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Near-inertial motions in and around the Palamós submarine canyon (NW Mediterranean) generated by a severe storm

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ABSTRACT

During 9–16 November 2001 the western Mediterranean Sea was lashed by one of the most extreme storms of the last decades. Current meter data from seven moorings in the Palamós submarine canyon (northwestern Mediterranean) are analyzed to understand the vertical propagation of near-inertial energy generated by the storm. The daily inertial rotary components are examined for evidence of free and forced near-inertial oscillations. Free near-inertial motions are increased during the storm, although they are larger outside the canyon than inside. Conversely, forced near-inertial motions are relatively large inside the canyon but are almost negligible outside. Based on the results of a three-dimensional ocean circulation model, these differences are shown to be caused by the presence of a storm-generated alongshore front. The mechanisms by which near-inertial energy propagates are distinct at each side of the front. On the onshore side of the front (inside the canyon), free near-inertial motions are rapidly carried away by normal inertial waves, and wave reflection off canyon wall is responsible for the dissipation of free near-inertial motions and enhancement of forced near-inertial motions. On the offshore side of the front (outside the canyon), on the other hand, free near-inertial motions propagates first downward with anomalously low frequency internal waves and are then advected southward and offshore by the mean flow.

1. Introduction

Near-inertial waves and internal tides both can induce significant ocean mixing, which affects pollutant dispersal, marine productivity and global climate (Alford, 2003). Near-inertial energy is generated in the upper ocean in response to sudden wind events and it propagates both horizontally and vertically (Gill, 1984). In the open ocean, the near-inertial wave propagation is largely determined by its horizontal scale, which is set by the scale and propagation speed of the traveling storm (Kundu and Thomson, 1985). However, the presence of fronts and coasts, and the convergence/divergence in the wind field can significantly influence the vertical propagation of near-inertial energy (Greatbatch, 1983; Xing et al., 2004).

The basic mechanism for draining near-inertial energy from the surface to the deep ocean through fronts was discussed by Kunze (1985). Basically, near-inertial waves propagating through a mean flow experience a Doppler shift due to the ambient relative vorticity. If the relative vorticity gradient is strong enough, near-inertial energy can be trapped in regions of negative relative vorticity and reflected downward locally to the deep ocean. For example, Zhai et al. (2005, 2007) showed the important role played by anticyclonic eddies for the vertical propagation of near-inertial energy through the surface layer. In cases that the near-inertial internal waves are generated in regions of positive relative vorticity, they propagate away in the horizontal but not in the vertical (Davies and Xing, 2002). However, sloping density fronts associated with mean vertical sheared flows may shift the near-inertial frequency, which results in trapping anomalously low frequency inertial waves in regions of positive vorticity and spreading them to depth (Mooers, 1975).

In addition to fronts and eddies, shelf topography is a key element controlling the distribution of near-inertial energy and the vertical propagation of near-inertial motions (Tintoré et al., 1995). Eriksen (1982) studied the reflection of linear internal gravity waves off a sloping bottom. He demonstrated that gentle bottom slopes amplify near-inertial waves by bottom reflection while steep slopes amplify internal wave energy at the tidal (semidiurnal) frequency. However, Federiuk and Allen (1996) using a two-dimensional primitive equation model of wind forced flow over continental shelf showed that bottom slope is not the determining factor on the propagation of near-inertial energy.

In this context, submarine canyons are one of the steepest topographic features that incise the shelf and slope, and are known to enhance the internal wave field (Hickey, 1995). Observations in submarine canyons show that internal tides and

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their harmonics are dramatically larger than those in the open ocean but near-inertial oscillations generally are absent (e.g. Kunze et al., 2002; Bosley et al., 2004; Puig et al., 2004). However, data collected in and around submarine canyons in the Mediterranean Sea, where tides are negligible, reveal that oscillations at the inertial frequency are the most significant (Puig et al., 2000; Palanques et al., 2005).

The first goal of this paper is to use current meter data from moorings in the vicinity of the Palamós canyon to examine the generation and propagation of near-inertial motions during an extreme storm which lashed the western Mediterranean basin on 9–16 November 2001. Sudden events of extreme adverse weather occur in the western Mediterranean from time to time, especially in autumn, as a consequence of the closed basin and the high insolation (Romero et al., 1999). However, intensity and duration of the November 2001 storm was exceptionally large. The Palamós submarine canyon is one of the major canyons that indent the continental margin of the Gulf of Lions and Catalan Sea in the northwestern Mediterranean (Jordi et al., 2005). Although near-inertial oscillations associated with active wind events are a pronounced feature on the shelf (García-Górriz et al., 2003), they are greatly reduced beyond the shelf edge (Salat et al., 1992; Rippeth et al., 2002). We are interested in how the presence of the canyon affects the vertical spreading of the near-inertial energy generated by the storm. The second goal of this paper is to further illustrate through numerical experiments the physical mechanisms that determine the leakage of near-inertial energy out of the mixed layer.

2. Data and methods

2.1. Atmospheric data

The Mediterranean hindcast of dynamic processes of the ocean and coastal areas of Europe (HIPOCAS) data set (Sotillo et al., 2005) is used to characterize the spatial distribution and the temporal evolution of the November 2001 storm. The data set was produced in the framework of the HIPOCAS project through a dynamical downscaling from the NCEP/NCAR global reanalysis (Kalnay et al., 1996) using the atmospheric limited area model REMO (Jacob and Podzun, 1997). The resolution of the HIPOCAS hindcast is $0.5^\circ \times 0.5^\circ$ in space over the Mediterranean Sea. Hourly hindcast outputs cover the period ranging from 1958 to 2001. In this study, 10 m wind, atmospheric pressure and heat and freshwater fluxes fields during November 2001 are used.

2.2. Current meter observations

Current data were collected from seven moorings deployed inside and in the vicinity of the Palamós canyon from March to November 2001 (Fig. 1). Main features of observed currents for the total period were described by Palanques et al. (2005). In this study we concentrate on the storm period (November 2001) when complete records are available from one upward-looking acoustic Doppler current profiler (ADCP) and ten current meters (the current meter locations and depths are listed on Table 1). For convenience, data are separated into two groups: upper level (150–279 m) and intermediate level (401–506 m). The sampling interval of the current meters and the ADCP was set to 30 min, with the exception of the instruments at M2 and M3 moorings which was set to 10 min.

The observed currents are used to produce daily mean currents and inertial rotary components (Brink, 1989; Qi et al., 1995):

$$u + iv \approx a + b\mathrm{e}^{\mathrm{i}(ft+\phi_b)} + c\mathrm{e}^{-\mathrm{i}(ft+\phi_c)} \tag{1}$$

where u and v are the observed eastward and northward velocity components, f is the inertial frequency, t is the time, a is the mean, b (c) is the counterclockwise (clockwise) amplitude, and ϕ_b (ϕ_c) is the counterclockwise (clockwise) phase. The variables a, b, ϕ_b, c and ϕ_c are evaluated using a least squares fit in a daily data window. This separation allows us to estimate the wave frequency $f + \delta\omega = f - \partial\phi/\partial t$, and the horizontal and vertical wavenumbers $K^2 = k^2 + l^2$ ($k = \partial\phi/\partial x$ and $l = \partial\phi/\partial y$) and $m = \partial\phi/\partial z$. Both clockwise and counterclockwise components are analyzed for evidence of free and forced near-inertial oscillations (Gonella, 1972). In the Northern Hemisphere inertial currents rotate clockwise and therefore, the major part of near-inertial energy is expected to be contained in the clockwise component. Conversely, inertial currents rotating counterclockwise are feasible only if they are forced by mechanisms such as bottom reflection, and they are expected to propagate over only a rather short distance (LeBlond and Mysak, 1978).

Additionally, a CTD survey was made in the canyon on November 26, 10 days after the storm. Fig. 2 shows comparison between averaged CTD profile and the November climatology profile obtained from the MedAtlas database (MEDAR Group, 2002). Typically, waters in the vicinity of the Palamós canyon are highly stratified during November with the pycnocline at around 60 m depth. However, stratification was weak and horizontally uniform and the pycnocline was much deeper, around 200–250 m depth, as a result of the storm.

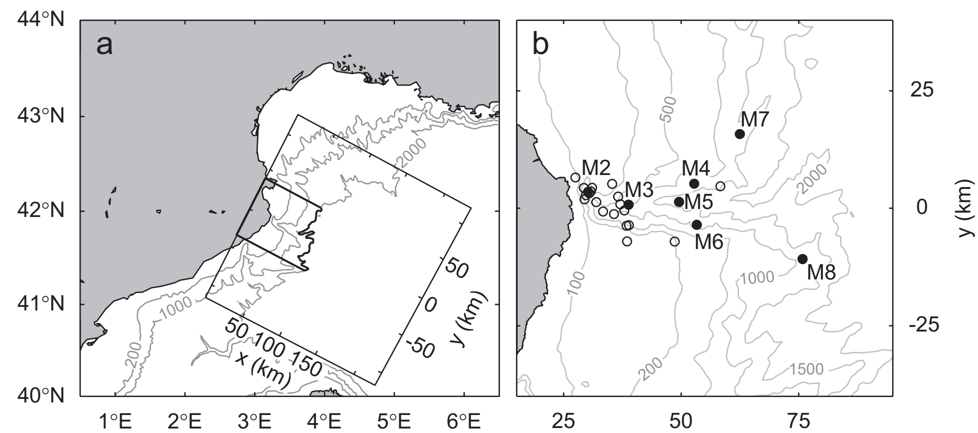

Fig. 1. (a) Bathymetry of the northwestern Mediterranean showing the model axes (thin black line) and the area of the real topography (enclosed with a thick black line). (b) Magnified view in the area of Palamós canyon showing the location of the current meter moorings (solid circles) and CTD stations (open circles).