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Teleconnections between the Adriatic and the Balearic meteotsunamis

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ABSTRACT

This paper investigates whether concurrent or subsequent meteotsunamis could happen at both the Balearic Islands and the Adriatic Sea as a consequence of either the simultaneous presence of the favourable synoptic pattern above both areas, or propagation of the pattern from one area to another. Meteotsunami events in sea level records from Dubrovnik (chosen to be the proxy for the occurrence of meteotsunami events in the Adriatic Sea) are compared to 32 known Ciutadella (the Balearic Islands) events. The analysis shows that a meteotsunami at the Adriatic Sea is likely to happen if the favourable synoptic pattern propagates or spreads from the Balearic Islands to the Adriatic Sea, causing meteotsunamis in both places. Upper level instabilities are recognized as the most important synoptic feature for the occurrence of meteotsunamis, as these instabilities can generate the atmospheric gravity waves which provoke meteotsunamis and also help to trap the atmospheric energy at lower levels.

1. Introduction

The Balearic Islands and the Adriatic Sea are the two places in the Mediterranean Sea where the most vigorous meteotsunamis have been observed. These destructive meteorologically induced high-frequency sea level oscillations are known to reach wave heights of 5 m in the Balearic Islands (Monserrat et al., 2006) and as much as 6 m in the Adriatic Sea (Hodžić 1979/1980). High-frequency sea level oscillations mentioned here and throughout the paper relate to sea level oscillations having periods shorter than 1 h.

On the Balearic Islands there are several bays and harbours which are prone to the high-frequency sea level oscillations caused by propagating air pressure disturbances. However, the strongest sea response is normally observed in the port of Ciutadella (Rabinovich and Monserrat, 1996). This small port in a long, narrow and shallow inlet on the western coast of Menorca Island seems to be somewhat of a natural meteotsunami catcher (Fig. 1). There are several reasons for this. Firstly of all, due to the elongated and shallow topography and the associated large *Q*-factor of the inlet (*Q*-factor is a parameter indicating amplification of incoming open sea waves and energy decay at resonant frequency), its eigenoscillations are quite energetic, even in the absence of obvious forcing. Normally, the inlet oscillates with the fundamental period of around 10 min and with wave heights between 5 and 10 cm (Monserrat and Thorpe, 1992). During a meteotsunami (locally known as "rissaga"), energetic open sea waves provoke the inlet's eigenoscillations to extreme heights through the mechanism of harbour resonance (see Raichlen, 1966). These energetic open sea waves are either shelf eigenoscillations (with periods of about 34 min and 24 min, Monserrat, 2008) or atmospherically forced open sea waves (with periods higher than 10 min, Monserrat, 2008). Both shelf eigenoscillations and atmospherically forced open sea waves are generated by distinct air pressure disturbances. These disturbances are propagating over the 60–120 m shelf depths to the southwest of Menorca (Monserrat et al., 2006).

The most common mechanism for generation of atmospherically forced open sea waves is the Proudman resonance (Proudman, 1929). A distinct air pressure disturbance propagating above the ocean can resonantly generate open sea waves, providing that the speed of the air pressure disturbance is equal to the speed c of barotropic waves ($c = \sqrt{gh}$, where g is the gravitational acceleration and h is the water depth). The generated open sea waves and the air pressure disturbance propagate together (coupled), with the air pressure disturbance constantly pumping energy to the sea waves. Accordingly, atmospherically forced open sea waves off Ciutadella are usually provoked by air pressure disturbances propagating over the 60–120 m shelf depths to the southwest of Menorca with a speed between 22 and 31 m/s. The open sea waves become quite energetic by the time they reach Ciutadella Inlet and can induce meteotsunami therein (e.g. Vilibić et al., 2008).

In contrast to the Balearic Islands where the strongest meteotsunamis are usually observed in Ciutadella only, strong meteotsunamis are observed in several bays and harbours of the Adriatic

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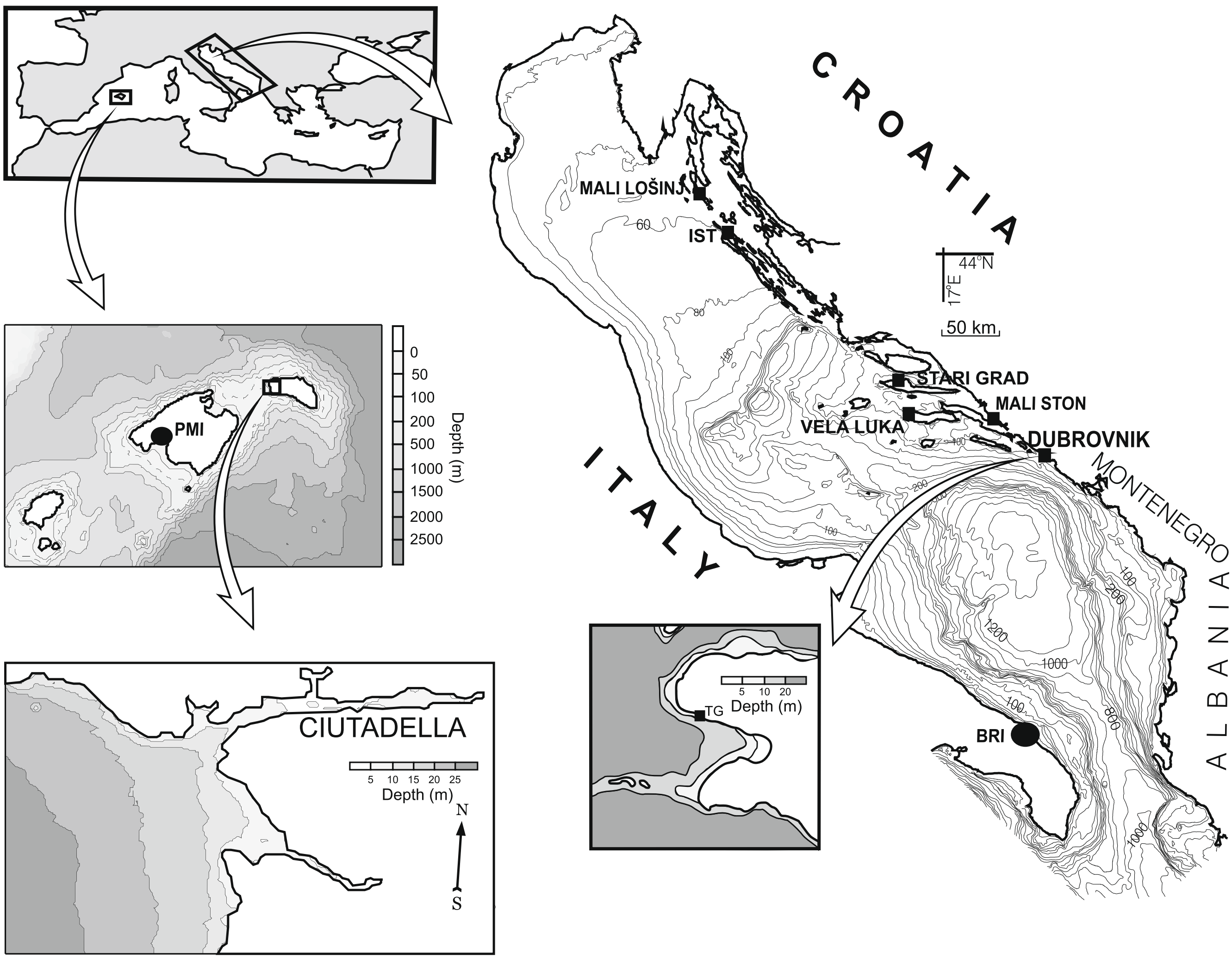

Fig. 1. Geographical location of the investigated areas. Insets of the Balearic Islands, Ciutadella, the Adriatic Sea and Dubrovnik bathymetries are shown. Black rectangles on the Adriatic Sea inset denote Dubrovnik and locations where destructive meteotsunamis have been observed. Black rectangle on the Dubrovnik inset denotes the tide gauge. Black circles on the Adriatic Sea and the Balearic Islands inset denote Palma de Mallorca (PM) and Brindisi (BRI) upper air sounding stations.

Sea. During the last 30 years, meteotsunamis of comparable intensity have struck five different bays in the northern and middle Adriatic Sea (Vela Luka Bay in 1978, Hodžić, 1979/1980; Široka Bay in 1984 and 2007, Šepić et al., 2009; Mali Ston and Stari Grad Bay in 2003, Vilibić et al., 2004; and Mali Lošinj Bay in 2008, Vilibić and Šepić, 2009). For locations see Fig. 1. Similarly to the Balearic Islands, distinct air pressure disturbances and a double resonance (Proudman and harbour) mechanism are the most probable generation mechanism of the Adriatic Sea meteotsunamis. Vilibić and Šepić (2009) note several reasons why the Adriatic meteotsunamis are widespread. Firstly, many bays/harbours with a large amplification factor are open to the west or southwest, the preferred direction for the arrival of incoming atmospherically forced energetic open sea waves. Secondly, wide shelves adjacent to most of these bays have depths favourable to Proudman resonance, between barotropic waves and air pressure disturbances propagating with speeds of about 20–26 m/s.

In addition to having a similar generation mechanism, the Balearic and the Adriatic meteotsunamis occur in similar synoptic conditions. Ramis and Jansà (1983) have concluded that the Balearic meteotsunamis usually occur from June to September (with some occurrences in May) under the following synoptic conditions: (i) low level Mediterranean air with a surface depression is (ii) capped by a warm and dry African air at a height of around 850 h Pa (∼1500 m); (iii) an inversion separates the low level Mediterranean and the upper level African air; (iv) weakly stable or unstable layers are present above the African air and (v) there is usually a pronounced vertical wind shear, with the strongest wind blowing from the southeast. Most of the Adriatic meteotsunamis occur during the summer under similar synoptic conditions (Vilibić and Šepić, 2009, and references therein). A warm and dry African air is typically placed above the Adriatic at a height of around 850 h Pa (∼1500 m). A pronounced temperature inversion is separating the African air from low level Mediterranean air. Furthermore, a weakly stable or unstable layer with a pronounced vertical wind shear is usually present above the African air, with the strongest wind blowing from the southwest to the northwest.

Further on, meteotsunamis of somewhat smaller amplitude than at the Balearic Islands and the Adriatic have also been observed in Malta (Drago, 1999), Sicily (Candela et al., 1999), Greece (Papadopoulos, 1993) and perhaps even at the Black Sea (Rangueloy et al., 2008). Analysis of synoptic conditions during four Maltese meteotsunamis done by Drago (1999) showed that some of them happened under synoptic conditions very similar to the ones found above the Balearic Islands and the Adriatic.

The described synoptic conditions apparently favour the generation of air pressure disturbances which can provoke meteotsunamis. The generation of these air pressure disturbances might occur