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Efficient non-hydrostatic modelling of 3D wave-induced currents using a subgrid approach

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A B S T R A C T

Wave-induced currents are an ubiquitous feature in coastal waters that can spread material over the surf zone and the inner shelf. These currents are typically under resolved in non-hydrostatic wave-flow models due to computational constraints. Specifically, the low vertical resolutions adequate to describe the wave dynamics – and required to feasibly compute at the scales of a field site – are too coarse to account for the relevant details of the three-dimensional (3D) flow field. To describe the relevant dynamics of both wave and currents, while retaining a model framework that can be applied at field scales, we propose a two grid approach to solve the governing equations. With this approach, the vertical accelerations and non-hydrostatic pressures are resolved on a relatively coarse vertical grid (which is sufficient to accurately resolve the wave dynamics), whereas the horizontal velocities and turbulent stresses are resolved on a much finer subgrid (of which the resolution is dictated by the vertical scale of the mean flows). This approach ensures that the discrete pressure Poisson equation – the solution of which dominates the computational effort – is evaluated on the coarse grid scale, thereby greatly improving efficiency, while providing a fine vertical resolution to resolve the vertical variation of the mean flow. This work presents the general methodology, and discusses the numerical implementation in the SWASH wave-flow model. Model predictions are compared with observations of three flume experiments to demonstrate that the subgrid approach captures both the nearshore evolution of the waves, and the wave-induced flows like the undertow profile and longshore current. The accuracy of the subgrid predictions is comparable to fully resolved 3D simulations – but at much reduced computational costs. The findings of this work thereby demonstrate that the subgrid approach has the potential to make 3D non-hydrostatic simulations feasible at the scale of a realistic coastal region.

1. Introduction

Coastal waters are highly dynamic regions where waves become increasingly nonlinear as they approach the shore, break, and eventually dissipate most of their energy in the surf zone. In this nearshore region, processes on the intra wave and wave-group scale excite various flow phenomena. This includes the generation of longshore currents and their instabilities (e.g., Özkan-Haller and Kirby, 1999), rip currents (e.g., MacMahan et al., 2006; Dalrymple et al., 2011), and nearshore eddies (e.g., MacMahan et al., 2004; Clark et al., 2012). Such wave-induced currents are an ubiquitous feature of the coastal region that can spread (floating) material over the surf zone and the inner shelf. Currents can, for example, transport sediments, which is relevant with respect to beach morphology, and disperse pollutants that are harmful for the environment (e.g., oil spills). Furthermore, rip currents can be hazardous with respect to swimmer safety (e.g., McCarroll et al., 2015).

During the last decades, our understanding of the nearshore hydrodynamics has greatly increased by means of laboratory experiments (e.g., Reniers and Battjes, 1997; Haller et al., 2002; Kennedy and Thomas, 2004), field observations (e.g., Ruessink et al., 2001; Feddersen and Guza, 2003; MacMahan et al., 2005), theoretical developments (e.g., Longuet-Higgins and Stewart, 1962; 1964; Craik and Leibovich, 1976; Andrews and Mcintyre, 1978; McWilliams et al., 2004; Mellor, 2016), and by three-dimensional numerical modelling (e.g., Groeneweg and Klopman, 1998; Reniers et al., 2009; Uchiyama et al., 2010; Kumar et al., 2012). The majority of such models assume that the flow dynamics evolve on larger scales (in space and time) compared to the fast wave motion, and that

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the wave dynamics are locally well represented by small amplitude (linear) wave theory based on geometric optics. These assumptions, which are often reasonable away from the surf zone, allow such models to operate on the scale of the mean flow dynamics, including mean forcing terms due to the wave motion. The dynamics of the wave motion are calculated separately using a phase-averaged wave model. However, in and near the surf zone, where the wave motion becomes strongly skewed and asymmetric due to nonlinear shoaling, and where the waves ultimately break, mean flow dynamics and transport processes are strongly affected by the nonlinear wave dynamics. Consequently, processes like wave breaking, and the influence of skewness and asymmetry on transport are strongly parametrised in these models.

In principle, phase-resolving wave models are available that can be feasibly applied to a realistic field site (say $\sim 10 \times 10$ wave lengths and ~ 1000 wave periods) to resolve these non-linear wave effects. These models, such as Boussinesq(-like) models (e.g., Madsen et al., 1991; Wei et al., 1995; Bonneton et al., 2011) and non-hydrostatic models (e.g., Yamazaki et al., 2009; Zijlema et al., 2011; Ma et al., 2012), all in some form exploit the fact that – in shallow water – the depth over wavelength ratio μ is usually small for the dominant wave motions (i.e., $\mu \ll 1$). Furthermore, they assume that changes in the vertical profile of the wave properties (such as the particle velocities) occur on a vertical scale $L_w (= d/\mu)$ that is comparable to the depth d. Because of this slow vertical variability of the wave motion, phase-resolving models have been able to successfully describe the wave dynamics by either approximating the vertical structure by some appropriate series expansion (Boussinesq models) or by dividing the water column in a few vertical layers (non-hydrostatic models). As long as conservation of momentum is ensured when bores develop, this approach can even be applied to simulate highly nonlinear wave dynamics in the surf zone (e.g., Kennedy et al., 2000; Bradford, 2011; Tissier et al., 2012; Smit et al., 2014). While efficient, the consequence is that the vertical structure of the mean flow is either not resolved (Boussinesq models) or very crudely approximated (non-hydrostatic models). This effectively implies that these models can only resolve the bulk horizontal circulations.

This is not a fundamental restriction of non-hydrostatic models as they can be applied with an arbitrary vertical resolution to resolve the vertical structure of the flow field (e.g., Bradford, 2014; Derakhti et al., 2016a; 2016b). However, a fine vertical resolution is required to resolve the vertical scale of the mean flow (L_c). In the nearshore, L_c can be a fraction of the local depth as flows can develop significant vertical shear. For example, cross-shore circulations can develop with an onshore directed mean flow in the upper part and an offshore directed return flow (or undertow) in the lower part of the water column. Consequently, $L_c/L_w \ll 1$, which implies that the vertical resolution is primarily dictated by the flow scales and not by the wave motion. Resolving the mean flow thus may require $\mathcal{O}(10)$ layers, which becomes impracticable at field scales. For practical applications at these scales, non-hydrostatic models are restricted to at most 1–3 layers (e.g., Rijnsdorp et al., 2015; Gomes et al., 2016; Nicolae Lerma et al., 2017) as the solution of the pressure Poisson equation – which already dominates the computational effort at low resolutions – becomes prohibitively expensive at higher resolutions. This is unfortunate because neither the evolution of the mean dynamics, which behave as shallow water flows, nor the evolution of the wave dynamics, for which 1–3 layers have been found sufficient, require the non-hydrostatic pressure (or vertical accelerations) to be resolved at the vertical scale of the mean flow. Arguably, in intermediate to shallow water a combined wave-flow model needs to resolve the horizontal accelerations on the fine mean flow scale L_c, whereas it can resolve the vertical accelerations and non-hydrostatic pressures on the coarser wave scale L_w.

This observation, and inspired by the work of Van Reeuwijk (2002) and Shi et al. (2015), motivates us to solve the vertical and horizontal momentum balances on essentially separate grids. The vertical balance (and pressure) is evaluated on a coarse grid of which the resolution is dictated by the wave motion, whereas the horizontal balance is solved on a finer grid to account for vertical shear. Given that the solution of the non-hydrostatic pressure field requires most computational effort, the overall model efficiency can be significantly improved by solving the vertical balance and the deviations from hydrostatic pressure at the scales of the wave motions, while maintaining a high vertical resolution to resolve the vertical structure of the wave-induced mean flow field. The hypothesis that the vertical grids on which the velocity and the pressure are calculated can be different for certain flow problems was first presented for linear wave motion by Van Reeuwijk (2002). It has seen little development until Shi et al. (2015) reintroduced the proposition – which they referred to as the 'Pressure Decimation and Interpolation (PDI)' method. They demonstrated that the non-hydrostatic pressure can be resolved on a separate coarse grid in the context of stratified flow problems.

The main difficulty with this approach is the consistent coupling between the coarse and fine grids. This coupling, which is achieved through the continuity equation and the pressure interpolation, influences whether or not the method conserves mass and momentum on all grid scales (e.g., the PDI method only conserves mass on the coarse grid, but not on the fine grid). In turn, this influences the dispersive properties of the short waves (as will be shown in this paper). As our primary interest is to efficiently resolve both the waves and the (wave-driven) sheared flows in the coastal zone, we will present a derivation of – what we call – a subgrid approach and the coupling between the grids that is tailored towards this application. Our approach differs from Shi et al. (2015) in how the pressure is interpolated, and that only the horizontal velocities are dynamically resolved on the fine grid. In our derivation it is most natural to view the resulting model as an extension of an existing coarse grid model with a subgrid model to account for vertical shear (and not as a reduction of a fine grid model). For that reason, we refer to our methodology as a subgrid approach.

In Section 2, we present the derivation of the subgrid approach and discuss its numerical implementation in the SWASH model[1] (Zijlema et al., 2011). This is followed by a linear analysis of the model equations to motivate our choice for the pressure interpolation (Section 3). To assess the performance of the method, we validated the model for three test cases that consider the evolution of the wave and flow field in a coastal environment (Section 4). Finally, we discuss and summarise our findings in Sections 5 and 6, respectively.

2. Numerical methodology

The starting point of this work is the Reynolds-averaged Navier–Stokes (RANS) equations for an incompressible fluid of constant density. We consider a fluid that is bounded in the vertical by the bottom $z = -d(x, y)$ and the free surface $z = \zeta(x, y, t)$; where t is time, $\langle x, y, z \rangle$ are the Cartesian coordinates, and the still water level is located at $z = 0$. In this framework, the governing equations read,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0, \tag{1}$$

[1] The SWASH code, including the subgrid approach, can be used freely under the GNU GPL license (http://swash.sourceforge.net).