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Resonant excitation of island-trapped waves in a shallow, seasonally stratified sea

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ABSTRACT

Analysis of oceanographic data collected during 2006 in the eastern Adriatic Sea indicated the presence of large internal waves (with a maximum range of about 30 m) at the diurnal frequency around the island of Lastovo. The amplitude ratio and phase difference between diurnal surface tides and diurnal isotherm fluctuations changed considerably between pronounced internal wave episodes, depending on stratification properties, thus suggesting possible resonant excitation of internal oscillations. On the contrary, no significant diurnal thermocline fluctuations were observed at two other islands (Biševo and Sušac). Theoretical analysis presented here focused on the trapping of long-period internal waves around a circular island corresponding to Lastovo and confirmed that stratification properties during the summer of 2006 around the island were close to resonant ones. The analysis also showed that Biševo and Sušac are too small to support diurnal near-resonant excitation. Application of a numerical model for the current flow around equivalent circular and elliptical islands in the stratified sea provided more details on resonant excitation. Theoretical and numerical modeling results particularly emphasized the importance of island dimensions, stratification properties (pyconocline depth and density defect) and the periodicity of the forcing. Furthermore, idealized numerical simulations demonstrated that the waves trapped at Lastovo behave as the gravest azimuthal mode of internal Kelvin-like waves, revolving in a clockwise direction around the island, and that the eccentricity of the island has almost no effect on the resonant period.

1. Introduction

The trapping of wave energy along coastlines has been studied for decades, and a comprehensive review of observational and theoretical studies has been given by Huthnance et al. (1986) and Brink (1991). Coastal-trapped waves (CTWs) are mainly generated by the along-shelf component of surface wind stress and they propagate with the coast on the right (left) in the Northern (Southern) Hemisphere.

Vertical pycnocline movements related to CTWs are important for various physical and biogeochemical processes (e.g., vertical mixing, transport of nutrients and sediment, biomass aggregation, fisheries etc.). The frequency and range of pycnocline displacement determine biological implications (Wolanski et al., 2004). Lucas et al. (2013) showed that diurnal pycnocline oscillations represent an important mechanism for phytoplankton distribution and productivity at a coastal upwelling zone near 30° latitude, where diurnal wind variability resonantly forces inertial currents.

Of particular interest are coastal-trapped waves which occur on closed shorelines, such as lakes or islands. Wave energy is then confined to a closed path and waves with an integral number of wavelengths can reinforce themselves, resulting in a resonant system with a discrete spectrum (Hogg, 1980). A theoretical background for island-trapped waves (ITWs) was given by Mysak (1967) for a circular island with a narrow sloping shelf and by Longuet-Higgins (1967, 1969, 1970) who examined wave trapping around a cylindrical island in a homogeneous, rotating fluid. They emphasized several important constraints, related to the frequency of the waves and geometry of the island and surrounding area. Specifically, Longuet-Higgins (1969, 1970) showed that for near-inertial and sub-inertial waves, perfect trapping around the island in a sea of constant depth is possible due to rotation only (Longuet-Higgins, 1969, 1970). On the other hand, Mysak (1967) and Rhines (1969) considered an island surrounded by a sloping shelf, showing that for $\sigma \ll f$, perfect trapping also occurs.

Caldwell and Eide (1976) experimentally studied barotropic island-trapped waves in a rotating tank with a parabolic form (resulting in uniform water depth parallel to the axis of rotation when the basin was rotating) and their results agreed well with Longuet-Higgins's theoretical predictions for island Kelvin waves.

The theory related to barotropic trapped motions around islands was extended to include stratification by Wunsch (1972), who introduced an effective ocean depth: a parameter related to the real depth, the stratification and the vertical mode number. Luther (1985,

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1995) and Lumpkin (1995) used similar approach to study ITWs around the Hawaiian Islands and accentuated that baroclinic modes of the respective model must be much larger than the horizontal scale of island flanks to justify a vertically-walled cylinder approximation of the island. This approximation proved to be adequate for the gravest sub-inertial baroclinic modes around the Hawaiian Islands, and their estimates for the island of Hawaii were confirmed by numerical simulations (Merrifield et al., 2002). However, the cylindrical island model is not sufficient to predict frequencies of higher sub-inertial baroclinic ITW modes (Hogg, 1980). Therefore, Brink (1999) presented a theory for linear island-trapped waves around a circular island with stratification and a bottom slope. The solutions are found numerically, using resonance iteration on a vertically-stretched grid.

The effect of irregularities on sub-inertial trapped modes is considered to be minimal, as long as their scale is smaller than the corresponding Rossby radius of deformation (Luther, 1985; Dyke, 2005). Moreover, Wallace and Willmott (1991) investigated coastal-trapped waves in elliptical lakes and around elliptical islands. They theoretically established that a circular model of the island is sufficient for determining the frequencies of island-trapped waves, while a full elliptical model is required to determine wave structures.

Observational data related to ITWs were relatively limited and their study was mostly based on the detection of energetic peaks in coastal sea level and temperature spectra related to theoretical wave modes around islands in a deep stratified ocean, with particular focus on the Hawaiian Islands and Bermuda (Wunsch, 1972; Hogg, 1980; Luther, 1985; Lumpkin, 1995). The numerical approach has been two-fold to date: Brink (1999) considered stratification and bottom relief around Bermuda to resolve ITW modes on a vertically-stretched grid, whereas Merrifield et al. (2002) selected the strongest wave event measured on the island of Hawaii during the 1980s to investigate structure and generation of sub-inertial trapped waves at the Hawaiian Islands. The latter study was based on numerical modeling with realistic bathymetry, stratification, and wind forcing.

ITWs in shallow and seasonally stratified seas were only recently documented, in the Adriatic Sea and in the northwestern Mediterranean Sea. Mihanović et al. (2009) and Orlić et al. (2011) related strong diurnal temperature oscillations at the island of Lastovo (Adriatic Sea) to the gravest baroclinic mode revolving around the island. Their analyses showed that thermocline oscillations were driven by diurnal tides and diurnal wind-forcing (sea breezes). The most pronounced thermocline fluctuations were related to diurnal winds, whilst barotropic tidal flow excited less intense but more prolonged island-trapped waves. The analysis of current and acoustic backscatter data from an acoustic Doppler current profiler (ADCP) moored in the shelf off Mallorca (Balearic Islands, Mediterranean Sea) revealed the existence of two ITW modes generated by local synoptic winds, causing significant sediment resuspension during an intense episode (Jordi et al., 2009).

Previous studies of ITWs primarily used theoretical or numerical models to reproduce resonant modes and to describe their structure. Here we aim to combine the analytical and numerical approach, and to present a detailed examination of resonant conditions for internal waves trapped around Lastovo (Adriatic Sea—Fig. 1) excited both by diurnal tides and sea/land breezes. Theoretical models of island-trapped waves are used to investigate the influence of island dimensions, surrounding bathymetry and forcing period. The sensitivity of resonant excitation of ITWs around Lastovo to island shape, stratification conditions and forcing frequencies is examined using idealized numerical simulations based on analytical results. This study is important for an understanding of physical and biogeochemical processes around the Adriatic islands, which are predominantly located in a shallow area of high bathymetric complexity. However, a similar approach can be applied to any island, taking into account appropriate physical conditions, island geometry, bathymetry and resonant parameters.

General information about the study area and empirical background related to ITWs in the Adriatic are presented in Section 2. Basic aspects of theoretical models of ITWs around a circular island in a basin with a flat bottom and with bottom relief, important for their application to an island approximating Lastovo, are given in Section 3. The numerical model used in the study is described in the same section. Theoretical models are applied and compared in Section 4, taking into account physical settings around Lastovo. Moreover, Section 4 includes idealized numerical studies of varying resonant conditions defined on the basis of the theoretical models, and their impact on ITWs around Lastovo.

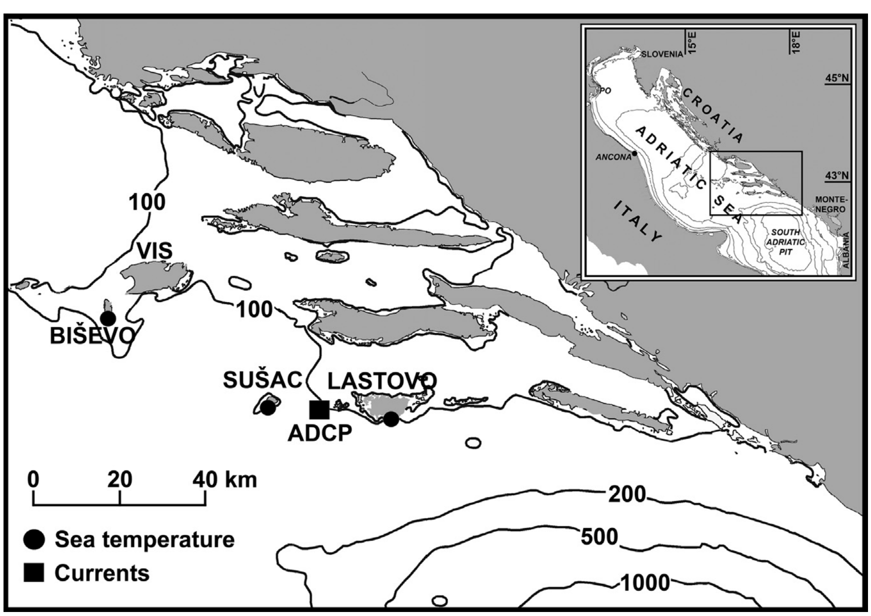

Fig. 1. Eastern part of the middle Adriatic—the study area during 2001 and 2006 experiments. Three temperature sensors were deployed on the south part of Lastovo in 2001, while a series of loggers recorded temperature at Biševo, Sušac and Lastovo during 2006, with current measurements carried out at an ADCP station between Sušac and Lastovo. Prežba and Mrčara Islands, positioned to the west of Lastovo, cannot be distinguished from Lastovo at the scale of this figure.