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A numerical model for free infragravity waves: Definition and validation at regional and global scales

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ABSTRACT

The spectral wave model WAVEWATCH III is extended from the windsea and swell band to lower frequencies, in order to represent free waves in the infragravity (IG) wave band. This extension is based on an empirical source of IG energy, which is defined along shorelines from the significant wave height and a mean period. The empirical proportionality factor is found to reproduce accurately the variations of free IG wave energy in coastal areas, where it was calibrated, and also has a good skill at global scales. In the open ocean, the model is particularly verified for frequencies in the range 5 to 14 mHz for which ocean bottom records are sensitive to the IG signal. The model captures between 30% and 80% of the variance in IG wave heights, depending on location, and reproduces the mean IG energies within 50%. Where the model reproduces best the IG variability, it can be used to fill in the gaps between recording stations, providing a first view of the global IG wave field.

Our first application is the estimation of the surface gravity wave contribution to the surface elevation spectra that will be measured by the Surface Water Ocean Topography (SWOT) satellite mission. The actual contribution of IG waves on measured along-track wavenumber spectra varies with the cross-track averaging method. Typically, the strongest IG signal is expected to occur for wavelengths between 2 and 10 km. For a given region, the spectral level at 10 km wavelength are not very sensitive to the local depth in the range 200 to 5000 m. At this wavelength, and on the east side of all mid-latitude ocean basins, the median spectral density associated to free IG waves is of the order of 0.4 cm^2/(cycle/km), equal to the expected quasi-geostrophic signature of surface currents. IG spectra rise above 4 times this level for 16% of the time. Even at 20 km wavelength, spectral levels above 1 cm^2/(cycle/km) are likely to occur more that 10% of the time for some oceanic regions.

1. Introduction

Infragravity (IG) waves are long period surface gravity waves which are important for nearshore or harbor hydrodynamics (e.g., Reniers et al., 2010; Okihiro et al., 1993; Jong et al., 2003). These IG waves are expected to be generated mostly along shorelines by nonlinear interactions of the shorter wind-generated waves (e.g., Munk, 1949; Herbers et al., 1994, 1995). This interaction transfers part of the energy from the wind-generated wind sea and swells, with periods shorter than 30 s, into sub-harmonics. For waves propagating over a flat bottom, this energy corresponds to long period oscillations traveling bound to the short wave groups but with the opposite phase. These bound components can be transformed into free waves, which then follow the linear surface gravity waves dispersion, with larger wavelengths and phase speeds. This transformation occurs where short wave energy varies rapidly, for example, in the surf zone (e.g., Henderson and Bowen, 2002). An additional source of free IG waves in the surf comes from variation of wave breaking location on the scale of wave groups (Symonds et al., 1982).

Several numerical models have been developed for IG waves in coastal areas. The underlying principles used in these models vary widely. Ruju et al. (2012) have chosen to solve for the full three-dimensional hydrodynamic equations, resolving the wavelengths of the wind-waves, while Zijlema et al. (2011) have simplified the vertical structure of the flow, but still resolve the short waves. Reniers et al. (2002, 2010) have developed a cheaper method, easily applicable to larger spatial and time scales. In that latter approach, the time and length scales of wave groups are resolved,

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but not the scales of the short waves. Finally a wide range of spectral models with varying degrees of complexity have been developed. In these models the computation time can be further reduced because only the slow time scale of spectral evolution need to be resolved. The more complex type of spectral model includes space–time integration of both spectrum and bispectrum (e.g., Herbers and Burton, 1997). This bispectrum carries the relative phases of wave components and this information is necessary to compute the transformation of bound waves into free waves. Parameterizations in models that only include the spectrum have to make some assumptions on the phases, and these have not yet been able to reproduce quantitatively the IG wave generation in typical coastal areas (Toledo and Agnon, 2012). All these models have been applied with an extension along the shore that hardly exceeds 100 km. To our knowledge, no numerical model has yet been proposed for free infragravity waves on the global scale, a problem for which existing models are not suited.

Future planned satellite missions, in particular Surface Water Ocean Topography (hereinafter SWOT, Durand et al., 2010) are targeting meso- and submeso-scale ocean circulation with horizontal scales down to 10 km. At such scales, the estimation of surface currents from the surface elevation is expected to require an accuracy of the order of 1 cm, which is more easily defined in terms of a spectrum. Surface quasi-geostrophic theory predicts that the spectrum of sea surface elevation decays like $k^{-11/3}$ towards short scales, where k is the magnitude of the wavenumber vector (Lapeyre and Klein, 2006). Using this asymptote, the extrapolations from spectra at longer wavelengths (e.g., Le Traon et al., 2008) gives a current signature in surface elevation of the order of 1.9 cm^2/(cycle/km) at a wavelength of 15 km, and 0.4 cm^2/(cycle/km) at a wavelength of 10 km. It should be noted that, for this latter scale, the surface current is not completely geostrophic (e.g., Klein et al., 2009).

From an examination of tsunami warning (DART) stations, Aucan and Ardhuin (2013) have found that in 3.3 km depth off the Oregon coast the spectral level of 0.5 cm^2/(cycle/km) at a wavelength of 15 km is exceeded 15% of the time due to infragravity waves alone, decreasing to 0.35 cm^2/(cycle/km) at a wavelength of 10 km (Aucan and Ardhuin, 2013). As we show below, these spectral level estimates were underestimated by a factor of two.

With a typical wavenumber slope ranging from -0.5 to -1, much shallower than the $-11/3$ slope expected for submesoscale currents, it appears likely that there is a scale, somewhere between 2 and 20 km, below which the infragravity signal will often exceed the signal of submesoscale currents. Hence, the routine processing of future SWOT data may well require some model of the global IG wave field, in order to flag the locations and times when resolution may be degraded by energetic IG waves. Indeed, contrary to the atmospheric corrections measured separately and the coherent part of the barotropic and internal tides, the random nature of the IG wave phases makes it impossible to correct for associated sea level variations, in the absence of a dense network of observations, or the measurement of the IG wave propagation during the time of integration of the radar. However, the surface elevation variance caused by IG waves is predictable, as we will show here.

Our objective is thus twofold. First, we want to confirm that the signal recorded by DART stations is consistent with plausible IG wave sources and dynamics at frequencies between 5 and 14 mHz. Second, we wish to extrapolate the measurements from the DART network beyond their spatial and spectral coverage. Both tasks require the development of a numerical model for free IG waves. This model may prove useful for the analysis of high resolution surface currents from the SWOT mission. It will also allow an estimation of the debated location and magnitude of seismic hum sources (see e.g., Rhie and Romanowicz, 2006).

This paper presents the first attempt at building such a model for the global ocean. Similar to early numerical models for ocean waves, this is a ‘first generation model’ in the sense that the source of free IG energy at the coast is parameterized from integrated wave parameters. The rationale for treating free IG waves only is that, for depths larger than about 50 m, these generally dominate the recorded signal, compared to bound components (Herbers et al., 1995; Webb et al., 1991). Besides, the bound components can be obtained from the local wave spectrum assuming a flat bottom, in the case of intermediate or deep water (Creamer et al., 1989; Herbers et al., 1992; Janssen, 2009).

Here we focus on waves with periods between 30 and 200 s. This choice is motivated by the fact that an IG period of 200 s already gives wavelengths larger than 15 km in water depths greater 600 m, consistent with our interest in the surface elevation spectrum around 10 km wavelength, with a priority on the deep ocean. Also, these longer waves are less dispersive and one may infer the properties of 500 s waves from those of 200 s waves, assuming a simple relation at the source between these two components. Contrary to the existing models that reproduce IG waves in coastal regions, we consider here a very crude approximation of the IG wave evolution in shallow water, in order to cover the global ocean. For this we present a parameterization of the free IG source at the shoreline, in Section 2. The accuracy of the model in terms of propagation in regional and global configurations is discussed in Section 3. Implications of modeled IG spectra in the context of SWOT are discussed in Section 4 and conclusions follow in Section 5.

2. The nearshore source of free infragravity waves: observations and parameterizations

Among the infragravity waves, it is important to distinguish the bound and free waves. Both are surface gravity waves with a vertical scale of attenuation of the motion that is proportional to their wavelength, but their wavelength can be very different for the same wave period. Namely, free waves follow the dispersion relation of linear waves (Laplace, 1776), while bound waves have a wavelength defined by the forcing. Because bound waves are negligible in the open ocean (Herbers et al., 1995) and can be predicted from the local sea state, we will only model the free infragravity waves. When comparing model results to measurements, we must be careful that bound components can have a significant contributions to measured pressure time series in shallow water. Herbers et al. (1994) showed that the bound part of the IG spectrum can be estimated with a bi-spectral analysis where both short waves and long waves are resolved in the measurements. This technique was already applied to the DUCK94 dataset by Evangelidis (1996) who concluded that the bound fraction of the IG bottom pressure variance is typically less than 20% for this dataset, with the highest fractions found during the most energetic wind-wave conditions. The free wave spectrum may further be decomposed into trapped and leaky modes (e.g., Herbers et al., 1995). The trapped modes are confined to continental shelves due to their refraction. The leaky modes, with propagation direction nearly perpendicular to the depth contours, are able to escape to deep water then travel across Oceans. Our model considers both trapped and leaky modes.

Because we cannot afford the spatial resolution required to solve for the non-linear phase-dependent evolution of the wave field on the scale of the few wavelengths closest to shore, we have sought to parameterize the nearshore source of free IG waves as a function of the short wave spectrum.

This source is introduced in the version 4.18 of the spectral wave model WAVEWATCH III, hereinafter WW3 (Tolman, 2008), in the subroutine that computes the equivalent source term corresponding to shoreline reflection. The following algorithm is