Ocean Modelling 111 (2017) 38–45

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Numerical study of Balearic meteotsunami generation and propagation under synthetic gravity wave forcing

Matjaž Ličer[a,b,*], Baptiste Mourre[a], Charles Troupin[a], Andreas Krietemeyer[a], Agusti Jansá[d], Joaquín Tintoré[a,c]

[a] SOCIB, Balearic Islands Coastal Observing and Forecasting System, Parc Bit, Edifici Naorte, 07121 Palma, Spain
[b] National Institute of Biology, Marine Biology Station, Fornače 41, 6330 Piran, Slovenia
[c] IMEDEA (CSIC-UIB), c/ Miquel Marques 21, 07190 Esporles, Spain
[d] UIB, Department of Physics, Carretera de Valldemossa, km 7.5, 07122 Palma de Mallorca, Spain

ARTICLE INFO

Article history:
Received 27 July 2016
Revised 27 January 2017
Accepted 6 February 2017
Available online 6 February 2017

Keywords:
Meteotsunami modelling
Meteotsunami propagation
Proudman resonance
Meteotsunami amplification

ABSTRACT

We use a high resolution nested ocean modelling system forced by synthetic atmospheric gravity waves to investigate Balearic meteotsunami generation, amplification and propagation properties. We determine how meteotsunami amplitude outside and inside of the Balearic port of Ciutadella depends on forcing gravity wave direction, speed and trajectory. We quantify the contributions of Mallorca shelves and Menorca Channel for different gravity wave forcing angles and speeds. The Channel is demonstrated to be the key build-up region determining meteotsunami amplitude in Ciutadella while northern and southern Mallorca shelves serve mostly as barotropic wave guides but do not significantly contribute to seiche amplitude in Ciutadella. This fact seriously reduces early-warning alert times in cases of locally generated pressure perturbations. We track meteotsunami propagation paths in the Menorca Channel for several forcing velocities and show that the Channel bathymetry serves as a focusing lens for meteotsunami waves whose paths are constrained by the forcing direction. We show that faster meteotsunamis propagate over deeper ocean regions, as required by Proudman resonance. We estimate meteotsunami speed under sub- and supercritical forcing and derive a first order estimate of its magnitude. We show that meteotsunamis, generated by supercritical gravity waves, propagate with a velocity which is equal to an arithmetic mean of the forcing velocity and local barotropic ocean wave speed.

1. Introduction

Meteotsunamis, i.e. tsunamis of meteorological origin (Monserrat et al., 2006; Vilibić et al., 2016), are ocean waves in the tsunami frequency band generated over open ocean by the high frequency air pressure modulations of atmospheric gravity waves, convective pressure jumps or other kinds of atmospheric instabilities (Monserrat et al., 2006; Renault et al., 2011). Their amplification mechanisms include Proudman resonance (the matching of the air pressure disturbance velocity U and local ocean barotropic velocity $c_b = \sqrt{gH}$), topographic amplifications over continental shelves and harbour resonances as ocean waves enter narrow bays and inlets, oscillating at frequencies close to the resonant frequencies of these partially enclosed basins. These processes have been thoroughly explained elsewhere, e.g. Monserrat et al. (2006),Šepić et al. (2015b) and Rabinovich (2009). Meteotsunamis have been observed all over the world oceans and their destructive port oscillations can also be found in the Mediterranean, for instance in the Balearic port of Ciutadella (see red square in the inset to Fig. 1) (Renault et al., 2011; Vilibić et al., 2008; Ramis and Jansà, 1983; Tintoré et al., 1988; Gomis et al., 1993; Jansà et al., 2007). Here they are known as 'rissagas', but other examples can be found along the Sicilian and Croatian Adriatic coasts (Vilibić and Šepić, 2009). Meteotsunamis can even occur sequentially along the trajectory of the same synoptic system (Šepić et al., 2015b; 2009).

Meteotsunami research efforts have been growing in the past decades and our understanding of the underlying processes has substantially improved. Nevertheless open issues remain. Even though Proudman resonance is known to play an important role in meteotsunami-related atmosphere-ocean energy transfer (Rabinovitch et al., 1999; Marcos et al., 2003; Whitmore and Knight, 2014; Šepić et al., 2015a), we still lack sufficient understanding of how a meteotsunami amplification is influenced by the resonant atmosphere-ocean interactions or by the local

* Corresponding author.
E-mail address: matjaz.licer@nib.si (M. Ličer).

http://dx.doi.org/10.1016/j.ocemod.2017.02.001
1463-5003/

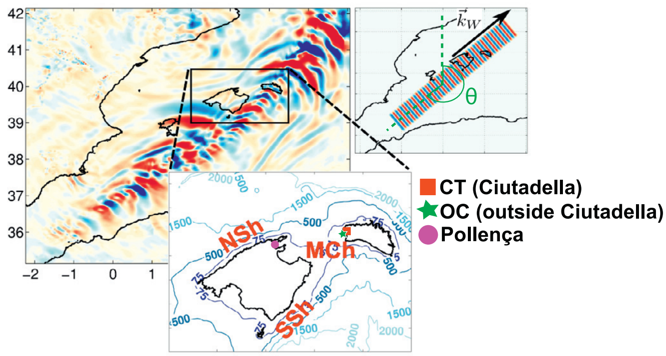

Fig. 1. Background left: BRIFS operational WRF model high-pass filtered air pressure wave on the 11 June 2015 (color scale is truncated at ± 0.3 hPa). Black box, zoomed-up in the inset: ROMS parent domain with the Balearic bathymetry contours in meters with marked northern shelf (NSh), southern shelf (SSh) and Menorca Channel (MCh). Tiny red square in the inset shows ROMS child domain over the Ciutadella harbour. Green star shows the location of interest outside the Ciutadella harbour (denoted as OC in the rest of the paper). Purple circle shows location of the town of Pollença, Mallorca. Top right: synthetic air pressure snapshot for the $\theta = 230^\circ$ incident angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bathymetry, as was noted recently in Vilibić et al. (2016). In this paper we revisit this issue by presenting rissaga generation and propagation studies under synthetic forcing by atmospheric gravity waves, similar to the wave train modelled for June 11, 2015, shown in Fig. 1. Similar waves have previously been observed over the region (Monserrat et al., 1991; Monserrat and Thorpe, 1992; Marcos et al., 2009). Here we study the details of the respective contributions of the Mallorca shelves and Menorca Channel (see Fig. 1 for location) to Ciutadella rissagas under gravity wave forcing conditions, and the role of Proudman resonance in determining the meteotsunami propagation paths over the shelves and the Menorca Channel. We conclude with an analysis of meteotsunami propagation speeds in the Menorca Channel during sub- and supercritical ($U > c_{b0}$) forcing regimes, where $c_{b0} \approx 27-28$ m s^{-1} is the Menorca Channel barotropic speed. The paper is organized as follows: Section 2.1 provides a brief description of the ocean modelling system. Section 2.2 describes synthetic atmospheric forcing used in the presented sensitivity analysis. Rissaga sensitivity on forcing speed and direction is described in Section 3.1, respective roles of the shelves and the Channel are presented in Section 3.2 and propagation speed analysis is contained in Section 3.3. This is followed by the conclusions in Section 4.

2. Modelling setup

2.1. ROMS model configuration

The ocean modelling system used in this study is similar to that presented in (Renault et al., 2011), which is also the oceanic component of the Balearic Islands Rissaga Forecasting System (BRIFS) run operationally on a daily basis at SOCIB. It is based on a double grid configuration of the ROMS model (Shchepetkin and McWilliams, 2005) with a 10-m resolution grid around Ciutadella Inlet (hereafter child model) nested in a 1-km resolution grid encompassing Mallorca and Menorca Islands (hereafter parent model).

Both modeling domains are depicted in Fig. 1. ROMS is a 3D free-surface, split-explicit primitive equation model with Boussinesq and hydrostatic approximations. Due to the 2-dimensional nature of the processes at play, the model uses homogeneous temperature and salinity as initial conditions. A quadratic parameterization is used for bottom drag. At the open lateral boundaries, Chapman and Flather conditions are used for free surface and 2D momentum respectively. While no external boundary input is used for the larger domain, the free surface and vertically integrated velocities of the parent model provide the lateral boundary conditions for the child model with a 2-min temporal resolution. BRIFS features a full WRF atmospheric model component to provide realistic high resolution atmospheric forcing for ROMS (see Fig. 1 for an illustration). Here, the simulations were forced by the 2-min resolution synthetic atmospheric pressure fields, similar to realistic WRF outputs, to analyse in detail the impact of the gravity wave properties on ocean model response.

2.2. Synthetic atmospheric boundary conditions

Pressure wave forcing fields, with parameters similar to existing observations (Monserrat et al., 1991; Monserrat and Thorpe, 1992, and SOCIB June 11, 2015 mean sea level pressure observations, available online via SOCIB THREDDS server at http://thredds.socib.es/thredds/catalog.html), were generated as follows. Each respective numerical experiment featured an atmospheric pressure wave travelling at a definite phase velocity U, incident angle θ and lateral arc width of 1°. Frequency ν_W was kept constant at 10^{-3} s^{-1} for all waves. This frequency implies a 16.7-min period, corresponding to a Ciutadella harbour amplification factor of 2.6, see e.g. (Rabinovich, 2009). Note that the ground state eigenperiod of the Ciutadella harbour equals 10.5 min with a harbour amplification factor of 9.0. This paper does not address the sensitivity of the rissaga to the forcing frequency, which scales the final harbour resonance, but focuses on the generation, amplification and propagation processess over the shelves before entering Ciutadella inlet. The angle θ is stated throughout the paper using the nautical notation: $\theta = 180^\circ$ – wave propagates from the south, $\theta = 270^\circ$ – wave propagates from the west. For each numerical experiment a separate pressure wave was generated for angles from $\theta = 180^\circ$ to 270° in steps of 10° and with phase velocities from $U = 21$ m/s to 36 m/s in steps of 1 m/s. The atmospheric pressure wave is then generated with $p(\vec{r}, t) = p_0 \cdot R(t, t_R) \cdot \cos(\vec{k}_W \cdot \vec{r} - \omega_W t)$, where p_0 is the pressure wave amplitude (set to 3 hPa, matching past observed values and implying pressure change rates of about 0.7 hPa/min), $R(t, t_R)$ is a pressure amplitude ramp function which linearly rises from 0 to 1 as t grows from 0 to ramp time t_R (set to $t_R = 16$ min). The quantity $\vec{k}_W = (2\pi R_\oplus / \lambda_W)[\cos\theta, \sin\theta]$ is the wave-vector, $R_\oplus$ is the mean Earth radius, $\lambda_W = U/\nu_W$ is the pressure wave wavelength, $\vec{r} = [\lambda, \phi]$ is the geo-referenced location on the Earth surface (λ and ϕ being longitude and latitude), $\omega_W = 2\pi\nu_W$ is the wave angular frequency and t is time. The pressure wave is then cropped in space and time to have the appropriate lateral width (0.5° to 1° arc degree) and duration (set to 6 h - note that the gravity wave shown in Fig. 1 endured for over 9 h).

3. Results and discussion

3.1. Rissaga sensitivity to pressure wave direction and speed: the influence of Proudman resonance.

To test the reliability of the modelling system's physics we first ran a separate 24-h simulation for each of the 160 forcing scenarios described in Section 2.2 to study how the SSH anomaly outside and inside Ciutadella harbour depends on two key parameters: pressure wave propagation angle θ and velocity U. These results are presented in Fig. 2. Note that they are consistent with those from Vilibić et al. (2008) even though our ocean model is forced by wave trains instead of a pressure step function as in Vilibić et al. (2008) or Orfila et al. (2011). Several features are present in Fig. 2. First, both matrices, outside (left panel in Fig. 2) and inside (right