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

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Abstract

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.

Keywords: nearshore circulation, wave-induced currents, wave breaking, subgrid, non-hydrostatic modelling, SWASH

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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 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

64 been able to successfully describe the wave dynamics by either approximating the vertical structure by
65 some appropriate series expansion (Boussinesq models) or by dividing the water column in a few vertical
66 layers (non-hydrostatic models). As long as conservation of momentum is ensured when bores develop, this
67 approach can even be applied to simulate highly nonlinear wave dynamics in the surf zone (e.g., Kennedy
68 et al., 2000; Bradford, 2011; Tissier et al., 2012; Smit et al., 2014). While efficient, the consequence is that the
69 vertical structure of the mean flow is either not resolved (Boussinesq models) or very crudely approximated
70 (non-hydrostatic models). This effectively implies that these models can only resolve the bulk horizontal
71 circulations.

72 This is not a fundamental restriction of non-hydrostatic models as they can be applied with an arbitrary
73 vertical resolution to resolve the vertical structure of the flow field (e.g., Bradford, 2014; Derakhti et al.,
74 2016a,b). However, a fine vertical resolution is required to resolve the vertical scale of the mean flow (L_c).
75 In the nearshore, L_c can be a fraction of the local depth as flows can develop significant vertical shear.
76 For example, cross-shore circulations can develop with an onshore directed mean flow in the upper part
77 and an offshore directed return flow (or undertow) in the lower part of the water column. Consequently,
78 $L_c/L_w \ll 1$, which implies that the vertical resolution is primarily dictated by the flow scales and not by
79 the wave motion. Resolving the mean flow thus may require $\mathcal{O}(10)$ layers, which becomes impracticable at
80 field scales. For practical applications at these scales, non-hydrostatic models are restricted to at most 1–3
81 layers (e.g., Rijnsdorp et al., 2015; Gomes et al., 2016; Nicolae Lerma et al., 2017) as the solution of the
82 pressure Poisson equation – which already dominates the computational effort at low resolutions – becomes
83 prohibitively expensive at higher resolutions. This is unfortunate because neither the evolution of the mean
84 dynamics, which behave as shallow water flows, nor the evolution of the wave dynamics, for which 1–3 layers
85 have been found sufficient, require the non-hydrostatic pressure (or vertical accelerations) to be resolved
86 at the vertical scale of the mean flow. Arguably, in intermediate to shallow water a combined wave-flow
87 model needs to resolve the horizontal accelerations on the fine mean flow scale L_c , whereas it can resolve
88 the vertical accelerations and non-hydrostatic pressures on the coarser wave scale L_w .

89 This observation, and inspired by the work of Van Reeuwijk (2002) and Shi et al. (2015), motivates us
90 to solve the vertical and horizontal momentum balances on essentially separate grids. The vertical balance
91 (and pressure) is evaluated on a coarse grid of which the resolution is dictated by the wave motion, whereas
92 the horizontal balance is solved on a finer grid to account for vertical shear. Given that the solution of
93 the non-hydrostatic pressure field requires most computational effort, the overall model efficiency can be
94 significantly improved by solving the vertical balance and the deviations from hydrostatic pressure at the
95 scales of the wave motions, while maintaining a high vertical resolution to resolve the vertical structure of
96 the wave-induced mean flow field. The hypothesis that the vertical grids on which the velocity and the
97 pressure are calculated can be different for certain flow problems was first presented for linear wave motion
98 by Van Reeuwijk (2002). It has seen little development until Shi et al. (2015) reintroduced the proposition

99 – which they referred to as the ‘Pressure Decimation and Interpolation (PDI)’ method. They demonstrated
100 that the non-hydrostatic pressure can be resolved on a separate coarse grid in the context of stratified flow
101 problems.

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

114 In Section 2, we present the derivation of the subgrid approach and discuss its numerical implementation
115 in the SWASH model¹ (Zijlema et al., 2011). This is followed by a linear analysis of the model equations to
116 motivate our choice for the pressure interpolation (Section 3). To assess the performance of the method, we
117 validated the model for three test cases that consider the evolution of the wave and flow field in a coastal
118 environment (Section 4). Finally, we discuss and summarise our findings in Section 5 and 6, respectively.

119 2. Numerical Methodology

120 The starting point of this work is the Reynolds-averaged Navier-Stokes (RANS) equations for an in-
121 compressible fluid of constant density. We consider a fluid that is bounded in the vertical by the bottom
122 $z = -d(x, y)$ and the free surface $z = \zeta(x, y, t)$; where t is time, $\langle x, y, z \rangle$ are the Cartesian coordinates, and
123 the still water level is located at $z = 0$. In this framework, the governing equations read,

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

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

$$\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} + g \frac{\partial \zeta}{\partial x} + \frac{\partial q}{\partial x} = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}, \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{\partial vu}{\partial x} + \frac{\partial vv}{\partial y} + \frac{\partial vw}{\partial z} + g \frac{\partial \zeta}{\partial y} + \frac{\partial q}{\partial y} = \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}, \quad (3)$$

$$\frac{\partial w}{\partial t} + \frac{\partial wu}{\partial x} + \frac{\partial wv}{\partial y} + \frac{\partial ww}{\partial z} + \frac{\partial q}{\partial z} = \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}, \quad (4)$$

124 where u is the velocity component in x -direction, v is the velocity component in y -direction, w is the velocity
 125 component in z -direction, g is the gravitational acceleration, and $\tau_{\alpha\beta}$ represent the turbulent stresses (where
 126 α or β denote the coordinates). The turbulent stresses are estimated using an eddy viscosity approximation
 127 (Appendix A). In this set of equations, the total pressure is decomposed in the hydrostatic $\rho g(\zeta - z)$ and
 128 non-hydrostatic component ρq , with q the normalised non-hydrostatic pressure.

129 Assuming that the vertical fluid boundaries are a single valued function of the horizontal coordinate, the
 130 following kinematic conditions apply at the free surface and (impenetrable and immobile) bottom,

$$w|_{z=\zeta} = \frac{\partial \zeta}{\partial t} + u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y}, \quad (5)$$

$$w|_{z=-d} = -u \frac{\partial d}{\partial x} - v \frac{\partial d}{\partial y}. \quad (6)$$

131 Integrating the local continuity equation, Eq. (1), over the water column and applying the relevant kinematic
 132 boundary conditions yields a global continuity equation that describes the temporal evolution of the free
 133 surface,

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} \int_{-d}^{\zeta} u dz + \frac{\partial}{\partial y} \int_{-d}^{\zeta} v dz = 0. \quad (7)$$

134 This global continuity equation provides a convenient form to ensure that the numerical approximations
 135 are mass conservative.

136 To get a unique solution, boundary conditions are required at all boundaries of the physical domain
 137 (i.e., the free surface, the bottom, and the horizontal boundaries). Neglecting the viscous stresses and the
 138 influence of surface tension, and assuming that the atmospheric pressure is constant (and equal to zero for
 139 convenience), the non-hydrostatic pressure is set to zero at the free surface $q|_{z=\zeta} = 0$ (e.g., Stelling and
 140 Zijlema, 2003). At the bottom, the vertical velocity is computed following Eq. (6). Furthermore, two
 141 tangential stresses are specified at the bottom, which are estimated using the law of the wall for a typical
 142 roughness height d_r (Launder and Spalding, 1974). Using suitable horizontal boundary conditions (typically
 143 based on a prescribed form of the horizontal velocity), and a turbulence closure model to compute the eddy
 144 viscosities (see Appendix A), this set of equations forms the basis of the model.

145 In essence, the assumption of a single-valued surface sets non-hydrostatic models apart from more com-
 146 plete descriptions such as volume of fluid (VOF) models (e.g., Lin and Liu, 1998). The single-valued surface
 147 does not allow non-hydrostatic models to capture the overturning of the surface, nor the generation of an
 148 air-water mixture when waves are breaking. This assumption implies that the model does not directly rep-
 149 resent the transformation of organized wave energy into turbulence during the breaking of waves. Instead,
 150 breaking waves are represented as shock waves and the breaking process is considered analogous with a
 151 hydraulic bore. Its energy dissipation is obtained by ensuring that the weak form of the equations conserve
 152 momentum. We stress that this only accounts for the bulk dissipation. Furthermore, the energy is lost from
 153 the system rather than inserted into the turbulent kinetic energy budget. Although the enhanced horizontal
 154 and vertical shear in the bore region does lead to an increased production of turbulent kinetic energy, this
 155 is likely an insufficient proxy for the turbulence generated by the breaking waves through, for example, the
 156 development of an air-water mixture. The turbulence injected in the water column by the breaking process,
 157 and the influence thereof on the mean flow is thus not fully accounted for and arguably requires explicit
 158 parametrisation. This is beyond the scope of the present work and is not taken into account.

159 Recognizing the existence of different vertical scales for the wave and mean flow dynamics, we intend to
 160 solve these equations on two different grids; a coarse grid that is assumed sufficiently accurate to describe
 161 the wave dynamics, and a fine subgrid that is able to represent the vertical shear of the mean flow. In the
 162 following, we present the balances on the coarse and fine vertical grid, and the coupling between the two.
 163 To keep the presentation focussed and concise, we retain a continuous description in space and time, and
 164 focus on the aspects of the subgrid approach. Furthermore, we will present the subgrid implementation
 165 for a two-dimensional vertical plane (i.e., ignoring the y -dimension). The extension to three dimensions is
 166 relatively straightforward, does not alter the numerical approach, and will therefore not be detailed here.

167 *2.1. Coarse grid balance*

168 The coarse grid divides the water column in a fixed number P of terrain-following layers (Fig. 1), with
 169 a spatially varying layer thickness $H_p \left(= \frac{d+\eta}{P} \right)$. A staggered arrangement is used to position the variables
 170 on the grid. The horizontal velocities U are located at the centre of the horizontal cell faces (Z_p), and
 171 the vertical velocities W and non-hydrostatic pressures Q are located at the centre of the vertical cell
 172 faces ($Z_{p\pm}$). Each coarse layer p is subsequently divided into a constant number N of subgrid layers k
 173 ($N = K/P$, where K is the total number of subgrid layers). Similar to the coarse grid variables, the subgrid
 174 variables are arranged using a staggered arrangement. In the following, lower-case symbols correspond to
 175 continuous variables (e.g., u), capital symbols with subscripts correspond to a coarse grid variable (e.g., U_p)
 176 and lower-case symbols with subscripts correspond to a subgrid variable (e.g., $u_{p,k}$).

177 The governing equation for the free surface is given by the global continuity equation. Since the depth
 178 integrated discharge is the sum of the layer discharges (which are by definition $H_p U_p$) the global continuity

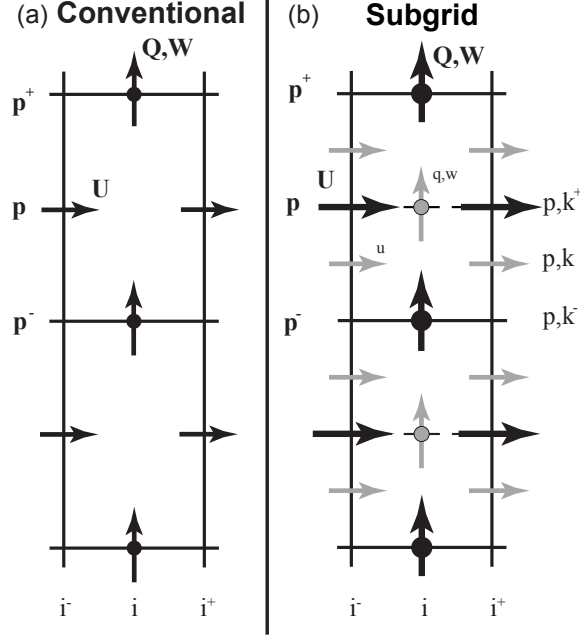


Figure 1: Staggered variable arrangement on the numerical grid. The left panel shows the arrangement according to the conventional SWASH model, and the right panel shows the arrangement used in the case of the subgrid method. In (b), the grey symbols correspond to the variables on the finer velocity grid, and the black symbols correspond to the variables on the coarse pressure grid. Note that the fine and coarse grid non-hydrostatic pressures and vertical velocities overlap at the vertical faces (p^+ and p^-) of a pressure layer.

179 equation is evaluated as,

$$\frac{\partial \zeta}{\partial t} + \sum_{p=1}^P \frac{\partial H_p U_p}{\partial x} = 0. \quad (8)$$

180 Vertically integrating the local continuity equation over a layer p , and making use of the Leibniz integration
181 rule, results in the following coarse grid local continuity equation,

$$\frac{\partial H_p U_p}{\partial x} + W_{p^+} - W_{p^-} - \bar{U}_{p^+} \frac{\partial Z_{p^+}}{\partial x} + \bar{U}_{p^-} \frac{\partial Z_{p^-}}{\partial x} = 0, \quad (9)$$

182 where the horizontal velocity at the interfaces \bar{U}_{p^\pm} are estimated from the U_p values by means of linear
183 interpolation.

184 The time evolution of $H_{p^+} W_{p^+}$ is dictated by the vertical momentum balance, Eq. (4), which after
185 vertical integration over the interval $Z_p \leq z \leq Z_{p+1}$ reads,

$$\frac{\partial H_{p^+} W_{p^+}}{\partial t} + \frac{\partial}{\partial x} \left(H_{p^+} \langle uw \rangle_{Z_{p^+}} \right) + \hat{W}_{p+1} \bar{\Omega}_{p+1} - \hat{W}_p \bar{\Omega}_p = -H_{p^+} \left\langle \frac{\partial q}{\partial z} \right\rangle_{Z_{p^+}}, \quad (10)$$

186 where we neglected the effect of turbulent stresses. Here, the angled brackets indicate averaging over a
187 coarse w -velocity layer,

$$\langle \dots \rangle_{Z_p^+} = \frac{1}{Z_{p+1} - Z_p} \int_{Z_p}^{Z_{p+1}} \dots dz,$$

188 and $\bar{\Omega}_p$ is the relative vertical advective velocity that is interpolated from the relative vertical velocities at
 189 the layer interfaces Ω_{p^+} , which are formally defined as,

$$\Omega_{p^+} = W_{p^+} - \frac{\partial Z_{p^+}}{\partial t} - \bar{U}_{p^+} \frac{\partial Z_{p^+}}{\partial x}.$$

190 The transported vertical momentum \hat{W}_p is obtained using a suitable (flux limited) interpolation from W_{p^+} ,
 191 and we set $\langle uw \rangle_{Z_{p^+}} \approx \bar{U}_{p^+} W_{p^+}$ (which is consistent with the assumption that W changes slowly within
 192 a pressure layer). Because of its favorable dispersive properties for the barotropic modes (e.g., Stelling
 193 and Zijlema, 2003), the layer averaged non-hydrostatic pressure gradient $\left\langle \frac{\partial q}{\partial z} \right\rangle_{Z_p}$ is approximated using the
 194 Hermetian relation,

$$\left\langle \frac{\partial q}{\partial z} \right\rangle_{Z_{p^+}} + \left\langle \frac{\partial q}{\partial z} \right\rangle_{Z_{p^-}} = 2 \frac{Q_{p^+} - Q_{p^-}}{H_p}.$$

195 Lastly, the time evolution of $H_p U_p$ follows from the coarse layer integrated horizontal momentum balance,
 196 Eq. (2),

$$\frac{\partial H_p U_p}{\partial t} + H_p \left\langle \frac{\partial uu}{\partial x} + \frac{\partial uw}{\partial z} \right\rangle_{Z_p} = -g H_p \frac{\partial \zeta}{\partial x} + H_p \left\langle \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial q}{\partial x} \right\rangle_{Z_p} + U \frac{\partial z}{\partial t} \Big|_{Z_{p^-}}^{Z_{p^+}} \quad (11)$$

197 in which $\langle \dots \rangle_{Z_p}$ indicate averaging over a coarse u -velocity layer with lower bound Z_{p^-} and upper bound
 198 Z_{p^+} .

199 Up to this point, our procedure closely follows the original SWASH model (e.g., Zijlema and Stelling,
 200 2008; Zijlema et al., 2011). In fact, if the as of yet unspecified (layer averaged) forcing terms related
 201 to advection, pressure, turbulent stresses, and the moving grid are expressed in terms of the coarse grid
 202 variables, we effectively regain the conventional set of equations that is approximated in SWASH. However,
 203 in that case, a large number of coarse pressure layers is required to resolve the vertical variability of the flow
 204 that is driven by the divergence of the stress in the horizontal balance.

205 2.2. Subgrid balance

206 Instead of closing the coarse grid equations directly, each pressure layer is divided into N subgrid layers.
 207 The aim of this subgrid approach is to dynamically account for the flow that is driven by the divergence of
 208 the stresses in the horizontal balance, even if these are not resolved on the coarse grid. For this purpose, we
 209 integrate Eq. (2) over a subgrid layer k to obtain the time evolution of the horizontal subgrid discharges,

$$\frac{\partial h_{p,k} u_{p,k}}{\partial t} + \frac{\partial h_{p,k} u_{p,k}^2}{\partial x} + \hat{u}_{p,k+\omega_{p,k+}} - \hat{u}_{p,k-\omega_{p,k-}} = -gh_{p,k} \frac{\partial \zeta}{\partial x} - h_{p,k} \left\langle \frac{\partial q}{\partial x} \right\rangle_{z_{p,k}} + h_{p,k} \left\langle \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \right\rangle_{z_{p,k}}, \quad (12)$$

210 where subscript p, k indicates the subgrid layer ($k = 1 \dots N$) in coarse layer p , and in which we introduced
 211 the approximation $\langle u^2 \rangle_{z_{p,k}} \approx u_{p,k}^2$. The angled brackets indicate averaging over a subgrid u -velocity layer,

$$\langle \dots \rangle_{z_{p,k}} = \frac{1}{z_{p,k+} - z_{p,k-}} \int_{z_{p,k-}}^{z_{p,k+}} \dots dz.$$

212 The transported horizontal momentum $\hat{u}_{p,k\pm}$ is obtained from a suitable (flux limited) interpolation from
 213 $u_{p,k}$, and $\omega_{p,k+}$ is the subgrid relative velocity (to be defined below). The turbulent stress terms are
 214 approximated on the fine grid,

$$\left\langle \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} \right\rangle_{z_{p,k}} \approx \frac{1}{h_{p,k}} \left[\frac{\partial h_{p,k} \tau_{xx,p,k}}{\partial x} - \bar{\tau}_{xx,p,k+} \frac{\partial z_{p,k+}}{\partial x} + \bar{\tau}_{xx,p,k-} \frac{\partial z_{p,k-}}{\partial x} + \tau_{xz,p,k+} - \tau_{xz,p,k-} \right],$$

215 with

$$\tau_{xx,p,k} = 2\nu_x \frac{\partial u_{p,k}}{\partial x}, \quad \tau_{xz,p,k+} = \nu_z \left[\frac{u_{p,k+1} - u_{p,k}}{h_{p,k+}} + \frac{\partial w_{p,k+}}{\partial x} \right], \quad \bar{\tau}_{xx,p,k+} = \frac{\tau_{xx,p,k} + \tau_{xx,p,k+1}}{2}.$$

216 The non-hydrostatic pressure gradient is evaluated based on subgrid pressures that are interpolated from
 217 the coarse grid pressures (Q_p). In the literature (Van Reeuwijk, 2002; Shi et al., 2015), different spline based
 218 interpolation techniques have been proposed to provide a smooth and accurate interpolation. In contrast
 219 with these studies, we use linear interpolation to approximate the subgrid non-hydrostatic pressures – this
 220 choice is motivated in Section 3. Here, we only wish to highlight that it is consistent with the assumption
 221 of slow intra-layer variations in the non-hydrostatic pressure. Consequently, the non-hydrostatic pressure at
 222 the subgrid layer interface p, k^+ is computed as,

$$\tilde{q}_{p,k+} = Q_{p-} + (z_{p,k+} - Z_{p-}) \frac{Q_{p+} - Q_{p-}}{H_p}.$$

223 The non-hydrostatic pressure gradient is subsequently evaluated as,

$$\left\langle \frac{\partial q}{\partial x} \right\rangle_{z_{p,k}} = \frac{1}{h_{p,k}} \left[\frac{\partial}{\partial x} \frac{h_{p,k} (\tilde{q}_{p,k+} + \tilde{q}_{p,k-})}{2} - \tilde{q}_{p,k+} \frac{\partial z_{p,k+}}{\partial x} + \tilde{q}_{p,k-} \frac{\partial z_{p,k-}}{\partial x} \right].$$

224 To couple the coarse grid with the subgrid description, the coarse layer discharges in Eq. (8–9) are
 225 defined as the sum of the subgrid layer discharges,

$$H_p U_p = \sum_{k=1}^N h_{p,k} u_{p,k}. \quad (13)$$

226 Furthermore, we need to define the subgrid vertical velocity $w_{p,k\pm}$ to close the set of equations. This subgrid
 227 velocity appears in the turbulent stress terms, and in the definition of the subgrid relative vertical velocity,

$$\omega_{p,k^+} = w_{p,k^+} - \frac{\partial z_{p,k^+}}{\partial t} - \bar{u}_{p,k^+} \frac{\partial z_{p,k^+}}{\partial x}. \quad (14)$$

228 Because vertical accelerations are assumed to be well described on the coarse grid, we do not introduce
 229 a dynamical equation for $w_{p,k\pm}$. Instead, we compute it based on the subgrid integrated local continuity
 230 equation,

$$\frac{\partial h_{p,k} u_{p,k}}{\partial x} + w_{p,k^+} - w_{p,k^-} - \bar{u}_{p,k^+} \frac{\partial z_{p,k^+}}{\partial x} + \bar{u}_{p,k^-} \frac{\partial z_{p,k^-}}{\partial x} = 0, \quad (15)$$

231 where $\bar{u}_{p,k\pm}$ are the horizontal velocities at the layer interfaces. In this manner, the subgrid vertical velocities
 232 inside a pressure layer are computed following,

$$w_{p,k^+} = W_{p^-} - \sum_{m=1}^k \frac{\partial h_{p,m} u_{p,m}}{\partial x} + \bar{u}_{p,k^+} \frac{\partial z_{p,k^+}}{\partial x}. \quad (16)$$

233 At the interfaces where the coarse and subgrid vertical velocities coincide (i.e., when $k = 1 \vee k = N$), the
 234 subgrid vertical velocities are set to be equal to the respective coarse grid vertical velocities. This also
 235 implies that the interpolated \bar{u}_{p,k^+} velocity in Eq. (16) has to match the interpolated velocity on the coarse
 236 grid \bar{U}_{p^+} in Eq. (9). Previously, we made the tentative choice to interpolate \bar{U}_{p^+} from the coarse grid
 237 velocities, but in principal the interface velocities could be obtained from either the fine or the coarse grid
 238 velocities. That said, for steep waves (or bottom gradients) the interface terms strongly contribute to the
 239 coarse-grid continuity equation and through it influence the non-hydrostatic distribution. In this case, a
 240 strong coupling between the coarse grid velocities and pressures is preferred. For this reason, we interpolate
 241 \bar{U}_{p^+} from U_p , and we take $\bar{u}_{p,k^+} = \bar{U}_{p^+}$ in Eq. (14-16) when $k = 1 \vee k = N$.

242 This completes the description of the subgrid approach, in which we approximate Eq. (1-7) with the
 243 semi-discrete set of Eq. (8-10) for $p = 1 \dots P$, and Eq. (12) for $k = 1 \dots N$ in each pressure layer, combined
 244 with the closure relations Eq. (13) and (16), coupled to a standard $k - \epsilon$ turbulence closure model that is
 245 solved using the fine grid velocities. While similar in spirit, the present approach differs from the method
 246 advocated by Shi et al. (2015) in two significant ways: a) we use linear interpolation for the pressure
 247 profile instead of cubic spline interpolation for reasons expanded upon in Section 3, and b) we do not solve
 248 dynamical equations for the subgrid vertical velocities, but instead retrieve $w_{p,k}$ from the subgrid local
 249 continuity equation. The latter ensures that incompressibility is ensured on both the subgrid and the coarse
 250 grid.

251 2.3. Numerical implementation

252 To highlight the essential steps of the subgrid framework, we retained a continuous description in hori-
 253 zontal space and time. However, to obtain a complete numerical model we need to replace the continuous

254 descriptions with discrete approximations. To this end, we closely follow the methodology of the original
255 SWASH model (Zijlema and Stelling, 2005, 2008; Zijlema et al., 2011). This not only allows us to imple-
256 ment the subgrid approach in the existing and well verified SWASH model, but this also allows us to directly
257 compare the model with and without subgrid approximations. Because the subgrid approach introduced
258 previously does not alter the methodology of SWASH fundamentally, and because the time and space dis-
259 cretisation are not fundamental to the approach advocated here, we will only describe the essential aspects
260 here.

261 The governing equations are discretised on a curvilinear spatial grid. The flow variables are positioned
262 on the grid using a staggered variable arrangement, in which pressures and vertical velocities are co-located
263 horizontally, and staggered with regards to the horizontal velocities (see Fig. 1). Consequently, horizontal
264 gradients of the surface, discharge and non-hydrostatic pressure can straightforwardly be approximated with
265 central differences. Time-integration of the coupling between hydrostatic pressure and horizontal velocities is
266 performed with the explicit leapfrog scheme, so that horizontal velocities and surface elevation are staggered
267 in space and time (following Hansen, 1956). Horizontal nonlinear advective terms are approximated with a
268 second order flux-limited explicit McCormack scheme (in space and time) using the approximations proposed
269 in Stelling and Duinmeijer (2003) to ensure momentum conservation (and thus the ability to handle shocks)
270 within the context of a staggered framework. Further, to avoid stringent stability conditions for thin water
271 layers, implicit time integration is used to account for the vertical exchange of momentum.

272 If we neglect the non-hydrostatic pressures, the resultant model is essentially a second-order accurate
273 (in space and time) layered shallow-water model. To incorporate the non-hydrostatic pressure, which is
274 implicitly determined by the coupling between the local continuity equation and the pressure, we use a
275 second-order accurate fractional step method, known as the pressure correction technique (van Kan, 1986),
276 to solve the set of discretised equations. This method constructs a discrete analogue of the pressure Poisson
277 equation by substituting the discrete form of the momentum equations into the discrete continuity equation.
278 For a model with M horizontal grid points and P pressure layers this results in a large but sparse linear
279 system of MP equations with MP unknowns which is subsequently solved using an iterative method to
280 obtain the non-hydrostatic pressure (see Zijlema and Stelling, 2005, 2008; Zijlema et al., 2011, for further
281 details).

282 Since its inception, the SWASH model has been successfully used to study various wave dynamics in
283 coastal regions. For example, the model has been used to simulate the nearshore evolution of short waves
284 (e.g., Smit et al., 2014; Buckley et al., 2014; Gomes et al., 2016), including their depth-induced breaking
285 and associated bulk dissipation (e.g., Smit et al., 2013), the evolution of infragravity waves in coastal
286 regions (e.g., Rijnsdorp et al., 2014, 2015; De Bakker et al., 2016), and runup oscillations at the beach (e.g.,
287 Ruju et al., 2014; Nicolae Lerma et al., 2017). To date, most studies focussed on laboratory scales due
288 to computational constraints. However, with the ever increasing computational capabilities, several recent

289 studies have demonstrated that field scale applications are now within the reach of state-of-the-art multi-core
 290 machines (Rijnsdorp et al., 2015; Gomes et al., 2016; Nicolae Lerma et al., 2017).

291 3. Linear analysis subgrid method

292 The basic assumption of the subgrid approach is that the leading order pressure distribution $q(z)$ can
 293 be parametrised with a finite number of discrete pressure points q_p located at the interfaces of the coarse
 294 pressure grid, so that pressure-layer profile in the subgrid layers is interpolated from the coarse grid values.
 295 In the previous section we tentatively used a linear distribution for the intra-layer pressure, and here we will
 296 expand on the reasons for that choice.

297 Following Shi et al. (2015) we describe the pressure by a spline curve $\tilde{q}(z)$ that in each coarse pressure
 298 layer takes the form of a polynomial of order N_p ,

$$\tilde{q}_p^{N_p} = \sum_{n=0}^{N_p} \alpha_{p,n} (z - Z_p)^{N_p}, \quad (17)$$

299 where, to avoid strongly oscillatory behaviour, generally $N_p \leq 3$. To uniquely specify the coefficients in
 300 terms of the discrete pressures (i.e., $\alpha_{p,n} = \sum_{m=0}^P \beta_{p,n,m} q_m$), we need $P(N_p + 1)$ restrictions. These follow
 301 from enforcing that the first $N_p - 1$ derivatives are continuous at the coarse-grid layer-interfaces, coupled
 302 with (for $P > 1$) the conditions at the surface and bottom (Shi et al., 2015),

$$\partial_z \tilde{q}|_{z=-d} = 0, \quad \partial_z^2 \tilde{q}|_{z=\zeta} = 0. \quad (18)$$

303 Although such splines are smooth functions, they may (except for $N_p = 1$) introduce new maxima in the
 304 intra-layer pressures².

305 In order to analyze the linear properties, we assume that the dominant errors are associated with the
 306 vertical discretisation and therefore consider a semi-discrete description in which the horizontal coordinate
 307 and time remain continuous (e.g., following Cui et al., 2012; Bai and Cheung, 2013; Smit et al., 2014).
 308 Further, we will assume monochromatic progressive wave motion (propagating in the positive x direction)
 309 in a domain of constant depth such that the ratio between the amplitude and a typical vertical scale (ϵ) is
 310 small.

²Monotone behaviour can be achieved for $N_p = 3$, if the derivatives are allowed to be discontinuous at the interface and instead we demand that $\partial_z \tilde{q}^{N_p} = 0$ at the layer interfaces. This is analogous to Van Reeuwijk (2002), who constructed monotone profiles for the pressure gradient (and therefore used a spline with $N_p = 4$ and enforced $\partial_z^2 \tilde{q}^{N_p} = 0$ at the interfaces). However, $\partial_z \tilde{q}^{N_p} = 0$ implies that vertical accelerations vanish at the cell interfaces and therefore will not be considered here.

311 The horizontal momentum equations then represent a leading order balance between pressure gradients
 312 (hydrostatic and non-hydrostatic) and the local accelerations. Substituting the parametrisation of the
 313 pressure, integrating over each individual subgrid layer (neglecting the layer motion, consistent with the
 314 assumption of $O(\epsilon)$ dynamics), and summing over all velocity layers within a coarse pressure layer we find
 315 that,

$$H_p \left[\frac{\partial U_p}{\partial t} + g \frac{\partial \zeta}{\partial x} \right] = - \frac{\partial}{\partial x} \int_{Z_{p^-}}^{Z_{p^+}} \tilde{q}_p \, dz = - \sum_{n=0}^{N_p} \sum_{m=0}^{K/P} \frac{\beta_{n,p,m}}{n+1} H_p^{n+1} \frac{\partial q_m}{\partial x}. \quad (19)$$

316 Consequently, the coarse grid velocity in a layer p depends on a weighted sum of the pressure gradients
 317 at the subgrid layers. For $N = 1$ (linear interpolation), the coarse grid velocity at p only depends on the
 318 gradients of the local pressure at Z_{p^\pm} . In contrast, for $N > 1$ the grid velocity potentially depends on all
 319 the pressure gradients in the water column.

320 Further, by integrating over a coarse layer (and using the Hermetian approximation for the vertical
 321 pressure gradient) we obtain at $O(\epsilon)$ the semi-discrete vertical momentum balance and continuity equation,

$$\frac{\partial W_p}{\partial t} + \frac{\partial W_{p-1}}{\partial t} + \frac{q_p - q_{p-1}}{H_p} = 0, \quad (20)$$

$$\frac{\partial U_p}{\partial x} + \frac{W_{p-1} - W_p}{H_p} = 0. \quad (21)$$

322 Coupled with the boundary conditions $W_P = \frac{\partial \zeta}{\partial t}$, $W_0 = 0$, and $q_P = 0$ we thus find that at $O(\epsilon)$ the
 323 semi-discrete coarse grid equations do not depend on the subgrid velocities. Consequently, the dynamics are
 324 completely described by the coarse grid balance, and the only influence of the fine grid description is that the
 325 parametrisation of the pressure curves defines the weights β assigned to the pressure gradients. To obtain
 326 the linear response, we subsequently seek for a given depth d progressive wave solutions for the coarse grid
 327 variables of the form $\hat{y}_k \exp(ikx - i\omega t)$, where \hat{y}_k is a complex amplitude, ω is the angular frequency, and k is
 328 the wavenumber. Substitution of this ansatz, and solving the resulting equations (see Appendix B) results in
 329 an explicit expression for the coarse grid variables, the numerical dispersion relation, and derived quantities
 330 such as group velocity and wave celerity. Note that all of these depend on the order of the interpolating
 331 spline through the weights β .

332 In shallow water (relative depth $kd \ll 1$) the non-hydrostatic pressure approaches zero over the vertical,
 333 and expressions for the celerity and group velocity all asymptotically approach the shallow water celerity of
 334 Airy theory (Fig. 2), regardless of the order N_p . However, away from the shallow water limit the dispersive
 335 properties of the methods start to diverge from one-another, and from the Airy wave theory. For example, if
 336 we consider two coarse vertical layers, the celerity and group velocity for $kd > 1$ is generally best predicted
 337 using a linear profile and remain reasonable up to $kd \approx 5$, whereas for $kd > 2$ the other profiles – and

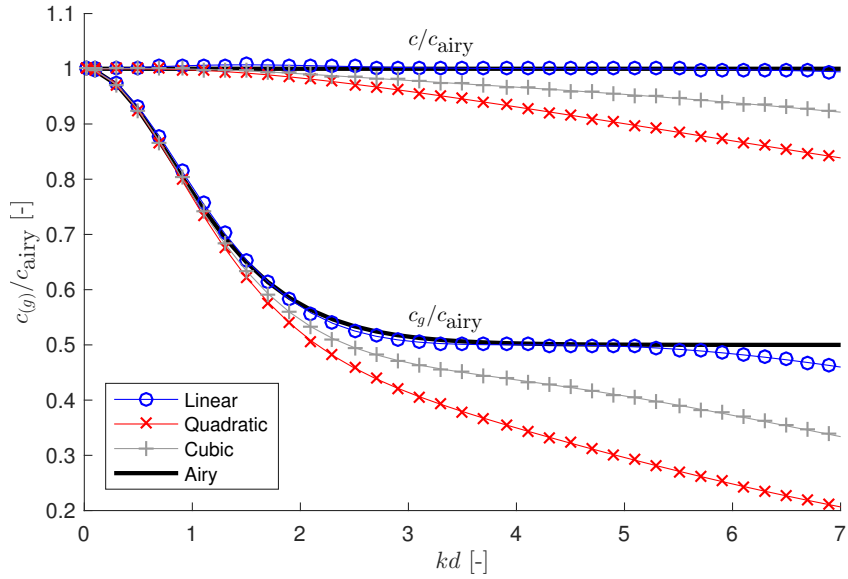


Figure 2: Dispersive properties as a function of relative depth kd for a semi discrete model with two pressure layers using linear (circle markers), quadratic (cross markers) or cubic (plus markers) splines compared with Airy linear wave theory (solid lines). The upper four curves represent the wave celerity $c = \omega/k$ whereas the lower curves depict the group velocity $c_g = \partial_k \omega$. All curves are normalised with the wave celerity from linear wave theory.

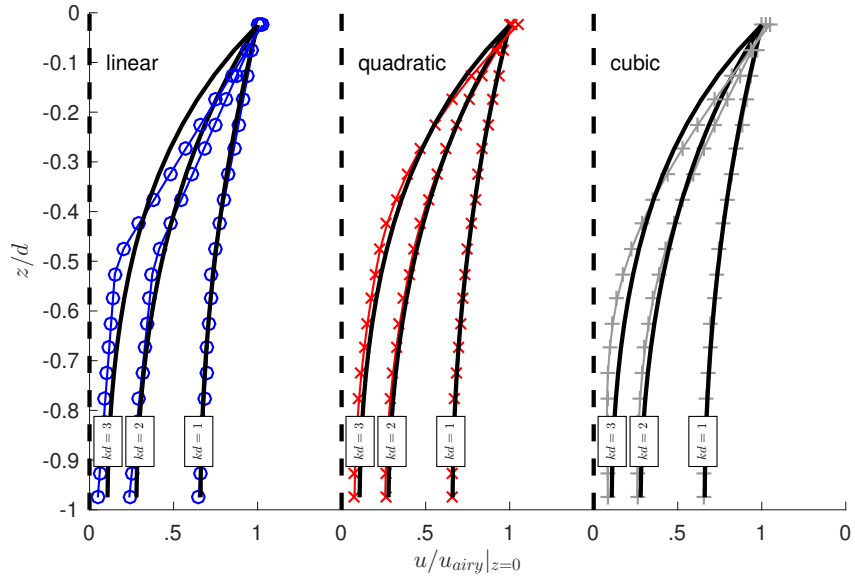


Figure 3: The horizontal velocity below the crest of a wave (scaled with the velocity at $z = 0$). Comparison between profiles obtained from Airy theory and the semi-discrete model with two pressure layers using linear (left panel), quadratic (center panel) and cubic splines (right panel). Within each panel separate curves are drawn for (from right to left) kd equals 1, 2 and 3.

338 the quadratic splines in particular – introduce large differences. Note that with linear interpolation the
339 dispersive properties of the subgrid method are identical to the conventional SWASH model for the same
340 number of pressure layers, independent of the number of subgrid layers.

341 Inspection of the resultant velocity profiles reveals that the higher order splines do lead to qualitatively
342 better descriptions of the vertical velocity profile (Fig. 3). The explanation that the linear method never-
343 theless has better dispersive properties is likely because the errors of the linear method in the lower and
344 upper part of the water column are of opposite sign. Consequently, despite qualitatively performing worse,
345 the errors cancel after integration, and both the net non-hydrostatic force per unit length and discharge per
346 unit length are generally approximated better (not shown), and in fact are approximated well over a range
347 of kd values similar to that of the wave celerity.

348 Although all the models improve their properties with increasing number of coarse grid layers, the choice
349 between the interpolation techniques is a trade off between better dispersive properties over a larger range
350 of kd values or more accurate velocity profiles at lower kd values. That said, we particularly envision the
351 subgrid method to be used to model flows that are driven by shallow water wave processes, for which the
352 wave induced profile does not vary strongly over the vertical, but the induced cross-shore and long-shore
353 flows can be strongly sheared (e.g., Özkan-Haller and Kirby, 1999; MacMahan et al., 2006; Clark et al., 2012).
354 To feasibly model these flows over domains of practical interest (say a coastal region spanning $\sim 1 \times 1$ km),
355 we are likely restricted to a relatively small number of coarse layers ($P \sim 2$). For these applications the
356 improved dispersive properties are useful as this allows for a correct evolution of the wave energy due to
357 shoaling and refraction – primarily influenced by group velocity and wave celerity, respectively – whereas
358 in shallow water ($kd < 1$), the linear representation is a reasonable approximation. These are the principal
359 reasons that we used the subgrid method combined with linear interpolation.

360 4. Test cases

361 To validate the subgrid model, we consider three experimental test cases. The first two are the flume
362 experiments by Ting and Kirby (1994) and Boers (1996), who made detailed measurements of the waves
363 and mean flows for regular waves propagating over a plane beach, and irregular waves over a barred beach,
364 respectively. The final test case considers the experiment of Visser (1991), who measured a longshore current
365 induced by regular waves propagating over a plane beach. For fully resolved simulations (where the number
366 of pressure layers equals the number of velocity layers), model results did not significantly improve for more
367 than 20 pressure layers (Appendix C.1). Therefore, we take a fully resolved 20 pressure layer model as
368 our baseline result. We compare the results of various combinations of velocity and pressure layers in the
369 subgrid method with this baseline model, and the observations. In the following, we distinguish between
370 these simulations according to the number of velocity and pressure layers used (e.g., 20V2P indicates a

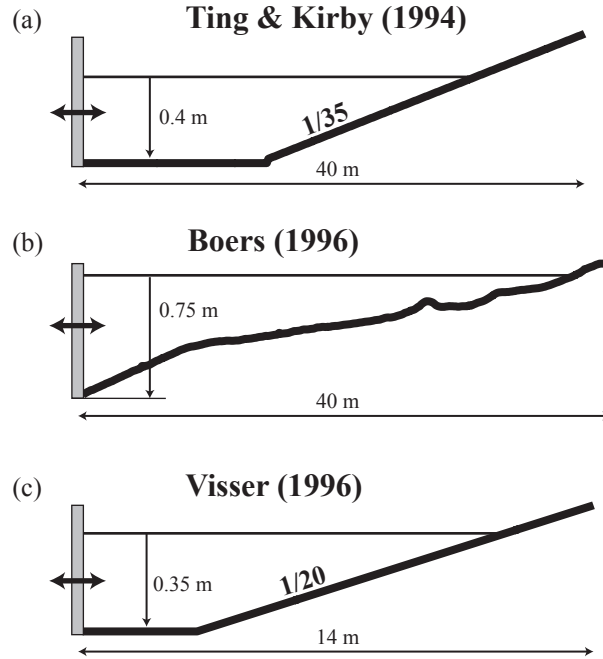


Figure 4: Experimental set-up of the three laboratory experiments.

371 simulation with 20 velocity layers and 2 pressure layers).

372 4.1. Regular waves breaking on a plane beach (Ting and Kirby, 1994)

373 In the experiment of Ting and Kirby (1994), cnoidal waves propagated over a 1/35 plane beach (see Fig.
 374 4a for a sketch of the experimental layout). They considered two wave conditions with a wave height of
 375 $H = 12.5$ cm and a wave period of $T = 2$ s and 5 s, respectively. The breaking waves were of the spilling
 376 type for $T = 2$ s and of the plunging type for $T = 5$ s.

377 To reproduce these experiments, the model was employed with a time step of $\Delta t = 0.005$ s, and a hori-
 378 zontal grid resolution of $\Delta x = 0.025$ m (corresponding to $O(100)$ points per wave length at the wavemaker).
 379 Following Smit et al. (2013), the numerical wavemaker was forced based on second-order cnoidal wave theory
 380 including a mass flux contribution to compensate for the non-zero mean mass influx. The roughness height
 381 was set at $d_r = 4 \times 10^{-4}$ m, a representative value for smooth concrete (e.g., Chow, 1959). Model results
 382 were analysed based on phase averaged time signals of the surface elevation, horizontal flow velocity, and
 383 turbulent kinetic energy with a length of 100 wave periods after steady state conditions were reached. To
 384 compare vertical profiles of velocity and turbulent kinetic energy, we interpolated the model predictions from
 385 the terrain-following framework to a fixed vertical grid. Variables that were located above the instantaneous
 386 free surface were set to zero. Subsequently, the mean velocities were computed at each cross-shore position
 387 by time-averaging the vertically interpolated model predictions.

388 To test the subgrid method, we ran 6 simulations with a varying number of pressure layers (ranging
389 2 – 20). Fig. 5 shows the cross-shore variation of the wave height H (relative to the local mean water
390 level), and the setup $\bar{\zeta}$ for both wave conditions. For the spilling wave condition, the waves shoal up to
391 $x \approx 8$ m, where the wave height starts to decrease as the waves are breaking (Fig. 5a). These patterns
392 are reproduced well by the 20V20P baseline simulation, including the onset of wave breaking near $x = 8$ m
393 and the dissipation of wave energy in the surf zone, although H is slightly over predicted for $x < 8$ m. The
394 baseline predictions also capture the typical magnitude of $\bar{\zeta}$, although it is under predicted just seaward of
395 the breakpoint (Fig. 5b). Here, the measured $\bar{\zeta}$ shows a sudden jump, which can possibly be attributed to
396 measurement inaccuracies as the physical reasons for this jump are unclear (Smit et al., 2013).

397 To quantify the model performance, we computed a skill index following Willmott (1981),

$$\text{Skill} = 1 - \frac{\sum_i^{N_i} (Q(i) - Q_M(i))^2}{\sum_i^{N_i} (|Q(i) - \bar{Q}_M| + |Q_M(i) - \bar{Q}_M|)^2}, \quad (22)$$

398 where $Q(i)$ is the predicted quantity of interest, $Q_M(i)$ is the measured quantity, the vertical lines indicate
399 the absolute value (e.g., $|Q|$), and the overline indicates the mean value (e.g., \bar{Q}_M). With this skill index
400 we quantify whether the model predictions agree with the measurements. For a skill of 1, the model and
401 measurements are in perfect agreement, whereas a skill of 0 indicates significant discrepancies. The skill

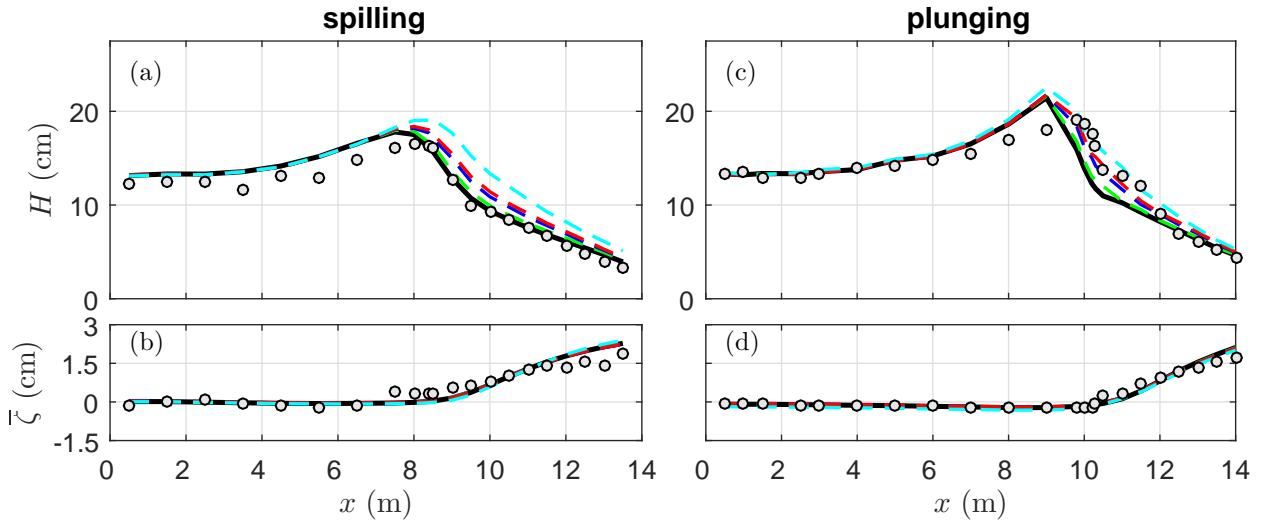


Figure 5: Comparison between predicted (lines) and measured (markers) wave parameters for the spilling (left panels) and plunging wave condition (right panels) of the Ting and Kirby (1994) experiment. The top panels, (a) and (c), show the cross-shore variation of the wave height (H) of the phase-averaged surface elevation (relative to the mean water level). The bottom panels, (b) and (d), show the cross-shore variation of the mean water level or setup ($\bar{\zeta}$). Results are given for the 20V2P (dashed cyan line), 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P simulation (black line).

402 confirms that the baseline predictions of H and $\bar{\zeta}$ are in agreement with the measurements (Table 1).

403 Subgrid model predictions (with 2 – 10 pressure layers) of the spilling wave condition are in agreement
 404 with both the measurements and the baseline simulation (Fig. 5a-b). As illustrated by the skill (Table
 405 1), discrepancies with the measured H and $\bar{\zeta}$ typically increase for a decreasing number of pressure layers.
 406 Nonetheless, the skill of all the subgrid simulations is comparable with that of the baseline simulation. This
 407 demonstrates that the subgrid method captures the wave evolution in the surf zone with an accuracy that
 408 is comparable to the baseline model.

409 For the plunging breaker condition, both the subgrid model and the baseline simulation resolve the
 410 measured cross-shore variation of H and $\bar{\zeta}$ with a skill that is comparable to the results of the spilling
 411 condition (Fig. 5c-d and Table 1). All simulations over predict H just seaward of the breaking location
 412 ($x \approx 8$ m), and under predict H just shoreward of this location (except for the 20V2P simulation). This
 413 indicates that wave breaking is initiated at slightly larger water depths in the model compared to the
 414 measurements, which is consistent with the detailed non-hydrostatic simulations of Derakhti et al. (2016a).

415 To verify if the subgrid method can resolve the vertical dependence of the flow, Fig. 6 shows the measured
 416 and predicted vertical profiles of the (normalised) mean cross-shore velocity \bar{u} and the mean turbulent kinetic
 417 energy \bar{k}_t at several locations near the breakpoint. For both wave conditions, the measured mean flow has
 418 a strong vertical shear as the flow is directed seaward near the bottom (commonly known as undertow) and
 419 directed shoreward near the free surface (Fig. 6a and 6c). Both the baseline simulation and the subgrid
 420 simulations reproduce the typical vertical structure of \bar{u} at the various locations, including the vertical
 421 position where the flow changes direction (at $z \approx 0$ m). However, the magnitude of the flow is generally over
 422 predicted with a comparable skill for both wave conditions (Table 1). Similar to \bar{u} , the vertical structure
 423 of the \bar{k}_t predictions agrees with the measurements, although its magnitude is over predicted at the sensor
 424 locations closest to the breakpoint (Fig. 6b and 6d). Like the predictions of H , and $\bar{\zeta}$, the subgrid and
 425 baseline predictions of \bar{u} and \bar{k}_t are of similar accuracy (Table 1). These results show that errors introduced
 426 by the subgrid method are an order of magnitude smaller compared to the differences between the measured

Table 1: Skill of the predicted bulk parameters versus the measurements for the Ting and Kirby (1994) experiment.

	Ting and Kirby (1994)									
	spilling					plunging				
	20V20P	20V10P	20V5P	20V4P	20V2P	20V20P	20V10P	20V5P	20V4P	20V2P
H	0.99	0.98	0.97	0.96	0.90	0.92	0.94	0.97	0.98	0.97
$\bar{\zeta}$	0.96	0.96	0.96	0.96	0.95	0.99	0.99	0.99	0.99	0.99
\bar{u}	0.84	0.85	0.86	0.86	0.87	0.83	0.84	0.84	0.84	0.85
\bar{k}_t	0.57	0.56	0.57	0.58	0.60	0.61	0.61	0.60	0.59	0.54

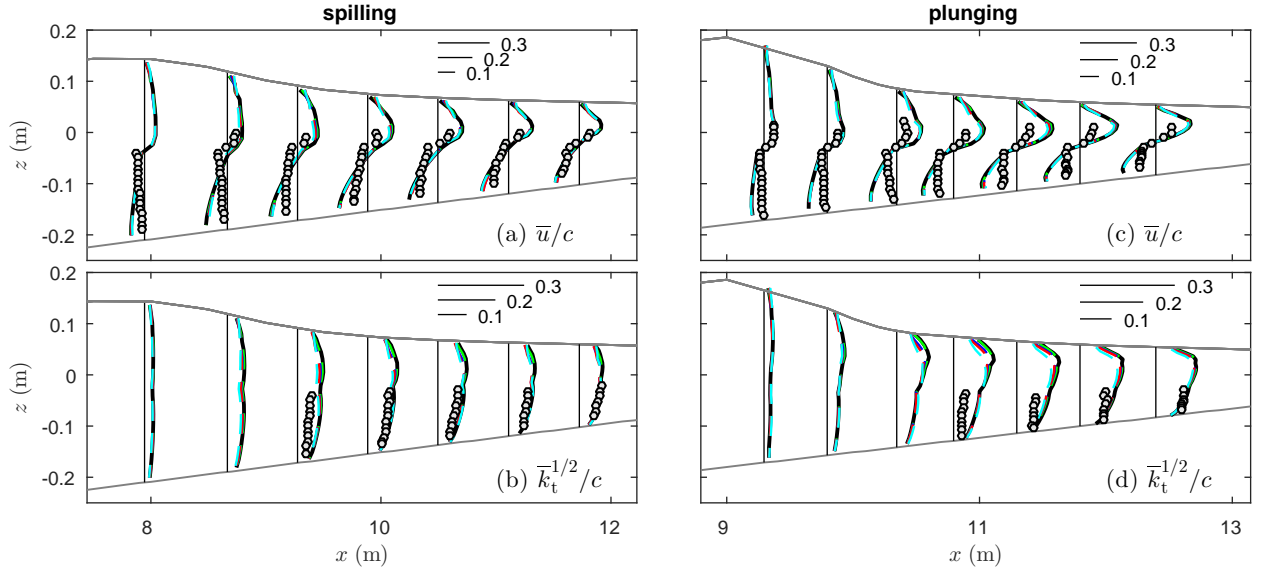


Figure 6: Comparison between predicted (lines) and measured (markers) vertical profiles of the normalised mean cross-shore velocity \bar{u}/c (top panels) and turbulent kinetic energy $\bar{k}_t^{1/2}/c$ (bottom panels) for the spilling (left panels) and plunging wave condition (right panels) of the Ting and Kirby (1994) experiment. The vertical line indicates the location and zero value for each of the vertical profiles. The horizontal oriented grey lines illustrate the wave crest level (top line) and the bottom (lower line). The horizontal lines in the top right of each panel indicates the magnitude of the respective parameter. Results are shown for the 20V2P (dashed cyan line), 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P simulation (black line). Both the velocity and the turbulent kinetic energy are normalised with the celerity of shallow water waves $c (= \sqrt{gd})$.

427 and predicted turbulent flow field.

428 4.2. Random waves breaking on a barred beach (Boers, 1996)

429 To validate the subgrid method for spectral waves over a realistic bottom topography, we compare model
 430 results with the laboratory experiment of Boers (1996). In this experiment, the wave and velocity field of
 431 random waves propagating over a barred beach profile were measured for a total of three wave conditions
 432 (see Fig. 4b for a sketch of the experiment layout), of which we selected the conditions with the highest and
 433 lowest wave height (i.e., case B and case C, respectively). In these two experiments, waves were generated
 434 at the wavemaker based on a JONSWAP spectrum with a significant wave height of $H_{m0} = 20.6$ cm and a
 435 peak period of $T_p = 2.03$ s for case B, and $H_{m0} = 10.3$ cm and $T_p = 3.33$ s for case C.

436 The model was employed with a time step of $\Delta t = 0.002$ s and a horizontal grid resolution of $\Delta x = 0.02$
 437 m. Waves were generated in accordance with Rijnsdorp et al. (2014), who used a weakly nonlinear weakly-
 438 reflective wavemaker based on measurements of the incident wave field at the first wave gauge. The roughness
 439 height and the vertical grid resolution were set in accordance with the simulations of the previous test case

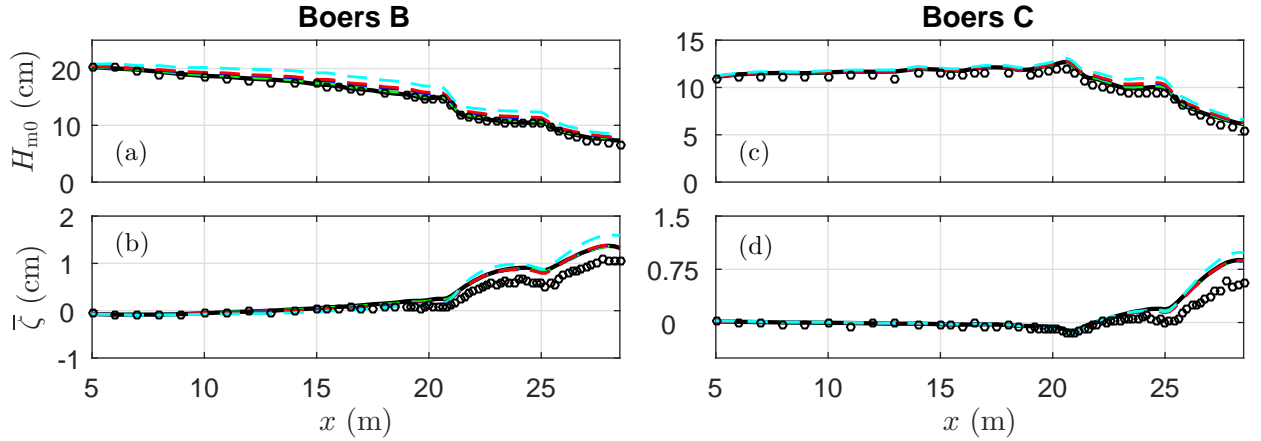


Figure 7: Comparison between predicted (lines) and measured (markers) wave parameters for the wave conditions of the Boers (1996) experiment (B: left panels, C: right panels). The top panels, (a) and (c), show the cross-shore variation of the wave height H_{m0} , and the bottom panels, (b) and (d), show the cross-shore variation of the mean water level or setup ($\bar{\zeta}$). Results are shown for the 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P baseline simulation (black line).

440 (Section 4.1). Simulations had a duration of 28 min, and the measured and predicted signals were analysed
 441 after 60 s of spin-up time.

442 For both wave conditions, the subgrid simulations reproduced the cross-shore variation of the measured
 443 significant wave height H_{m0} (Fig. 7a and 7c), which was computed based on the variance of the surface
 444 elevation signal ($H_{m0} = 4\sqrt{\langle \zeta^2 \rangle}$, where $\langle \dots \rangle$ indicates averaging in time). Furthermore, the baseline and
 445 subgrid predictions are of similar accuracy (Table 2), although errors in the subgrid predictions typically
 446 increase for a decreasing number of pressure layers P . For both wave conditions, the trend and overall
 447 magnitude of the $\bar{\zeta}$ predictions agree with the measurements, although $\bar{\zeta}$ is over predicted shoreward of
 448 $x \approx 20$ m (Fig. 7b and 7d).

449 As a final comparison for this flume experiment, Fig. 8 shows the vertical structure of the normalised

Table 2: Skill of the predicted bulk parameters versus the measurements for the Boers (1996) experiment.

	Boers (1996)									
	B					C				
	20V20P	20V10P	20V5P	20V4P	20V2P	20V20P	20V10P	20V5P	20V4P	20V2P
H_{m0}	1.00	1.00	0.99	0.98	0.95	0.98	0.98	0.97	0.96	0.92
$\bar{\zeta}$	0.94	0.94	0.95	0.95	0.91	0.90	0.90	0.91	0.91	0.87
\bar{u}	0.83	0.83	0.83	0.83	0.82	0.81	0.82	0.82	0.83	0.82
\bar{k}_t	0.92	0.92	0.93	0.92	0.92	0.86	0.87	0.87	0.87	0.89

450 \bar{u} and \bar{k}_t at 8 positions in the surf zone for the two considered wave conditions. For both wave conditions,
 451 the \bar{u} predictions show general patterns that are comparable with the measurements as the model captures
 452 the typical undertow profile in the surf zone (Fig. 8a and 8c). However, the magnitude of the mean flow is
 453 typically over predicted, and the predicted vertical variation of the flow is typically stronger compared to the
 454 measurements (e.g., $x > 23$ m for case C). For \bar{k}_t , both its magnitude and vertical variation generally agree
 455 with the measurements (Fig. 8b and 8d). Quantitatively, Table 2 shows that the differences between the
 456 predicted and measured mean flow field \bar{u} are comparable to the Ting and Kirby (1994) test case (Section
 457 4.1, Table 1), whereas \bar{k}_t is predicted with better skill. Again, discrepancies between the model and the
 458 measurements are not related to the subgrid method as the accuracy of the subgrid and baseline predictions
 459 is comparable for all parameters (Table 2).

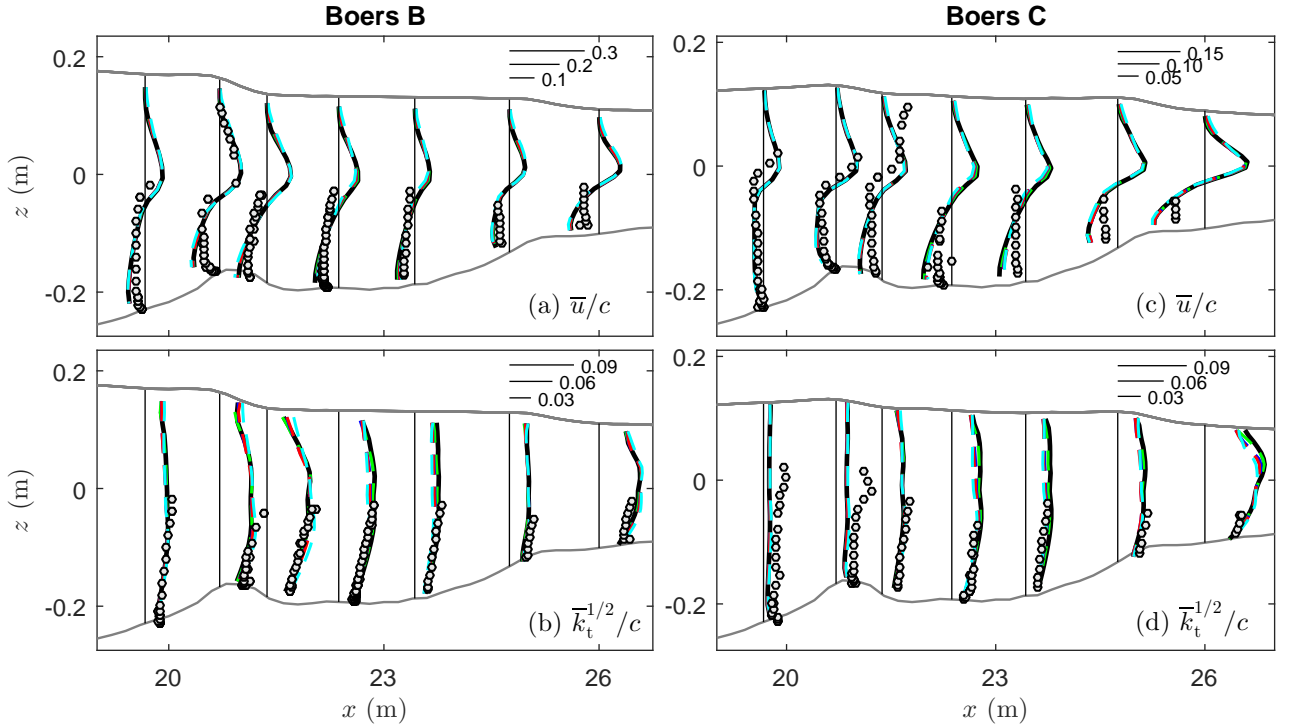


Figure 8: Comparison between predicted (lines) and measured (markers) vertical profiles of the normalised time-averaged cross-shore velocity \bar{u}/c (top panels) and turbulent kinetic energy $\bar{k}_t^{1/2}/c$ (bottom panels) for the two wave conditions of Boers (1996) (B: left panels, C: right panels). The vertical line indicates the location and zero value for each of the vertical profiles. The horizontal oriented grey lines illustrate the wave height (top line) and the bottom (lower line). The horizontal lines in the top right of each panel indicates the magnitude of the respective parameter. Results are shown for the 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P simulation (black line). Both the velocity and the turbulent kinetic energy are normalised using the celerity of shallow water waves $c (= \sqrt{gd})$.

460 4.3. Regular waves breaking on a two-dimensional plane beach (Visser, 1991)

461 In the final test case, model results are compared with measurements of Visser (1991), who considered
 462 the generation of a longshore current on a plane beach by the breaking of regular waves (see Fig. 4c for the
 463 cross-section of the experimental layout). Following Chen et al. (2003) and Ma et al. (2012), we consider
 464 experiment no. 4 of Visser (1991), in which a regular wave with a height of 7.8 cm and a period of 1.02 s
 465 was generated at the wavemaker with an incident angle of 15.4° .

466 The time step in the model simulation was set at $\Delta t = 0.005$ s, and the grid resolution was set at
 467 $\Delta x = 0.03$ m and $\Delta y = 0.044$ m (resulting in 400×128 grid cells). At the offshore boundary, waves were
 468 generated based on the target wave conditions with a weakly-reflective wavemaker based on linear wave
 469 theory. To simulate waves on an unbounded beach, a periodic boundary condition was used at the lateral
 470 boundaries of the domain. Following the previous test cases, the roughness height was set at $d_r = 4 \times 10^{-4}$
 471 m.

472 The wave heights H predicted by the high-resolution simulations (with and without the subgrid method)
 473 match with the measurements throughout the domain, including the decay of the wave height as the waves
 474 start to break at $x \approx 5$ m (Fig. 9a). Furthermore, all model simulations capture the refraction of the waves

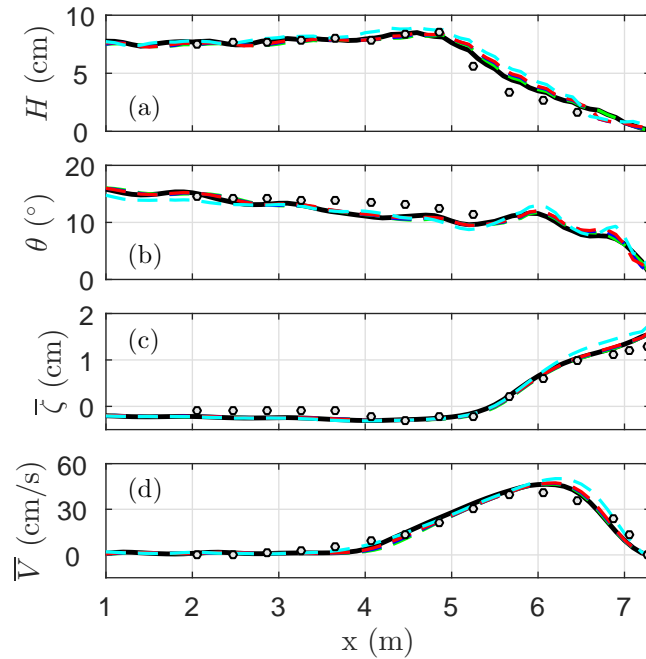


Figure 9: Comparison between predicted (lines) and measured (markers) bulk parameters for the Visser (1991) experiment. The panels show the cross-shore variation of the wave height H (a), wave direction θ (b), mean water level or setup $\bar{\zeta}$ (c), and the (depth-averaged) longshore current \bar{V} (d). Results are shown for the 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P simulation (black line).

Table 3: Skill of the predicted bulk parameters versus the measurements for the Visser (1991) experiment.

	Visser (1991)				
	20V20P	20V10P	20V5P	20V4P	20V2P
H	0.98	0.98	0.97	0.97	0.95
θ	0.73	0.73	0.73	0.75	0.69
$\bar{\zeta}$	0.98	0.98	0.98	0.98	0.96
\bar{V}	0.99	0.98	0.99	0.99	0.98

475 as they propagate shoreward, indicated by the agreement between the predicted and measured wave angle θ
476 (Fig. 9b). In this two-dimensional domain, gradients in radiation stress due to wave breaking are balanced
477 by a setup in x -direction and a longshore current in y -direction. For all model simulations, the typical
478 magnitude and variation of the setup $\bar{\zeta}$ and the mean depth-averaged longshore current \bar{V} agree with the
479 measurements (Fig. 9c and Fig. 9d). The general model-data agreement observed in Fig. 9 is confirmed

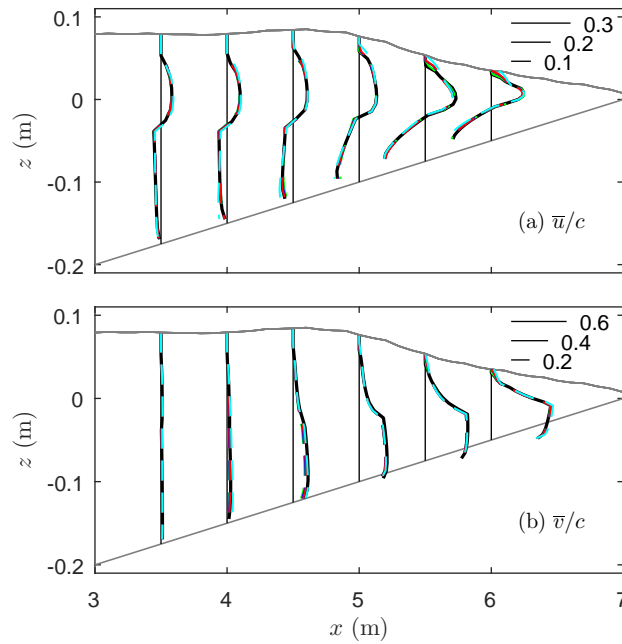


Figure 10: Predictions of the vertical profiles of the normalised time-averaged cross-shore velocity \bar{u}/c (a) and alongshore velocity \bar{v}/c (b) for the Visser (1991) experiment. The vertical line indicates the location and zero value for each of the vertical profiles. The horizontal oriented grey lines illustrate the wave height (top line) and the bottom (lower line). The horizontal lines in the top right of each panel indicates the magnitude of the respective parameter. Results are shown for the 20V4P (dashed red line), 20V5P (dashed blue line), 20V10P (dashed green line), and the 20V20P simulation (black line). Both the velocity and the turbulent kinetic energy are normalised using the celerity of shallow water waves $c (= \sqrt{gd})$.

480 by the skill index (Table 3). Furthermore, the skill confirms that the accuracy of the subgrid and baseline
 481 predictions is comparable for all four parameters.

482 Unfortunately, measurements of the mean vertical flow profile are not available for this experiment.
 483 Nonetheless, to demonstrate the ability of the subgrid method in reproducing the vertical structure of the
 484 flow field, Fig. 10 shows the predicted vertical profile of the mean cross-shore \bar{u} and mean alongshore
 485 velocity \bar{v} at several positions near the shoreline. Similar to the previous test cases, the subgrid method
 486 reproduces the vertical \bar{u} profile of the baseline predictions, including the undertow near the bed and the
 487 shoreward-directed flow in the upper part of the water column (Fig. 10a). Besides the cross-shore directed
 488 flow, the subgrid model also reproduces the vertical variation of the alongshore directed flow field \bar{v} (Fig.
 489 10b). Compared to \bar{u} , the alongshore directed flow field \bar{v} has a weaker vertical variability in the lower part
 490 of the water column. The subgrid simulations capture these patterns, even when only a few pressure layers
 491 are used.

492 5. Discussion

493 5.1. Efficiency

494 The main motivation of the subgrid method is to make full 3D simulations of the wave and flow field
 495 feasible at spatial and temporal scales of a realistic field site (e.g., a domain spanning $\sim 10 \times 10$ wave lengths
 496 and a duration of ~ 1000 wave periods). To quantify the efficiency gain, we consider the computational
 497 time of various simulations (including and excluding the subgrid method) with a 2V2P simulation for the

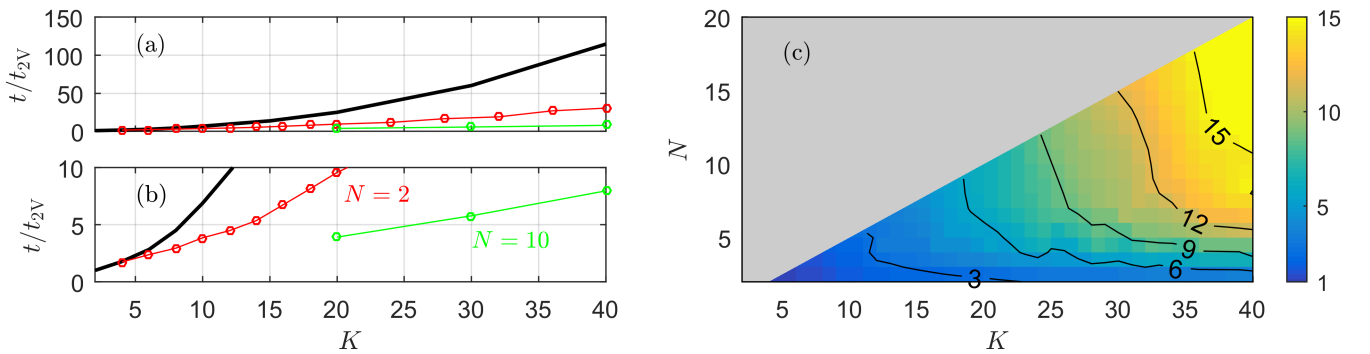


Figure 11: Panel (a): ratio of the computational time relative to a 2V2P simulation for the Visser (1991) experiment (t/t_{2V}). The ratio is depicted for non-hydrostatic simulations using the conventional model (full black line) and the subgrid approach (red and green line with circle markers). For the subgrid approach, two sets of simulations are shown with a constant number of velocity layers per pressure layer, where $N (= K/P)=2$ (red line) and $N = 10$ (green line), respectively. Panel (b): similar to panel (a) but with a changed vertical axis to highlight the results of the subgrid simulations. Panel (c): speed up versus a baseline simulation with the same number of velocity layers. The speed up is computed as the ratio of the computational time for a specific simulation t_i to the computational time of the corresponding baseline simulation t_b (Speed up = t_i/t_b).

498 Visser (1991) experiment (Fig. 11a-b). Without the subgrid model, the computational effort increases
 499 nonlinearly when the number of layers K is increased (Fig. 11a, full black line). Such nonlinear scaling
 500 is primarily due to the increased effort required to solve the Poisson equation. When using the subgrid
 501 model, the computational effort is significantly reduced, as illustrated by the red and green line with circle
 502 markers, which correspond to simulations with two ($N = 2$) and ten velocity layers ($N = 10$) per pressure
 503 layer, respectively. For example, a 20V2P simulation takes about 4 times longer to run compared to a 2V2P
 504 simulation (Fig. 11b), whereas a 20V20P simulation takes about 25 times longer (Fig. 11a). This indicates
 505 that for this case the subgrid model is about 6 times faster than a baseline simulation with the same number
 506 of velocity layers (i.e., a speed up of 6). To further illustrate this, Fig. 11c shows the speed up of the subgrid
 507 simulations (with various N and K combinations) relative to a baseline simulation with the same number of
 508 velocity layers. The speed up of the subgrid simulations increases significantly as N and K increase. These
 509 results show that the computational effort of a high-resolution simulation can be reduced by up to an order
 510 of magnitude when using the subgrid method. Although the computational effort remains significant for
 511 such detailed simulations, the subgrid method makes them viable on state-of-the-art multi-core machines
 512 for select engineering and scientific purposes.

513 5.2. Accuracy

514 This work demonstrates that the subgrid model resolved the mean flow with an accuracy that is compara-
 515 ble to the fully resolved model. For the three test cases, we found that the skill (relative to the measurements)
 516 of the subgrid and baseline predictions was comparable for all considered wave and flow parameters. To
 517 analyse the accuracy of the subgrid simulations in more detail, Fig. 12 shows the root mean square error
 518 (RMSE) of the subgrid predictions with respect to a 20V20P baseline simulation. The RMSE was computed
 519 as,

$$\text{RMSE} = \sqrt{\frac{1}{N_i} \sum_i^{N_i} (Q(i) - Q_R(i))^2}, \quad (23)$$

520 where Q_R is the prediction of the 20V20P baseline simulation. Compared to the baseline simulations, the
 521 RMSE of all depicted parameters decreases for a increasing number of pressure layers P , with convergence
 522 typically scaling as P^{-b} with $b \approx 0.9$ (Appendix C.2). Overall, the RMSE of the subgrid predictions are
 523 small compared to their typical measured values (e.g., the maximum RMSE of H is about 3 cm, whereas
 524 $H = \mathcal{O}(10)$ cm). Supported by the previous observations (Table 1-3), these results illustrate that the
 525 discrepancies introduced by the subgrid method are much smaller compared to the differences between the
 526 model predictions and the measurements. Even with a few pressure layers the introduction of the subgrid
 527 method does not adversely alter the accuracy of the model predictions.

528 These results are in accordance with our assumption that in the model equations the mean flow dynamics
 529 and wave dynamics essentially operate on two separate vertical scales, each of which can be evaluated

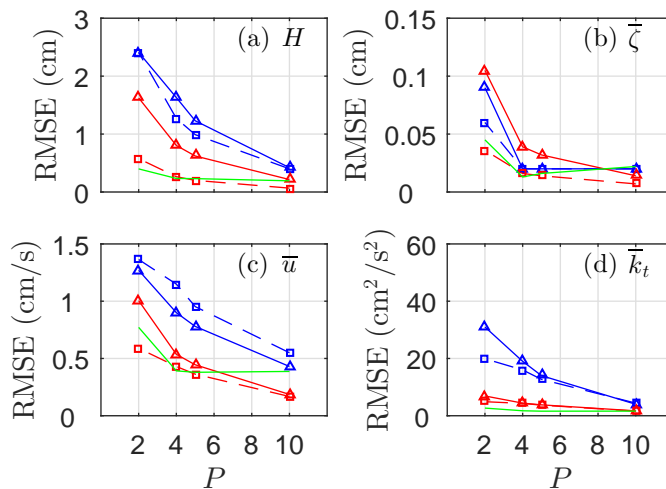


Figure 12: RMSE of all test cases relative to a 20V20P baseline simulations for the (significant) wave height H (a), mean water level $\bar{\zeta}$ (b), mean cross-shore velocity \bar{u} (c), and mean turbulent kinetic energy \bar{k}_t (d). The colors indicate the test case; where blue corresponds to Ting and Kirby (1994), red to Boers (1996), and green to Visser (1991). For the first two test cases, the full line with triangular markers and the dashed line with square markers corresponds to the experiment with the largest and smallest wave height, respectively.

530 on separate grids. Arguably, the agreement between the fully resolved model and the subgrid model is
 531 sufficient to highlight this, whereas the comparison with observations mostly highlights deficiencies that
 532 are also present in the fully resolved model. We stress that, in the present form, predictions of the mean
 533 flow dynamics are more than reasonable, but acknowledge that discrepancies between the measured and
 534 predicted flow field can be found. These are typically largest in the surf zone, near the bed, and in the
 535 upper part of the water column. They can presumably (at least in part) be attributed to deficiencies in
 536 the turbulent closure approximations; such as the omission of wave breaking-generated turbulence at the
 537 free surface, and an incomplete description of the bottom boundary layer. Furthermore, flow predictions in
 538 the surf zone are sensitive to the specific closure model (Brown et al., 2016), and the standard $k - \epsilon$ model
 539 adopted here may not be the most suitable closure model in this highly dynamic region. Regardless, these
 540 deficiencies are not specific to the subgrid method presented here, but are inherited from the fully resolved
 541 model, and thus do not invalidate the subgrid approach.

542 5.3. Wave breaking

543 As the waves approach the shore, waves start to steepen and strong vertical gradients in the horizontal
 544 particle velocities develop (with larger velocities near the surface compared to the bottom), and they even-
 545 tually break when the wave shape becomes unstable. Neither the subgrid model nor the fully resolved model
 546 contain any parameters that control the onset or cessation of this wave breaking, or the dissipation rate. As

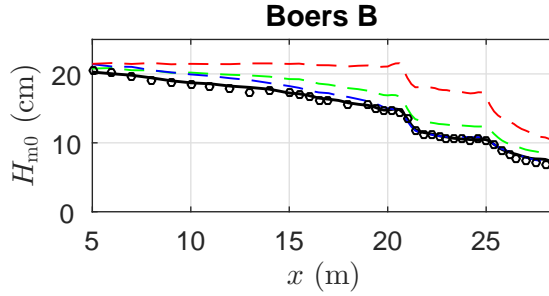


Figure 13: Comparison between predicted (lines) and measured (markers) wave heights H_{m0} for the case B of the Boers (1996) experiment. Results are shown for the 20V2P (dashed green line), 2V2P without HFA (dashed red line), 2V2P with HFA (dashed blue line), and 20V20P baseline simulation (black line).

547 long as the model properly conserves momentum over flow discontinuities, both the transition of a wave into
 548 a bore and its dissipation rate follow naturally. In the context of the SWASH model this was established
 549 previously by Smit et al. (2013). However, they also found that incipient breaking in SWASH is delayed
 550 considerably if a low vertical resolution is used. Their hypothesis for this delayed transition (confirmed
 551 with numerical simulations) was that at low vertical resolutions the horizontal velocities near the surface
 552 are underestimated, so that the kinematic conditions for the onset of breaking (i.e., particle velocities larger
 553 than the wave celerity) are shifted shoreward (Refer to Smit et al., 2013, for more details). For that reason,
 554 SWASH simulations with low vertical resolutions (e.g., a 2V2P simulations) typically employ a heuristic
 555 approximation (referred to as the hydrostatic front approximation, or HFA) to ensure that wave breaking
 556 occurs at the correct location.

557 The subgrid methodology introduced in the present work was primarily intended to resolve the vertical
 558 variations in the mean flow. Effectively, all terms except for the vertical accelerations and non-hydrostatic
 559 pressure gradients are resolved on the fine grid, including the horizontal advection terms. The enhanced
 560 velocities near the surface due to wave non-linearity appear to be well resolved in a subgrid model with
 561 20 velocity layers, regardless of the number of pressure points, as the location of incipient breaking is well
 562 approximated. For instance, if we consider case B of the Boers (1996) experiment, and compare a 2V2P
 563 model (with and without HFA) to the subgrid simulations, we see that the 20V2P subgrid model predicts
 564 the reduction in wave height much better than the 2V2P without HFA (Fig. 13, dashed green versus dashed
 565 red line). In fact, the predictions of the 20V2P subgrid model are comparable to the 20V20P baseline
 566 model, and the 2V2P model with HFA enabled. However, if one is solely interested in the wave dynamics,
 567 the subgrid method is not directly competitive with a 2V2P model with HFA in terms of computational
 568 efficiency, as the subgrid method still requires a high number of velocity layers. Nonetheless, these results are
 569 encouraging as they imply that for typical coastal applications the subgrid method requires no empirically
 570 based approximation to account for the wave-breaking induced bulk dissipation of the wave motion.

571 6. Conclusions

572 In this work, we have presented a subgrid approach for the wave-resolving non-hydrostatic modelling
573 framework that aims to efficiently simulate the vertical structure of wave-induced currents in coastal regions.
574 With this approach, the wave and mean flow dynamics are essentially solved on different grids: a coarse
575 grid for the vertical accelerations and pressure gradients, and a fine (or sub-) grid to resolve the horizontal
576 accelerations and stress divergence. The principal advantage of this approach is that the effort required to
577 solve the pressures through the Poisson equation can be reduced by an order of magnitude. We implemented
578 the subgrid approach in the open-source non-hydrostatic wave-flow model SWASH, and validated the re-
579 sulting model for the wave and current field using a total of three test cases that comprise a range of wave
580 conditions (including regular waves on a plane beach and random waves on a realistic bottom topography).
581 Subgrid predictions were compared to the measurements, and to a high-resolution fully resolved SWASH
582 simulation (with an equal number of coarse and fine grid layers)

583 For all considered test cases, the subgrid simulations captured the measured cross-shore variation of the
584 wave field with an accuracy that is comparable to the fully resolved SWASH simulations. This includes
585 the initiation of wave breaking and the bulk dissipation of wave energy in the surf zone. The subgrid
586 method resolved the cross-shore evolution of the bulk wave parameters with as few as two pressure layers.
587 Remarkably, the subgrid method required no additional measures to initiate wave breaking, in contrast with
588 conventional SWASH simulations that employ a coarse vertical resolution (e.g., Smit et al., 2013).

589 Discrepancies between the predicted and measured turbulent flow field were typically an order of magni-
590 tude larger compared to the wave field. Despite these differences, the model reproduced the typical vertical
591 structure of the mean flow, including the undertow near the bottom and the shoreward-directed flow near
592 the free surface. More importantly, the subgrid and fully resolved predictions were of similar accuracy, which
593 demonstrates that the model accuracy was not significantly influenced by the introduction of the subgrid
594 method. We anticipate that model predictions can be improved by adopting a different turbulence closure
595 model (e.g., the nonlinear instead of the standard $k-\epsilon$ model), by including (a parametrisation of) the wave-
596 breaking induced turbulence at the free surface, and by improving the modelling of the bottom-boundary
597 layer.

598 Overall, the results of this study have shown that the introduction of the subgrid method in SWASH
599 allows us to efficiently resolve the wave and flow field in the coastal region with an accuracy that is comparable
600 to the fully resolved SWASH model. The primary advantage of the subgrid method is its gain in efficiency
601 when resolving the three-dimensional flow field, which makes high resolution model applications viable at
602 intermediate spatial and temporal scales.

603 **Acknowledgements**

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 606 and the Government of Western Australia.

607 **Appendix A. Turbulent stress approximations**

608 The turbulent stresses $\tau_{\alpha\beta}$ are approximated from the eddy viscosity approximations,

$$\begin{aligned}
 \tau_{xx} &= \nu \frac{\partial u}{\partial x}, & \tau_{xy} &= \tau_{yx} = \frac{\nu}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right), \\
 \tau_{yy} &= \nu \frac{\partial v}{\partial y}, & \tau_{yz} &= \tau_{zy} = \frac{\nu}{2} \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \right), \\
 \tau_{zz} &= \nu \frac{\partial w}{\partial z}, & \tau_{zx} &= \tau_{xz} = \frac{\nu}{2} \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right),
 \end{aligned} \tag{A.1}$$

609 where ν is the eddy viscosity estimate from a closure approximation. In 3D wave-averaged circulation
 610 models, the vertical and horizontal gradients of the vertical velocity are typically neglected. Furthermore,
 611 separate eddy viscosities are commonly introduced for the horizontal and vertical mixing (i.e., ν_h and ν_v ,
 612 respectively) to account for the differences between the resolutions of the horizontal and vertical scale. In
 613 this case, the stress terms can be approximated as

$$\tau_{xx} = \nu_h \frac{\partial u}{\partial x}, \quad \tau_{yy} = \nu_h \frac{\partial v}{\partial y}, \quad \tau_{zz} = 0, \quad \tau_{xy} = \tau_{yx} = \frac{\nu}{2} \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right), \quad \tau_{yz} = \tau_{zy} = \nu_v \frac{\partial v}{\partial z}, \quad \tau_{zx} = \tau_{xz} = \nu_v \frac{\partial u}{\partial z}. \tag{A.2}$$

614 A more complete description of the turbulent stresses in the surf zone requires to account the wave breaking
 615 generated turbulence, which is beyond the scope of the present work. For that reason we have opted to retain
 616 the approximate relations coupled to a $k - \epsilon$ model (Launder and Spalding, 1974) to estimate the vertical
 617 eddy viscosity ν_v , and Smagorinsky-type approximation (Smagorinsky, 1963) to estimate the horizontal
 618 eddy viscosity ν_h . Note that a more complete description may improve the inter-comparison between model
 619 results and observations, but the relative performance between a subgrid and fully resolved model is likely
 620 unaffected.

621 **Appendix B. Linear Semi-Discrete Analysis**

622 To determine the linear response of the system for different parametrisations of the pressure curve we
 623 express the semi-discrete linear system for constant depth in matrix vector form,

$$\mathbf{A}_{\partial_t, \partial_x} \mathbf{y} = 0, \tag{B.1}$$

624 where $\mathbf{y}^T = [\zeta, U_1, \dots, U_P, W_0, \dots, W_{P-1}, q_1, \dots, q_P]$ is the solution vector of the coarse grid variables, and

$$\mathbf{A}_{\partial_t, \partial_x} = \begin{bmatrix} \partial_t & [0, \dots, 0] & [1, 0, \dots, 0] & [0, \dots, 0] \\ g \begin{bmatrix} 1 \\ \vdots \\ 1 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \partial_x & \mathbf{I} \partial_t & \mathbf{0} & H^{-1} \mathbf{P} \partial_x \\ \mathbf{0} & \mathbf{0} & \frac{1}{2}(\mathbf{I} + \mathbf{D}^+) \partial_t & -(\mathbf{I} - \mathbf{D}^-) H^{-1} \\ \mathbf{I} \partial_x & (\mathbf{I} - \mathbf{D}^+) H^{-1} & \mathbf{0} & \end{bmatrix}, \quad (\text{B.2})$$

625 is the $3P + 1$ by $3P + 1$ matrix that represents the dynamics of the semi-discrete system; and which from
 626 top to bottom consists of semi-discrete representations of the kinematic surface boundary condition, the
 627 horizontal momentum balance, the vertical momentum balance, and local continuity. Here \mathbf{I} and $\mathbf{0}$ are the
 628 P by P identity and zero matrices, respectively, and $D_{i,j}^{\pm} = \delta_{i,j \pm 1}$ denotes a matrix where the upper (+) or
 629 lower (-) off-diagonal is unity. Finally,

$$\mathbf{P}_{i,j} = \sum_{n=0}^{N_p} \frac{\beta_{n,i,j}}{n+1} H_i^{n+1}, \quad (\text{B.3})$$

630 represents the influence of the layer integrated pressure curve.

631 To analyze the linear response for a progressive wave, we substitute the ansatz,

$$\mathbf{y} = \hat{\mathbf{y}} \exp(ikx - i\omega t), \quad (\text{B.4})$$

632 where $\hat{\mathbf{y}}^T = [\hat{\zeta}, \hat{U}_1, \dots, \hat{U}_P, \hat{W}_1, \dots, \hat{W}_{P-1}, \hat{q}_1, \dots, \hat{q}_P]$ denotes the vector of complex amplitudes. Conse-
 633 quently, for wave like solutions $\hat{\mathbf{y}}$ we have $\mathbf{A}_{-i\omega, ik} \hat{\mathbf{y}} = 0$, and for non-trivial solutions to exist we demand
 634 that the matrix is singular, that is, $\text{Det}(\mathbf{A}_{-i\omega, ik}) = 0$. This gives a condition that implies that the wavenum-
 635 ber and angular frequency are related, which when solving for ω gives the numerical dispersion relation
 636 $\omega = \omega(k)$. To determine $\hat{\mathbf{y}}$ we substitute the dispersion relation, and parametrise the nullspace of $\mathbf{A}_{-i\omega(k), ik}$
 637 in terms of the free surface amplitude.

638 Appendix C. Convergence

639 Appendix C.1. Baseline model

640 To decide on the number of velocity layers to be used in this paper, we tested the convergence behaviour
 641 of the model for an increasing vertical grid resolution (without using the subgrid method). For this purpose,
 642 a series of simulations was conducted for the spilling wave condition of the Ting and Kirby (1994) experiment
 643 with a varying number of vertical layers ($K = 10 - 40$). To test the convergence behaviour of the model,
 644 we computed the RMSE for the wave height (H) and the mean cross-shore velocity (\bar{u}) at all experimental

645 sensor locations. As expected, the RMSE of both variables reduces for an increasing number of vertical
 646 layers (Fig. C.1). In general, differences with the baseline simulation are largest for \bar{u} . For both parameters,
 647 the convergence rate is approximately 1.5. For $K \geq 20$ layers the wave and flow parameters were predicted
 648 with small errors compared to the 40 layer simulation. Based on these findings, we used 20 velocity layers
 649 in the simulations of this work.

650 *Appendix C.2. Subgrid model*

651 The convergence behaviour of numerical models generally depends on the accuracy of the numerical
 652 schemes used in the model. For example, when second-order schemes are used for the spatial derivatives,
 653 the model results are expected to converge quadratically when the grid resolution is refined. However, due
 654 the the use of a coarse and fine grid to resolve the various variables, the convergence rate of the subgrid model
 655 is not obvious. For that reason, we conducted a convergence test for the spilling wave condition of the Ting
 656 and Kirby (1994) experiment. We considered a series of simulations with an increasing number of pressure
 657 layers ($P = 2 - 10$), and with a constant number of 20 velocity layers. To quantify the convergence of the
 658 subgrid method, we computed the RMSE for two parameters (H , and \bar{u}) relative to a 20V20P reference
 659 simulation. Convergence is approximately linear for both parameters, although it is slightly better for the
 660 wave heights H than for the mean cross-shore flow (Fig. C.2).

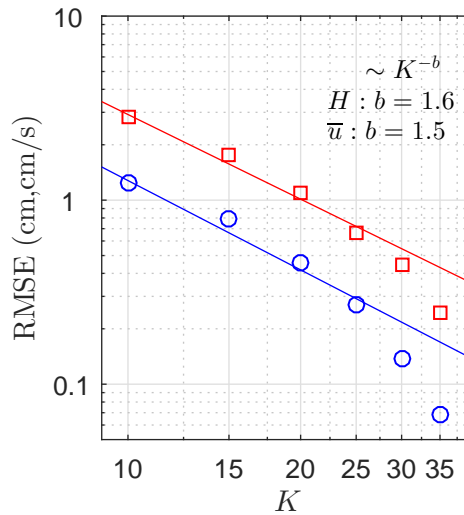


Figure C.1: RMSE of the wave height H (blue line with circle markers), and time-averaged cross-shore velocity \bar{u} (red line with square markers) for a varying number of vertical layers K versus a 40V40P reference simulation. The markers indicate the computed SI, and the line indicates the best fit for a K^{-b} power function. For all three parameters, the coefficient b is depicted in the top right corner of both panels.

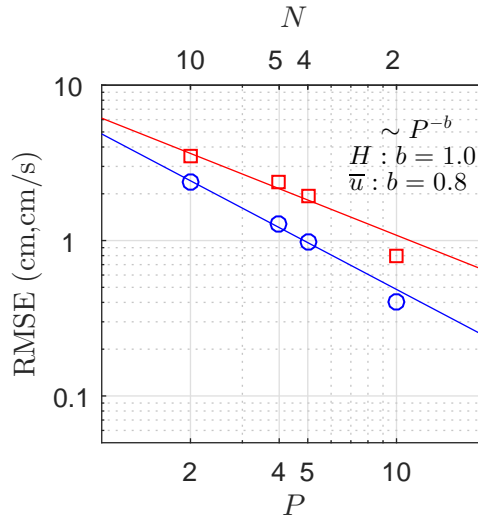


Figure C.2: RMSE of the wave height H (blue line with circle markers), and time-averaged cross-shore velocity \bar{u} (red line and square markers) for a varying number of pressure layers P with a constant number of 20 velocity layers versus a 20V20P baseline simulation. The markers indicate the computed error, and the line indicates the best fit for a P^{-b} power function. For all three parameters, the coefficient b is depicted in the top right corner of both panels. The top axis indicate the number of velocity layers per pressure layer $N(=K/P)$.

References

- Andrews, D.G., McIntyre, M.E., 1978. An exact theory of nonlinear waves on a Lagrangian-mean flow. *Journal of Fluid Mechanics* 89, 609.
- Bai, Y., Cheung, K.F., 2013. Dispersion and nonlinearity of multi-layer non-hydrostatic free-surface flow. *Journal of Fluid Mechanics* 726, 226–260.
- Boers, M., 1996. Simulation of a surf zone with a barred beach; report 1: Wave heights and wave breaking. Technical Report. Delft University of Technology.
- Bonneton, P., Barthelémy, E., Chazel, F., Cienfuegos, R., Lannes, D., Marche, F., Tissier, M., 2011. Recent advances in Serre-Green Naghdi modelling for wave transformation, breaking and runup processes. *European Journal of Mechanics - B/Fluids* 30, 589–597.
- Bradford, S.F., 2011. Nonhydrostatic Model for Surf Zone Simulation. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 137, 163–174.
- Bradford, S.F., 2014. Vertical grid design for more accurate and efficient surf zone simulation. *Coastal Engineering Journal* 56.
- Brown, S.A., Greaves, D.M., Magar, V., Conley, D.C., 2016. Evaluation of turbulence closure models under spilling and plunging breakers in the surf zone. *Coastal Engineering* 114, 177–193.
- Buckley, M., Lowe, R., Hansen, J., 2014. Evaluation of nearshore wave models in steep reef environments. *Ocean Dynamics* 64, 847–862.
- Chen, Q., Kirby, J.T., Dalrymple, R.A., Shi, F., Thornton, E.B., 2003. Boussinesq modeling of longshore currents. *Journal of Geophysical Research* 108.
- Chow, V.T., 1959. *Open-channel hydraulics*. McGraw-Hill.
- Clark, D.B., Elgar, S., Raubenheimer, B., 2012. Vorticity generation by short-crested wave breaking. *Geophysical Research Letters* 39.

683 Craik, A.D.D., Leibovich, S., 1976. A rational model for Langmuir circulations. *J. Fluid Mech* 73, 401–426.

684 Cui, H., Pietrzak, J.D., Stelling, G.S., 2012. Improved efficiency of a non-hydrostatic, unstructured grid, finite volume model.
685 *Ocean Modelling* 54-55, 55–67.

686 Dalrymple, R.A., MacMahan, J.H., Reniers, A.J.H.M., Nelko, V., 2011. Rip Currents. *Annual Review of Fluid Mechanics* 43,
687 551–581.

688 De Bakker, A.T.M., Tissier, M.F.S., Ruessink, B.G., 2016. Beach steepness effects on nonlinear infragravity-wave interactions:
689 A numerical study. *Journal of Geophysical Research: Oceans* 121, 554–570.

690 Derakhti, M., Kirby, J.T., Shi, F., Ma, G., 2016a. Wave breaking in the surf zone and deep-water in a non-hydrostatic RANS
691 model. Part 1: Organized wave motions. *Ocean Modelling* .

692 Derakhti, M., Kirby, J.T., Shi, F., Ma, G., 2016b. Wave breaking in the surf zone and deep water in a non-hydrostatic RANS
693 model. Part 2: Turbulence and mean circulation. *Ocean Modelling* .

694 Feddersen, F., Guza, R.T., 2003. Observations of nearshore circulation: Alongshore uniformity. *Journal of Geophysical Research*
695 108, 3006.

696 Gomes, E.R., Mulligan, R.P., Brodie, K.L., McNinch, J.E., 2016. Bathymetric control on the spatial distribution of wave
697 breaking in the surf zone of a natural beach. *Coastal Engineering* 116, 180–194.

698 Groeneweg, J., Klopman, G., 1998. Changes of the mean velocity profiles in the combined wavecurrent motion described in a
699 GLM formulation. *Journal of Fluid Mechanics* 370, S0022112098002018.

700 Haller, M.C., Dalrymple, R.A., Svendsen, I.A., 2002. Experimental study of nearshore dynamics on a barred beach with rip
701 channels. *Journal of Geophysical Research* 107, 3061.

702 Hansen, 1956. Theorie zur Errechnung des Wasserstandes und der Strömungen in Randmeeren nebst Anwendungen. *Tellus* 8,
703 289–300.

704 van Kan, J., 1986. A Second-Order Accurate Pressure-Correction Scheme for Viscous Incompressible Flow. *SIAM Journal on*
705 *Scientific and Statistical Computing* 7, 870–891.

706 Kennedy, A.B., Chen, Q., Kirby, J.T., Dalrymple, R.A., 2000. Boussinesq Modeling of Wave Transformation, Breaking, and
707 Runup. I: 1D. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 126, 39–47.

708 Kennedy, A.B., Thomas, D., 2004. Drifter measurements in a laboratory rip current. *Journal of Geophysical Research: Oceans*
709 109.

710 Kumar, N., Voulgaris, G., Warner, J.C., Olabarrieta, M., 2012. Implementation of the vortex force formalism in the coupled
711 ocean-atmosphere-wave-sediment transport (COAWST) modeling system for inner shelf and surf zone applications. *Ocean*
712 *Modelling* 47, 65–95.

713 Launder, B.E., Spalding, D.B., 1974. The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics*
714 *and Engineering* 3, 269–289.

715 Lin, P., Liu, P.L.F., 1998. A numerical study of breaking waves in the surf zone. *Journal of Fluid Mechanics* 359, 239–264.

716 Longuet-Higgins, M.S., Stewart, R.W., 1962. Radiation stress and mass transport in gravity waves, with application to surf
717 beats'. *Journal of Fluid Mechanics* 13, 481–504.

718 Longuet-Higgins, M.S., Stewart, R.W., 1964. Radiation stresses in water waves; a physical discussion, with applications. *Deep*
719 *Sea Research* 11, 529–562.

720 Ma, G., Shi, F., Kirby, J.T., 2012. Shock-capturing non-hydrostatic model for fully dispersive surface wave processes. *Ocean*
721 *Modelling* 43-44, 22–35.

722 MacMahan, J.H., Reniers, A.J.H.M., Thornton, E.B., Stanton, T.P., 2004. Surf zone eddies coupled with rip current morphol-
723 ogy. *Journal of Geophysical Research: Oceans* 109.

724 MacMahan, J.H., Thornton, E.B., Reniers, A.J.H.M., 2006. Rip current review. *Coastal Engineering* 53, 191–208.

725 MacMahan, J.H., Thornton, E.B., Stanton, T.P., Reniers, A.J.H.M., 2005. RIPEX: Observations of a rip current system.

726 Marine Geology 218, 113–134.

727 Madsen, P.A., Murray, R., Sørensen, O.R., 1991. A new form of the Boussinesq equations with improved linear dispersion
728 characteristics. *Coastal Engineering* 15, 371–388.

729 McCarroll, R.J., Castelle, B., Brander, R.W., Scott, T., 2015. Modelling rip current flow and bather escape strategies across a
730 transverse bar and rip channel morphology. *Geomorphology* 246, 502–518.

731 McWilliams, J.C., Restrepo, J.M., Lane, E.M., 2004. An asymptotic theory for the interaction of waves and currents in coastal
732 waters. *Journal of Fluid Mechanics* 511, 135–178.

733 Mellor, G., 2016. On theories dealing with the interaction of surface waves and ocean circulation. *Journal of Geophysical
734 Research: Oceans* 121, 4474–4486.

735 Nicolae Lerma, A., Pedreros, R., Robinet, A., Sénéchal, N., 2017. Simulating wave setup and runup during storm conditions
736 on a complex barred beach. *Coastal Engineering* 123, 29–41.

737 Özkan-Haller, H.T., Kirby, J.T., 1999. Nonlinear evolution of shear instabilities of the longshore current: A comparison of
738 observations and computations. *Journal of Geophysical Research* 104, 25953–25984.

739 Reniers, A.J.H.M., Battjes, J.A., 1997. A laboratory study of longshore currents over barred and non-barred beaches. *Coastal
740 Engineering* 30, 1–21.

741 Reniers, A.J.H.M., MacMahan, J.H., Thornton, E.B., Stanton, T.P., Henriquez, M., Brown, J.W., Brown, J.A., Gallagher, E.,
742 2009. Surf zone surface retention on a rip-channeled beach. *Journal of Geophysical Research* 114, C10010.

743 Rijnsdorp, D.P., Ruessink, G., Zijlema, M., 2015. Infragravity-wave dynamics in a barred coastal region, a numerical study.
744 *Journal of Geophysical Research: Oceans* 120, 4068–4089.

745 Rijnsdorp, D.P., Smit, P.B., Zijlema, M., 2014. Non-hydrostatic modelling of infragravity waves under laboratory conditions.
746 *Coastal Engineering* 85, 30–42.

747 Ruessink, B.G., Miles, J.R., Feddersen, F., Guza, R.T., Elgar, S., 2001. Modeling the alongshore current on barred beaches.
748 *Journal of Geophysical Research: Oceans* 106, 22451–22463.

749 Ruju, A., Lara, J.L., Losada, I.J., 2014. Numerical analysis of run-up oscillations under dissipative conditions. *Coastal
750 Engineering* 86, 45–56.

751 Shi, J., Shi, F., Kirby, J.T., Ma, G., Wu, G., Tong, C., Zheng, J., 2015. Pressure Decimation and Interpolation (PDI) method
752 for a baroclinic non-hydrostatic model. *Ocean Modelling* 96, 265–279.

753 Smagorinsky, J., 1963. General circulation experiments with the primitive equations. *Monthly Weather Review* 91, 99–164.

754 Smit, P., Janssen, T., Holthuijsen, L., Smith, J., 2014. Non-hydrostatic modeling of surf zone wave dynamics. *Coastal
755 Engineering* 83, 36–48.

756 Smit, P., Zijlema, M., Stelling, G., 2013. Depth-induced wave breaking in a non-hydrostatic, near-shore wave model. *Coastal
757 Engineering* 76, 1–16.

758 Stelling, G., Zijlema, M., 2003. An accurate and efficient finite-difference algorithm for non-hydrostatic free-surface flow with
759 application to wave propagation. *International Journal for Numerical Methods in Fluids* 43, 1–23.

760 Stelling, G.S., Duinmeijer, S.P.A., 2003. A staggered conservative scheme for every Froude number in rapidly varied shallow
761 water flows. *International Journal for Numerical Methods in Fluids* 43, 1329–1354.

762 Ting, F.C.K., Kirby, J.T., 1994. Observation of undertow and turbulence in a laboratory surf zone. *Coastal Engineering* 24,
763 51–80.

764 Tissier, M., Bonneton, P., Marche, F., Chazel, F., Lannes, D., 2012. A new approach to handle wave breaking in fully non-linear
765 Boussinesq models. *Coastal Engineering* 67, 54–66.

766 Uchiyama, Y., McWilliams, J.C., Shchepetkin, A.F., 2010. Wavecurrent interaction in an oceanic circulation model with a
767 vortex-force formalism: Application to the surf zone. *Ocean Modelling* 34, 16–35.

768 Van Reeuwijk, M., 2002. Efficient simulation of non-hydrostatic free-surface flow. Msc thesis. Delft University of Technology.

- 769 Visser, P.J., 1991. Laboratory measurements of uniform longshore currents. *Coastal Engineering* 15, 563–593.
- 770 Wei, G., Kirby, J.T., Grilli, S.T., Subramanya, R., 1995. A fully nonlinear Boussinesq model for surface waves. Part 1. Highly
771 nonlinear unsteady waves. *Journal of Fluid Mechanics* 294, 71.
- 772 Willmott, C.J., 1981. On the validation of models. *Physical Geography* 2, 184–194.
- 773 Yamazaki, Y., Kowalik, Z., Cheung, K.F., 2009. Depth-integrated, non-hydrostatic model for wave breaking and run-up.
774 *International Journal for Numerical Methods in Fluids* 61, 473–497.
- 775 Zijlema, M., Stelling, G., Smit, P., 2011. SWASH: An operational public domain code for simulating wave fields and rapidly
776 varied flows in coastal waters. *Coastal Engineering* 58, 992–1012.
- 777 Zijlema, M., Stelling, G.S., 2005. Further experiences with computing non-hydrostatic free-surface flows involving water waves.
778 *International Journal for Numerical Methods in Fluids* 48, 169–197.
- 779 Zijlema, M., Stelling, G.S., 2008. Efficient computation of surf zone waves using the nonlinear shallow water equations with
780 non-hydrostatic pressure. *Coastal Engineering* 55, 780–790.