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Propagation regimes and populations of internal waves in the Mediterranean Sea basin

Oxana Kurkina [a], Ekaterina Rouvinskaya [a, *], Tatiana Talipova [a, b], Tarmo Soomere [c]

[a] Nizhny Novgorod State Technical University n.a. R.E. Alekseev, Minin Str. 24, Nizhny Novgorod, 603950 Russia
[b] Institute of Applied Physics, Ulyanov Str. 46, Nizhny Novgorod, 603950 Russia
[c] Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia

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ABSTRACT

The geographical and seasonal distributions of kinematic and nonlinear parameters of long internal waves are derived from the Generalized Digital Environmental Model (GDEM) climatology for the Mediterranean Sea region, including the Black Sea. The considered parameters are phase speed of long internal waves and the coefficients at the dispersion, quadratic and cubic terms of the weakly-nonlinear Korteweg–de Vries-type models (in particular, the Gardner model). These parameters govern the possible polarities and shapes of solitary internal waves, their limiting amplitudes and propagation speeds. The key outcome is an express estimate of the expected parameters of internal waves for different regions of the Mediterranean basin.

1. Introduction

Internal waves (IWs) and internal solitons are common in virtually all water bodies that contain stratified water masses (Jackson and Apel, 2004; Vlasenko et al., 2005; Massel, 2015). They carry substantial amounts of energy through the water column, drive key hydrophysical processes such as mixing and overturning (Ledwell et al., 2000) and support the functioning of marine ecosystem in many ways, e.g., via internal wave–zooplankton interactions (van Haren, 2014b), affecting distribution patterns of chlorophyll (Vázquez et al., 2009). Their inimitable impact becomes evident near and at the bottom where they create substantial loads to engineering structures such as piles or risers of drilling rigs or underwater pipelines (Cai et al., 2006; Si et al., 2012) and exert a wide range of impacts on the bottom sediments and evolution of the seabed via, e.g., significant vertical mixing directly at the seabed (Carr et al., 2010), sediment resuspension (Stastna and Lamb, 2008) or generation of nepheloid layers (Puig et al., 2004). These processes often lead to substantial rearrangement of the seabed, for example, to the development of sediment waves (Ribó et al., 2016), pockmarks (León et al., 2014) or even large subaqueous sand dunes (Reeder et al., 2011).

The properties, appearance and the role and impact of IWs substantially depends on the typical stratification conditions in the particular sea area. The properties of water masses which govern the motion of IWs are normally largely different and often highly inhomogeneous in the horizontal direction in different parts of the World Ocean. This feature underlines the importance of regional aspects in IW studies.

In this paper we focus on the analysis of kinematic and nonlinear properties that govern the propagation regimes of long internal waves in the Mediterranean Sea (MS) and the Black Sea (BS). Several kinds of IWs can exist in the MS because of the variety of forcing factors and the complexity of its bathymetry. The generation of IWs is explained by the tidal currents, strong winds or river plumes (Nash and Moum, 2005). Additionally to these drivers, events of the Atlantic water inflow through the Gibraltar Strait (Izquierdo et al., 2001; Vázquez et al., 2008; Vlasenko et al., 2009; Ramírez-Romero et al., 2014) and interaction of tidal currents with shallow underwater ridges in the Straits of Gibraltar and Messina (Alpers et al., 2008) serve as a frequent source of IW generation. As other mechanisms of IW generation are also often active in this basin, such waves are often noted or numerically replicated in virtually all parts of the MS, for example, the Straits of Gibraltar (Alpers et al., 2008; Chioua et al., 2013) and Messina (Alpers and

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* Corresponding author.
E-mail address: e.rouvinskaya@gmail.com (E. Rouvinskaya).

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Salusti, 1983), the Alborán Sea (van Haren, 2015), Gulf of Lions (Schott et al., 1996), Gulf of Valencia (Van Haren et al., 2013), the deep Western Mediterranean (van Haren, 2014a), the Adriatic Sea (Vilibic et al., 2004; Mihanović et al., 2009), Gulf of Patras and the Rio-Antirio straits (Fourniotis and Horsch, 2015), the Aegean Sea (Alford et al., 2012; Gregg et al., 2012), and several locations of the eastern MS (van Haren and Gostiaux, 2011), including the Levantine Sea, where IW-induced velocities can be rather large (Ivanov et al., 1993a; Pelinovsky et al., 1995).

Such waves and their packets occur regularly (Ivanov et al., 1993a), persist for substantial time intervals (Goryachkin et al., 1991; Ivanov et al., 1993b) and seem to play a core role in the functioning of the MS and in the development of several (near-) bottom features. Internal wave activity is suggested to be the preferential mechanism for the transport and deposition of sediment, and for the maintenance of the observed sediment wave fields along the Gulf of Valencia continental slope (Ribó et al., 2016). Small-scale IWs apparently drive a thick weakly stratified deep-sea bottom 'boundary layer' in the central-north Alborán Sea (van Haren, 2015). Inflow regimes associated with large IWs coming from the Camarinal Sill (Ramírez-Romero et al., 2012) are responsible for around 30% of total annual nitrate transport from the Atlantic Ocean into the Mediterranean basin and for a similar proportion of the supply of planktonic resources to the pelagic ecosystem of the Alborán Sea (Ramírez-Romero et al., 2014).

Generation of IWs in microtidal seas such as the Black Sea is possible due to several other dynamic processes such as direct atmospheric forcing (Ivanov et al., 1987) the development and relaxation of coastal upwellings (Vlasenko et al., 1998), vortices of different scales, surge phenomena, oscillations of hydrological fronts (Vlasenko et al., 2005), or river plumes (Nash and Moum, 2005). Thus, IWs are also a common phenomenon in the BS as confirmed by numerous *in situ* measurements (e.g., Filonov, 2000; Ivanov and Lisichenok, 2002), numerical simulations (Stanev et al., 2002) and remote sensing observations of surface manifestations of IWs (Mityagina and Lavrova, 2009, 2010; Lavrova et al., 2009, 2010, 2014).

An intrinsic feature of an IW field is the possibility of the existence of a wide variety of fundamentally different kinds of waves and types of motion in different regions of the same basin. This first concerns nonlinear IWs and, most importantly, solitary IWs (denoted as ISW in what follows). The variability of water density in space and time implies the possibility of changing the properties of single internal waves, their propagation pathways, regions of breaking and associated areas of intense mixing and resuspension of bottom sediments depending on the region and season. In particular, several core properties of nonlinear wave regimes such as wave polarities and limiting amplitudes of ISWs may change during their propagation. Even some motions (e.g., breather-like waves) may be converted into solitary waves of a different kind under fairly realistic conditions (Rouvinskaya et al., 2015).

A feasible way to qualitatively characterize the core properties of the “climate” of nonlinear IWs offers an analysis of the coefficients of the basic equation – Gardner equation. This equation governs the propagation and transformation of such IWs in realistic (that is, horizontally nonhomogeneous) water basin. The signs and magnitudes of different constituents of this equation make it possible to evaluate the sea areas where principally different kinds of solitary waves predominate. For example, classic of Korteweg–de Vries (KdV) solitons, wide table-like disturbances of different polarity, breathers or structurally unstable “algebraic” solitons are all valid solutions of Gardner equation. More importantly, such analysis highlights the typical areas where internal waves alter their appearance. The relevant processes range from smooth adjustment or transformation of the waves to intense breaking and associated phenomena such as rapid mixing or powerful near-bottom motions.

To date, maps of propagation regimes of IWs have been constructed for single regions such as the Gotland Deep in the central Baltic Sea (Talipova et al., 1998), the entire Baltic Sea (Kurkina et al., 2011b, 2014), the nearshore of Israel in the eastern Mediterranean Sea (Pelinovsky et al., 1995), the Arctic Sea (Poloukhin et al., 2003, 2004), the South China Sea (Grimshaw et al., 2010) and the Northern China Sea (Liao et al., 2014). A similar world map of coefficients of the underlying KdV equation, inferred from the long-term mean annual hydrologic data with 1° latitude-longitude resolution, is presented in (Grimshaw et al., 2007). This resolution, however, is not sufficient for smaller basins such as the BS or sub-basins of the MS. Although the first such estimations for the BS are given in (Ivanov et al., 1994), a detailed investigation of the parameters governing the IW appearance and propagation regimes for the MS and BS hasn't been carried out yet.

The present paper is going to fill in this gap. Our focus is on the geographical and seasonal distributions of so-called kinematic and nonlinear parameters of long IWs, which are, in essence, coefficients of linear and nonlinear terms of Gardner equation for nonlinear IWs. Spatial distributions of these parameters are derived from the Generalized Digital Environmental Model (GDEM) database in the MS and the BS This data set reflects the climatology of the temperature and salinity of the global oceans. The key outcome is an express estimate of the expected IW parameters and their spatial inhomogeneity for different regions of the MS.

The paper is organized in the following way. The equations of the KdV family in the context of IWs propagating over a horizontally homogeneous sea and in a variable background are shortly presented together with the classification of core properties of single-soliton solutions of the relevant integrable equation in Section 2. Spatial distributions of prognostic kinematic and nonlinear characteristics of the IW field in these two basins are examined in Section 3. The possibilities of frequent presence of disturbances that match the discussed branches of solutions to Gardner equation and their possible amplitudes in MS and BS are discussed in Section 4.

2. Methods and data

2.1. Evolution equations for weakly nonlinear IWs

The weakly nonlinear theory of long IWs in a vertical section of a stratified basin assumes that the internal wave field (in particular, the vertical isopycnal displacement $\zeta(z,x,t)$) can be expressed as a power seri (Pelinovsky et al., 2007)

$$\zeta(z,x,t) = \eta(x,t)\Phi(z) + \eta^2(x,t)F(z) + \ldots \qquad (1)$$

in terms of the function $\eta(x,t)$ that describes the transformation of a wave along the x-axis (of wave propagation) and its evolution in time t. The power series (1) is commonly truncated so that it includes only the linear and quadratic terms (that is, describes the wave evolution up to the 2nd order in nonlinearity). Here x is the horizontal axis, z is the vertical axis directed upwards, the function $\Phi(z)$ (so-called vertical mode) describes the vertical structure of the long IW under investigation, and $F(z)$ is the first nonlinear correction to $\Phi(z)$.

The function $\Phi(z)$ is a solution of an eigenvalue problem. To formulate this problem, we employ the Boussinesq approximation that usually is valid for natural sea stratifications. For simplicity and transparency and because there is no systematized data available, we do not take into account vertically sheared flows. However, background currents can be easily included into the model