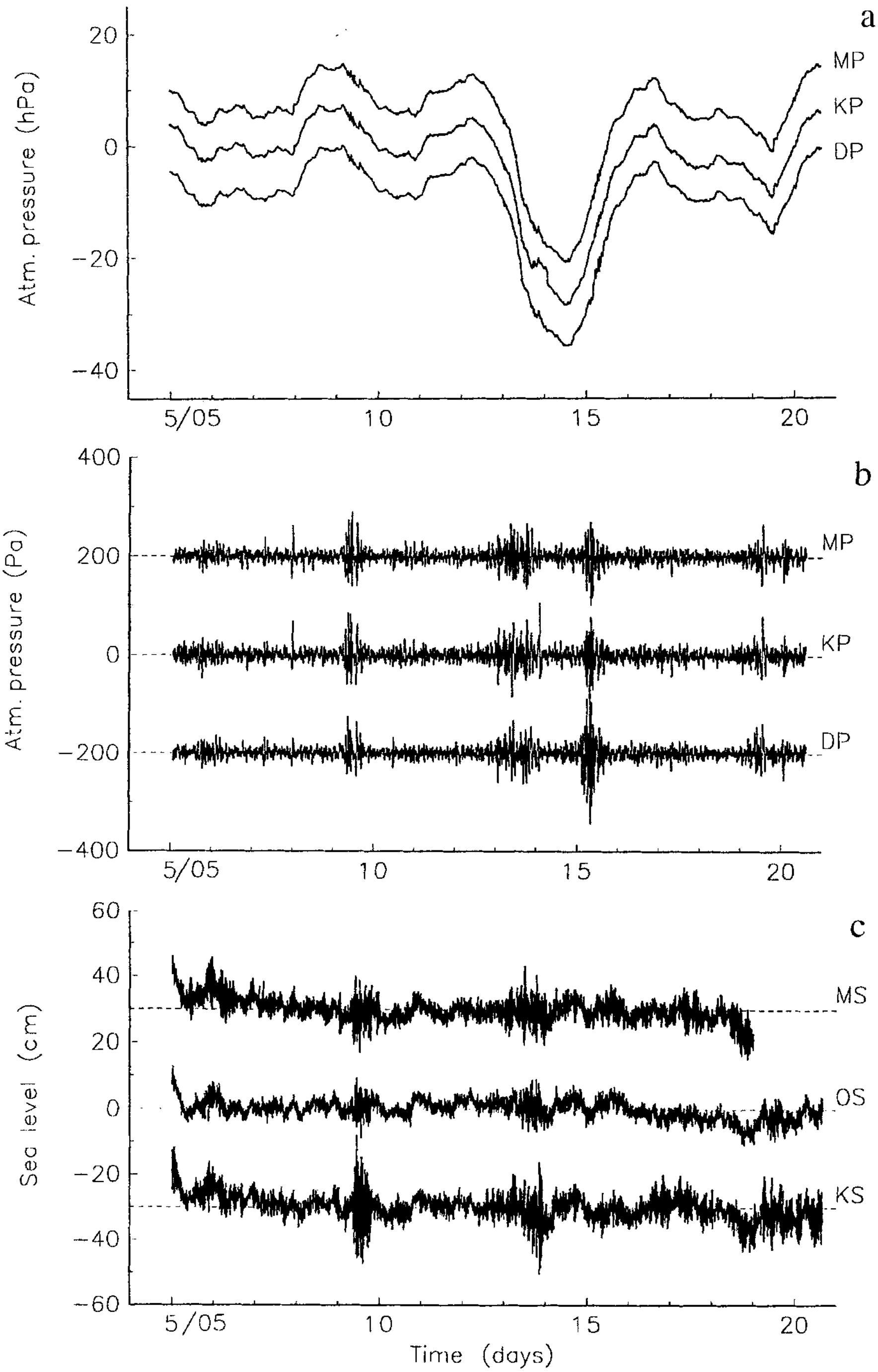

Fig. 6. Simultaneous records of atmospheric pressure (a), high-pass filtered atmospheric pressure (b) and bottom pressure (c) obtained in the region of Shikotan Island in May 1991. Signals have a different offset for better visualization.

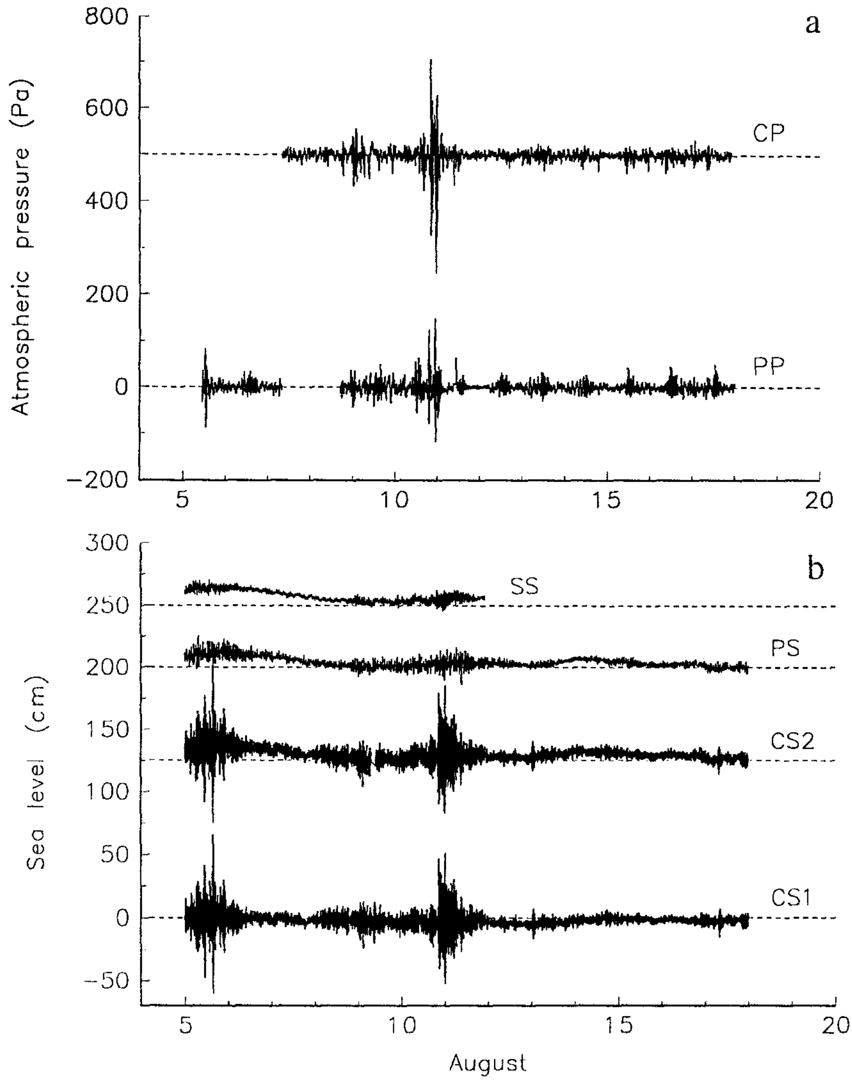

Fig. 7. Simultaneous sections of records of high-pass filtered atmospheric pressure (a) and sea level (b) in the region of the Balearic Islands, 1989. Signals have a different offset for better visualization.

bottom pressure spectrum CS1. Reduction of coherence and admittance functions (Figures 8c,d) at frequencies less than 0.016 cpm shows that the static oscillations contain here about 30–40% of the total low-frequency energy. The differences at high frequencies have another nature. They are related to the insufficient accuracy and resolution of the CS2 instrument; its spectrum at these frequencies has a 'white noise' character (Figures 8a,b). The first period (9–28 July) was relatively calm, the second one (5–17 August) was much more energetic (two *rissagas* with wave height more than 1 m occurred in Ciutadella inlet on 5 and 11 August). The long wave spectra in the second case were about half order higher. Consequently, the coherence and admittance functions between CS1 and CS2 were also greater and significant values were observed at higher frequencies (Figures 8c,d).

The most important result of this analysis was that the coherence and admittance functions were close to 1.0 for the oscillations with intermediate periods (from 4–7 to 65 min), which are the main interest of the present study. Hence both instruments gave practically identical estimates of the oscillations in this frequency band. In the following text the term 'sea-level' will be used as a general term for both types of records. The equivalence of CS1 and CS2 measurements demonstrated the high reliability of the corresponding observations and made it possible to use the CS2 data to fill the gaps in the CS1 record. Continuous three-month series of 1 min data (from 1 July to 26 September) were obtained in this way (marked as CS in the text below) and used for further analysis of seiches in Ciutadella inlet.

5. General Spectral Properties

The entire of available sea-level and atmospheric pressure data from 1989 and 1990 in the region of the Balearic Islands and from May 1991 at Shikotan Island are used to estimate the general spectral characteristics of the atmospheric pressure and sea-level oscillations in these regions.

Some results of spectral analysis of atmospheric waves in Palma and Ciutadella and sea-level oscillations in Ciutadella for a few particular events in 1989–90 have previously been presented by Monserrat *et al.* (1991) and Monserrat and Thorpe (1992). There were also a few papers devoted to the examination of tsunami and background records in Malokurilskaya and Krabovaya Bays of Shikotan Island (e.g. Djumagaliev *et al.*, 1993; Rabinovich *et al.*, 1993). A preliminary review on spectra of bottom pressure records in different bays and inlets of Shikotan and atmospheric pressure spectra at the island was published by Djumagaliev and Rabinovich (1993). Here, by analysis of long series, rather than of particular cases, it becomes possible to suppress the influence of individual atmospheric events and to determine the principal resonant features of the region related mainly to the local topography. A further comparison of the general (long term) and individual (short term) spectra may also be helpful to distinguish the character of the external atmospheric forcing at sea surface and to define the concrete generation mechanism of the strong seiches *(meteorological tsunamis)* in both regions.

The same procedure, as described in the previous section, is used here to analyse the 1989 and 1990 data in the Balearic Islands. The spectral window was chosen to be 2048 min for 1989 (where the sampling interval was mostly 1 min) and 1024 min for 1990 data (sampling interval of 30 sec). The spectra of series having gaps (e.g. PS) were estimated independently for every continuous piece and then averaged over all pieces. Degrees of freedom of these general spectra were very high: from $\nu = 92$ (SS) up to $\nu = 244$ (CS) for low frequencies, and several times more for

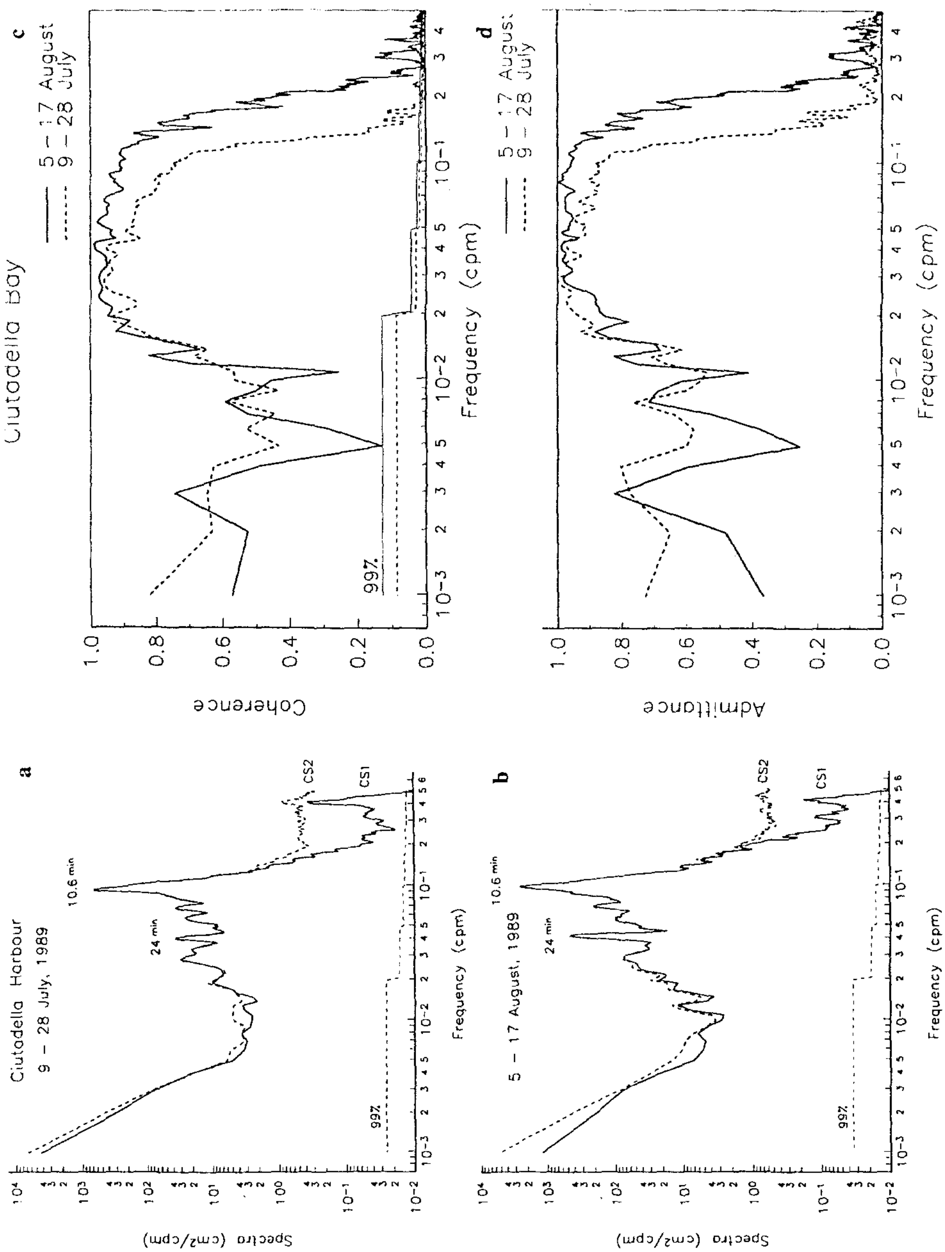

Fig. 8. Bottom pressure (CS1) and sea level (CS2) spectra of two stations installed in Ciutadella inlet for two different observation periods: 9–28 July 1989 (a) and 5–17 August 1989 (b). Coherence and admittance functions between CS1 and CS2 for the two observation periods are included in (c) and (d) respectively.

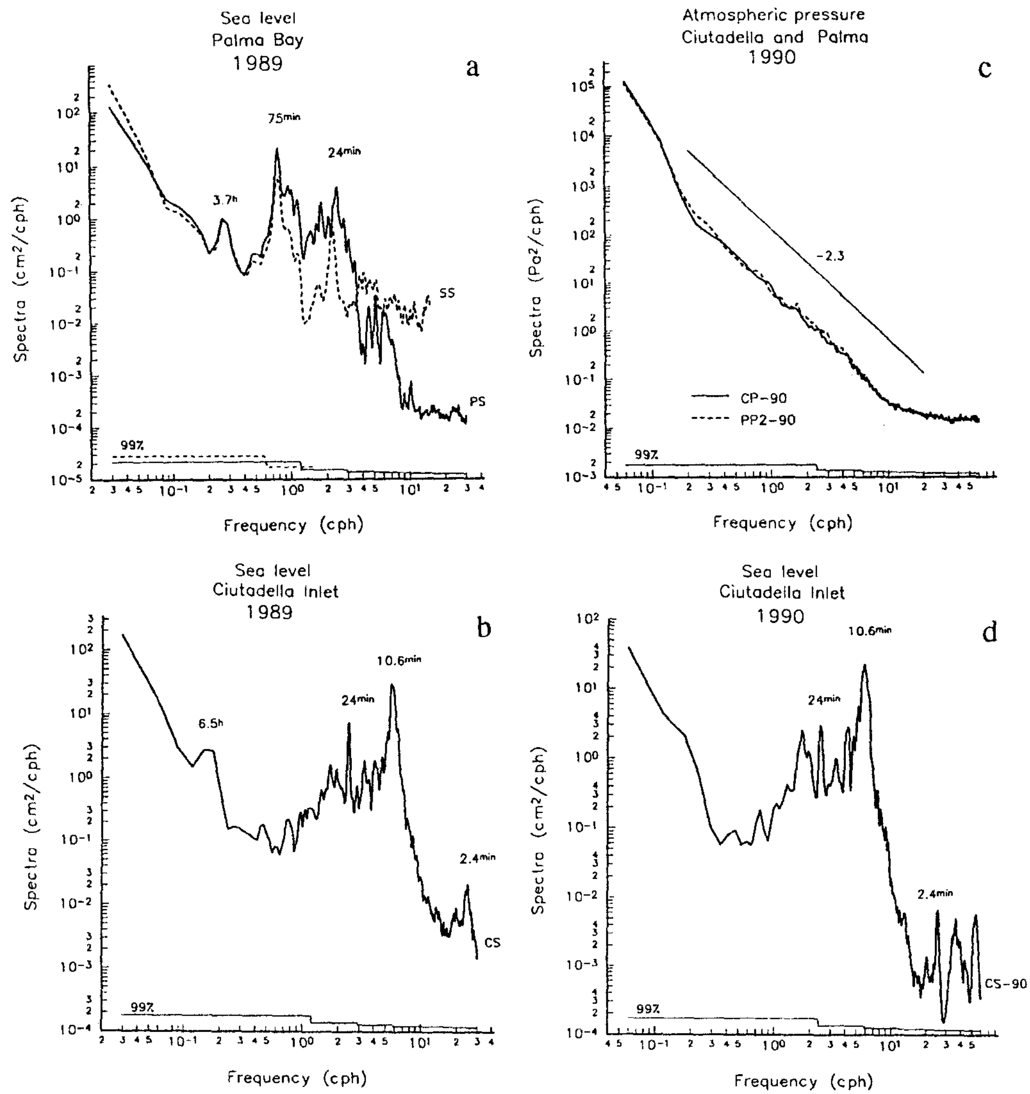

Fig. 9. General spectra for sea-level at the stations PS and SS in Palma Bay, 1989 (a), sea-level at the station CS in Ciutadella inlet, 1989 (b), atmospheric pressure at the stations CP and PP2, 1990 (c) and sea-level at the station CS, 1990 (d). A straight line showing the atmospheric pressure power law decay is included in (c).

high frequencies (because of additional frequency averaging). The corresponding results are presented in Figure 9.

Spectra in Palma Bay have a rather complicated character. Three main spectral peaks are clearly seen both in spectra of Palma de Mallorca (PS) and Sol de Mallorca (SS): 3.7 h, 75 min and 24 min (the last maximum is shifted a little to lower frequencies at the SS spectrum having a period of about 27 min). There are also a few weaker maxima with periods 33, 13.2, 11.6, 9.6–10.0, and 5.9 min, which are better seen in the PS spectrum than in the SS spectrum (Figure 9a). Apparently, the observed low-frequency maxima are related to the eigenfrequencies of Palma Bay and southwestern Mallorca shelf; some of the high-frequency extrema are probably related to eigenoscillations of Palma harbour. Although several peaks are noticeable in the PS and SS spectra, they are not very energetic, except probably that with a period of 75 min. Evidently, the wide entrance of Palma Bay (Figure 3c) increases the number and variety of the observed seiche modes but reduces their Q-factors. This may be a reason why large-amplitude seiches have never been observed in this bay (Table I).

In contrast to Palma Bay, Ciutadella is an elongated, shallow, and narrow inlet (Figure 3b). The sea-level spectra in Ciutadella (CS) both in 1989 and 1990 have a strong dominant peak with a period of about 10.6 min (Figures 9b,d). As it was found from simple theoretical analysis (Tintoré *et al.*, 1988) and numerical computations (the corresponding paper is in preparation), this peak is related to the grave (Helmholtz) mode of the inlet. Previous investigations (Tintoré *et al.*, 1988; Monserrat *et al.*, 1991) demonstrated that precisely oscillations with this period cause the destructive *rissaga* phenomenon in Ciutadella, which is why they are significant for the present study. However, there are some other interesting features in the CS spectra. In particular, a sharp maximum with a period of about 24 min, apparently connected to the oscillations over the shelf of Menorca Island. As seen from Figures 8a,b, this spectral peak was much more prominent during an energetic period, 5–17 August 1989, than in a calm period, 9–28 July 1989. There is also another peak, probably related to *shelf oscillations* with a period of 33 min. This maximum is particularly well seen in the 1990 spectrum (Figure 9d). Other high-frequency maxima, with periods less than 3 min, are presumably high-order *inlet modes*: in the 1989 spectrum (with Nyquist frequency $f_N = 0.5$ cpm $= 30$ cph) two peaks are seen with periods 2.9 and 2.4 min (Figure 9b); in the 1990 spectrum ($f_N = 1.0$ cpm $= 60$ cph) two additional maxima appeared with periods 1.65 and 1.10 min (Figure 9d). These modes are not energetic but the corresponding spectral peaks are sharp and well defined. A weak low-frequency maximum in the 1989 spectrum (Figure 9b) has a period of 6.5 h, close to the quarterdiurnal tidal period, and probably is caused by the influence of shallow-water tides; in the 1990 spectrum this peak is not seen because the spectral window in 1990 was chosen to be only 1024 min.

Atmospheric pressure spectra estimated from different stations in the Balearic Islands coincide (Figure 9c) suggesting that local topography plays an insignificant role in their formation. The spectra are smooth and monotonic and decrease with increasing frequency according to an $\omega^{-2.3}$ power law which is in good agreement with observations by Kovalev *et al.* (1991) and Djumagaliev and Rabinovich (1993), but steeper than those described by Herron *et al.* (1969) or Gossard and Hooke (1975) ($\omega^{-2.0}$).

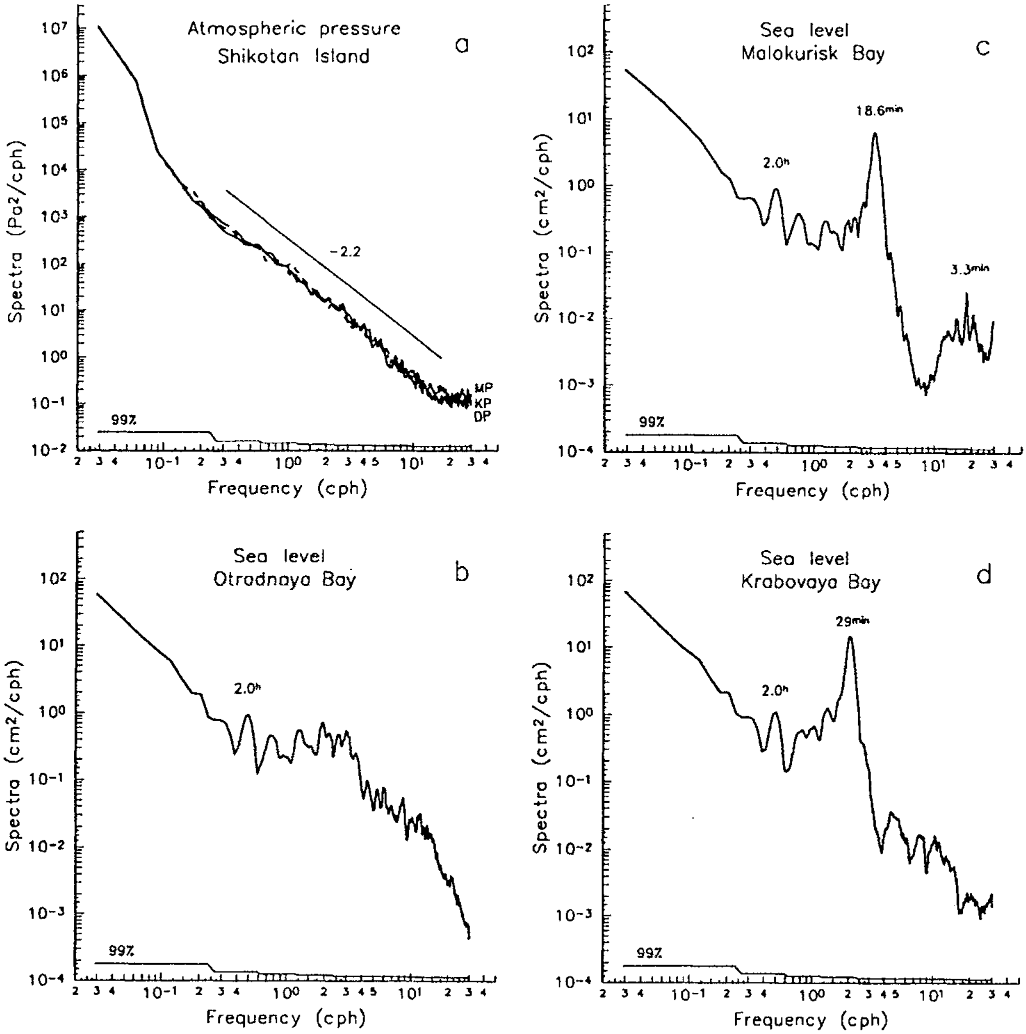

Fig. 10. Atmospheric pressure spectra for the three stations (MP, KP, and DP) (a) and sea-level spectra for the stations OS (b), MS (c), and KS (d) located in the region of Shikotan Island. A straight line showing the atmospheric pressure power law decay is included in (a).

Spectra of sea-level (bottom pressure) oscillations in the bays of Shikotan Island were estimated with the same spectral Kaiser–Bessel window (2048 min) with halfwindow overlapping. Degrees of freedom at low frequencies $\nu = 42$ for Krabovaya and Otradnaya Bays (KS and OS) and $\nu = 36$ for Malokurilskaya Bay (MS). The main results presented in Figure 10b,c,d are in good agreement with results of previous analysis by Djumagaliev and Rabinovich (1993).

Malokurilskaya Bay is a bottle-like bay with a narrow mouth and wide elliptic inner basin (Figure 5c). The main spectral maximum of the oscillations inside the bay has a very prominent period of 18.6 min (Figure 10c). As was demonstrated by Djumagaliev *et al.* (1989) and Rabinovich and Levyant (1992) this maximum is related to the Helmholtz (fundamental bay) mode. The Q-factor of this mode is quite high, about 12. The high-frequency peaks with periods 3.9, 3.3, and 2.8 min are in good agreement with the theoretical periods computed by Rabinovich and Levyant (1992) for the 2nd, 3rd and 4th eigenmodes. Absence of the 1st (rocking) mode peak in the MS spectrum is apparently related to the closeness of the MS station position to the corresponding nodal line.

Krabovaya Bay is an elongated and narrow inlet, resembling the shape of Ciutadella inlet. The character of the spectrum in this inlet (KS) is very similar to that one in Malokurilskaya Bay. The predominant peak with period of about 29 min and a weak spectral peak with a period 13.5 min are very close to the computed periods 30 and 14.5 min of the grave and 1st eigenmodes of the inlet (Rabinovich *et al.*, 1993). The grave (Helmholtz) mode in Krabovaya Bay has almost the same Q-factor as the analogous mode in Malokurilskaya Bay but is more energetic (Figure 10d).

The form of Otradnaya Bay is similar to Krabovaya Bay (Figure 5c) but the oscillations here are quite different. In particular, in contrast to KS and MS there are no dominant peaks in the OS spectrum (Figure 10b). No significant seiches were recorded in this inlet during the observation period. The reasons for such a difference is obscure, possibly it can be explained by the very shallow swampy character of Otradnaya Bay. Nonlinear effects and strong energy dissipation may prevent significant standing oscillations within this domain.

One spectacular aspect of these three spectra (MS, KS, and OS) is their very good agreement at the frequencies below those of the grave modes. In particular, 5 spectral maxima with periods 3.1, 2.0, 1.3 hr, 48, and 32 min are present in all spectra (the last one is not well seen in the KS spectrum because of the closeness to the main resonant maximum 29 min). The spectra of atmospheric pressure are very smooth and monotonic (Figure 10a), thus it can be assumed that these oscillations are related to free propagating and standing long waves over the northern shelf of Shikotan Island.

It is clearly shown from the present analysis that there are several common features in sea-level spectra in the regions of the Balearic and Kuril Islands, especially in the spectra of Ciutadella (CS), Malokurilskaya (MS) and Krabovaya (KS). As has been previously mentioned, Ciutadella and Krabovaya are both elongated, narrow, and shallow inlets; Malokurilskaya is an elliptic shallow bay with a narrow mouth. Strong seiches are usually recorded in just such domains (Honda *et al.*, 1908; Nakano and Unoki, 1962); Nagasaki Bay and Vela Luka (referred in the Introduction) are typical examples. Gomis *et al.* (1993) explained this peculiarity of seiche generation by using a simple theoretical model of a rectangular flat-bottom basin which applies well to Ciutadella and Krabovaya inlets. The amplification factor (F) for this model has the form:

$$F = \frac{A_{\text{in}}}{A_{\text{out}}} = \left(\frac{4L}{\pi d}\right)\left(\frac{H_{\text{out}}}{H_{\text{in}}}\right) \qquad (1)$$

where A_{in} and A_{out} are the wave amplitudes inside and outside the inlet, H_{in} and H_{out} are the corresponding depths, L is the inlet length and d its width. This expression shows that increasing the inlet length, or reducing its width or depth, the oscillations inside the inlet amplifies. Certainly, this is true up to a certain limit, then friction and nonlinearity will begin to weaken entering waves, as appears to happen in Otradnaya Bay.

The most obvious peculiarity of these spectra is a strong maximum related to the fundamental (Helmholtz) seiche mode. Within the inner basins this mode dominates strongly. At frequencies higher than the fundamental, the long wave energy declines rapidly. A similar character was observed, for example, by Okihiro *et al.*, (1993) at Barbers Point Harbour, Oahu, Hawaii. Apparently, a narrow bay entrance plays a role of low-frequency wave filter in the same way as a hole in a tide gauge stilling well (Satake *et al.*, 1988). Nevertheless, the peaks caused by high-order seiche modes are seen quite clearly in spectra (Figures 9b,d, 10c,d). The shelf oscillations dominate the low-frequency band of the spectra.

The atmospheric pressure spectra in both regions are similar. They are smooth and stable. The difference in the power law ($\omega^{-2.3}$ in Ciutadella and Palma, and $\omega^{-2.2}$ at Shikotan Island) is insignificant: an analysis of more than one year (1989-90) atmospheric pressure records in Malokurilsk (MP station) showed that power over different periods and seasons varied between -2.06 and -2.40 but the average value was -2.26 (Djumagaliev and Rabinovich, 1993), practically the same as was observed in Kamchatka region (Kovalev *et al.*, 1991) and is observed now in the Balearic Islands. No maxima are noticeable in these long term atmospheric pressure spectra which may be related to the observed maxima of background sea-level spectra, therefore it is clear that the latter are explained by topographic influence.

6. Statistical Analysis of Strong Events

The complete set of available sea-level data in the Balearic and Kuril Islands was used to identify strong events, i.e. large-amplitude seiches, in the investigated bays and inlets, and to determine their statistical characteristics and relation to atmospheric pressure fluctuations.

High-pass filter with a 3 hr Kaiser–Bessel window was used to suppress the low-frequency variations. Filtered series were used to analyse individual seiche oscillations and to estimate their trough-to-crest heights and periods. Changes of these seiche heights in time are presented in Figures 11–12. It can be seen that they are unstable, intervals of high activity are followed by periods of calmness. From the synchronous pieces of the 1989 records in Palma Bay and Ciutadella, it is clearly seen that seiches at all three points (SS, PS, CS) intensified simultaneously (Figure 11), apparently because of the same atmospheric source, although with significant differences in wave heights at the different stations. Seiches in the bays of Shikotan Island (Malokurilskaya, Otradnaya, and Krabovaya) had an analogous character, their intensification occurred at about the same time in all three basins but their wave heights were different.

A subjective criterion was used to select the strongest events for the observation periods: the critical wave height was taken to be 40 cm for Ciutadella (CS) and 20 cm for Krabovaya Bay (KS). In Ciutadella 8 events were found with wave heights exceeding this level in July–September 1989 (Figure 11b) and 2 events in August-September 1990 (Figure 11d); 3 events were selected in the Krabovaya record in May 1991 (Figure 12b).

All these events were subject to detailed analysis. The 'beginning time' of the event was assumed to be when seiche heights had exceeded 30 cm in Ciutadella (CS) and 10 cm in Krabovaya (KS) and the 'end time' when they became definitively below these values. The statistics (duration, mean period and wave height) were estimated for these time intervals. The same characteristics were determined also for other stations for the simultaneous time intervals (selected using the CS and KS records), independently of the actual seiche heights at those stations. The corresponding results are presented in Tables II and III.

From the 8 events mentioned in Table II for the CS-1989 record, seiche heights were more than 60 cm in 6 cases, and more than 1 m in 3 cases. The most spectacular event occurred on 4–7 July 1989, when a wave height of 196.7 cm was recorded (see Figure 11b). The maximum wave height observed in Palma (PS) during this event was 32.3 cm, i.e. about 6 times less than in Ciutadella. Similar ratios between maximum waves at CS and PS were found for two other strong cases (5–6 and 11 August 1989), the corresponding ratio at the CS and SS stations were 7–12. However, the analogous ratios for the mean heights were smaller: about 3 for CS/PS and 6-9 for CS/SS (Table II).

No seiches as large as in 1989 were observed in Ciutadella inlet in 1990 (Figure 11d). The strongest oscillations happened on 25 September 1990 when the wave height achieved 92.8 cm. Unfortunately, there were no PS and SS data in 1990, nor in September 1989, to increase statistics and to have more a complete comparison of simultaneous long wave oscillations in Palma Bay and in Ciutadella.

The seiches in the bays of Shikotan, the Kuril Islands, were of the same order as observed in Palma Bay but much weaker than in Ciutadella inlet. The maximum oscillations for the observation period took place in Krabovaya Bay on 5 May 1991 when a wave height of 37.4 cm was recorded. The simultaneous seiche oscillations in Malokurilskaya Bay (MS) were for this event about 1.5 times weaker than in Krabovaya Bay (KS) but 1.5 times stronger than in Otradnaya Bay (OS). Similar ratios occurred also for other events.

The significant differences in wave heights at different stations (see Figure 11) demonstrate a strong individual reaction of various domains and points to the same (or similar) external forcing. In particular, the oscillations at the PS station were about twice as high as at the SS station, obviously because the former was located at the head of Palma Bay and the latter near to the mouth (see Figure 3c). On the other hand, the strong superiority of seiche heights in Ciutadella inlet, in comparison

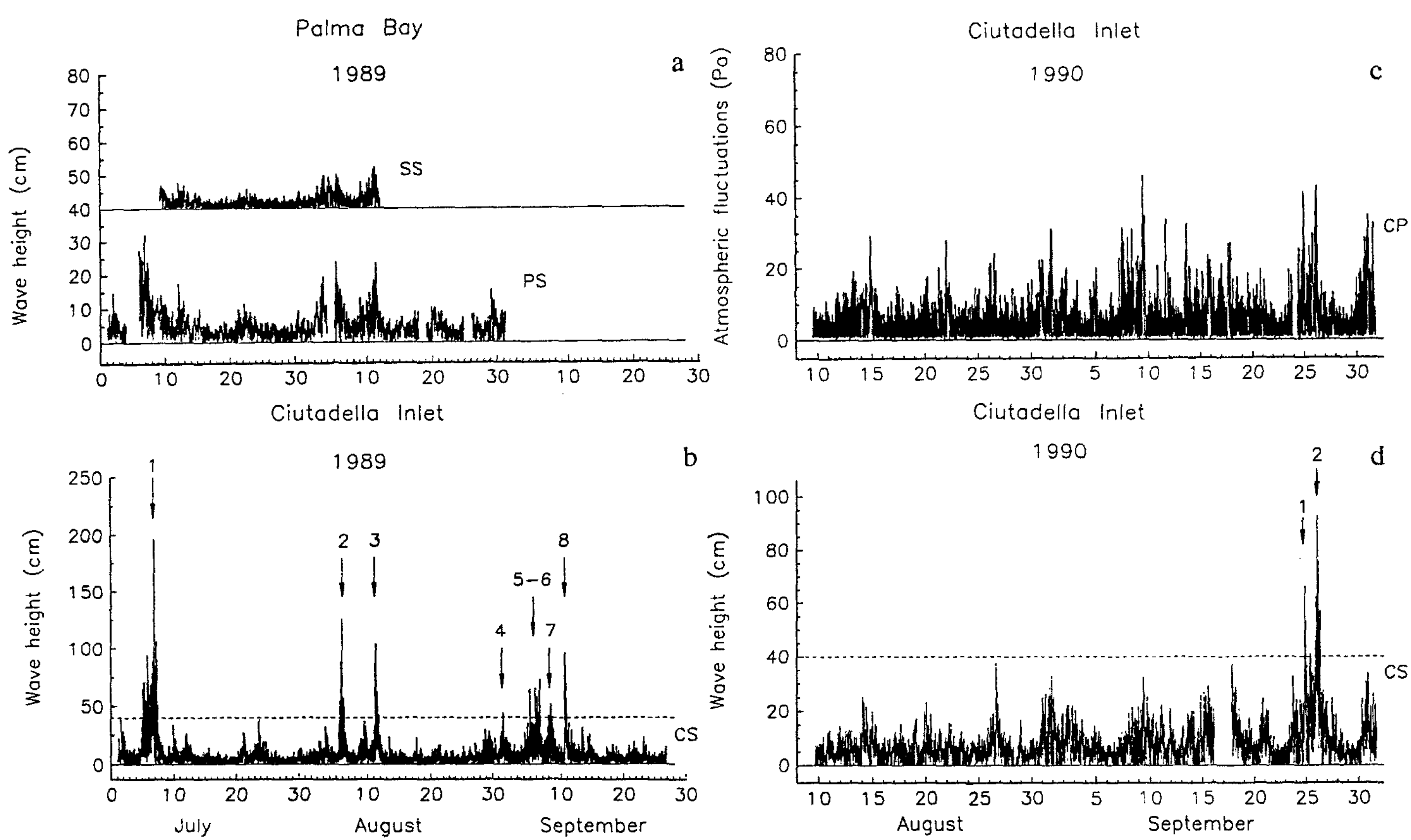

Fig. 11. Wave heights of sea-level oscillations at the stations PS and SS in Palma Bay (a) (signals have a different offset for better visualization) and at the station CS in Ciutadella inlet (b) in July–September 1989; and of atmospheric (c) and sea level (d) oscillations in Ciutadella in August–September 1990. Eight events with sea-level wave heights in Ciutadella (CS) more than 40 cm are numbered in 1989 and two events in 1990.

Table II. Statistical characteristics of large seiche oscillations recorded in the Balearic Islands in 1989–90

Event				Stations								
				Ciutadella			Palma			Sol de Mallorca		
No.	Beginning time	Duration (hours)	Type	Max height (cm)	Mean height (cm)	Mean period (min)	Max height (cm)	Mean height (cm)	Mean period (min)	Max height (cm)	Mean height (cm)	Mean period (min)
	1989											
1	04/07 21:20	63.4	C/A	196.7	39.1	10.7	32.3	14.3	27.5	–	–	–
2	05/08 03:35	19.2	B	126.8	34.2	10.5	23.9	9.3	25.8	10.3	3.7	10.9
3	10/08 20:38	10.2	A	103.8	44.4	11.7	23.5	10.8	25.9	15.1	5.9	15.7
4	31/08 10:58	0.9	C	44.3	38.5	10.8	–	–	–	–	–	–
5	04/09 18:09	4.6	C	64.4	26.2	11.1	–	–	–	–	–	–
6	05/09 05:27	30.0	C	72.8	23.7	10.8	–	–	–	–	–	–
7	07/09 16:40	21.5	C	51.5	18.6	10.3	–	–	–	–	–	–
8	10/09 10:42	7.7	B	95.8	42.4	11.5	–	–	–	–	–	–
	1990											
1	24/09 12:31	4.8	B	66.4	28.5	9.6	–	–	–	–	–	–
2	25/09 12:45	11.5	C	92.8	36.6	10.9	–	–	–	–	–	–

TABLE III. Statistical characteristics of large seiche oscillations recorded in the region of Shikotan Island in May 1991

Event				Stations								
				Krabovaya			Otradnaya			Malokurilskaya		
No.	Beginning time	Duration (hours)	Type	Max height (cm)	Mean height (cm)	Mean period (min)	Max height (cm)	Mean height (cm)	Mean period (min)	Max height (cm)	Mean height (cm)	Mean period (min)
1	09/05 07:14	9.6	B	37.4	21.8	28.6	15.2	5.9	15.4	23.8	9.3	18.3
2	13/05 12:00	12.0	A	34.0	13.8	26.7	15.3	5.7	15.8	21.7	10.8	18.1
3	19/05 06:00	>24.0	C	21.9	8.5	26.1	12.9	3.8	15.1	–	–	–

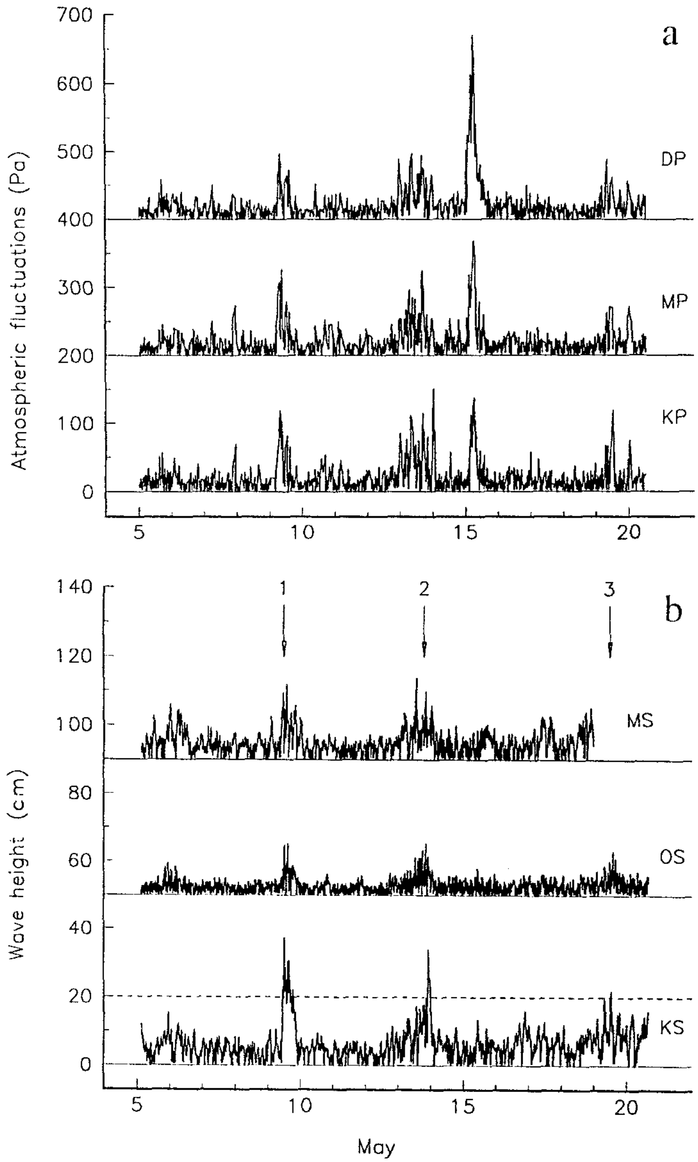

Fig. 12. Wave heights of atmospheric (a) and sea level (b) oscillations in the region of Shikotan Island in May 1991. Three events with sea-level wave heights in Krabovaya Bay (KS) more than 20 cm are numbered. Signals have a different offset for better visualization.

with Palma Bay (by 5–10 times) are surely related to the influence of the local topography and geometry of these two basins.

The observed mean periods of individual seiche oscillations in Ciutadella, Krabovaya and Malokurilskaya have been found to be very close to the periods of the corresponding dominant spectral peaks (see Figures 9b,d, 10c,d), i.e. to the periods of the grave (Helmholtz) modes of the corresponding basins. The observed mean period in Palma also agreed well with the sharp peak at 24 min in the PS spectrum (Figure 9a). However, those in Sol de Mallorca and in Otradnaya do not correspond to any prominent maxima in the SS and OS spectra, apparently due to the unstable character of the oscillations at these stations.

Simultaneous records of atmospheric pressure and sea level in Ciutadella in August–September 1990 and in Shikotan Island in May 1991 give us an excellent opportunity to compare these processes and to study the seiche generation mechanism in these regions. The corresponding plots of time variations of atmospheric and sea-level heights for both regions are presented in Figures 11c,d and 12. The definite atmospheric pressure forcing on sea level is evident from these figures: the seiche intensification (not only for the strongest events but practically for all of them) was observed at the time of increase of atmospheric pressure activity. The reverse is not true, in some cases significant atmospheric waves did not excite seiches at all or excited only insignificant oscillations (see next section). This means that the generation mechanism of the seiches in these regions is far from trivial.

Unfortunately, it was not possible to carry out the same kind of comparison for the whole 1989 Ciutadella sea-level data (CS) because of the absence of adequate atmospheric data (CP) in this year (there were very many gaps in the CP record - see Figure 4a). However, this analysis could be performed for some specific events. For example, Monserrat *et al.* (1991) using the CP and CS records examined the strongest *rissaga* event (No. 1) occurring on 4–7 July 1989 and found good correlation between sea level and atmospheric pressure in Ciutadella. Good agreement between atmospheric and sea level activity is clearly seen in Figure 7.

A visual analysis of the oscillation character during strong events can be used to classify these events in different types, apparently related to different mechanisms of seiche generation:

– A. *Impulse type* – strong initial oscillation(s) and then fast or slow decay of seiche heights;
– B. *Resonance type* – a gradual amplification of consecutive oscillations till the maximum is achieved, then (sometimes) a period of stability, and a gradual reduction;
– C. *Complex type* – a few consecutive abrupt and gradual amplifications and reductions of seiche oscillations.

Note that type *A* is quite similar to usual records of tsunami waves observed in coastal areas (Wiegel, 1964; Murty, 1977) responding to the physical similarity between these two processes.

The 3 events which occurred in Krabovaya Bay in May 1991 are good examples of these three types (Figure 13). *Abiki* waves observed in Nagasaki Bay on 16 March 1988 (Figure 1a) may be related to type *B* and seiches in Longkou Harbour on 1 September 1980 (Figure 1b) are a fair example of type *A*.

All events observed in the region of the Balearic and Kuril Islands were classified using this scheme. The corresponding information is included in Tables II and III.

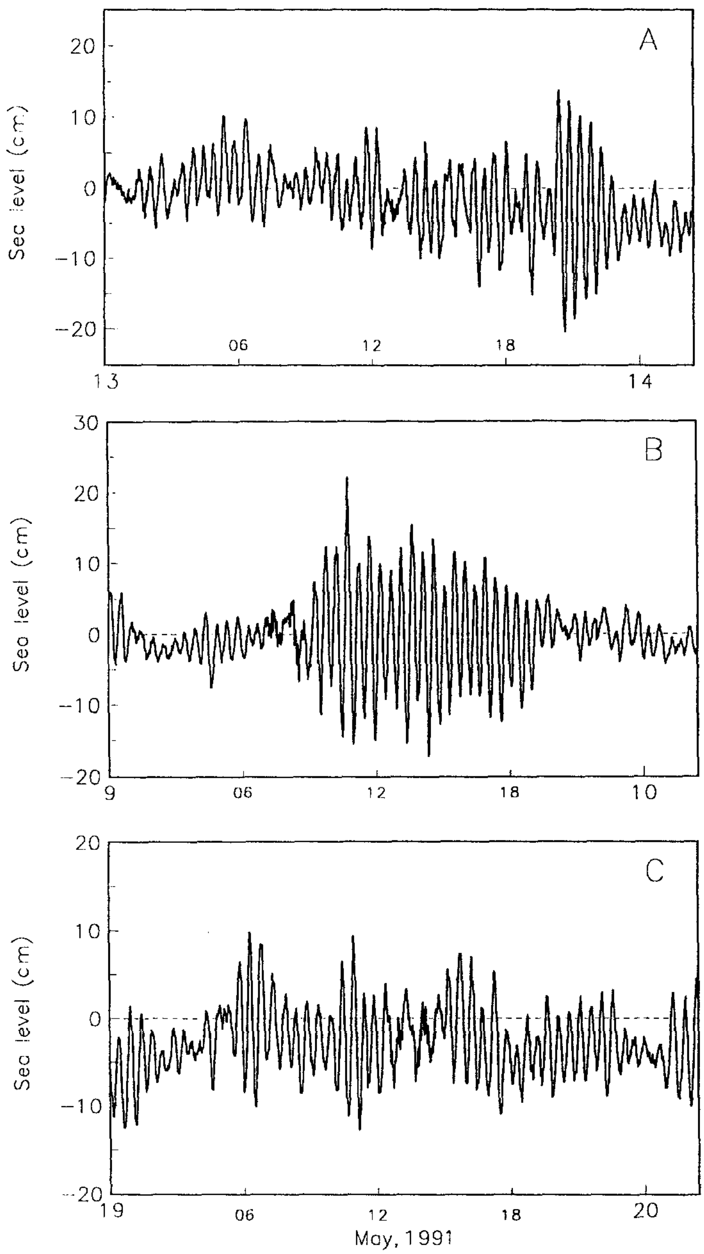

Fig. 13. Three recording sections of significant seiches observed in Krabovaya Bay (KS) in May 1991 which may be considered as examples of different types (*A*, *B*, and *C*) of 'seiche events'.

Certainly the 'pure' types *A* and *B* are infrequent and such classification is a little conditional and subjective but it was found to be useful for further investigation of the atmospheric pressure forcing on sea level (Rabinovich and Monserrat, 1995).

7. Discussion

Two key questions related to the problem of generation of *meteorological tsunamis* in general and to the *rissaga* phenomenon in Ciutadella inlet, in particular, are the following:

- *Why* are such strong sea-level oscillations generated in just some specific places?
- *What* kind of external sources (external conditions) causes these strong events?

The stable recurrence of such disastrous events in the same places proves that they are certainly strongly related to the topography and geometry of the corresponding bays, inlets, or harbours. Ciutadella inlet, Menorca Island (as well as Nagasaki Bay, Japan, and some other basins) is just one of such remarkable places. Simultaneous sea-level measurements in Ciutadella inlet and Palma Bay, presented above, demonstrated that during the same events, seiches in Ciutadella are about 6 times larger. What is the reason?

Miles and Munk (1961) demonstrated that the relative intensity of seiche oscillations in harbours and bays is determined first of all by the *Q-factor* of the corresponding basin. Reducing the harbour entrance by wave-protection constructions increases the *Q*-factor and therefore the harbour oscillations. From this point of view it is quite understandable why the narrow inlet of Ciutadella has much stronger seiches than the open-mouthed Palma Bay. However, there are many other narrow-mouthed inlets and harbours in the Balearic Islands with seiches much weaker than in Ciutadella.

Gomis *et al.* (1993) tried to explain this fact by the influence of the inlet geometry. They estimated the amplification factor (1) for three inlets in this region (Ciutadella, Mahon, and Porto Colom) and showed that in Ciutadella it is much larger than in the other two inlets. But in the region of the Japanese Islands there are several other bays and inlets with this factor no lesser (or even greater) than in Nagasaki Bay although abnormal seiches are known only in the latter basin.

Rabinovich (1993) supposed that the extreme seiche oscillations observed in some places are forced by some kind of *double resonance effect*, e.g., by the coincidence of resonant frequencies of the shelf and inner basin, or eigenfrequencies of the harbour and outer bay, and so on. The relatively small probability of such coincidences is the main reason of the rareness of basins where large-amplitude seiches are reported.

In any case, this question is still open. Field experiments not only within Ciutadella inlet but also on the outer shelf and in the nearby inlets may be very useful for understanding the *'rissaga'* phenomenon. Such measurements were partly performed in 1992–94 and the corresponding data are currently under examination. Another possibility is to carry out numerical experiments to estimate resonant and amplification properties of the inlet and adjoining shelf. This planned by the authors for the near future.

Answering the second question it can surely be said that the main source of *rissaga* waves, as well as seiches in the region of the Kuril Islands, are atmospheric pressure oscillations and jumps. Figure 11 demonstrates this fact quite clearly. However, the character of sea-level responses to the atmospheric perturbations is not evident. For example, the strongest atmospheric oscillations in the 1990 observation period in Ciutadella were recorded on 9 September (Figure 11c) but seiche oscillations that time were weaker than in some other cases in August and September (Figure 11d); atmospheric waves during the first *rissaga* of 1990 (on 24 September) and during the second one (on 25 September) had almost the same magnitude (about 0.4 hPa) (Figure 11c) yet seiches in the second case were 1.5 times higher (Figure 11d).

Probably the most spectacular example of this kind is a passage of very strong atmospheric oscillations over Shikotan Island on 15 May 1991 with wave heights up to 3 hPa which practically did not generate seiches in the investigated bays at all (Figure 12). This suggests that other aspects of the atmospheric pressure activity should play a role such as, for example, wave frequency or direction of propagation of these waves. The examination of all these peculiarities of seiche generation in the regions of the Balearic and Kuril Islands is a subject of the second part of this study (Rabinovich and Monserrat, 1995).

8. Summary and Conclusions

Destructive sea-level waves are regularly observed in some coastal areas of the world ocean where they are known by different local names. These oscillations have similar periods and spatial scales to tsunami waves and may affect the coasts in a similar destructive way. However, they are not generated by seismic activity but by atmospheric disturbances. A review of such phenomena was presented and the name *'meteorological tsunami'* used to refer to these hazardous ocean waves.

'Rissaga' waves observed in Ciutadella and other bays and inlets of the Balearic Islands and the seiche oscillations observed in Shikotan Island, South Kuriles, are just examples of these waves. Using measurements of sea level and atmospheric pressure recorded in both regions in 1989–91, a comparative analysis has been carried out to investigate the general characteristics of these waves and possible generation mechanisms.

Bottom pressure and sea-level records from the instruments installed in Ciutadella Inlet (Balearic Islands) were processed together and it was found that in the frequency band of interest (waves with periods from a few minutes to a few hours) there is practically no difference (coherence and admittance functions are very close to 1.0).

An analysis of long series (constructed both from sea-level and bottom pressure observations) suppressed the influence of individual atmospheric events on sea surface and defined the general spectral properties of the sea waves related to the local topography of the corresponding region. Clear resonant peaks were detected in the records of Ciutadella inlet and Malokurilskaya and Krabovaya Bays (Shikotan Island). These peaks (10.6, 18.6, 29 min, respectively) were conditioned by the fundamental (grave) mode of each bay. The situation was found to be quite different for Palma Bay (Balearic Islands), where several energetic peaks arose, related apparently both to eigenmodes of the bay and shelf oscillations. This being consistent with the fact that Palma Bay (in contrast to the bays mentioned above) is a relatively large bay with a wide entrance.

Statistics of strong seiche events for both regions have been presented. In the region of the Balearic Islands, 10 events have been identified using the Ciutadella record (8 in 1989 and 2 in 1990). For the events when the data from Palma Bay were also available, a simultaneous increase of seiche intensity was also detected in that bay, although the wave heights in Ciutadella were always much higher than in Palma Bay. In Shikotan Island 3 events have been identified in May 1991, occurring simultaneously in all three investigated bays although with a different intensity.

From the synchronic atmospheric pressure and sea-level records it was found that seiches intensify when atmospheric activity increases. However, different inlets respond to the same atmospheric source in different manners, apparently due to the influence of local topography and geometry.

It has been confirmed from this analysis that the strongest seiches are observed in shallow and elongated inlets with a narrow mouth (Ciutadella, Krabovaya). The lack of strong seiches in Otradnaya (Shikotan Island), being a narrow and very shallow inlet, suggests that friction and nonlinear processes weaken incoming waves and produce a limit to this theory when the inlet becomes too narrow or shallow.

Three different types of strong events (large-amplitude seiches) were identified by a visual analysis namely, *impulse, resonance, and complex*. The distinctions between the types are probably related to the different generation mechanisms and this is the subject of further investigation.

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