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Fully well balanced entropy controlled DGSEM for shallow water flows: global flux quadrature and cell entropy correction

Yogiraj Mantri[b], Philipp Öffner[c], Mario Ricchiuto[a]

[a] *Inria, U. Bordeaux, CNRS, Bordeaux INP, IMB UMR 5251, 200 Avenue de la Vieille Tour, 33405 Talence cedex, France*
[b] *Vellore Institute of Technology, India*
[c] *Johannes Gutenberg-University, Mainz, Germany*

Abstract

In this paper we propose a high order DGSEM formulation for balance laws which embeds a general well balanced criterion agnostic of the exact steady state. The construction proposed exploits the idea of a global flux formulation to infer an *ad-hoc* quadrature strategy called here *global flux quadrature*. This quadrature approach allows to establish a one to one correspondence, for a given local set of data on a given stencil, between the discretization of a non-local integral operator, and the local steady differential problem. This equivalence is a discrete well balanced notion which allows to construct balanced schemes without explicit knowledge of the steady state, and in particular without the need of solving a local Cauchy problem. The use of Gauss-Lobatto DGSEM allows a natural connection to continuous collocation methods for integral equations. This allows to fully characterize the discrete steady solution with a superconvergence result. The notion of entropy control is also included in the construction via appropriately designed cell artificial viscosity corrections. The accuracy and equilibrium preservation of these corrections are characterized theoretically and numerically. In particular, thorough numerical benchmarking, we confirm all the theoretical expectations showing improvements in accuracy on steady states of one or more orders of magnitude, with a simple modification of a given DGSEM implementation. Robustness on more complex cases involving the propagation of sharp wave fronts is also proved. Preliminary tests on multidimensional problems shows improvements on the preservation of vortex like solutions with important error reductions, despite of the fact that no genuine 2D balancing criterion is embedded.

Keywords: balance laws, general steady equilibria, discontinuous Galerkin, spectral element, full well balancing, entropy conservation, Gauss-Lobatto integration
2010 MSC: 68Q25, 68R10, 68U05

1. Introduction

Hyperbolic balance laws play a fundamental role in various phenomena in natural science and engineering. A system of balance law is given by the following form

$$\partial_t U + \nabla \cdot F(U) = S(U; \varphi(x)), \tag{1}$$

with U denoted the array of conserved variables, F is the flux function, and S is the array of source terms. The numerical approximation of (1) is a very active research topic, with a lot of fundamental contributions developed for model systems as the Euler equations with gravity [19, 60, 62], or shallow water (SW) equations with various sources accounting for topography variations, friction and/or Coriolis forces [9, 20, 21, 46].

Email addresses: `yogiraj.mantri@vit.ac.in` (Yogiraj Mantri), `poeffner@uni-mainz.de` (Philipp Öffner), `mario.ricchiuto@inria.fr` (Mario Ricchiuto)

This paper focuses on the second system, including possibly all the effects mentioned.

The source term in (1) leads to an almost infinitely rich set of possible solutions., and in particular to a large number of different forms of steady equilibria between the source terms and the flux derivatives. When looking at physical applications involving small perturbations of such equilibria, the ability of a numerical method to preserve or at least to resolve with enhanced accuracy such steady states is an unanimously acclaimed design criterion. This is usually referred to full well balanced, or just well balanced depending on the authors. Even in one space dimension, the challenge of devising well balanced numerical approximations agnostic of the form of the steady state is still open. There is already quite a large literature on the subject, with several different approaches to managed this issue. To give some context to our work we will recall some, however note that by no means the references recalled provide a complete bibliography on the subject.

In cases in which the steady solution is characterized by the existence of a set of invariants which are uniform at steady state, say $V = V_0$, a first approach consists in devising discretizations consistent with an approximation of the modified form of (1) reading (in one space dimension)

$$\partial_t U + A_V(U, \varphi(x))\partial_x V = 0, \tag{2}$$

There is a variety of methods using some form of this idea either in terms of polynomial reconstruction/approximation, or of differencing/discrete divergence evaluation [13, 41, 55, 56, 64, 18]. Clearly this approach requires the a-priori knowledge of the form of V.

In the finite volume setting to construct well balanced schemes is obtained by enhancing the Riemann solvers providing the numerical fluxes with additional contact-like steady waves across which a cell integrated balance flux difference-source can be imposed. This method allows to retain very general equilibria, without any a-priori knowledge of their form [46, 9, 36].

A more general strategy, which can be implemented in any numerical setting (finite elements, finite difference, finite volume, etc) has been introduced in [14]. The main idea is to correct the discretized equations by means of a steady residual obtained by evaluating the discrete evolution operator in correspondence of a local discrete solution of the Cauchy problem $\partial_x F = S$. This is quite a flexible setting and has been applied to a variety of schemes and models, and with different strategies to obtain the solution of the (nonlinear) Cauchy problem [14, 35, 38, 34, 33]. The advantage of this approach is that it gives a clear definition of the notion of discrete well balanced scheme. The drawback is that the reference solution wrt which the scheme is balanced needs to be explicitly evaluated.

Lastly, we mention the family of so-called global flux methods, which have initially been introduced in [30], and applied first to design non-linear shock capturing methods for balance laws in [12, 24], and more recently as a path to obtain fully well balanced methods (see e.g. [19, 17, 45]). This approach relies on the observation that (up to a constant) the non-local operator

$$G(U, x) = F(U(x)) - \int_{x_0}^{x} S(U(s), \varphi(s))ds, \tag{3}$$

provides a natural invariant for the steady equations. So recasting (1) as

$$\partial_t U + \partial_x G(U, x) = 0, \tag{4}$$

provides a reasonable path to obtain fully well balanced schemes. As shown in [6] this approach also has relations with flux difference splitting and residual distribution methods consistently embedding the source integral in the splitting, and can thus be related to many classical versions of this idea [58, 8, 61, 50]. While providing very interesting results for many different models and solutions, one of the drawbacks of this approach is that, differently from the correction method with explicit evaluation of the solution of the steady Cauchy problem, there is so far no work on the precise characterisation of the meaning of the steady solution. For this reason in [11] the authors have chosen to combine the use of (4) with the correction approach to have a more precise definition of well balanced.

In addition to the above constraints, system (1) is usually endowed with an entropy pair $(\eta(U), F_\eta(U))$ verifying the additional constraint [22, 40]

$$\partial_t \eta + \nabla \cdot F_\eta(U) \overset{(\leq)}{=} S_\eta(U; \varphi(x)), \tag{5}$$

where $\eta = \eta(U)$ denotes the mathematical entropy (a convex function), $F_\eta(U)$ is the entropy flux, and $S_\eta(U; \varphi(x))$ represents dissipation/production term. In (5) the equality holds for smooth solutions, while weak admissible solutions are characterized by the inequality. A degree of control on the production of entropy is thus a desirable feature in numerical schemes. A numerical method is called entropy conservative if it fulfills the equality in (5) and entropy dissipative if it ensures the inequality for one specific entropy [59]. There exist many different techniques which have been applied to obtain entropy conservation (dissipation), e.g. artificial viscosity and correction techniques [1, 3, 4, 37], the summation-by-parts framework combined with entropy conservative (EC) two-points fluxes (flux differencing) [16, 26, 54] , or multi-point approaches via with combination of EC fluxes [28, 44]. Some of this work has been generalized to embed some notion of well balanced. Here, we refer to [27, 52, 63] for the SW literature.

In this paper we propose a high order DGSEM formulation for balance laws which embeds a fully discrete general well balanced criterion agnostic of the exact steady state. The construction proposed exploits the idea of a global flux formulation to infer an ad-hoc quadrature strategy called here global flux quadrature. This is then used to establish a one to one correspondence between the discretization of the local steady Cauchy problem, and a discretization of the non-local integral operator underlying the definition of the global flux. If the discretizations exploit the same data on the same stencil, the steady solution can be obtained indifferently by means of one of the two methods. This equivalence allows to construct balanced schemes without explicit knowledge of the steady state, and without the need of solving explicitly the local Cauchy problem. In this paper, we use a Gauss-Lobatto DGSEM setting which allows a natural connection to continuous collocation methods for integral equations. Thus we are able to fully characterize the discrete steady solution, and moreover provide a superconvergence result. The notion of entropy control is also included in the construction via appropriately designed cell artificial viscosity corrections following [1, 4, 2, 29, 49]. The accuracy and equilibrium preservation of these corrections are characterized theoretically and numerically.

The paper is organized as follows: The main notation for the shallow water equations are recalled in section §2, where we also recall several families of steady equilibria, depending on the terms included in the sources, and the definition of the mathematical entropy. In section §3 we recall the basics of the DGSEM approach underlying the paper, introducing some of its properties and the notation necessary for the remainder of the paper. The main idea of the paper is discussed in section §4 devoted to the explicit derivation of the global flux quadrature approach, and to the characterization of its properties for the particular case of the Gauss-Lobatto DGSEM method. The entropy correction is studied in section §5, while a simple multi-dimensional extension is proposed in section §6. Section §7 provides a thorough verification of the theoretical expectations, as well as some applications to challenging cases and to multi-dimensional problems showing the great potential of the approach proposed. Some conclusive remarks and future perspectives are drawn in section §8.

2. Shallow water equations

This paper focuses on the shallow water (SW) equations, widely used in geophysical applications. Despite their relative simplicity wrt other systems, they offer an excellent test bed for well balanced methods due to the variety of source terms they embed. The two dimensional form of the system reads

$$\partial_t \begin{pmatrix} h \\ hu \\ hv \end{pmatrix} + \partial_x \begin{pmatrix} hu \\ hu^2 + p(h) \\ huv \end{pmatrix} + \partial_y \begin{pmatrix} hv \\ huv \\ hv^2 + p(h) \end{pmatrix} = -h \begin{pmatrix} 0 \\ \partial_x \varphi + c_f u + \omega v \\ \partial_y \varphi + c_f v - \omega u \end{pmatrix}, \tag{6}$$

where h denotes the water depth, $\vec{\mathsf{v}} = (u, v)$ is the horizontal velocity, $p = gh^2/2$ is hydrostatic pressure with g the gravity acceleration, $\varphi = gb$ denotes the gravitational potential with bottom topography $b(x, y)$, $c_f = c_f(h, \vec{\mathsf{v}})$ is friction coefficient, and ω denotes the Coriolis coefficient. It is customary and useful also to introduce the additional variable $\zeta = h + b$, representing the altitude of the free surface and the total energy density $E = g\zeta + k$.
An interesting variant of (6) is the pseudo-one dimensional rotating SW system proposed in [15]

$$\partial_t \begin{pmatrix} h \\ hu \\ hv \end{pmatrix} + \partial_x \begin{pmatrix} hu \\ hu^2 + p(h) \\ huv \end{pmatrix} = -h \begin{pmatrix} 0 \\ \partial_x\varphi + c_f u + \omega v \\ -\omega u \end{pmatrix}. \tag{7}$$

This is a one dimensional system which has all the richness of the multi-dimensional one in terms of sources and steady states, as we will shortly discuss.

The shallow water equations are endowed with a convex entropy pair (η, F_η) given by

$$\eta = p(h) + hk\,, \quad F_\eta = hu\,(gh + k) \tag{8}$$

with $k = u^2/2 + v^2/2$ the kinetic energy. In the case of (7) the associated balance law reads

$$\partial_t\eta + \partial_x F_\eta \overset{(\leq)}{=} -hu\partial_x\varphi - \underbrace{c_f hu^2}_{\mathcal{D}_f} \tag{9}$$

with $\mathcal{D}_f \geq 0$ implicitly defined above representing the dissipation due to friction. For time independent potentials, The form of the entropy production term allows to introduce a total entropy pair $(\eta_\varphi, F_{\eta_\varphi})$ which for (7) is given via

$$\eta_\varphi = p(h) + hk + h\varphi\,, \quad F_{\eta_\varphi} = hu\,(gh + k + \varphi) = hu\,(g\zeta + k) \tag{10}$$

which satisfies the simpler balance

$$\partial_t\eta_\varphi + \partial_x F_{\eta_\varphi} \overset{(\leq)}{=} -\mathcal{D}_f \leq 0 \tag{11}$$

which reduces to a special conservation law for smooth solutions and in absence of friction.

2.1. Incomplete zoology of steady equilibria

We recall here some of the classical equilibria of system (7) and (6) which will be used in the numerical validation. We limit the description to five types of solutions, involving three combinations of sources, but many more can be imagined.

Frictionless one dimensional equilibria. This is the most classical case considered. It involves two families of steady equilibria. For smooth solutions, the most general form of these equilibria is defined by the relations to obtain the invariants

$$hu(x) = q_0\,, \;\; g\zeta(x) + k(x) = E_0, \tag{12}$$

with q_0 and E_0 given values of the volume flux and total energy density. Of course this is also a special solution of (6) if $v = 0$, otherwise a similar one can be defined in the frame of reference with the x axis aligned to the velocity. The moving equilibrium (12) can be determined analytically by solving a cubic equation, given q_0 and E_0 and the bathymetry $b(x)$ (see e.g. [48]).

A very well known particular case is the so-called *lake at rest* state defined by

$$u(x) = 0\,, \;\; \zeta(x) = \zeta_0 \tag{13}$$

This is the most widely used analytical state to construct well balanced methods, and first historically studied [8].

Note that at the analytical level, for smooth cases anyways, we can replace (12) by a global flux definition reading:

$$hu = q_0\,, \quad Q := hu^2 + p(h) + \int_{x_0}^{x} gh\partial_x b = Q_0 \tag{14}$$

For smooth cases the two definitions coincide.

Frictionless pseudo-one dimensional equilibria with Coriolis effects. This is a more general case of the previous one, including transversal velocity and Coriolis effects. It also involved two families of solutions, depending on whether $u = 0$ or not. When $u = 0$ we have solutions which are defined by

$$hu = 0\,, \quad \zeta = \zeta_0 - \frac{1}{g}\int_{x_0}^{x} \omega v(s) ds \tag{15}$$

In this case the transverse velocity v is essentially a free parameter. This is some sort of generalized analytical lake at rest state, accounting for movement in directions transversal to those of the main bathymetric variations.

For the moving case, combining the first and last equation in (7), with the steady limit of (11) one can show that verify, provided $u \neq 0$

$$hu = q_0\,, \quad g\zeta + k = E_0\,, \quad v - \omega x = v_0 \tag{16}$$

Equation (16) needs to be solved analytically given values of q_0, E_0 and v_0, and the bathymetry $b(x)$. Particular smooth solutions can also be obtained by defining $b(x)$ for given variations of h and u. An example will be given in the results section. As before, for smooth cases we can equivalently provide a global flux version of (16), which reads

$$hu = q_0\,, \quad Q := hu^2 + p(h) + \int_{x_0}^{x} (gh\partial_x b + \omega hv) = Q_0\,, \quad V := huv - \int_{x_0}^{x} \omega hu = V_0 \tag{17}$$

For smooth cases the solutions defined by (17) or (16) are equivalent.

One dimensional equilibria with friction. This is a moving equilibrium with friction and slope variations but no Coriolis force. It cannot in general be defined analytically. It is characterized by the relations ($v = 0$ since it is one dimensional)

$$hu = q_0\,, \quad g\zeta + k = E_0 - \int_{x_0}^{x} c_f u\, ds \tag{18}$$

A trivial particular case for it is $b'(x) = \xi_0$ =const, which admits as exact solution a special state $h = h_0$ and $u = u_0$ verifying the algebraic relations

$$h_0 u_0 = q_0\,, \quad c_f(h_0, u_0)u_0 = -g\xi_0 \tag{19}$$

These can be solved for given values of q_0 and of the slope ξ_0, and the friction law (see e.g. [56]). More general examples obtained integrating (18) are proposed e.g. in [46].

The global flux definition of these states differs a little from (18) and is given by

$$hu = q_0\,, \quad Q := hu^2 + p(h) + \int_{x_0}^{x} (gh\partial_x b + c_f(h,u)hu) = Q_0 \tag{20}$$

3. dG-SEM discretization: main notation and setting

3.1. Main notation

We consider a tessellation of the d-dimensional spatial domain Ω in non overlapping elements K, obtained as tensor products of 1d elements. In other words $K = K_x \times K_y \times K_z$, with K_j a segment of width h in the direction j (cf figure 1). As it is classical, we consider in each direction a linear map $x(\xi) : K_x \mapsto [0,1]$, and similarly in the other directions. In the multidimensional case we will denote by $\{\xi_j\}_{j=1,d}$ the reference coordinates. On each 1d reference element we consider a standard Gauss-Lobatto (GL) collocated finite element approximation spanned by $\{\phi_i(\xi)\}_{i=0,p}$ degree p one dimensional Lagrange basis functions corresponding to the $p+1$ GL points $\{\xi_i\}_{i=0,p}$. For a given function u we thus set in 1d

$$u_{\mathrm{h}} := \sum_{j=0}^{p} \phi_j(x(\xi))u_j \tag{21}$$

while in 2D we have the usual tensor product representation

$$u_{\mathrm{h}} := \sum_{i,i=0}^{p} \phi_i(y(\zeta))\phi_j(x(\xi))u_{ij} \tag{22}$$

interpolating the solution on a grid of Gauss-Lobatto points $\{\xi_{ij}\}_{i,j=0,p}$ as in figure 1, with $\xi_{ij} = \xi_i\zeta_j$.

The temporal domain $[0,T]$ is classically discretized by temporal slabs $[t^n, t^{n+1}]$, with $\Delta t^n = t^{n+1} - t^n$, and $\Delta t = \min_n \Delta t^n$. The superscript ^{n} will be dropped when no confusion is possible.

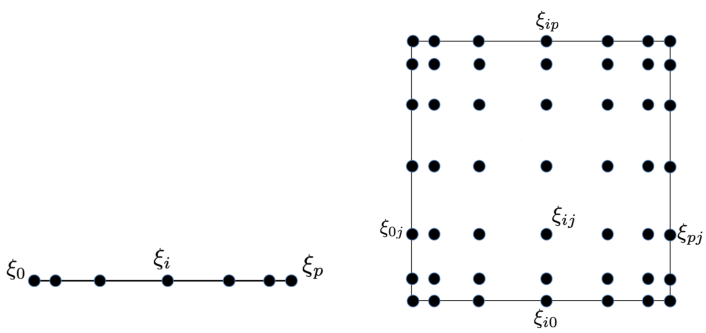


Figure 1: One- and two-dimensional Gauss-Lobatto approximation.

3.2. DGSEM for 1d conservation laws

We consider for the moment the approximation of solutions of

$$\partial_t U + \partial_x F(U) = 0 \tag{23}$$

On an generic element K, we start from the standard dG variational form

$$|K| \int_0^1 \varphi_i(\xi)\partial_t U_{\mathrm{h}} - \int_0^1 \partial_\xi \varphi_i(\xi) F_{\mathrm{h}} + (\varphi_i \hat{F}_{\mathrm{h}}(U_{\mathrm{h}}, U_{\mathrm{h}}^+))_{\xi=1} - (\varphi_i \hat{F}_{\mathrm{h}}(U_{\mathrm{h}}, U_{\mathrm{h}}^+))_{\xi=0} = 0. \tag{24}$$

Following the classical spectral element approach, the quadrature used is the one associated to the GL nodes also used for the nodal approximation. The resulting semi-discrete equations can be written in matrix form as [43, 42]

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} - \widetilde{D}_x^T \mathbf{F} + \mathcal{M}^{-1}\mathcal{B}\widehat{\mathbf{F}} = 0, \tag{25}$$

where $\mathcal{M} = \mathrm{diag}(\{w_i\}_{i=0,p})$ with $w_i = \mathrm{h}\phi_i(\xi_i)$ the Gauss-Lobatto quadrature weights, $\widetilde{D}_x = \mathcal{M} D_x \mathcal{M}^{-1}$ with $(D_x)_{ij} = \partial_\xi \phi_i(\xi_j)$, and with $\mathcal{B} = \mathrm{diag}(-1, \ldots, 1)$ the matrix sampling boundary values. The arrays $\mathbf{U}$, $\mathbf{F}$, $\widehat{\mathbf{F}}$ contain nodal values of the solution/flux/num. fluxes.

3.3. SBP, strong form, and residual distribution

The nodal DGSEM method is known to enjoy a summation by parts property which allows to recast the semi-discrete equations (25) as [43, 31, 32]

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} + \widetilde{D}_x \mathbf{F} + \mathcal{M}^{-1}\mathcal{B}(\widehat{\mathbf{F}} - \mathbf{F}) = 0. \tag{26}$$

In other words, we can recast the DGSEM semi-discrete equations using residual or fluctuation distribution form reading

$$w_i \frac{dU_i}{dt} + \Phi_i + \Psi_i^L + \Psi_i^R = 0 \tag{27}$$

with cell and face residuals arising for the GL quadrature of

$$\begin{gathered} \Phi_i := \int_K \phi_i \partial_x F_\mathrm{h} \\ \Psi_i^L := [\phi_i(\hat{F}_\mathrm{h} - F_\mathrm{h})]_{\xi=0}\ , \quad \Psi_i^R := [\phi_i(\hat{F}_\mathrm{h} - F_\mathrm{h})]_{\xi=1} \end{gathered} \tag{28}$$

Consistency and accuracy conditions here can be characterized in terms of the properties of the split residuals, as discussed in thorough detail in [5, 6]. More importantly, from the point of view of preservation of steady states, this form is very interesting. Indeed, due to the nodal Gauss-Lobatto approximation, continuous solutions with the constant flux $F_\mathrm{h} = F_0$ are exact discrete steady states.

Note that for general numerical fluxes of the form

$$\hat{F}_\mathrm{h} = \alpha F_\mathrm{h}^+ + (1-\alpha) F_\mathrm{h} + \mathcal{D}(U_\mathrm{h}^+ - U_\mathrm{h}) \tag{29}$$

where α can be a scalar or a matrix weight, and $\mathcal{D}$ a positive definite matrix, the DGSEM semi-discrete equation (25) can also be written as

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} + \widetilde{D}_x \mathbf{F} + \mathcal{M}^{-1}\mathcal{B}(\alpha [\![\mathbf{F}]\!]) + \mathcal{M}^{-1}\mathcal{B}(\mathcal{D}[\![\mathbf{U}]\!]) = 0. \tag{30}$$

having introduced the interface jumps $[\![\cdot]\!] = (\cdot)^+ - (\cdot)^-$.

4. Discrete full well balancing and global flux quadrature

We now consider the numerical approximation of a (hyperbolic) system of balance laws

$$\partial_t U + \partial_x F(U) = S(U; \varphi(x)) \tag{31}$$

A steady states $U^*(x)$ of (31) can be described by the non-linear ODE

$$F'(U^*)(x) = S(U^*; \varphi(x)) \tag{32}$$

At the continuous level, (32) can be equivalently expressed as a non-local integral equation

$$F(U^*)(x) = F_0 + \int_{x_0}^{x} S(U^*; \varphi)(s) \tag{33}$$

for a given initial integration point x_0, for example the left-end of the domain, and with appropriate definition of the initial state F_0. Integral relations as (33) are the most general way of defining reference solutions, as shown by some of the definitions of section §2.1. At the discrete level, however, given a high order strategy to discretize the local equation (32), it is in general not true that the discrete equations for all point (or average) values correspond to a discretization of (33). We thus give the following definition.

Definition 1 (Discrete fully well balanced)**.** *A scheme discretizing* (1) *in one space dimension is said to embed a discrete full well balanced property if the steady discrete solution for all the local point (or averaged) values can be equivalently obtained as from the steady limit of the scheme itself, or from a direct discretization of the non-local equation* (33)*. A discrete well balanced scheme is exactly well balanced wrt the discrete solution defined by the discretized integral equation.*

The last definition admits that given a set of point/averaged values, we are able to construct with the same data both a local approximation of the balance law, reducing to a discretization of (32) at steady state, as well as a consistent discretization of (33), and that the two are equivalent at steady state.

Fully well balanced schemes verifying this definition have been proposed e.g. in [35, 38]. In this works the authors exploit the corrected approach recalled in the introduction, initially proposed in [14], combined with a collocation method to formulate the discrete integral equations. This approach thus requires the explicit computation of U^*. In this work we proceed differently, and show that for a specific approximation of the integral of the source arising in the finite element statement the above equivalence holds. This provides an approach which does not required the evaluation of U^*.

We start from the global formulation in which we replace the source by the derivative of an unknown flux R in the DG variational form

$$\int_K \phi_i S = \int_K \phi_i \partial_x R \tag{34}$$

We then evaluate R from some approximation of the integral relation

$$R(U;\varphi(x)) = r_0 + \int_{x_0}^{x} S(U;\varphi)(s) \tag{35}$$

where x_0 denotes the left end of the spatial domain, and r_0 the left value of the source flux. Note that this value is essentially an integration constant not affecting the solution. It is set to $r_0 = 0$ in the following. Introducing the global flux $G = F - R$, we then simply apply the standard DGSEM approach to the global flux form of (31)

$$\partial_t U + \partial_x G(U;\varphi(x)) = 0 \tag{36}$$

This is obviously a good setting to obtain consistency with (33), since at steady state $F = R$. The details of this consistency depend on how $R(U;\varphi(x))$ is evaluated at mesh nodes, or otherwise said on how (35) is approximated. In the DGSEM setting, the most natural approach is to introduce discrete elemental approximations in the local polynomial space for all the quantities involved, and in particular for S_h, R_h, and φ_h, as described in section §3. Then, in each element K we compute the nodal values $\{R_i\}_{i=0,p}$ as

1. Set $R_0 = r^-$
2. For $i = 1, p$ set $R_i = R_{i-1} - \int_{x_{i-1}}^{x_i} S_\mathrm{h}(x)$

with r^- a local integration constant to be defined.

Remark 2 (Nodal continuity for the data)**.** *For a given $\varphi(x)$ the discrete approximation φ_h is built in this work by means of standard nodal interpolation. On Gauss-Lobatto points this interpolation leads an approximation with* no jumps at element boundaries *despite the discontinuous approximation of the solution. We do not account for explicit discontinuities of $\varphi(x)$ in this work.*

Using the SEM expansion for S_h we can recast the the previous expressions in a compact form by introducing the following $(p+1)\times(p+1)$ integration matrix $\mathcal{I}$

$$\mathcal{I}_{jk} := \int_0^{\xi_j} \phi_k(\xi)\, d\xi. \tag{37}$$

With the previous definition we now have

$$\mathbf{R} = \mathbf{R}^- - \mathrm{h}\,\mathcal{I}\mathbf{S} \tag{38}$$

where now $\mathbf{R}$ is the array of nodal values of R, $\mathbf{R}^-$ has entries all equal to r^-, and $\mathbf{S}$ contains the nodal values of the source. The semi-discrete global flux DGSEM equations can now be readily written in matrix form (cf. (26)) as

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} + \widetilde{D}_x\mathbf{G} + \mathcal{M}^{-1}\mathcal{B}(\widehat{\mathbf{G}} - \mathbf{G}) = 0\,, \tag{39}$$

with $\mathbf{G} = \mathbf{F} - \mathbf{R}$, or equivalently in the fluctuation form (27) by setting

$$\Phi_i := \int_K \phi_i \partial_x G_\mathrm{h}\ , \quad \begin{cases} \Psi_i^L := [\phi_i(\hat{G}_\mathrm{h} - G_\mathrm{h})]_{\xi=0}, \\ \Psi_i^R := [\phi_i(\hat{G}_\mathrm{h} - G_\mathrm{h})]_{\xi=1}. \end{cases} \tag{40}$$

To proceed further we use an explicit form of the numerical fluxes similar to (29), namely

$$\hat{G}_\mathrm{h} = \alpha G_\mathrm{h}^+ + (1-\alpha)G_\mathrm{h} + \mathcal{D}(U_\mathrm{h}^+ - U_\mathrm{h}) \tag{41}$$

Making explicit use of (38) and of (29) we can write global flux DGSEM as

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} + \widetilde{D}_x\mathbf{F} + \mathcal{M}^{-1}\mathcal{B}(\alpha[\![\mathbf{F}]\!]) + \mathcal{M}^{-1}\mathcal{B}(\mathcal{D}[\![\mathbf{U}]\!]) = \mathrm{h}\,\widetilde{D}_x\mathcal{I}\mathbf{S} + \mathcal{M}^{-1}\mathcal{B}(\alpha[\![\mathbf{R}]\!]) \tag{42}$$

The last term only involves jumps in the source flux, depending on the definition of the local integration constant r^-. Consistently with Remark 4.2, in this work we have not accounted for this jump. This is equivalent to the choice $r^- = (R_p)^{K^-}$, the last value of the left neighbouring element. This leads to the following *DGSEM formulation with global flux quadrature of the source*:

$$\frac{\mathrm{d}\mathbf{U}}{\mathrm{d}t} + \widetilde{D}_x\mathbf{F} + \mathcal{M}^{-1}\mathcal{B}(\alpha[\![\mathbf{F}]\!]) + \mathcal{M}^{-1}\mathcal{B}(\mathcal{D}[\![\mathbf{U}]\!]) = \mathrm{h}\,\widetilde{D}_x\mathcal{I}\mathbf{S} \tag{43}$$

The only remaining ingredient is the definition of the nodal value of the source.

Remark 3 (Global flux quadrature)**.** *The above formula shows that with our choices the global flux DGSEM approach boils down to a very specific quadrature of the source whose weights are provided for each nodal degree of freedom by the integration tableau $\mathcal{I}$. For this reason we find it more appropriate to speak of* global flux quadrature *corresponding for a given function f to the discrete approximation*

$$\int_K \phi_i f_h\, dx = h\,(\widetilde{D}_x\mathcal{I}\mathbf{f})_i \tag{44}$$

rather than global flux method. Note that this view is note only philosophical. The formula above shows that the global flux quadrature is actually a fully local method. This full locality may be broken had we retained jumps of the source flux R, in which case its assembly could be required explicitly at each time step. The management of discontinuous data representations, and strategies to retain this locality are the focus of current work.

4.1. Discrete equilibria and connection with collocation methods

For smooth solutions, the DGSEM formulation with global flux quadrature of the source has a neat connection with continuous collocation methods for ODEs. Summarised by the following proposition.

Proposition 4 (Exact jump free discrete steady states)**.** *Let U^* denote the solution of the steady discrete Gauss-Lobatto DGSEM equations* (43) *with global flux quadrature and no jumps at element interfaces. The nodal values of U^* can be equivalently obtained upon integration of the nonlinear ODE* (32) *with the fully implicit continuous collocation RK-LobattoIIIA method with initial condition U_0 satisfying $F(U_0) = F_0$, with F_0 given.*

Proof. The proof is trivially obtained by noticing that continuous steady states satisfy in each element $F_i = R_i \; \forall\, i \in \{0, p\}$, and that the entries of the matrix $\mathcal{I}$ associated to the Gauss-Lobatto points/bases is by definition the integration tableau of the $p+1$ stages fully implicit RK-LobattoIIIA ODE solver [51]. □

The proposition states simply that at steady state the DGSEM method with global flux quadrature provides a direct approximation of (33) in which S is replaced by the piecewise Lagrange polynomial through the Gauss-Lobatto interpolation points. As a corollary of the last proposition we have the following property, direct consequence of the properties of the LobattoIIIA method [51, 39].

Corollary 5 (Super-convergence at collocation points)**.** *Let U^* denote the solution of the steady discrete Gauss-Lobatto DGSEM equations* (43) *with global flux quadrature and no jumps at element interfaces. The element endpoint values of U^* are approximations of order $2p$ to the exact steady solution, while the internal values have accuracy h^{p+2}.*

Proof. See [51], as well as Theorem 7.10 in [39]. □

The use of the global flux quadrature allows to make a direct link between the DGSEM method and continuous collocation RK methods applied to the ODE, or equivalently Gauss-Lobatto integration directly applied to (33) by sub-intervals of size h. As already mentioned, other methods exploit collocation ODE integrators to construct a reference steady solution agnostic of the type of source term, as e.g. [35, 38]. Differently from these approaches however, the one proposed here does not required necessarily the evaluation of the exact discrete solution, which is somehow implicit in the form of the scheme. The drawback is that there is no flexibility in the choice of the collocation method which is naturally associated to the finite element space. In particular, for Gauss-Lobatto elements it is characterized by corollary 4.5: h^{2p} for element end-points, and h^{p+2} for internal degrees of freedom. Note that this super-convergece is agnostic of the form of the source term.

4.2. Well balanced nodal source for the shallow water equations

The DGSEM approach with global flux quadrature described in the previous section requires the definition of the nodal values of the source. For the quasi-1D shallow water system (7), if $\mathbf{u} = (u, v)$ denotes the velocity vector, and $\mathbf{u}^\perp = (v, -u)$ its orthogonal, both the friction term $c_f u$, and the Coriolis terms $\omega \mathbf{u}^\perp$ can be easily evaluated nodally. The tricky part is how to define the value of the term $h\partial_x \varphi = gh\partial_x b$ related to the potential effects due to bathymetric variations.

In this work we have used two approaches. The first is a straightforward analytical evaluation of $\partial_x b(x)$:

$$S_l = -h_l \begin{pmatrix} 0 \\ g\partial_x b(x_l) + c_f u_l + \omega v_l \\ -\omega u_l \end{pmatrix} \tag{45}$$

To be exactly well balanced for the hydrostatic equilibrium, we adapt an idea proposed in [65]. Denoting by ζ the free surface level $\zeta = h + b$, we set

$$S_l = -\begin{pmatrix} 0 \\ g\zeta_l \partial_x b_{\mathrm{h}}(x_l) - \partial_x p_{\mathrm{h}}(b)(x_l) + c_f h_l u_l + \omega h_l v_l \\ -\omega h_l u_l \end{pmatrix} \tag{46}$$

where now b_{h} is the finite element expansion built using the nodal values of the bathymetry, and similarly for $p_{\mathrm{h}}(b) = g(b^2/2)_{\mathrm{h}}$. With this definition we can prove the following simple result.

Proposition 6 (Exact well balanced for lake at rest)**.** *If the interpolation polynomial b_h is continuous, then the DGSEM formulation with global flux quadrature* (43)*, and with nodal source given by* (46) *is exactly well balanced for lake at rest states $\zeta = \zeta^* = const$, and $\mathbf{u} = 0$.*

Proof. To obtain the result we can analyze term by term scheme (43) to show that under the hypotheses made $dU/dt = 0$. First of all note that since $b_{\rm h}$ is continuous, and so is ζ^* which is constant, this means that the jumps of h vanish for this particular state. Since also $h\mathbf{u} = 0$ is constant, then we have $[\![\mathbf{U}]\!] = 0$ and so $[\![\mathbf{F}]\!] = 0$ at all element boundaries. The remaining term can be written as

$$\frac{d\mathbf{U}}{dt} = -\widetilde{D}_x(\mathbf{F} - \mathbf{F}_0 - {\rm h}\mathcal{I}\mathbf{S})$$

with here $\mathbf{F}_0$ the array containing the values $F(U_0)$ with U_0 the value of the unknowns in the first Gauss-Lobatto point within the element. Because of the hypotheses made, only the hydrostatic terms remain in $\mathbf{F}$ and $\mathbf{S}$. For the source, we can write

$$\begin{aligned}({\rm h}\mathcal{I}\mathbf{S})_i = &\int_{x_0}^{x_i} g\zeta^* \sum_{l=0,p} \phi_l(x_l)\partial_x b_{\rm h}(x_l) - \int_{x_0}^{x_i} g \sum_{l=0,p} \phi_l(x_l)\partial_x\partial_x p_{\rm h}(b)(x_l)\\ &\int_{x_0}^{x_i} g\zeta^* \sum_{l=0,p} \partial_x\phi_l(x_l) b_l - \int_{x_0}^{x_i} g \sum_{l=0,p} \partial_x\phi_l(x_l) p_{\rm h}(b_l)\end{aligned}$$

having used the approximation identity $\partial_x f_{\rm h} = \sum_{l=0,p} \partial_x\phi_l(x) f_l = \sum_{l=0,p} \phi_l(x)\partial_x f_{\rm h}(x_l)$. As a consequence we get

$$({\rm h}\mathcal{I}\mathbf{S})_i = g\zeta^* \int_{x_0}^{x_i} \partial_x b_{\rm h} - \int_{x_0}^{x_i} \partial_x p_{\rm h}(b) = g\zeta^*(b_i - b_0) - g\left(\frac{b_i^2}{2} - \frac{b_0^2}{2}\right)$$

Using again the fact that $b_i + h_i = \zeta^* = b_0 + h_0$ we deduce $({\rm h}\mathcal{I}\mathbf{S})_i = p_{\rm h}(h_i) - p_{\rm h}(h_0)$, which leads to $\mathbf{F} - \mathbf{F}_0 - {\rm h}\mathcal{I}\mathbf{S} = 0$, and thus the result. □

This second approach will be referred to in the results section as *modified global flux quadrature*, begin obtained with a modification of the nodal source terms allowing to guarantee the exact preservation of lake at rest states.

5. Entropy control via cell corrections: flux vs energy conservation

We consider now the issue of the compatibility between the consistency with constant global flux, underpinning notion of the previous section, and the consistency with a given pair entropy/entropy flux. In absence of friction, smooth solutions of the quasi one dimensional shallow water equations (7) embed an additional conservation for the total entropy η_φ with flux F_{η_φ} defined in (10). Defining the total energy density $E = g\zeta + k$, we can readily show that analytical steady states of (7) (without friction) are characterized by the invariants

$$\begin{aligned} hu &= q_0\\ E &= E_0\\ v - \omega x &= v_0\end{aligned} \tag{47}$$

These three invariants are compatible with both the steady equations and a constant distribution of the entropy flux F_{η_φ}. The same equations, in global flux form provide a steady state described by the invariance of the global flux components:

$$\begin{aligned} hu &= q_0\\ hu^2 + p + r_u &= Q_0\\ huv + r_v &= V_0\end{aligned} \tag{48}$$

having denoted by r_u and r_v the components of the source flux arising from the second and third equations. These three relations are by construction compatible with the discrete full well balanced property, and the related super-convergence property of Corollary 4.5. At the continuous level all is fine.

At the discrete level, however, the global flux quadrature is exactly consistent only with (48), and only within its error with the first. In other words, when looking at the preservation of discrete steady states, depending on the data initialization strategy chosen we may two different situations.

1. We use exact analytical expressions, satisfying (47), to initialize the data. In this case we may use the analytical expressions for the entropy fluxes to construct entropy conservative/dissipative schemes. In this case, scheme (43) will still be discretely fully well balanced, within the conditions of Corollary 4.5;
2. We choose to initialize with the global flux solution U^* of Proposition 4.4. In this case, the resulting accuracy will still be the one of Corollary 4.5, but scheme (43) would be exactly well balanced wrt this initial steady state. For this initialization however using the standard analytical expressions for the entropy fluxes would break this property.

The objective of the following subsections is to propose a modification of the schemes which allows to solve this dichotomy, and provide a degree of control on the entropy production of the method independently on the initialization procedure.

5.1. Cell entropy correction method

There exist several well established techniques to embed dG-FEM methods with degree of control of the entropy evolution. We refer to the introduction for a short overview. The approach used here is based on the idea of [1, 4] to introduce local corrections in the form of a SPD bilinear term with a free coefficient allowing to impose a desired constraint in terms of entropy balance.

To briefly describe the method, we start from the frictionless case. We consider the fluctuation form (27) (with (40)) to which we add the correction term:

$$w_i \frac{dU_i}{dt} + \Phi_i + \Psi_i^{\mathrm{L}} + \Psi_i^{\mathrm{R}} + \alpha_K \mathcal{D}_i^K = 0 \ , \quad \mathcal{D}_i^K := \int_K \partial_x \phi_i \, A_0 \partial_x W_{\mathrm{h}} \tag{49}$$

where W is the appropriate set of entropy variables such that

$$\partial \eta = W^t \partial U \tag{50}$$

and A_0 is the inverse of the Hessian $A_0^{-1} = \partial_{UU}\eta = \partial W / \partial U$. To obtain the entropy balance we need only to dot (49) by W_i^t and sum over $i = \{0, p\}$. This readily leads to the cell entropy evolution equation

$$|K| \frac{d\bar{\eta}_K}{dt} + \Phi_\eta^K + \alpha_K \|\partial_x W\|^2_{L^2_{A_0}(K)} = 0 \tag{51}$$

having introduced the average cell entropy $\bar{\eta}_K$, and cell entropy production of the scheme Φ_η^K:

$$\begin{aligned} \bar{\eta}_K &:= \frac{1}{|K|} \int_K \eta_{\mathrm{h}} \\ \Phi_\eta^K &:= \sum_{i=0,p} W_i^t \left(\Phi_i + \Psi_i^{\mathrm{L}} + \Psi_i^{\mathrm{R}} \right) \end{aligned} \tag{52}$$

From (51) we can see that, unless the solution is locally constant, the entropy production associated to the correction term multiplied by α_K is strictly positive. This allows to use the free parameter to gain direct control on entropy production. Let $\hat{F}_\eta$ denote a consistent numerical entropy flux, and set

$$\Psi_\eta^K := \oint_{\partial K} \hat{F}_\eta \tag{53}$$

reducing in 1D to

$$\Psi_\eta^K = (\hat{F}_\eta)_K^R - (\hat{F}_\eta)_K^L \tag{54}$$

Also, following [5, 6], for a given smooth exact solution $U^e(x,t)$, and given smooth compactly supported test function $v(x,t)$ define the consistency error

$$\mathcal{E} := \sum_K \sum_{i\in K} v_i \left\{ w_i \frac{dU_i^e}{dt} + \Phi_i(U_{\rm h}^e) + \Psi_i^R(U_{\rm h}^e) + \Psi_i^L(U_{\rm h}^e) + \alpha_K(U_{\rm h}^e)\mathcal{D}_i^K(U_{\rm h}^e) \right\} \tag{55}$$

The proposition below characterizes the construction used here, following [1, 4].

Proposition 7 (Entropy correction: local/global entropy balance, consistency)**.** *The corrected DGSEM scheme obtained from* (49) *setting*

$$\alpha_K = \frac{\Psi_\eta^K - \Phi_\eta^K}{\|\partial_x W_h\|^2_{L^2_{A_0}(K)}} \tag{56}$$

verifies the elemental entropy balance

$$|K|\frac{d\bar{\eta}_K}{dt} + \Psi_\eta^K = 0 \tag{57}$$

and, for homogeneous or periodic boundary conditions, the global entropy conservation equation

$$\sum_K |K|\frac{d\bar{\eta}_K}{dt} = 0 \tag{58}$$

Moreover, the scheme verifies a consistency estimate of the type $|\mathcal{E}| = \mathcal{O}(h^{p+1})$.

Proof. Properties (56) and (57) are a straightforward consequence of (55). Concerning the consistency estimate, the proof follows e.g. Section 3.2 in [5] and is reported in appendix. □

The above proposition shows that the correction approach allows to readily recover a local entropy balance law with a simple choice of the scalar coefficient α_K. Moreover, the correction does not spoil the formal consistency of the scheme which remains of order h^{p+1}. However, as discussed in the beginning of section §5, the well balanced properties of the corrected scheme depend on the properties of the numerical entropy flux $\hat{F}_\eta$.

Remark 8 (Friction and dissipation)**.** *In presence of friction (or other dissipative relaxation terms), the above construction needs to be modified by including the effects of these terms in the definition of the entropy balance* Ψ_η^K *which becomes*

$$\Psi_\eta^K := \oint_{\partial K} \hat{F}_\eta + \mathcal{D}_f \tag{59}$$

with $\mathcal{D}_f$ *a consistent approximation of the dissipation*

$$\mathcal{D}_f \approx 2\int_K h c_f k \geq 0 \tag{60}$$

with k *the kinetic energy. In this case, proposition 5.1 still holds, but* (58) *becomes*

$$\sum_K |K|\frac{d\bar{\eta}_K}{dt} = -\sum_K \mathcal{D}_f \leq 0 \tag{61}$$

5.2. Entropy fluxes compatible with global flux quadrature

We propose here two possible definitions of the numerical entropy flux required in (53) and (54). The first is given by

$$\hat{F}_\eta(U_{\rm h}^+, U_{\rm h}^-) = \lambda F_\eta(U_{\rm h}^+) + (1-\lambda)F_\eta(U_{\rm h}^-) \tag{62}$$

with $\lambda \geq 0$ some scalar coefficient, and $F_\eta(U)$ the *analytical entropy flux*. We then define the local entropy balance as (we consider the one dimensional case for simplicity)

$$\begin{aligned}\Psi_\eta^K =& \hat{F}_\eta(U_{\rm h}^+, U_{\rm h}^-)^R - \hat{F}_\eta(U_{\rm h}^+, U_{\rm h}^-)^L + 2\sum_{i=0,p} w_i c_{fi} h_i k_i \\ =& \lambda [\![F_\eta]\!]^R + \int_K \partial_x F_\eta + (1-\lambda)[\![F_\eta]\!]^L + 2\sum_{i=0,p} w_i c_{fi} h_i k_i\end{aligned} \tag{63}$$

where the second identity is trivially obtained by adding and removing the internal values of F_η on the element's boundaries. Following the discussion from the beginning of section §5, this definition is compatible with analytical steady states verifying (47). It is however not exactly compatible with the global flux solutions of the DGSEM scheme with global flux quadrature, which verify instead (48).

To obtain a definition which is exactly compatible the global flux quadrature approach proposed in this work we modify (63) as

$$\Psi_\eta^K = \lambda [\![F_\eta]\!]^R + \int_K W_{\rm h}^t \partial_x G_{\rm h} + (1-\lambda)[\![F_\eta]\!]^L \tag{64}$$

This definition embeds all the non-differential effects in the global flux term in the middle, and it is compatible with global flux solutions verifying (48). In particular, the resulting corrected scheme is exactly consistent with the discrete solutions U^* of Proposition 4.4.

6. A 2D extension

We briefly discuss here a possible extension to the two dimensional shallow water model (6). This extension is based on a tensor product implementation of the one dimensional DGSEM scheme, as well as on a dimensionally split generalization of the notion of global flux. The study of the genuinely multi-dimensional case is object of current work and left out of this paper. We refer to section §3.1 for the notation, and to [43, 31, 32] for more details on the implementation.

We start by rewriting (6) as

$$\partial_t U + \partial_x F_x + \partial_y F_y = S\,, \tag{65}$$

having set

$$F_x = \begin{bmatrix} hu \\ hu^2 + p(h) \\ huv \end{bmatrix}, \quad F_y = \begin{bmatrix} hv \\ huv \\ hv^2 + p(h) \end{bmatrix}. \tag{66}$$

The dimension by dimension generalization used here is similar to the one proposed initially in [30], and boils down to adding an appropriately defined diagonal flux tensor to the conservative flux. In other words, we recast (6) as System (65) can be written succinctly as

$$\partial_t U + \partial_x G_x + \partial_y G_y = 0 \tag{67}$$

where

$$G_x = F_x + [0\ R_x\ 0]^t\,, \quad G_y = F_y + [0\ 0\ R_y]^t\,, \tag{68}$$

having defined

$$R_x := \int_x h(\partial_x \varphi + c_f u + \omega v) d\xi\,, \quad R_y := \int_y h(\partial_y \varphi + c_f v - \omega u) d\eta. \tag{69}$$

The above definition allows to construct direction by direction fully well balanced schemes which preserve global fluxes/equilibrium variables G_x in the x direction, and G_y in the y direction.

We discretize (67) with a classical tensor DGSEM strategy using the Gauss-Lobatto points of the right picture on figure 1. All computations done, and using a notation similar to that of the previous sections, within each element K we obtain $(p+1)^2$ equations for the degrees of freedom U_{ij} which can be compactly written as

$$\begin{aligned}\frac{d\mathbf{U}}{dt}&+\widetilde{\mathbf{D}}_x\mathbf{F}_x+\mathcal{M}_x^{-1}\mathcal{B}_x(\alpha[\![\mathbf{F}_x]\!]_x)+\mathcal{M}_x^{-1}\mathcal{B}_x(\mathcal{D}[\![\mathbf{U}]\!]_x)\\&+\widetilde{\mathbf{D}}_y\mathbf{F}_y+\mathcal{M}_y^{-1}\mathcal{B}_y(\alpha[\![\mathbf{F}_y]\!]_y)+\mathcal{M}_y^{-1}\mathcal{B}_y(\mathcal{D}[\![\mathbf{U}]\!]_y)=\mathrm{h}\widetilde{\mathbf{D}}_x\mathbf{I}_x\mathbf{S}_x+\mathrm{h}\widetilde{\mathbf{D}}_y\mathbf{I}_y\mathbf{S}_y\end{aligned} \tag{70}$$

where now the array $\mathbf{U}$ contains line ordered values of the solution at the Gauss-Lobatto collocation points, $\mathbf{F}_x$ and $\mathbf{F}_y$ the flux values at collocation points, while $\widetilde{\mathbf{D}}_x$ and $\widetilde{\mathbf{D}}_y$ denote mono-dimensional derivative matrices with a structure depending on the numbering used for $\mathbf{F}_x$ and $\mathbf{F}_y$. If $\mathbf{F}_x$ is line ordered, and $\mathbf{F}_y$ is ordered by columns both derivative matrices have a block diagonal structure, with block entries given by the corresponding one dimensional matrices. As before with $\mathcal{M}$ we denote the one dimensional mass matrices in each direction, and $\mathcal{B}_{x/y}$ are the matrices selecting values on the left/right and top/bottom element boundaries, while $[\![\cdot]\!]_{x/y}$ denote the horizontal/vertical jumps at the left/right and top/bottom element boundaries. Finally, the right hand side contains the source terms, integrated using one dimensional global flux quadrature involving the derivative matrices, and block matrices $\mathbf{I}_{x/y}$ whose entries are the same as the one-dimensional ODE collocation methods, and whose structure depends on the ordering of the entries of the $\mathbf{S}_{x/y}$ arrays which are values at collocation points of the sources

$$S_x := -[0\ h(\partial_x\varphi + c_f u + \omega v)\ 0]^t\,,\quad S_y := -[0\ 0\ h(\partial_y\varphi + c_f v - \omega u)]^t \tag{71}$$

The entropy correction in 2D is evaluated with natural extensions of the one dimensional formulas, see e.g. [29] and references therein for details.

7. Numerical results

We have thoroughly tested the scheme proposed to verify all the theoretical properties presented in the previous sections, as well as to investigate its application to resolution of complex solutions to test its robustness. We also provide results on 2D flows which show the advantage of the global flux quadrature, despite of the simplicity of the extension proposed.

7.1. Verification of Corollary 4.5

We start by verifying the theoretical predictions on the super convergence of the scheme. We performed two sets fo tests. The first consists in computing explicitly the discrete steady solution (or global flux solution) U_{h}^* by solving, element by element, the nonlinear algebraic equations associated to the condition $G_{\mathrm{h}} = G_0$. The second set of tests involves initializing the solution with the exact analytical steady state, and letting the scheme evolve it until a given finite time. In both cases we report the grid convergence for finite element approximations of degree $p = 1, 2, 3, 4$. For the second tests, we compare the global flux quadrature to the classical approach in which the source term is integrated following a classical DGSEM implementation as

$$\int_K \phi_i S_{\mathrm{h}} \to \mathcal{M}\mathbf{S}\,.$$

Only moving equilibria are considered, since the lake at rest is exactly preserved using (46). Small perturbations of the latter are studied later.

Frictionless one dimensional equilibria. We start from the first family of equilibria from section §2.1, analytically defined by (12). We compute solutions for two classical smooth states: a sub-critical one with $(q_0, E_0) = (4.42\mathrm{m}^2/\mathrm{s}, 22.05535\mathrm{m}^2/\mathrm{s}^2)$; a super-critical one for which $(q_0, E_0) = (4.42\mathrm{m}^2/\mathrm{s}, 28.8971\mathrm{m}^2/\mathrm{s}^2)$

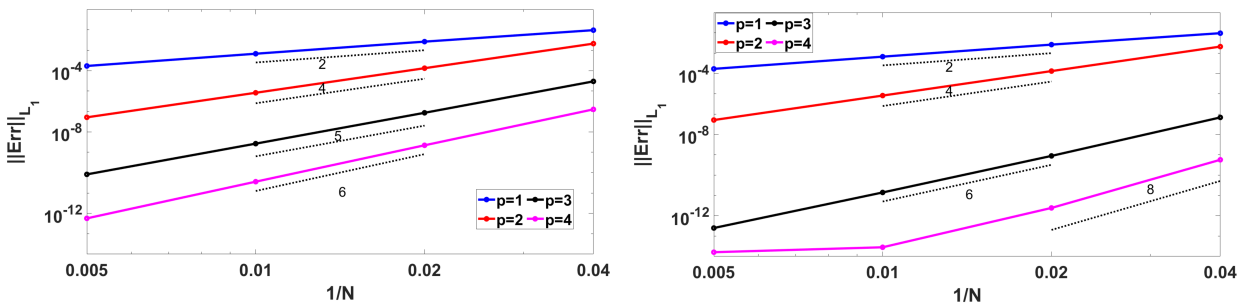
(the gravity constant is set to $g = 9.80665\text{m/s}^2$ here). The computational domain is 25m long, and the bottom topography is taken as

$$b(x) = \begin{cases} 0.2 - 0.05(x-10)^2 & x > 8 \text{ and } x < 12 \\ 0 & \text{else} \end{cases} . \tag{72}$$

As already mentioned, first we study the difference between the discrete steady state corresponding to constant global fluxes (global flux solution) and the analytical one. Following the predictions of Corollary 4.5, we compute two versions of the discrete L_1-error

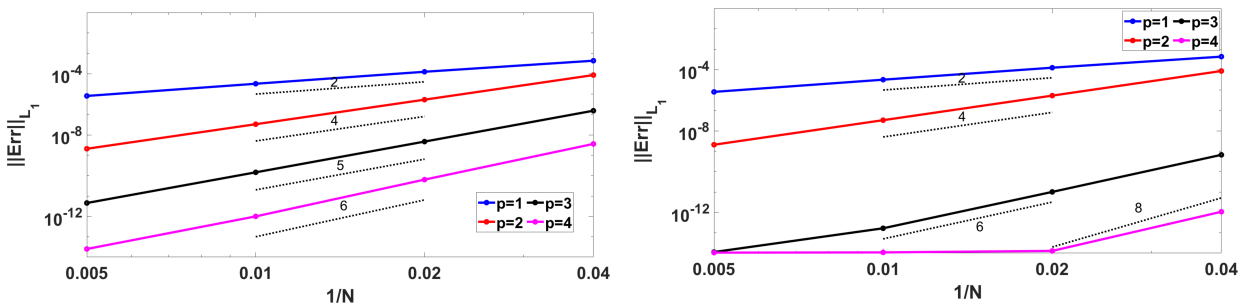
$$\|\text{Err}\|_{L_1} := \frac{1}{M} \sum_{j=1,M} |U_j^* - U^e(x_j)|$$

the first with j running over all the degrees of freedom of all the elements, the second running over only the element end-points. The logarithmic plots for $1/N$-L_1 error for h with $p = 1, 2, 3, 4$ and $N = 25, 50, 100, 200$ are as shown in Figure 2 and Figure 3 for sub- and super-critical case respectively.



(a) All nodes (b) End nodes

Figure 2: Frictionless one dimensional flow: sub-critical case. Error of the global flux solution for polynomial spaces of degree $p = 1, 2, 3, 4$, measured with all nodes (left) and only end nodes (right).

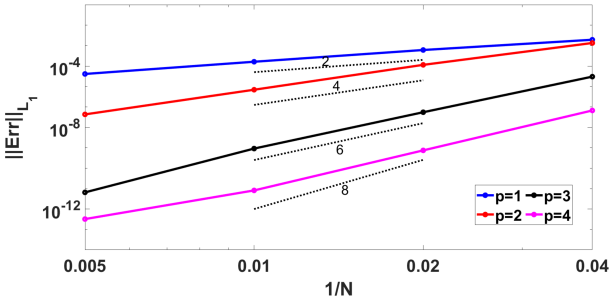


(a) All nodes (b) End nodes

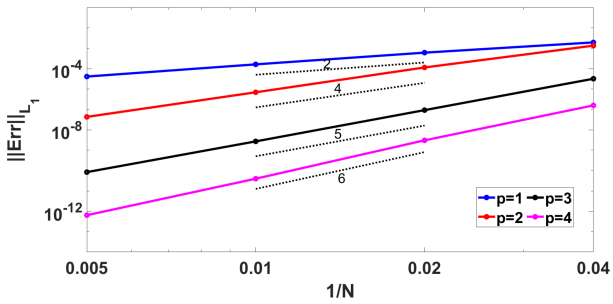
Figure 3: Frictionless one dimensional flow: super-critical case. Error of the global flux solution for polynomial spaces of degree $p = 1, 2, 3, 4$, measured with all nodes (left) and only end nodes (right).

We can see that the convergence rates from Figure 2 and Figure 3 are as predicted in Corollary 4.5 i.e. by using all nodes to measure the L_1 error the convergence is of order $p + 2$, whereas by using only the end nodes, the order of convergence is $2p$. It is to be noted that with $p = 1$, nodes for Gauss Lobatto are at the ends of the cells, and hence the order of convergence is 2, even in Figure 2(a) and Figure 3(a). It can

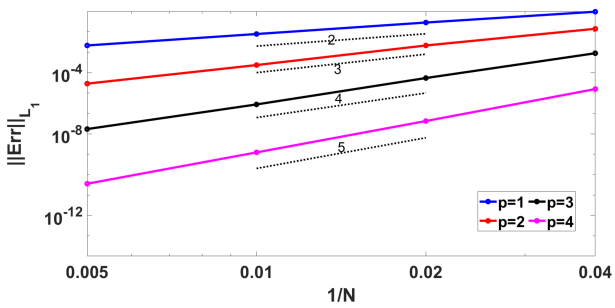
also be noted that with $p = 4$ the error at endpoints reaches machine accuracy on coarse meshes, which of course affects the slopes which appear somewhat reduced.



(a) WB, end nodes



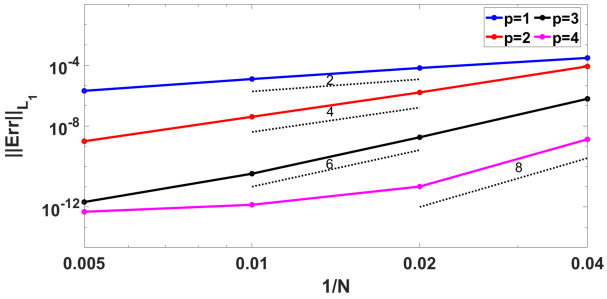
(b) WB, all nodes



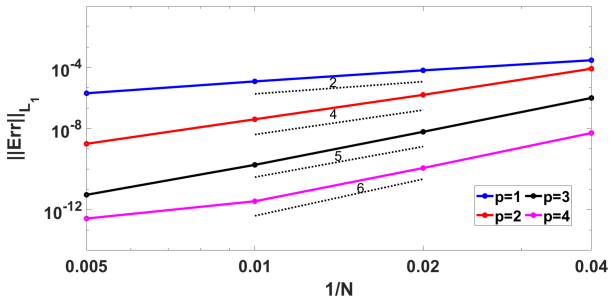
(c) NWB

Figure 4: Frictionless one dimensional flow: sub-critical case. Error at finite time for polynomial spaces of degree $p = 1, 2, 3, 4$. Top: end-nodes error. Bottom: global flux quadrature (left) and non-well balanced method (right).

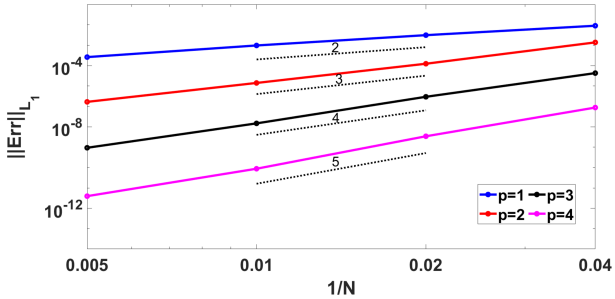
Next, we initialize the solution at degrees of freedom using the analytical value, and we run both the global flux quadrature based and non-well balanced schemes up to $T = 2$s. The logarithmic plots for $1/N$-L_1 error with $p = 1, 2, 3, 4$ and $N = 25, 50, 100, 200$ with error for well-balanced schemes measured using both all and end nodes and non-well-balanced scheme with all-nodes is as shown in Figures 4 and 5.



(a) WB, end nodes



(b) WB, all nodes



(c) NWB

Figure 5: Frictionless one dimensional flow: super-critical case. Error at finite time for polynomial spaces of degree $p = 1, 2, 3, 4$. Top: end-nodes error for the global flux quadrature method. Bottom: total error for the global flux (left) and non-well balanced method (right).

The results show that, without computing the global flux solution, the proposed method still delivers super-convergent results following the predictions of Corollary 4.5. Moreover, we can see that the gain in accuracy wrt to the analytical solution on a given mesh compared to the classical DGSEM implementation is of more than two orders of magnitude. This brings the error of higher order approximation very rapidly to very low values, allowing to resolve very small perturbations as we will see shortly.

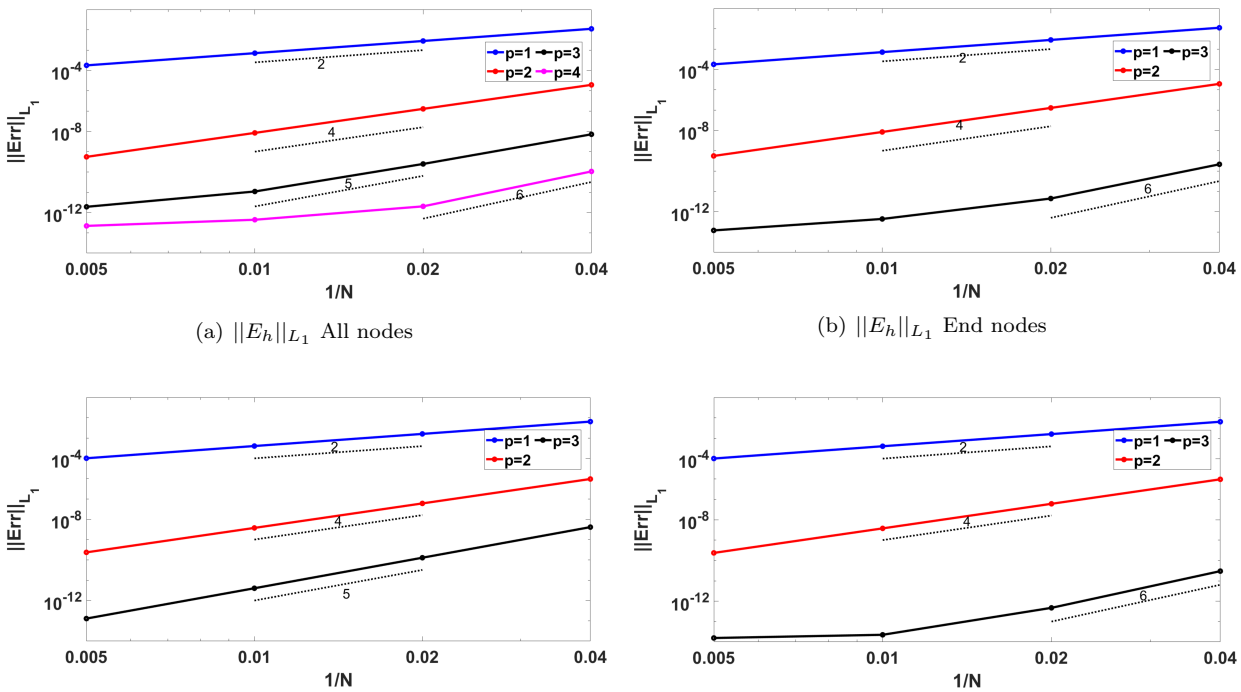
Frictionless pseudo-one dimensional equilibria with Coriolis effects. We consider next the solutions defined by (16). We choose the manufactured state also used in [23] given within $x \in [0, 1]$ by (here the gravity is set to $g = 1\text{m/s}^2$):

$$h = e^{2x}, \quad hu = 1, \quad hv = -\omega x e^{2x} \tag{73}$$

with bathymetry

$$b(x) = -\frac{1}{2}\omega^2 x^2 - e^{2x} - \frac{1}{2}e^{-4x}$$

We perform the same comparisons done for the previous case. We report in Figure 6 the error convergence plots for the global flux solutions, using the discrete norms involving all the degrees of freedom, as well as only the endpoints. For completeness we report both the solutions for h and for the transversal momentum which is not constant.



(a) $||E_h||_{L_1}$ All nodes

(b) $||E_h||_{L_1}$ End nodes

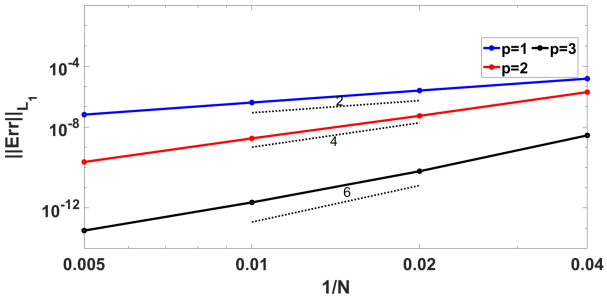
(c) $||E_{hv}||_{L_1}$ All nodes

(d) $||E_{hv}||_{L_1}$ End nodes

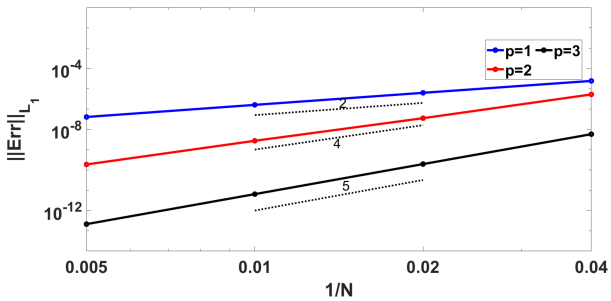
Figure 6: Pseudo-1D equilibria with Coriolis effects. Error convergence of the global flux solution with $p = 1, 2, 3, 4$ for depth (top) and traversal momentum (bottom). Error at all the degrees of freedom (left), and only elements endpoints (right).

As before, the convergence rates confirm Corollary 4.5. For this case, with $p = 4$ the errors reach machine accuracy extremely fast, already on the coarsest mesh for most cases. These cases are not shown in the plots for clarity. The $p = 3$ errors show a similar trend at end-nodes. This makes these schemes in practice almost exactly well balanced with the analytical state.

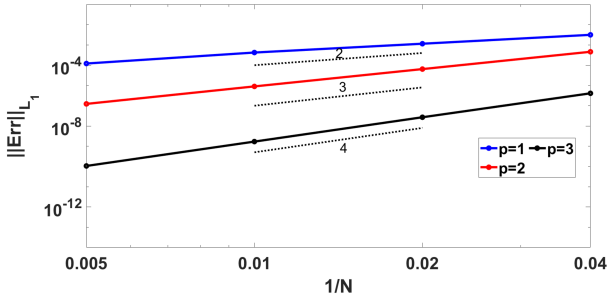
Next we run the well-balanced and non-well-balanced schemes with initial condition given by analytical equilibrium (73). The L_1 error at $T = 1$ with all nodes for both the schemes is as shown in Figure 7 for the depth, and in Figure 8 for the transversal momentum. We only report the results for $p = 1, 2, 3$. We omit the $p = 4$ results as for which the global flux quadrature method is within machine accuracy of the exact solution. We can see that the results once again verify the rates predicted by Corollary 4.5, with convergence order of $p + 2$ for the total error, and $2p$ for the end points error when using the global flux quadrature. As for the previous case, the comparison with the non-well balanced DGSEM implementation shows a gain in error of several orders of magnitude.



(a) $||E_h||_{L_1}$ WB, all nodes

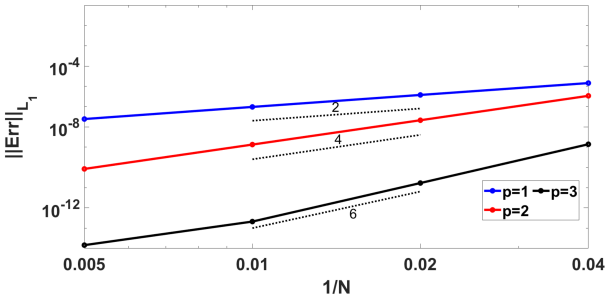


(b) $||E_h||_{L_1}$ WB

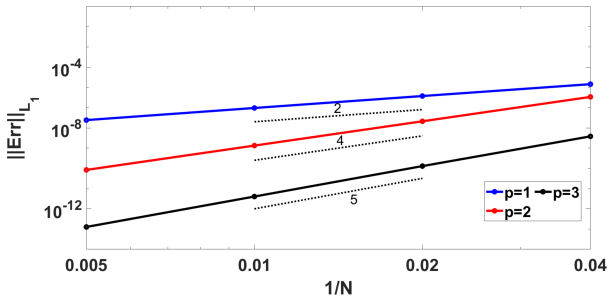


(c) $||E_h||_{L_1}$ NWB

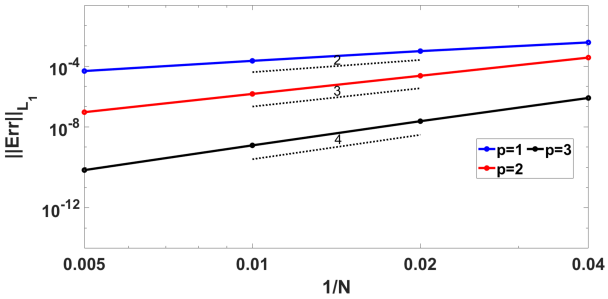
Figure 7: Pseudo-1D equilibria with Coriolis effects. Error convergence of the global flux solution with $p = 1, 2, 3, 4$ for the depth. Top: end-nodes error for the global flux quadrature method. Bottom: total error for the global flux (left) and non-well balanced method (right)



(a) $||E_{hv}||_{L_1}$ WB all nodes



(b) $||E_{hv}||_{L_1}$ WB all nodes



(c) $||E_{hv}||_{L_1}$ NWB

Figure 8: Pseudo-1D equilibria with Coriolis effects. Error convergence of the global flux solution with $p = 1, 2, 3, 4$ for the tranverse momentum. Top: end-nodes error for the global flux quadrature method. Bottom: total error for the global flux (left) and non-well balanced method (right)

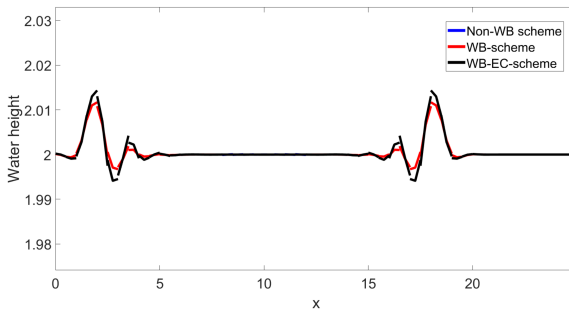
7.2. Perturbations of steady states

Next, we check the evolution of a small perturbation to equilibrium flows. In all the tests below we have perturbed initial depth as

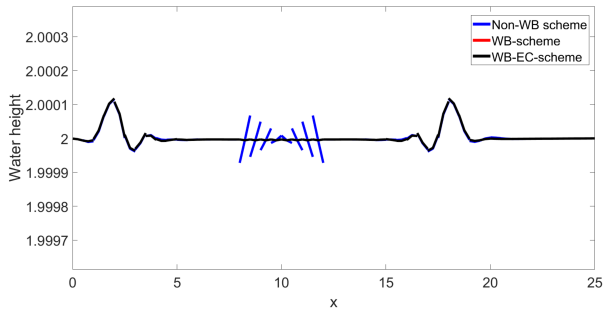
$$h(0, x) = h^*(x) + \xi e^{-\frac{(x-x_0)^2}{100}}. \tag{74}$$

where $h^*(x)$ is the height of water for steady state. Unless specified otherwise $h^*(x)$ is given by the exact analytical steady solution.

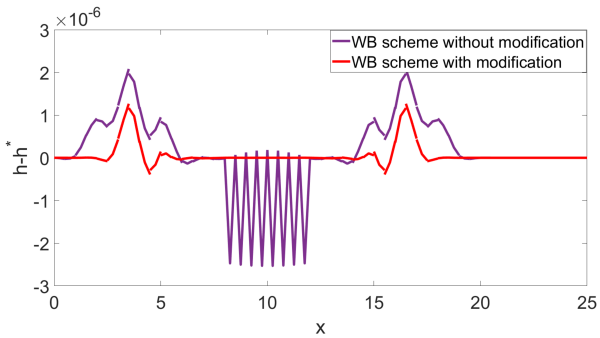
Lake at rest. For the first case we consider $u(0, x) = 0$ and $h^*(x) + b(x) = 2m$ where b is as given in (72), and the spatial domain is $x \in [0, 25]m$. We consider three values for the amplitude of ther perturbation $\xi = 10^{-1}m$, $\xi = 10^{-3}m$, and $\xi = 10^{-8}m$. We set $x_0 = 10$ in (74), and plot the solution at $T = 1.5$. We compare the non-well-balanced scheme, and the well balanced scheme using (46) with and without entropy correction. Note that for this case the choice of the analytical entropy flux or of the modified one to define the cell correction has not effect. This aspect will be studied later in the results section. The results obtained here with $p = 2$ is as shown in Figure 9.



(a) $\xi = 10^{-1}m$



(b) $\xi = 10^{-3}m$



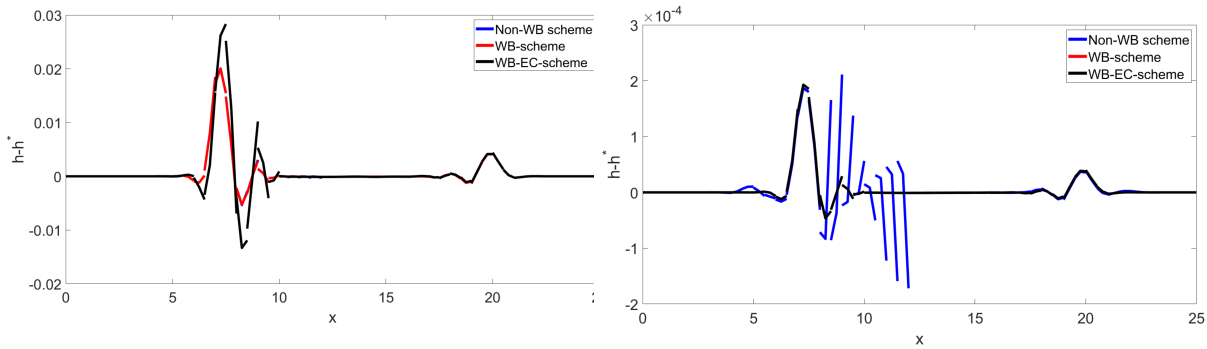
(c) $\xi = 10^{-5}m$

Figure 9: Perturbation of the lake at rest. Top: NWB DGSEM (blue) and global flux quadrature approach with (black) and without (red) cell entropy correction for $p = 2$. Bottom: global flux quadrature without entropy correction using the basic nodal source definition (45) (magenta) and the modified one (46) (red)

From the results in Figure 9, one can see that with $p = 2$ the largest amplitude perturbation is well resolved by all methods. However, as we go lower with the amplitude of the perturbation we see the spurious oscillations of the non-well balanced scheme. For the last case, the results of the latter cannot even be plotted on the same scale since the amplitude of the error wrt the steady solution is several orders of magnitude higher than the perturbation. For completeness, we also report in the same figure a comparison of the global flux quadrature method with the straightforward definition of the nodal source (45), and with the modified one (46). To compare the two we have to use a much smaller amplitude perturbation of $\xi = 10^-5$m, the results for the other values being almost superimposed. This shows the advantage of having an exact definition of preservation when extremely small perturbations are considered on coarse meshes.

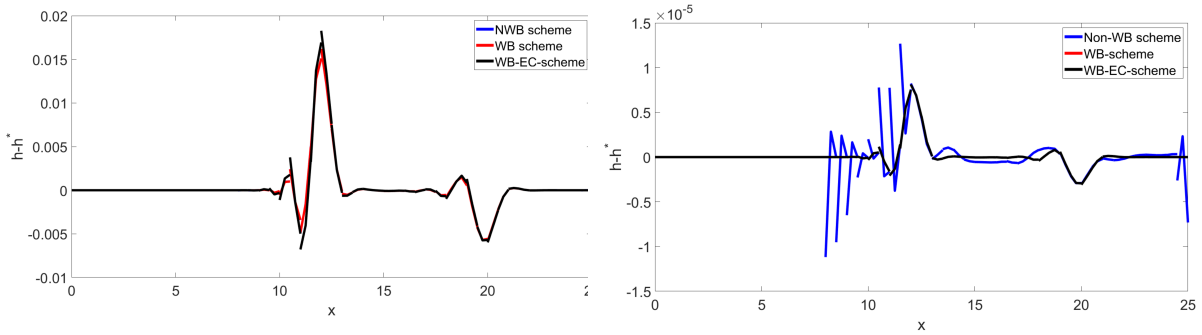
Frictionless one dimensional moving equilibria. We consider again the equilibria defined by (12) setting respectively $(q_0, E_0) = (4.42\text{m}^2/\text{s}, 22.05535\text{m}^2/\text{s}^2)$, and $(q_0, E_0) = (4.42\text{m}^2/\text{s}, 28.8971\text{m}^2/\text{s}^2)$. The bathymetry is given in (72), and the spatial domain is $x \in [0, 25]m$. As in the previous case, we consider te evolution of perturbations of different amplitudes of the analytical steady depth for $p = 2$. We compare the non well-balanced DGSEM, with the one using global flux quadrature with and without cell entropy correction.

For the sub-critical case we have considered perturbations of order $\xi = 10^{-1}m$, and $\xi = 10^{-3}$m, initially set at $x_0 = 10$. The results at $T = 1.5$s are plotted on Figure 10 in terms of $h(x,t) - h^*(x)$. We perform a similar exercise for the supercritical flow, only considering $\xi = 2 \times 10^{-2}$m, and $\xi = 10^{-5}$m. The initial perturbation is this time set at $x_0 = 6.25$. The results are reported in Figure 11.



(a) $\xi = 10^{-1}$ (b) $\xi = 10^{-3}$

Figure 10: Perturbation of frictionless 1d sub-critical equilibrium. Perturbation plot for the NWB DGSEM (blue), and for the DGSEM with global flux quadrature with (black) and without (red) cell entropy correction for $p = 2$.



(a) $\xi = 2 * 10^{-2}$ (b) $\xi = 10^{-5}$

Figure 11: Perturbation of frictionless 1d super-critical equilibrium. Perturbation plot for the NWB DGSEM (blue), and for the DGSEM with global flux quadrature with (black) and without (red) cell entropy correction for $p = 2$.

For both sub-and supercritical flow the behaviour observed is similar to the one seen for the lake at rest state. For $p = 2$ relatively large perturbations are not affected by the well-balanced nature of the scheme, however as the amplitude of the perturbations decreases, the non-balancing error leads to spurious artefacts of amplitude larger than the physical waves.

For completeness we also report a $p-$convergence study for the sub-critical case using the global flux quadrature scheme with entropy correction. The result is reported in Figure 12 showing a classical behaviour: passing from $p = 1$ to $p = 2$ almost removes the phase error; passing to $p = 3$ and $p = 4$ allows to remove both phase, and amplitude errors.

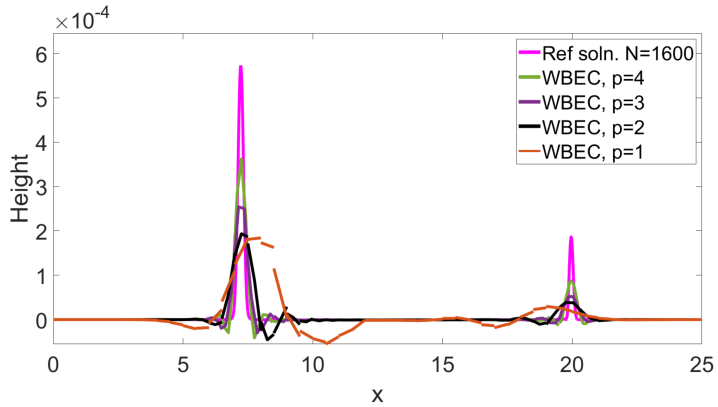
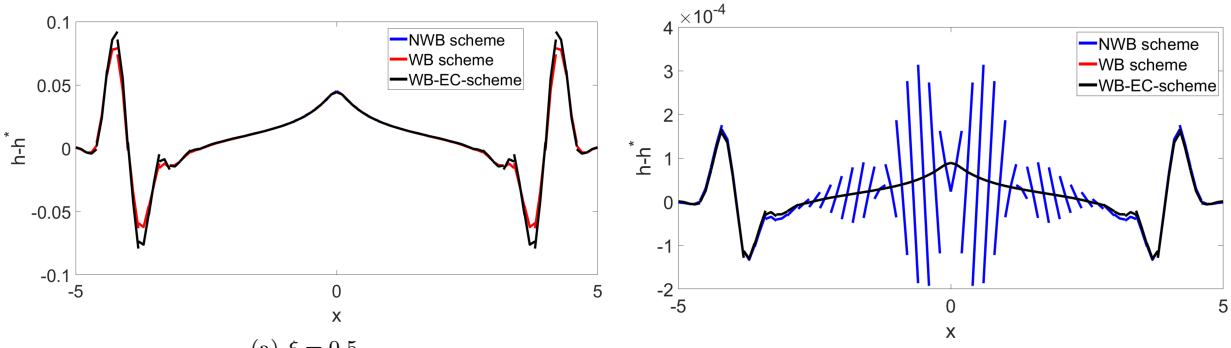


Figure 12: Perturbation of frictionless 1d sub-critical equilibrium. p-convergence study of the perturbation at $T = 1.5$s.

Pseudo-one equilibrium at rest with transverse Coriolis effects. We consider here the two first configuration of the two discussed in section §2.1, given analytically by the relations (15). In particular, on the domain $[-5, 5]$m we consider the transverse velocity field

$$v(x) = \frac{gx}{2} e^{-x^2}. \tag{75}$$

and set $g = 1\text{m/s}^2$, and $\omega = 2\text{s}^{-1}$. The values for $h^*(x)$ are calculated analytically from (15). We consider perturbations with $\xi = 0.5$m, and $\xi = 10^{-3}$m, initially centered at $x_0 = 0$. The perturbation $h - h^*(x)$ at $T = 2$s is studied. We compare the global flux quandrature DGSEM with $p = 2$ with the corresponding non well balanced formulation. Results are plotted in Figure 13. As for the previous cases the largest perturbation is evolved in a similar manner by all the schemes. However, only the well balanced formulations correctly capture small amplitude variations as shown by the right plot in the figure.

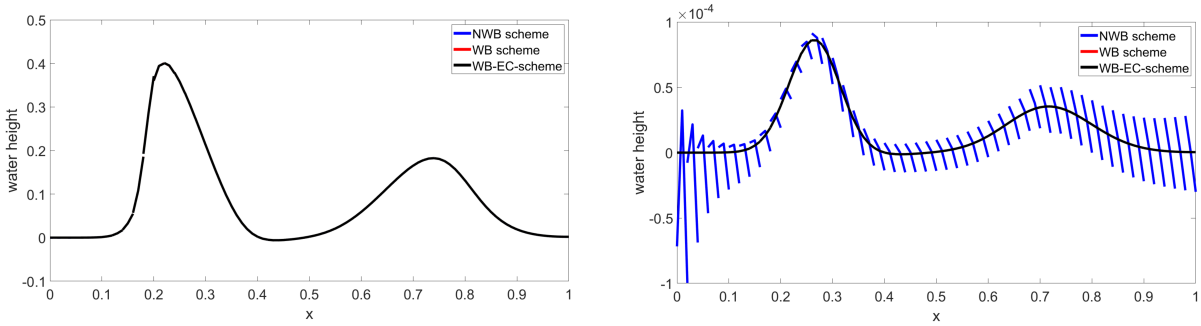


(a) $\xi = 0.5$

(b) $\xi = 10^{-4}$

Figure 13: Pseudo-1d equilibrium at rest with transverse Coriolis effects. Perturbation computed with the $p = 2$ DGSEM using the non well balanced (blue), and the global flux quadrature forms with (black) and without (red) entropy correction.

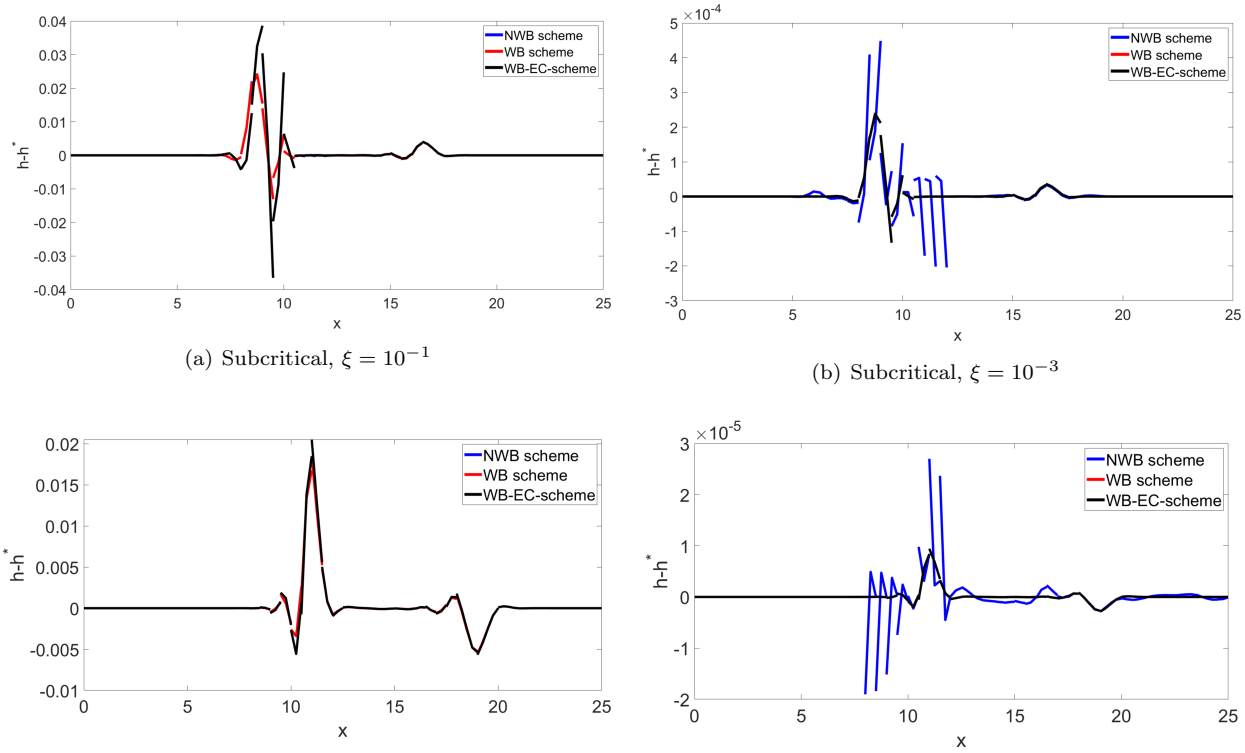
Frictionless pseudo-one dimensional equilibria with Coriolis effects. We repeat the above test for the steady solution given by (73). We add to the analytical equilibrium studied in section §7.1 perturbations of amplitudes $\xi = 0.5$m, and $\xi = 10^{-4}$m. We compute the evolution with $p = 2$ until $T = 1.5$s with all the different DGSEM formulations with $p = 2$. In particular, Figure 14 compares the perturbation $h - h^*(x)$ obtained with the global quadrature formulations and with the non-well-balanced scheme. We can see just as the other examples that the non-well-balanced scheme fails to capture a small perturbation, which is not the case with the global flux quadrature approach.



(a) $\xi = 0.5$ (b) $\xi = 10^{-4}$

Figure 14: Pseudo-1d equilibrium with Coriolis effects. Perturbation computed with the $p = 2$ DGSEM using the non well balanced (blue), and the global flux quadrature forms with (black) and without (red) entropy correction.

Moving equilibria with friction. As a last case we consider a variation of the sub- and super-critical flows given by (12) and already investigated, only with the addition of friction effects. In this case, the analytical solution is characterized by (18), and a reference solution can be computed e.g. evaluating the integrals on a refined mesh. We consider the same sub-critical and super-critical states as before on the domain $[0, 25]$m, and bathymetry (72). For simplicity we use constant values of the friction coefficient, set to $c_f = 0.03$ in the sub-critical case, and $c_f = 0.05$ in the super-critical case. As before we add perturbations of different amplitudes. To best visualize the difference between all the schemes, we have studied this time $\xi = 10^{-1}$m and $\xi = 10^{-3}$m in the sub-critical case. For the super-critical equilibrium we have set $\xi = 2 \times 10^{-2}$m, and $\xi = 10^{-5}$m. We compute the solution with $p = 2$ until $T = 1.5$s. We compare the solutions obtained with the different schemes in Figure 15. The results lead to similar conclusions as for all the other equilibria, and source term types.



(a) Subcritical, $\xi = 10^{-1}$

(b) Subcritical, $\xi = 10^{-3}$

(c) Supercritical, $\xi = 2 \times 10^{-2}$

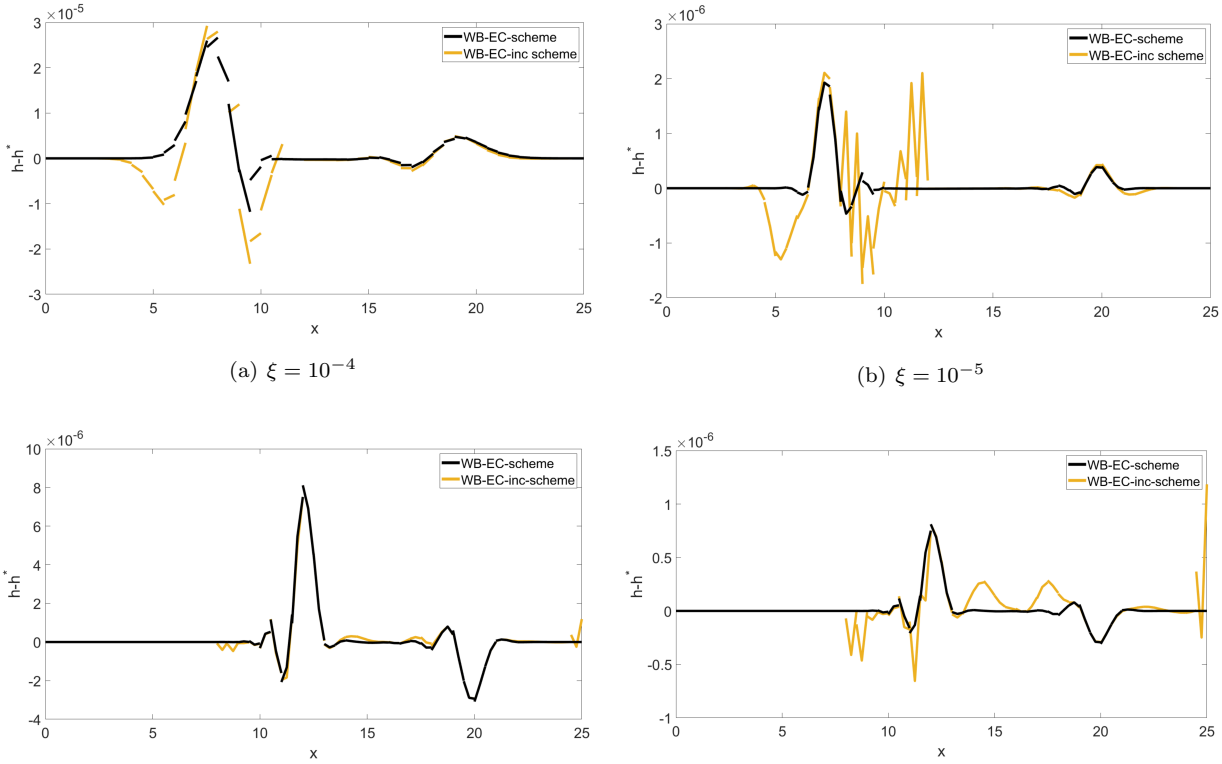
(d) Supercritical, $\xi = 10^{-5}$

Figure 15: Perturbation of moving equilibria with friction. Tope: sub-critical case. Bottom: super-critical case. Comparison of the DGSEM with $p = 2$ global quadrature formulations with (black) and without (red) cell entropy correction, with the non well balanced one (blue).

7.3. Entropy control vs well balancing

We have so far considered entropy correction terms always consistent with the initialization used. In this section we check the impact of this consistency, as well as the effect of the adding the cell correction on the fully discrete evolution of the entropy.

To begin with, we consider a slight variation of the study of the previous section, and we perturb the initial data given by the global flux solutions for the moving one dimensional sub-critical and supercritical flows without friction. We consider small perturbations with amplitudes 10^{-4}m and 10^{-5}m for the sub-critical case, and 10^{-5}m and 10^{-6}m for the super-critical one. The results, in Figure 16, show that for small amplitude perturbations properly accounting for the initialization strategy is important. Despite of the fact that the super-convergence of the global flux solution to the analytical one, the use of analytical entropy fluxes in this case spoils the well balanced character of the scheme, leading to spurious waves comparable to the physical ones. Note that this effect is a much weaker effect than the one observed with the non-well balanced method. However, in some cases it may be necessary to have machine-accuracy preservation of a physically relevant initial state, and initializing with the global flux solution may be relevant. In these cases, the use of (64) in the entropy correction is necessary.



(a) $\xi = 10^{-4}$

(b) $\xi = 10^{-5}$

(c) $\xi = 10^{-5}$

(d) $\xi = 10^{-6}$

Figure 16: Frictionless 1D moving equilibria. Perturbations of the discrete global flux solution in the sub-critical (top) and super-critical (bottom) case. Comparison between using consistent (black) and inconsistent (yellow) entropy corrections.

We now look at the impact of the entropy correction term on the fully discrete time evolution of the total entropy/energy $\sum_K \int_K \eta_{\mathrm{h}}$. Note that nothing special is done concerning the time integration, so the conservation property holds exactly only in the time continuous case. Fully discrete variants can be obtained by other means, but are not considered here (see e.g.[53, 2, 29]). Time integration is in particular performed with standard RK schemes of the same formal order of the underlying spatial discretization. We will comment on two examples. The first is the perturbation of amplitude $\xi = 10^{-1}$m of the sub-critical and supercritical moving equilibria without friction. The evolution of entropy until time $T = 50$s in the $p = 2$ case for the NWB, and for the global flux quadrature with and without cell entropy correction are shown in Figure 17. We can see that in both cases the entropy correction allows to reduce the variation of entropy in time, improving its conservation.

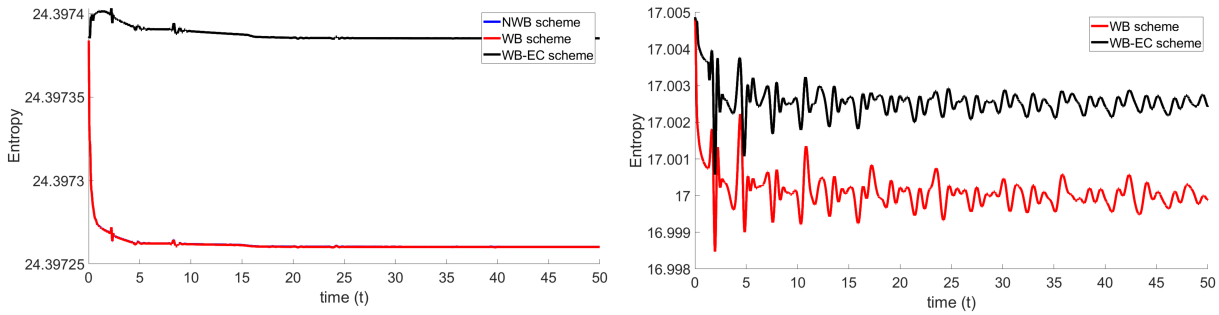
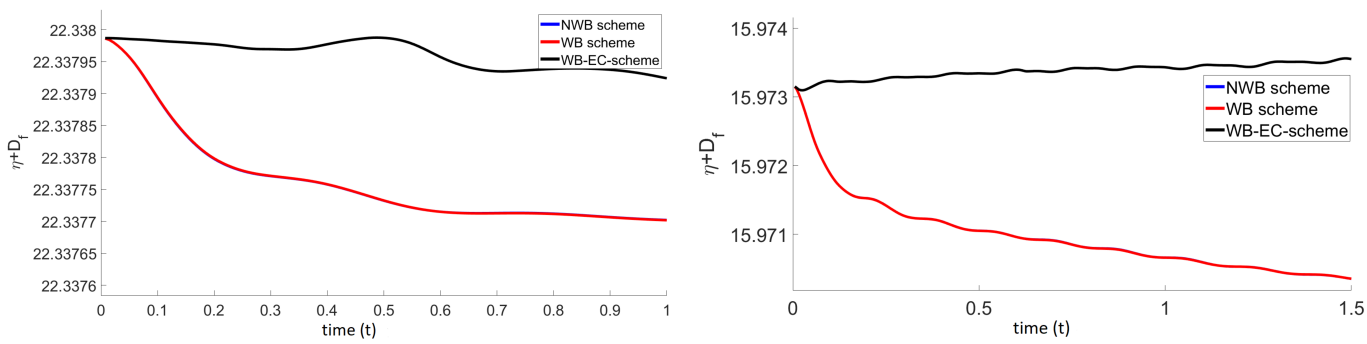


Figure 17: Time discrete evolution of the total energy in the domain for a perturbation of amplitude $\xi = 10^{-1}$m to sub-critical (left) and super-critical frictionless moving 1d equilibrium (right). Global quadrature DGSEM with entropy correction (black) compared to the basic global quadrature DGSEM (red) and to the non well balanced DGSEM (blue).

As a second example, we consider a perturbation $\xi = 0.1$ of moving equilibria with friction in sub-critical and supercritical conditions. The entropy evolution is shown in Figure 18. In the figures, following Remark 3, we study the evolution of the corrected total entropy balance

$$N_{\text{tot}} := \sum_K \left(|K|\bar{\eta}_\varphi + \int_{t_0}^{t} \mathcal{D}_f \right)$$

which should constant and equal to $\sum_K |K|\bar{\eta}_\varphi(t = 0)$. We see from Figure 18 that with the entropy correction term allows to obtain good control of the dissipation of the scheme.



(a) Sub-critical, $\xi = 10^{-1}$

(b) Super-critical, $\xi = 10^{-1}$

Figure 18: Perturbation of moving equilibria with friction: evolution of the entropy balance. Left: sub-critical flow. Right: supercritical flow.

7.4. 2d examples and applications

We consider now the application of the scheme proposed to more complex tests. On one hand we want to investigate the advantage of using the tensor product extension proposed, which is only well balanced along mesh lines, on genuinely 2D problems. On the other, we want to test the method on problems involving sharp propagating fronts, and complex structures to assess its robustness.

7.4.1. 2d perturbations of 1d equilibria

We start from a simple benchmark: the evolution of 2D perturbations to one dimensional exact steady solutions. We consider first the lake at rest with initial condition with $\zeta_0 = 5.47$m, and $hu = hv = 0$. The

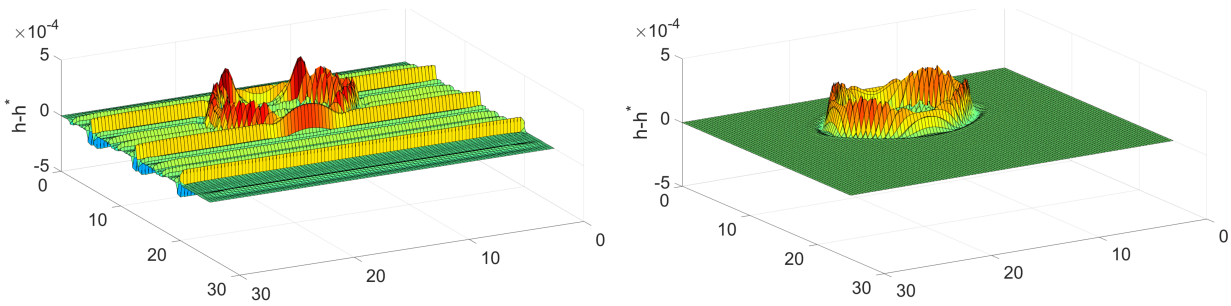
bathymetry is given by a series of bumps defined as

$$b(x) = \begin{cases} 0.2 - (x - (4.5k - 0.75))^2/20 & 4.5k - 3 < x < 4.5k + 1.5,\ k = 1, 2, 3, 4, 5 \\ 0 & \text{otherwise} \end{cases}$$

We add a two dimensional perturbation to this equilibrium flow defined as (see also Figure 20(a))

$$h = h^* + 0.05e^{-100((x-10)^2+(y-12.5)^2)}. \tag{76}$$

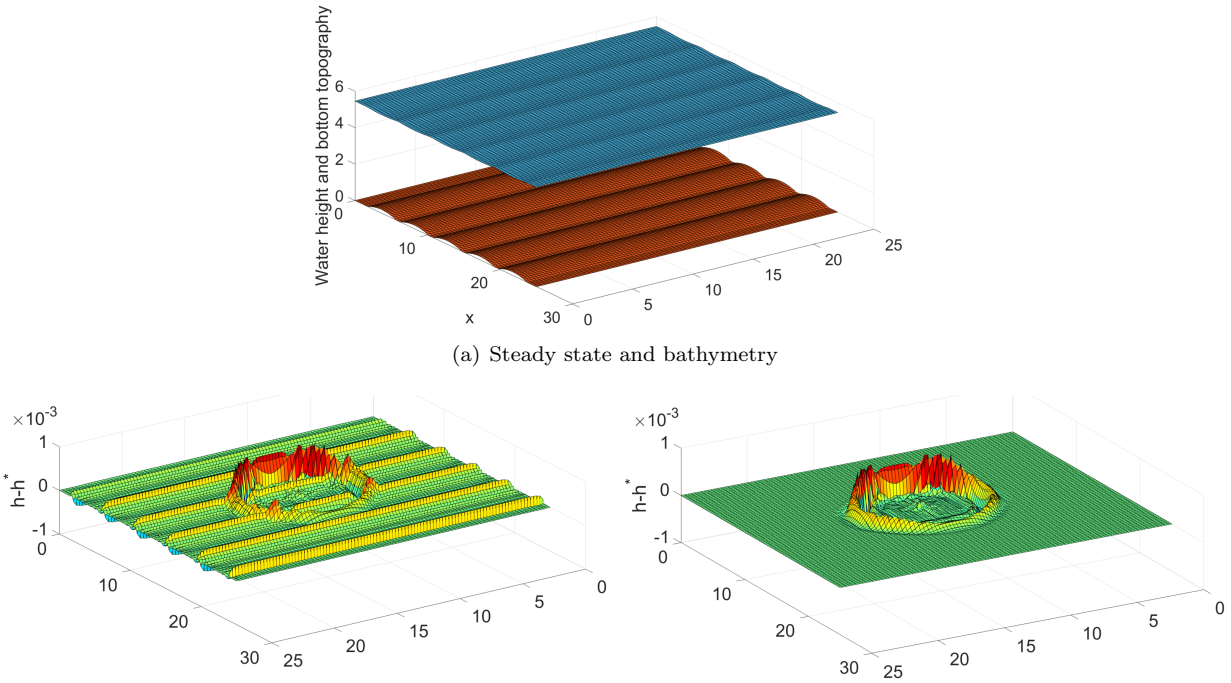
We evolve the solution until $T = 2$s on a 50×50 mesh with both the non-well-balanced and global flux quadrature schemes with $p = 2$. The results are compared on Figure 19. As expected, the non well balanced formulation introduced spurious numerical oscillations of size comparable to the amplitude of the perturbation. These perturbations are completely absent in the well balanced formulation which preserves the steady state exactly.



(a) NWB (b) WB

Figure 19: Numerical solution for $h - h^*$ with NWB, WB, WB-EC discontinuous Galerkin scheme

Next we consider a 1D equilibrium where initial condition is calculated using (12) taking $q_0 = 5.6865$ and $E_0 = 54.183738$. As in the previous example, we add the perturbation (76) which is evolved until $T = 2$s on a 50×50 mesh with both the non-well-balanced and global flux quadrature schemes with $p = 2$. The results are as shown in Figure 20. The NWB scheme is not able to capture the perturbation accurately as the numerical error are as large as the physical perturbation. The global flux quadrature approach allows to obtain a correct preservation of the background flow, and a nice evolution for the perturbation. It may be noted that the results of well-balanced scheme with entropy correction are extremely close, so only the first is shown.



(a) Steady state and bathymetry

(b) NWB

(c) WB

Figure 20: Numerical solution for $h - h^*$ with NWB, WB discontinuous Galerkin scheme

2d stationary vortex with bathymetry. This is a genuinely 2D steady state. It is a variation of a test often used in literature, see e.g [7] with added bathymetric effects. The initial condition is given by

$$h^*(r,0)+b(x,y) = 1+\xi^2 \begin{cases} \frac{5}{2}(1+5\xi^2)r^2 & r \leq \frac{1}{5} \\ \frac{1}{10}(1+5\xi^2) + 2r - \frac{3}{10} - \frac{5}{2}r^2 & \\ \qquad + \xi^2[4ln(5r) + \frac{7}{2} - 20r + \frac{25}{2}r^2] & \frac{1}{5} < r \leq \frac{2}{5} \\ \frac{1}{5}(1 - 10\xi^2 + 20\xi^2 ln(2)) & r > \frac{2}{5} \end{cases} \quad u^*(x,y,0) = -\xi y \Upsilon(r), \quad v^*(x,y,0) = \xi$$

(77)

where $r = \sqrt{x^2+y^2}$. For this test we consider $\xi = 0.1$ and bathymetry defined as

$$b(x,y) = \begin{cases} 0.1(1 - 6.25(x^2+y^2)) & \text{if } (x^2+y^2) < 0.16 \\ 0 & \text{otherwise} \end{cases}$$

As scaled visualization of the initial free surface is reported on the left on Figure 21. We report in the same figure the grid convergence with the global flux quadrature and with the non well method for different degree approximations. Note that (77) only provides C^0 continuity. As shown in [57] this will limit the convergence attainable with high order schemes to roughly second order, which is the slope obtained here. The convergence plot however also shows that, despite the fact that we do not embed a genuinely two dimensional well balanced criterion, the global flux quadrature formulation still provides a considerable decrease in error especially for $p = 2$ and $p = 3$. In particular, the errors of the WB $p = 2$ are quite comparable with those of the fourth order non well balanced DGSEM.

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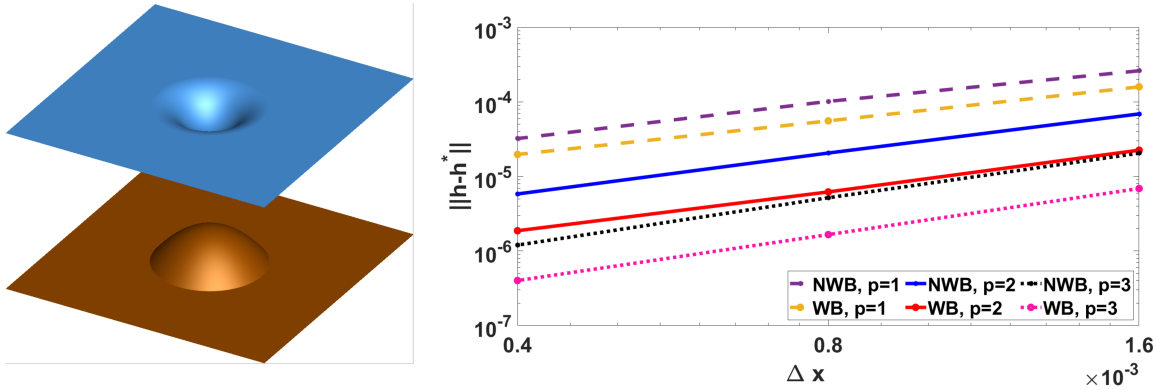
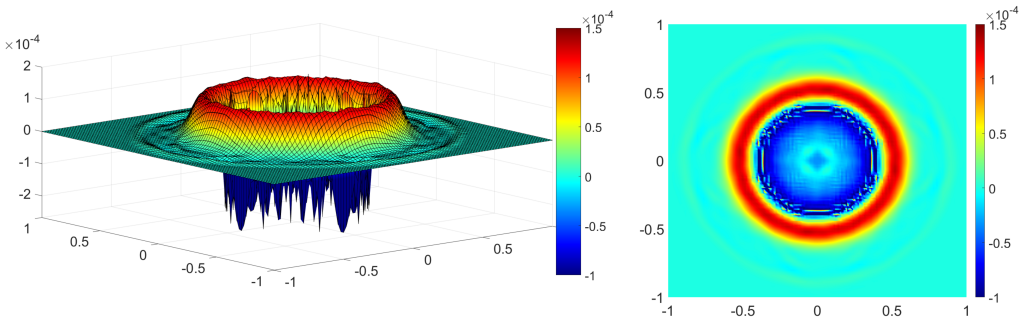


Figure 21: Steady vortex. Left: scaled 3D view of the initial solution (free surface and bathymetry). Right: grid convergence with $p = 1, 2, 3$.

We also test the evolution of a small perturbation added to water height and given by,

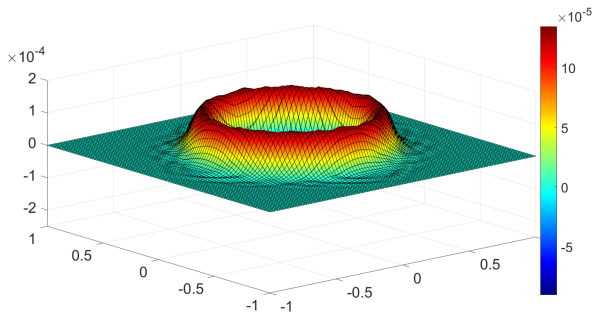
$$h = h^* + 10^{-3} e^{-100(x^2+y^2)}$$

The perturbation is evolved up to $T = 0.05$ with the third order schemes on a 50×50 grid. Snapshots of the perturbation at the final time are reported in Figure 22. The NWB scheme introduces spurious oscillations in the solution over time, while the well balanced method provides a much cleaner resolution of the waves.

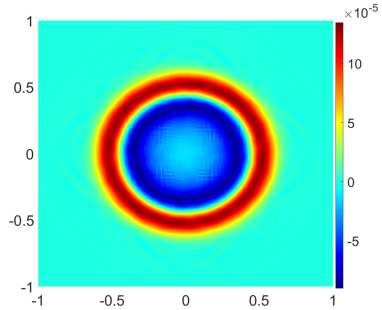


(a) NWB

(b) NWB



(c) WB



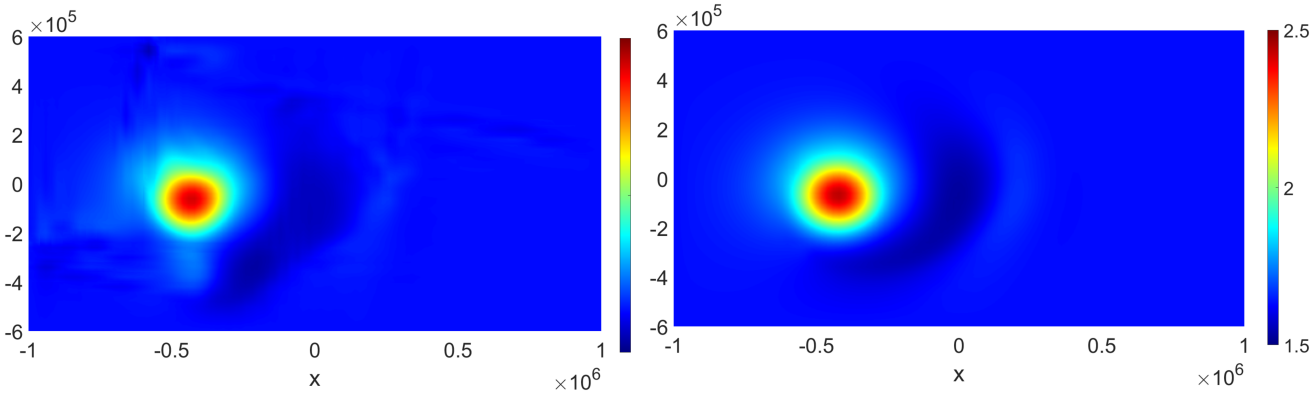
(d) WB

Figure 22: Numerical solution for $h - h^*$ with NWB, WB discontinuous Galerkin scheme

Anticyclonic vortex propagation. This is a moving variant of the previous case. It consists of a vortex propagating westward due to the effect of the variation of the Coriolis coefficient which is modified as

$$\omega = \omega_0 + \beta y$$

to model the effects curvature effects using a tangent plane aproximations. The domain a rectangular basin of 2000×1200. The initial condition is given by a Gaussian distribution of the free surface centered at the origin of the domain, prescribed together with a velocity field which is in geostrophic balance. We refer to [15, 47] and references therein for details on the test setup, and values of the different parameters. The solution is computed with the third order schemes until a final time corresponding to 8 weeks on a relatively coarse mesh of 50×30km.



(a) NWB (b) WB

Figure 23: Anticyclonic vortex propagation.

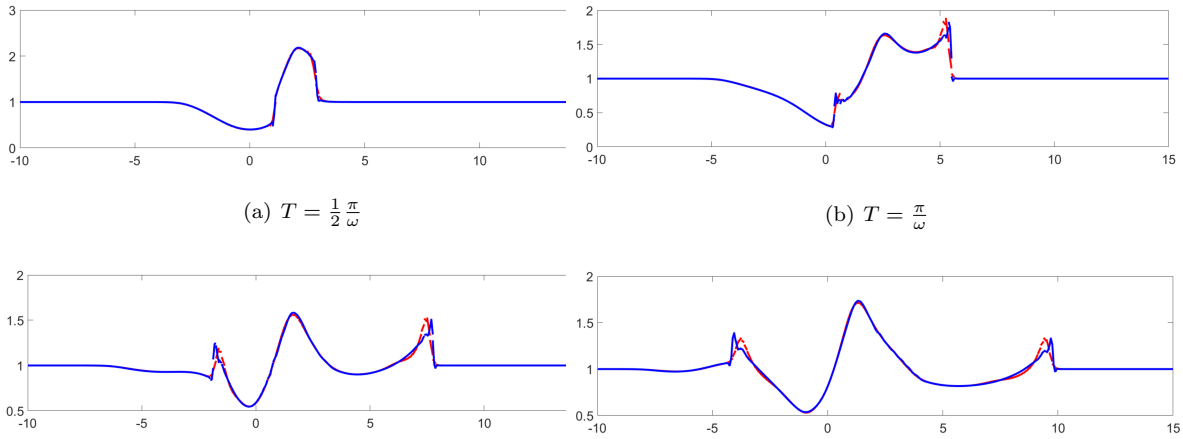
We plot the free surface contour levels obtained with the non well balanced and global flux quadrature methods on Figure 23. The results confirm the observations made for the steady vortex: the well balanced scheme provides a much cleaner solution, while some spurious waves around the vortex are clearly visible in the non well balanced result.

Geostrophic adjustment in 1d and 2d. We consider now the simulation of the complex wave dynamics of the geostrophic adjustment in one and two space dimensions. We start from the one dimensional numerical test for geostrophic adjustment used in [10]. The initial conditions are given by

$$h(x, y, 0) = 1, \quad u(x, y, 0) = 0 \tag{78}$$

$$v(x, y, 0) = 2\frac{(1 + \tanh(4\frac{x}{L} + 2))(1 - \tanh(4\frac{x}{L} - 2))}{(1 + \tanh(2))^2} \tag{79}$$

with $L = 2$m, and $\omega = 1\text{s}^{-1}$, $g = 1\text{m/s}^2$ in the rotating shallow water equations. The initial disturbance in the momentum leads to two fast inertial gravity waves and shock formation. Figure 24 gives the solution for free water surface at time $T = \frac{1}{2}\frac{\pi}{\omega}, \frac{\pi}{\omega}, \frac{3}{2}\frac{\pi}{\omega}, 2\frac{\pi}{\omega}$ computed using a second and third order well-balanced discontinuous Galerkin scheme with a grid of $N = 200$ in the domain $[-10, 15]$m.



(a) $T = \frac{1}{2}\frac{\pi}{\omega}$ (b) $T = \frac{\pi}{\omega}$

(c) $T = \frac{3}{2}\frac{\pi}{\omega}$ (d) $T = 2\frac{\pi}{\omega}$

Figure 24: Solution with 2nd and 3rd order well-balanced DG scheme at $T = \frac{1}{2}\frac{\pi}{\omega}, \frac{\pi}{\omega}, \frac{3}{2}\frac{\pi}{\omega}, 2\frac{\pi}{\omega}$

From the solution we see that both the schemes are able to capture the two fast waves accurately in time, with sharp front almost free of oscillations despite the absence of any limiter. The third order scheme is less diffusive and is able to capture the shock front more accurately.

Next, consider the two-dimensional extension of this test, proposed in [15]. In this case the initial conditions are as follows

$$h(x, y, 0) = 1 + 0.25 * (1 - \tanh(\frac{\sqrt{2.5x^2 + y^2/(2.5)} - 1}{0.1})) \tag{80}$$

$$u(x, y, 0) = v(x, y, 0) = 0 \tag{81}$$

on the spatial domain $[-10, 10]\text{m} \times [-10, 10]\text{m}$. The initial free surface is visualized in figure 25, while Figure 26 reports the free surface at times $T = 4, 8, 12, 20\text{s}$ obtained with the third order well balanced method using a 50×50 mesh.

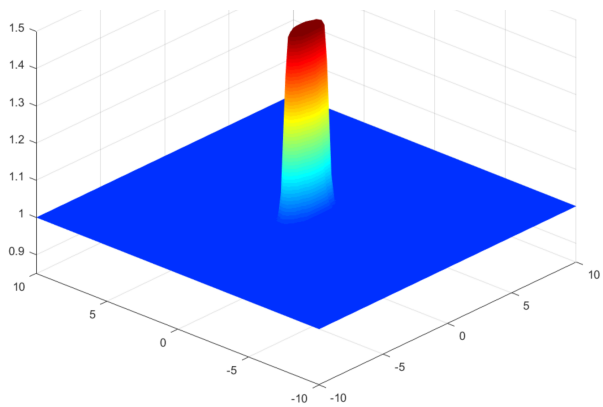
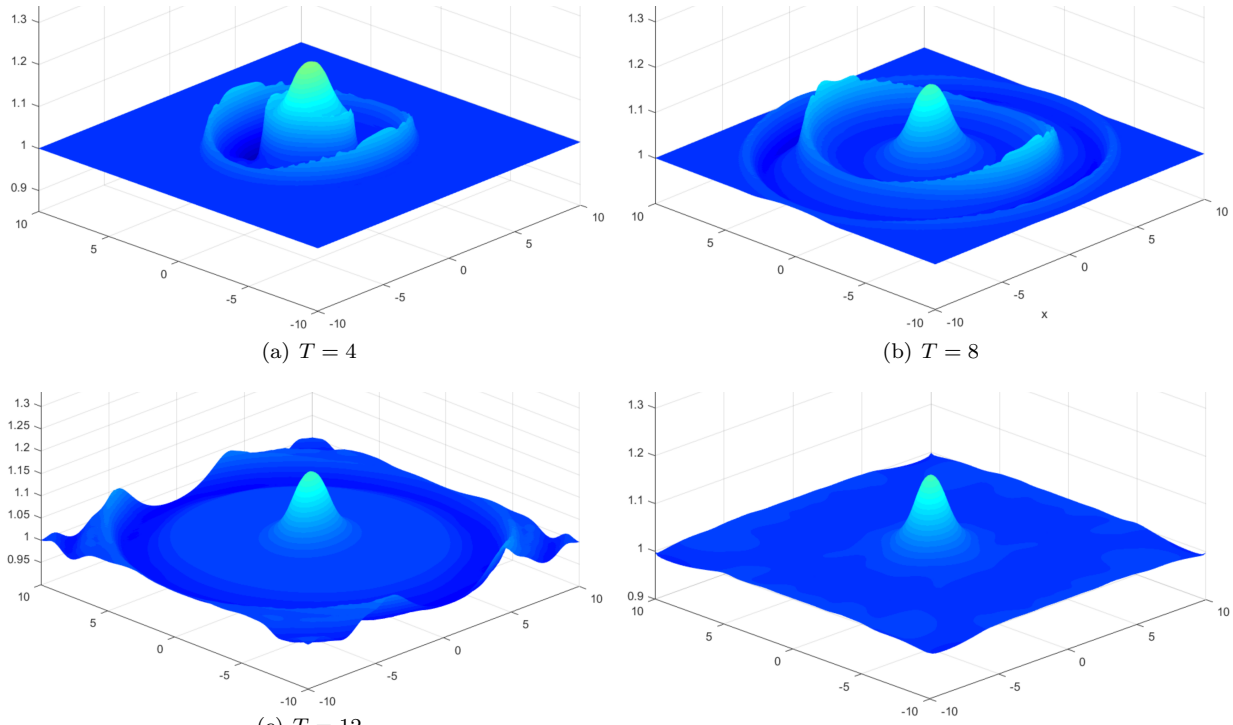


Figure 25: Initial free surface for the 2d geostrophic adjustment problem by [15]



(a) $T = 4$ (b) $T = 8$

(c) $T = 12$ (d) $T = 20$

Figure 26: 2d geostrophic adjustment problem. Water surface at $T = 4, 8, 12, 20$

The solution for this problem is given by two shock waves which move radially away from the center leaving behind some mass which rotates at the initial position. We see that the well-balanced scheme is able to capture these shock waves accurately and the final equilibrium is achieved without any unphysical effects due to the scheme.

Kelvin front generation on the equatorial β-plane. As a last test, we show the capabilities of the scheme proposed to capture the generation of short secondary waves. The test considered involves the formation and propagation of Kelvin and Rossby waves with a generation of a Kelvin front and secondary Poincaré waves. The set up is the the same as in [47, 25]. The computational domain $[0, 70] \times [0, 12]$ is divided into 140×24 cells. The initial condition and bottom topography are given by,

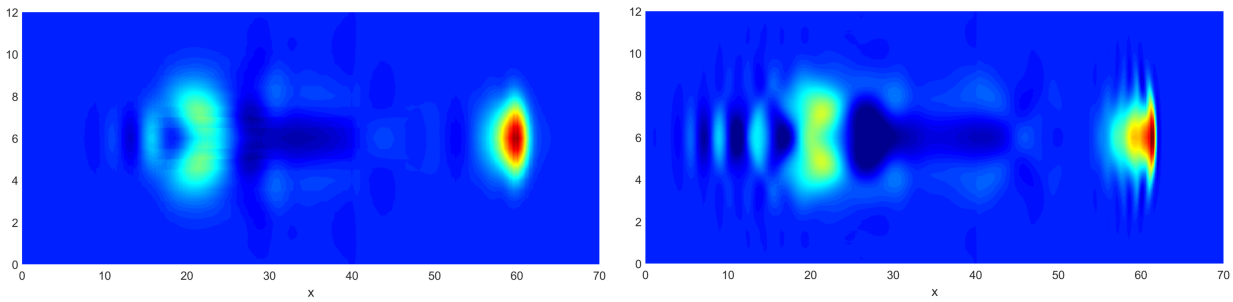
$$h(x, y, 0) = 2 - b(x, y) + 0.8exp\Big(- \frac{(x-30)^2 + (y-6)^2}{3}\Big)$$

$$b(x, y) = \begin{cases} 0 & x \leq 40 \\ 0.025x - 1 & x > 40 \end{cases}$$

with $g = 1\text{m/s}^2$. As for the moving vortex case, the Coriolis coefficient is modified to model the effects of curvature. In this case, following [47] we set $\omega(y) = y - 6$. Figure 27 shows the solution at $T = 20$ with a second and third order well balanced discontinuous Galerkin scheme.

The solution consists of the short wavelength Kelvin waves which carry energy eastwards and the long wavelength Rossby waves carrying energy westward. The nonlinear Kelvin waves steepen and eventually break forming a broken wave front propagating eastward which leads to generation of the secondary Poincaré waves. From the solution in Figure 27, we see that both the 2nd and 3rd order scheme are able to capture the general physical behavior of both the Kelvin and Rossby waves. However only the third order scheme

is able to capture the Poincaré waves. Indeed, the solution obtained with the second order method gives a Kelvin front too diffused to trigger the generation of these secondary waves.



(a) 2nd order

(b) 3rd order

Figure 27: Numerical solution for $h + b$ with 2nd and 3rd order discontinuous Galerkin scheme

8. Conclusions and perspectives

In this work we have studied a new formulation to construct numerical methods verifying a discrete fully well balanced criterion agnostic of the form of the steady solution sought. In one space dimension, the underlying discrete well balanced criterion is based on an equivalence between the local differential problem (ODE) defining the steady solution, and the non-local integral equation obtained from the steady ODE.

The discrete well balanced criterion proposed is based on the equivalence of independent discretizations of the two problems using the same data. The application of this idea to DGSEM schemes using Gauss-Lobatto interpolation shows that with a simple, and yet non-straightforward, modification of the integral of the source term we obtain an equivalence with Gauss collocation methods for the integral equation. This provides a discrete well balanced DGSEM approach, named a global flux quadrature based DGSEM, for which we have a clear characterization of the discrete steady state, with provable super-convergence estimates to general exact analytical steady states.

In addition, a cell correction term is proposed to verify cell entropy balance. The accuracy and the consistency of this term with the discrete well balanced condition proposed is characterized. The numerical benchmarks for the shallow water equations in one space dimension confirm all the theoretical properties on a wide variety of equilibria, involving several different source terms.

Numerical tests in two space dimensions show that the generalization of the global flux quadrature proposed allows error reductions of roughly one order of magnitude on smooth vortex like solutions. Applications on complex problems involving sharp fronts and complex wave patterns confirm the accuracy and show the robustness of the method.

Several perspectives are being explored including the design of non-linear variants allowing to handle genuinely discontinuous solutions, other discretization techniques (e.g. finite volumes), and more general formulations in particular for time-dependent and multi-dimensional problems.

Appendix A. Proof of the consistency estimate of Proposition 5.1

The proof follows [5]. Using the SBP property of the DGSEM applied to the sampled exact solution, and the nodal continuity of the latter, and omitting the boundary conditions, we can write

$$\begin{aligned}\mathcal{E} = \int_\Omega v_\mathrm{h} \partial_t U_\mathrm{h}^e - \int_\Omega \partial_x v_\mathrm{h} F_\mathrm{h}(U_\mathrm{h}^e) - \int_\Omega \partial_x v_\mathrm{h} R_\mathrm{h}^e \\ + \sum_K \mathcal{R}_K^{\mathsf{GL}} + \sum_K \alpha_K(U_\mathrm{h}^e) \int_K \partial_x v_\mathrm{h} A_0(U_\mathrm{h}^e) \partial_x U_\mathrm{h}^e\end{aligned} \tag{A.1}$$

with $\mathcal{R}_K^{\mathsf{GL}}$ the Gauss-Lobatto quadrature error, and where we remark that all the face terms have cancelled out due to the continuity of the smooth exact solution U^e, and to the sum over the elements. Using the continuity of the exact solution, the smoothness of the test function v, and thus the continuity of its interpolated approximation v_{h}, we can also write

$$\begin{aligned}\mathcal{E} = \overbrace{\int_\Omega v_{\mathrm{h}} \partial_t (U_{\mathrm{h}}^e - U^e)}^{\mathrm{I}} - \overbrace{\int_\Omega \partial_x v_{\mathrm{h}} (F_{\mathrm{h}}(U_{\mathrm{h}}^e) - F(U^e))}^{\mathrm{II}} - \overbrace{\int_\Omega \partial_x v_{\mathrm{h}} (R_{\mathrm{h}}^e - R^e)}^{\mathrm{III}} \\ + \sum_K \mathcal{R}_K^{\mathsf{GL}} + \sum_K \alpha_K(U_{\mathrm{h}}^e) \int_K \partial_x v_{\mathrm{h}} A_0(U_{\mathrm{h}}^e) \partial_x U_{\mathrm{h}}^e\end{aligned} \tag{A.2}$$

where the source flux R^e is obtained by exact integration of (assuming the initial state on the left hand of the domain to be zero)

$$R^e = \int_{x_0}^x S(U^e, s) \tag{A.3}$$

We now proceed to a term by term estimate. Following [5] we start from noting that for a test function $v \in C^k(\Omega)$ with $k \geq 1$ we can readily claim that

$$\|v_{\mathrm{h}}\| \leq C_1 < \infty\,, \quad \|\partial_x v_{\mathrm{h}}\| \leq C_2 < \infty \tag{A.4}$$

having omitted the L^2_Ω subscript from the norms to simplify the notation. This allows to bound terms I and II by the approximation error as

$$|\mathrm{I}| \leq \tilde{C}_1(\Omega, \|v\|)\, \mathrm{h}^{p+1}\,, \quad |\mathrm{II}| \leq \tilde{C}_2(\Omega, \|\partial_x v\|)\, \mathrm{h}^{p+1} \tag{A.5}$$

To bound term III we first consider the estimate of the quadrature rest. Under the the smoothness hypotheses made, for a finite element approximation of degree p in one dimension we can use the exactness of the Gauss-Lobatto formulas for polynomials of degree $2p-1$. To estimate the integration rest, one can e.g. introduce a local truncated Taylor series of the exact integrand and consider the first term not integrated exactly which can be bounded by an $\mathcal{O}(\mathrm{h}^{2p})$. This leads on each element to an integration rest of order $\mathcal{R}_K^{\mathsf{GL}} = \mathcal{O}(\mathrm{h} \times \mathrm{h}^{2p}) = \mathcal{O}(\mathrm{h}^{2p+1})$. Since the number of elements in one space dimension are of $\mathcal{O}(\mathrm{h}^{-1})$ we deduce that $\sum_K \mathcal{R}_K^{\mathsf{GL}} \leq C_{\mathsf{GL}} \mathrm{h}^{2p}$.

To estimate $(R_{\mathrm{h}}^e - R^e)(\bar{x})$ for a given point $\bar{x}$, we introduce the set $\mathcal{K}_{\bar{x}}$ of elements such that $x < \bar{x}$ within the element, and we denote by $K_{\bar{x}}$ the element containing the point. We can thus write

$$R_{\mathrm{h}}^e - R^e = \sum_{K \in \mathcal{K}_x} \left(\int_K S_h - \int_K S(U^e, x) \right) + \int_{x_{K_{\bar{x}}}^L}^{\bar{x}} S_h - \int_{x_{K_{\bar{x}}}^L}^{\bar{x}} S(U^e, x) \tag{A.6}$$

with all integrals computed exactly. As before for all the elements in $\mathcal{K}_{\bar{x}}$ we can use the properties of the Gauss-Lobatto formulas, and bound the first term by a $\mathcal{O}(\mathrm{h}^{2p+1})$. For the second term we can use the aapproximation error to estimate $S_{\mathrm{h}} - S$, and we end with

$$|R_{\mathrm{h}}^e - R^e| \leq C_1^S \mathrm{h}^{2p} + C_2^S \mathrm{h}^{p+2} = \bar{C}^S \min(\mathrm{h}^{2p}, \mathrm{h}^{p+2}) \tag{A.7}$$

We are left with the estimate of the cell correction term, evaluated using sampled values of the exact solution. We start by re-writing the coefficient α_K, re-writing the second in (52), (54), and (56) which under the current hypotheses become (cf. also equation (63))

$$\Phi_\eta^K(U_{\mathrm{h}}^e) = \int_K (W_{\mathrm{h}}^e)^t \partial_x G_{\mathrm{h}}\,, \quad \Psi_\eta^K(U_{\mathrm{h}}^e) = \int_K \partial_x F_\eta(U_{\mathrm{h}}^e)\,, \tag{A.8}$$

Noting that

$$\int_K \partial_t \eta_{\mathrm{h}} = \sum_{i=0,p} w_i \frac{d\eta_i}{dt} = \sum_{i=0,p} w_i W_i^t \frac{dU_i}{dt} \tag{A.9}$$

we can readily write

$$\Psi_\eta^K(U_\mathrm{h}^e) - \Phi_\eta^K(U_\mathrm{h}^e) = \int_K \left[(\partial_t \eta_\mathrm{h}(U_\mathrm{h}^e) + \partial_x F_\eta(U_\mathrm{h}^e)) - (W_\mathrm{h}^e)^t(\partial_t U_\mathrm{h}^e + \partial_x G_\mathrm{h}(U_\mathrm{h}^e))\right] + \mathcal{O}(\mathrm{h}^{2p+1}) \tag{A.10}$$

where, following the previous reasoning, the last term is the Gauss-Lobatto quadrature error on the $(W_\mathrm{h}^e)^t(\partial_t U_\mathrm{h}^e$ term. The remaining terms can be easily estimate based on standard approximation arguments following [5]:

$$\int_K (\partial_t \eta_\mathrm{h}(U_\mathrm{h}^e) + \partial_x F_\eta(U_\mathrm{h}^e)) = \int_K (\underbrace{\partial_t \eta_\mathrm{h}(U_\mathrm{h}^e) - \partial_t \eta^e}_{\mathcal{O}(\mathrm{h}^{p+1})} + \underbrace{\partial_x (F_\eta(U_\mathrm{h}^e) - F_\eta^e)}_{\mathcal{O}(\mathrm{h}^p)}) = \mathcal{O}(\mathrm{h}^{p+1}) \tag{A.11}$$

and similarly

$$\int_K (W_\mathrm{h}^e)^t(\partial_t U_\mathrm{h}^e + \partial_x G_\mathrm{h}(U_\mathrm{h}^e)) = \int_K (W_\mathrm{h}^e)^t \Big(\underbrace{\partial_t U_\mathrm{h}^e - \partial_t U^e}_{\mathcal{O}(\mathrm{h}^{p+1})} + \underbrace{\partial_x (G_\mathrm{h}(U_\mathrm{h}^e) - G^e)}_{\mathcal{O}(\mathrm{h}^p)} \Big) = \mathcal{O}(\mathrm{h}^{p+1}) \tag{A.12}$$

Using the boundedness of $\partial_x v_\mathrm{h}$, of $\partial_x U_\mathrm{h}^e$, and of $\partial_x W_\mathrm{h}^e$ we can thus estimate

$$\alpha_K(U_\mathrm{h}^e) = \frac{\Psi_\eta^K(U_\mathrm{h}^e) - \Phi_\eta^K(U_\mathrm{h}^e)}{\|\partial_x W_\mathrm{h}^e\|} = \mathcal{O}(\mathrm{h}^{p+1}) \tag{A.13}$$

and

$$\alpha_K(U_\mathrm{h}^e) \int_K \partial_x v_\mathrm{h} A_0(U_\mathrm{h}^e) \partial_x U_\mathrm{h}^e = \mathcal{O}(\mathrm{h}^{p+2}) \tag{A.14}$$

Using again the fact that in one dimension the number of elements is of $\mathcal{O}(\mathrm{h}^{-1})$ we conclude that

$$|\sum_K \alpha_K(U_\mathrm{h}^e) \int_K \partial_x v_\mathrm{h} A_0(U_\mathrm{h}^e) \partial_x U_\mathrm{h}^e| = \mathcal{O}(\mathrm{h}^{p+1}) \tag{A.15}$$

which used with the previous estimates leads to the desired result.

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