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Practical evaluation of five partly discontinuous finite element pairs for the non-conservative shallow water equations

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SUMMARY

This paper provides a comparison of five finite element pairs for the shallow water equations. We consider continuous, discontinuous and partially discontinuous finite element formulations that are supposed to provide second-order spatial accuracy. All of them rely on the same weak formulation, using Riemann solver to evaluate interface integrals. We define several asymptotic limit cases of the shallow water equations within their space of parameters. The idea is to develop a comparison of these numerical schemes in several relevant regimes of the subcritical shallow water flow. Finally, a new pair, using non-conforming linear elements for both velocities and elevation (P_1^{NC}–P_1^{NC}), is presented, giving optimal rates of convergence in all test cases. P_1^{NC}–P_1 and P_1^{DG}–P_1 mixed formulations lack convergence for inviscid flows. P_1^{DG}–P_2 pair is more expensive but provides accurate results for all benchmarks. P_1^{DG}–P_1^{DG} provides an efficient option, except for inviscid Coriolis-dominated flows, where a small lack of convergence is observed.

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KEY WORDS: finite element; shallow water equations; discontinuous Galerkin; non-conforming element; Riemann solver; convergence

1. INTRODUCTION

The shallow water equations are a classical model used in a wide area of physics and engineering. They govern flows in estuaries, enable modeling of dam-breaks, floods and tides, and are a key building block for ocean modeling as well as atmosphere modeling. Different numerical methods

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have been designed for the shallow water equations. Finite volumes are very popular for small scale applications as well as atmosphere modeling, whereas ocean models are mainly based on finite difference methods [1], as described for instance in the book [2]. In the finite element framework, major contributions have been developed with both discontinuous and continuous elements.

The discontinuous Galerkin (DG) method has been growing interest since the late nineties, and gives accurate results for hyperbolic conservation laws. Basically, it consists of a volume term built as in all finite element methods, and an interface term built as in finite volume methods. High-order shape functions can be easily incorporated and at the interfaces, an efficient upwind flux calculation can be performed to tackle the treatment of wave phenomena. Thanks to the absence of continuity constraints on the inter-element boundaries, h-adaptivity [3, 4] and p-adaptivity [5] can be easily implemented. Efficient slope and flux limiters enable positive and shock-capturing versions of the scheme [6–8]. For atmosphere modeling, the high-order capabilities of this scheme are really attractive [9, 10], and the increasing use of DG follows the trend to replace spectral transform methods with local ones. Coastal modeling also benefits from this method [11–13], and high Froude number flows are accurately captured by these kinds of schemes [8, 14]. However, the implementation of elliptic dissipative terms requires some specific modifications, as reviewed in [15]. The local-DG method (LDG) and the interior penalty (IP) method are among the most popular solutions. LDG introduces a mixed formulation for velocities and stress and can be difficult to handle with an implicit time-stepping [16], while IP requires the introduction of a penalty parameter that worsen the conditioning of the discrete spatial operator [17].

Continuous linear finite elements are compelling as they provide high geometric flexibility, they are supposed to be much more accurate than first-order methods, and have less degrees of freedom than linear DG methods. Further, they naturally handle elliptic operators used as subgrid scale models. Several choices can be made between stable mixed methods and stabilized methods. Stabilized methods were first designed for scalar advection–diffusion equations, where the standard Galerkin method gives an oscillating result when the mesh Peclet number is too large [18]. For shallow water models, [19–22] use a symmetric formulation that is stabilized with the Petrov–Galerkin approach.

In this paper, we do not analyze stabilized continuous finite element methods, instead we choose to use naturally stable finite elements. Furthermore, to develop a fair comparison with all stabilized continuous formulations, it would require a very systematic analysis that is out of the scope of this paper.

The search for an efficient mixed formulation for the shallow water equations without explicit stabilization is described in a series of papers [23–29]. The favorite candidate is the $P_1^{NC} - P_1$ pair, namely linear non-conforming P_1^{NC} for the velocities and linear conforming P_1 for the elevation. This pair was first presented in [30] within the framework of two-layer models. The idea is simple: try to mimic the staggering of variables used in finite difference schemes in the finite element framework. Reference [23] is a seminal review paper on mixed methods for finite element shallow water and initiated several works on the P_1^{NC}–P_1 mixed element pair. Further, this pair has been shown to be free of spurious elevation modes [27], and it has been tested with both Eulerian and Lagrangian discretizations of advection terms [26]. In the inviscid limit, the semi-Lagrangian discretization of [26] exhibits a strong noise in the velocity field, which needs to be filtered out. The Eulerian formulation described in this paper appears to avoid this noise, due to the stabilizing effect of the upwind scheme on advection terms. The analysis of dispersion and dissipation properties is performed in [28] where a semi-analytical dispersion relation is derived on structured grids. Dissipation and dispersion relations are computed numerically on unstructured

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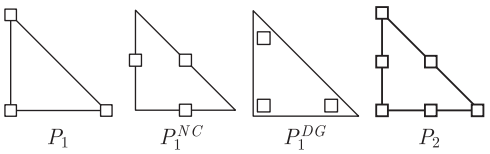

Figure 1. Sketch of the different finite elements used.

grids in [31]. It appears that the $P_1^{\mathrm{NC}} - P_1$ pair works really well on structured grids, but is suboptimal on unstructured grids, in terms of accuracy [29] and in terms of dispersion. Recently, a new mixed element, $P_1^{\mathrm{DG}} - P_2$, has been presented. Such an element exhibits stability and good rates of convergence for the Stokes problem and the wave equation [32] and has been proven to be LBB stable [33].

Within its space of parameters, the shallow water system has several asymptotic limit cases. In the steady viscous limit, the well-known Stokes system is found. The linear non-rotating and inviscid shallow water equations reduce to a wave equation. When Coriolis force is the leading term, we observe a geostrophic equilibrium. An almost optimal finite element method is known for each of those problems. The Stokes problem is a saddle-point problem, and the finite element formulation needs to satisfy the LBB condition, which for Galerkin formulations lead to choose a larger discrete space for velocities than for elevation, for instance P_2–P_1. The velocities and elevation have a symmetric role in the wave equation, thus using the same space for both fields is the natural solution. In the geostrophic limit, the space for velocities is the gradient of the space for elevation and a pair like P_1^{DG}–P_2^{DG} appears to be best suited. Of course, in real life applications, those different regimes are mixed, and a formulation at least stable in all ranges of parameters is sought. Our typical domain of application is estuarine, coastal and ocean modeling. Therefore, we do not focus on supercritical flows, where shocks require specific handling, while we are aware that this regime is of crucial importance for smaller scale applications.

In this paper, we focus on numerical schemes where the stabilizing strategies are only applied on the interface terms. It must be noted that it would be also possible to add stabilizing terms in the surface terms as it is usual in continuous stabilized formulations. In general, continuous stabilizing terms corresponds to adding diffusion with a coefficient depending on the element size, in a more or less consistent manner. For discontinuous methods, the interfaces integrals are estimated with an upwind bias introducing the right amount of dissipation to keep the scheme stable. We provide here a comparison between different finite element pairs that all rely on the same weak formulation: $P_1^{\mathrm{DG}} - P_1^{\mathrm{DG}}$, $P_1^{\mathrm{NC}} - P_1^{\mathrm{NC}}$, $P_1^{\mathrm{NC}} - P_1$, $P_1^{\mathrm{DG}} - P_1$ and $P_1^{\mathrm{DG}} - P_2$. A sketch of those elements is given in Figure 1.

The outline of this paper is the following: Section 2 explains the methodology followed to derive all the formulations in the framework of one-dimensional linear shallow water equations, Section 3 details the formulation for the five finite element pairs considered, and finally, we assess the qualities and drawbacks of each formulation in Section 4.

2. ONE-DIMENSIONAL ILLUSTRATION OF KEY CONCEPTS

In this section, the main concepts used in this paper are illustrated for the one-dimensional wave equation, which is the simplest idealization of the shallow water equations. The one-dimensional

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wave equation reads

$$\frac{\partial^2 \eta}{\partial t^2} = gh \frac{\partial^2 \eta}{\partial x^2} \tag{1}$$

and is equivalent to the following system of equations, known as the linearized inviscid shallow water equations in a non-rotating framework:

$$\frac{\partial \eta}{\partial t} + h \frac{\partial u}{\partial x} = 0 \tag{2}$$

$$\frac{\partial u}{\partial t} + g \frac{\partial \eta}{\partial x} = 0 \tag{3}$$

where u is the depth-averaged velocity, η the free-surface elevation, h the depth at rest and g the gravitational acceleration.

We analyze the selection of mixed continuous or discontinuous spaces and the design of a suitable Riemann solver. In particular, three different finite element pairs are considered:

- $P_1 - P_1$ elements, for velocity and elevation, respectively.
- $P_1^{\mathrm{DG}} - P_1^{\mathrm{DG}}$ elements, the one-dimensional equivalent to the $P_1^{\mathrm{DG}} - P_1^{\mathrm{DG}}$ two-dimensional pair and the closest to the $P_1^{\mathrm{NC}} - P_1^{\mathrm{NC}}$ pair.
- $P_1^{\mathrm{DG}} - P_1$ elements, which is the closest to two-dimensional $P_1^{\mathrm{NC}} - P_1$ and $P_1^{\mathrm{DG}} - P_1$.

All mixed methods rely on the same weak formulation:

$$\left\langle \frac{\partial \eta}{\partial t} \hat{\eta} \right\rangle + \left\langle h \frac{\partial u}{\partial x} \hat{\eta} \right\rangle = 0 \tag{4}$$

$$\left\langle \frac{\partial u}{\partial t} \hat{u} \right\rangle + \left\langle g \frac{\partial \eta}{\partial x} \hat{u} \right\rangle = 0 \tag{5}$$

with $\langle \quad \rangle$ denoting the integral over Ω, and $\hat{\eta}$ and $\hat{u}$ the test functions. This domain Ω is then discretized into a mesh or a collection of non-overlapping elements Ω_e. Equations (4) and (5) can be expressed as a sum of the integrals on each element:

$$\sum_e \left(\left\langle \frac{\partial \eta}{\partial t} \hat{\eta} \right\rangle_{\Omega_e} + \left\langle h \frac{\partial u}{\partial x} \hat{\eta} \right\rangle_{\Omega_e} \right) = 0 \tag{6}$$

$$\sum_e \left(\left\langle \frac{\partial u}{\partial t} \hat{u} \right\rangle_{\Omega_e} + \left\langle g \frac{\partial \eta}{\partial x} \hat{u} \right\rangle_{\Omega_e} \right) = 0 \tag{7}$$

Finally, in order to incorporate the local Neumann boundary condition, we integrate the gradient terms by part:

$$\sum_e \left(\left\langle \frac{\partial \eta}{\partial t} \hat{\eta} \right\rangle_{\Omega_e} + hu^* \hat{\eta} \Big|_{\partial \Omega_e} - \left\langle hu \frac{\partial \hat{\eta}}{\partial x} \right\rangle_{\Omega_e} \right) = 0 \tag{8}$$

$$\sum_e \left(\left\langle \frac{\partial u}{\partial t} \hat{u} \right\rangle_{\Omega_e} + g\eta^* \hat{u} \Big|_{\partial \Omega_e} - \left\langle g\eta \frac{\partial \hat{u}}{\partial x} \right\rangle_{\Omega_e} \right) = 0 \tag{9}$$

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where $f|_{\partial\Omega_e}$ denotes the difference between f at the right end of the element and f at the left end. The values of the fields at both ends of each interval are denoted with a star superscript, because they need to be uniquely defined for both neighboring elements of the interface. The way to define u^* and η^* is the key ingredient to obtain a stable and accurate numerical formulation. Along interior interfaces, for continuous test functions, the boundary integral on the one element is canceled out by the boundary integral on the other element, but it is not the case for discontinuous test functions.

2.1. Riemann solver

To derive consistent values of fluxes u^* and η^* at the interface, relying on the characteristic structure of the equations, it is usual to introduce Riemann solver for numerical methods. Riemann solvers are a solution to deduce consistent values of fluxes. It allows to add just enough numerical dissipation to keep the scheme stable. For a scalar advection equation, using the upwind value at the interface introduces the right amount of dissipation that prevents the oscillations of the numerical solution. The Riemann solvers can be viewed as the generalization of the upwinding technique for systems of equations.

In matrix notation, the shallow water system of Equations (2) and (3) read as:

$$\begin{pmatrix}\eta_{,t}\\ u_{,t}\end{pmatrix}+\underbrace{\begin{pmatrix}0 & h\\ g & 0\end{pmatrix}}_{A}\begin{pmatrix}\eta_{,x}\\ u_{,x}\end{pmatrix}=\begin{pmatrix}0\\ 0\end{pmatrix} \tag{10}$$

Let us now perform a change of variable such that the matrix A becomes diagonal. We then obtain the shallow water equations in terms of the characteristic variables:

$$\begin{pmatrix}U\\ V\end{pmatrix}=R^{-1}\begin{pmatrix}\eta\\ u\end{pmatrix}=\begin{pmatrix}\dfrac{\eta}{2}+u\dfrac{\sqrt{h/g}}{2}\\ \dfrac{\eta}{2}-u\dfrac{\sqrt{h/g}}{2}\end{pmatrix} \tag{11}$$

where R is the matrix whose columns are eigenvectors of A:

$$R=\begin{pmatrix}1 & 1\\ \sqrt{g/h} & -\sqrt{g/h}\end{pmatrix} \tag{12}$$

The system in terms of the characteristic variables corresponds to two uncoupled advection equations:

$$\begin{pmatrix}U_{,t}\\ V_{,t}\end{pmatrix}+\begin{pmatrix}\sqrt{gh} & 0\\ 0 & -\sqrt{gh}\end{pmatrix}\begin{pmatrix}U_{,x}\\ V_{,x}\end{pmatrix}=\begin{pmatrix}0\\ 0\end{pmatrix} \tag{13}$$

We define the $*$ variables using the upwind value that depends on the sign of the eigenvalue:

$$U^*=U^L,\quad V^*=V^R \tag{14}$$

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where the L and R superscripts denote values taken at the left and right side of the interface, respectively. Expressing the original variables in terms of the characteristic ones, we get:

$$\eta = U + V, \quad u = \sqrt{\frac{g}{h}}(U - V) \tag{15}$$

and we derive the classical well-known expressions:

$$\eta^* = U^L + V^R = \{\eta\} + \sqrt{\frac{h}{g}}[u], \quad u^* = \sqrt{\frac{g}{h}}(U^L - V^R) = \{u\} + \sqrt{\frac{g}{h}}[\eta] \tag{16}$$

with $\{a\} = (a^L + a^R)/2$ the mean and $[a] = (a^L - a^R)/2$ the jump.

The same methodology can be applied to the hybrid continuous/discontinuous finite element pair. The interface terms in the elevation equation disappear due to the continuity of the test functions, as corresponding equal contributions are added at a node by the two elements surrounding the interface. If η is continuous, (16) degenerates to:

$$\eta^* = \eta + \sqrt{\frac{h}{g}}[u], \quad u^* = \{u\} \tag{17}$$

To assess the quality of this formulation with the three finite element pairs, we have performed a convergence analysis on a wave problem with periodic boundary conditions (Figure 2). We observe second-order accuracy for each discretization. The optimal rate of convergence observed with the hybrid discretization $P_1^{\mathrm{DG}} - P_1$ shows that using a mixed discontinuous–continuous pair of elements is not *a priori* a bad idea, even if the number of degrees of freedom is different, and hence the symmetry of the discretization is broken.

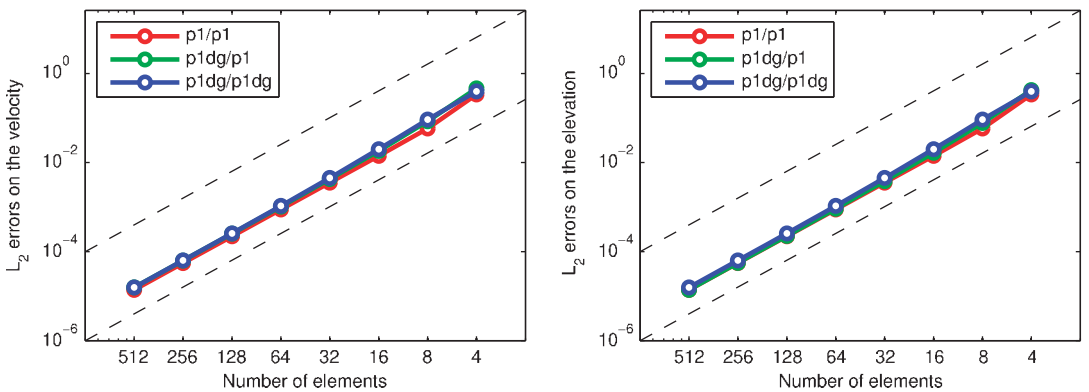

Figure 2. Convergence analysis for the wave equation with periodic boundary conditions. Second-order convergence is observed on both fields for three mixed linear continuous/discontinuous discretizations.

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3. TWO-DIMENSIONAL DISCRETIZATION OF THE SHALLOW WATER EQUATIONS

Let us now consider the complete shallow water equations including inertia terms, Coriolis effects, viscous terms, and both wind and bottom stresses. It is usual to distinguish two classical formulations, when deriving a numerical scheme. On the one hand, the conservative formulation in terms of the total depth H and the transport $H\mathbf{u}$ read as:

$$\frac{\partial H}{\partial t}+\nabla\cdot(H\mathbf{u})=0 \tag{18}$$

$$\frac{\partial H\mathbf{u}}{\partial t}+\nabla\cdot(H\mathbf{u}\mathbf{u})+f\mathbf{k}\times(H\mathbf{u})+gH\nabla(H-h)=\nabla\cdot(H\nu(\nabla\mathbf{u}))+\frac{\boldsymbol{\tau}^s+\boldsymbol{\tau}^b}{\rho} \tag{19}$$

with h the depth at rest, f the Coriolis factor, $\mathbf{k}$ the vertical unit vector, $\boldsymbol{\tau}^s$ and $\boldsymbol{\tau}^b$ the surface and bottom stresses, ρ the density and ν the eddy viscosity. On the other hand, the non-conservative formulation in terms of free-surface elevation η (with $H=h+\eta$) and velocity $\mathbf{u}$ read as:

$$\frac{\partial\eta}{\partial t}+\nabla\cdot((h+\eta)\ \mathbf{u})=0 \tag{20}$$

$$\frac{\partial\mathbf{u}}{\partial t}+\mathbf{u}\cdot(\nabla\mathbf{u})+f\mathbf{k}\times\mathbf{u}+g\nabla\eta=\frac{1}{H}\nabla\cdot(H\nu(\nabla\mathbf{u}))+\frac{\boldsymbol{\tau}^s+\boldsymbol{\tau}^b}{\rho H} \tag{21}$$

It is customary to use the conservative formulation when deriving finite difference schemes for the shallow water equations in order to obtain a conservative numerical scheme. However, in a continuous framework, both formulations are strictly equivalent.

In this paper, we use the non-conservative form of the shallow water equations to derive the weak formulation, with a nonlinear approximate Riemann solver deduced from the conservative form of the same equations. This approach might appear exotic but it is motivated by the following facts. First, it is natural to write a Riemann solver in terms of the fluxes of quantities to be conserved. Second, it would be attractive to write a weak conservative formulation but in this case, the elevation gradient term has to be split into two parts, a flux term and a source term:

$$gH\nabla(H-h)=\frac{g\nabla(H^2-h^2)}{2}-g(H-h)\nabla h \tag{22}$$

With DG methods, both terms are not treated in the same way. It has been shown that the scheme may exhibit non-physical oscillations if the integration is not accurate enough [13]. Therefore, a weak non-conservative formulation seems more efficient and robust in the considered numerical discretization.

3.1. Non-conservative weak formulation

The weak form of this non-conservative formulation read as:

$$\sum_e\left(\left\langle\frac{\partial\eta}{\partial t}\ \hat{\eta}\right\rangle_{\Omega_e}+\langle\nabla\cdot((h+\eta)\ \mathbf{u})\ \hat{\eta}\rangle_{\Omega_e}\right)=0 \tag{23}$$

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$$\sum_e \left(\left\langle \frac{\partial \mathbf{u}}{\partial t} \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} + \langle \mathbf{u} \cdot (\nabla \mathbf{u}) \cdot \hat{\mathbf{u}} \rangle_{\Omega_e} + \langle f(\mathbf{k} \times \mathbf{u}) \cdot \hat{\mathbf{u}} \rangle_{\Omega_e} + g \langle (\nabla \eta) \cdot \hat{\mathbf{u}} \rangle_{\Omega_e} \right)$$
$$= \sum_e \left(\left\langle \frac{1}{H} \nabla \cdot (H \nu (\nabla \mathbf{u})) \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} + \left\langle \frac{\boldsymbol{\tau}^s + \boldsymbol{\tau}^b}{\rho H} \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} \right) \tag{24}$$

Again integrating by parts, we get:

$$\sum_e \left(\left\langle \frac{\partial \eta}{\partial t} \hat{\eta} \right\rangle_{\Omega_e} + \langle \langle (h+\eta^*) u_n^* \hat{\eta} \rangle \rangle_{\partial \Omega_e} - \langle (h+\eta)\ \mathbf{u} \cdot \nabla \hat{\eta} \rangle_{\Omega_e} \right) = 0 \tag{25}$$

$$\sum_e \left(\left\langle \frac{\partial \mathbf{u}}{\partial t} \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} + \langle \langle u_n^* \mathbf{u}^* \cdot \hat{\mathbf{u}} \rangle \rangle_{\partial \Omega_e} - \langle \nabla \cdot (\mathbf{u} \hat{\mathbf{u}}) \cdot \mathbf{u} \rangle_{\Omega_e} \right.$$
$$\left. + \langle f(\mathbf{k} \times \mathbf{u}) \cdot \hat{\mathbf{u}} \rangle_{\Omega_e} + g \langle \langle \eta^* \hat{u}_n \rangle \rangle_{\partial \Omega_e} - g \langle \eta (\nabla \cdot \hat{\mathbf{u}}) \rangle_{\Omega_e} \right)$$
$$= \sum_e \left(\left\langle \left\langle v \left\{ \frac{\partial \mathbf{u}}{\partial n} \right\} \cdot \hat{\mathbf{u}} \right\rangle \right\rangle_{\partial \Omega_e} - \langle \nu (\nabla \mathbf{u}) : (\nabla \hat{\mathbf{u}}) \rangle_{\Omega_e} \right.$$
$$\left. + \left\langle v \frac{1}{H} (\nabla H) \cdot (\nabla \mathbf{u}) \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} + \left\langle \frac{\boldsymbol{\tau}^s + \boldsymbol{\tau}^b}{\rho H} \cdot \hat{\mathbf{u}} \right\rangle_{\Omega_e} \right) \tag{26}$$

The vector quantities multiplied by the outward normal are denoted with an n subscript. Again, the variables used in the boundary integrals are doubled-valued, and are denoted with a star superscript. However, for the diffusive flux, it is natural to take the centered values denoted by $\{\ \}$, as diffusive phenomena are isotropic. As explained in the Introduction, a specific treatment is needed to obtain a stable and accurate discretization of the diffusive term when using discontinuous elements for the velocities. In this case, the following term is added on the right-hand side of equation (26):

$$\sum_e (-\langle \langle \sigma \hat{\mathbf{u}} \cdot [\mathbf{u}] \rangle \rangle) \tag{27}$$

with σ a penalization parameter defined as:

$$\sigma = \frac{\nu (p+1)(p+2)}{h} \tag{28}$$

with h a typical length scale of the element, and p the polynomial order of the finite element space. This value of the penalization parameter has been proposed in [34].

3.2. Approximate nonlinear Riemann solver

Unfortunately, a Riemann solver cannot be applied on the non-conservative form of the equations, as they are not in flux form. To derive the Riemann solver, we use the conservative form (18)

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and (19) of the shallow water equations, where the dissipation, Coriolis and diffusion terms are neglected. Considering u as the velocity normal to the interface, and v the velocity tangent to the interface, the flux read as:

$$F=\begin{pmatrix} F_H \\ F_{Hu} \\ F_{Hv} \end{pmatrix}=\begin{pmatrix} Hu \\ Huu+\dfrac{g}{2}H^2 \\ Huv \end{pmatrix} \tag{29}$$

The exact Riemann solver requires the resolution of a nonlinear problem at each integration point. It is usually preferred to use an approximate Riemann solver. In order to deduce such an approximate Riemann solver, the next step consists of linearizing the fluxes. The Jacobian matrix of the fluxes is:

$$J=\begin{pmatrix} 0 & 1 & 0 \\ -u^2+gH & 2u & 0 \\ -uv & v & u \end{pmatrix} \tag{30}$$

Finally, we use the Roe averages to obtain an approximate Jacobian matrix $J_{\text{linearized}}$, as in classical textbooks [35]. This rule can be deduced easily from the Rankine–Hugoniot relation:

$$J_{\text{linearized}}\begin{pmatrix} [H] \\ [Hu] \\ [Hv] \end{pmatrix}=[F] \tag{31}$$

As the first line of the Jacobian matrix is linear, the Rankine–Hugoniot relation leads to an underdetermined system. To obtain a unique solution of the system, we select the arithmetic mean for H, and we get the classical Roe averages:

$$H_{\text{Roe}}=\{H\} \tag{32}$$

$$u_{\text{Roe}}=\frac{u_L\sqrt{H_L}+u_R\sqrt{H_R}}{\sqrt{H_L}+\sqrt{H_R}} \tag{33}$$

$$v_{\text{Roe}}=\frac{v_L\sqrt{H_L}+v_R\sqrt{H_R}}{\sqrt{H_L}+\sqrt{H_R}} \tag{34}$$

By substituting (H,u,v) by $(H_{\text{Roe}},u_{\text{Roe}},v_{\text{Roe}})$ in the Jacobian, the approximate Riemann values of the conservative variables can be deduced as the exact solution of the linearized problem, as shown in the illustrative one-dimensional wave equation. The values of the conservative and non-conservative variables at the interface are given by:

$$H^*=\{H\}+\frac{1}{\sqrt{gH_{\text{Roe}}}}([Hu]-u_{\text{Roe}}[H]) \tag{35}$$

$$(Hu)^*=\{Hu\}+\frac{1}{\sqrt{gH_{\text{Roe}}}}(u_{\text{Roe}}[Hu]-u_{\text{Roe}}^2[H]) \tag{36}$$

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$$(Hv)^* = (Hv)_{\text{upwind}} + v_{\text{Roe}}(\{H\} - H_{\text{upwind}}) + \frac{1}{\sqrt{gH_{\text{Roe}}}}(v_{\text{Roe}}[Hu] - u_{\text{Roe}}v_{\text{Roe}}[H]) \tag{37}$$

$$\eta^* = H^* - h \tag{38}$$

$$u^* = \frac{(Hu)^*}{H^*} \tag{39}$$

$$v^* = \frac{(Hv)^*}{H^*} \tag{40}$$

4. MESH REFINEMENT METHODOLOGY

4.1. Description of the meshes

Convergence tests are carried out with a family of 25 meshes adapted to the reference solution of the flow except for both wave problems where uniform unstructured meshes are used. We use adapted meshes rather than uniform meshes, since some of the studied flows have western boundary layers that need to be sufficiently resolved to observe the asymptotic convergence of the schemes. Using uniform meshes would require many more elements to observe asymptotic behavior. Note that this is different from mesh adaptation in time, where the mesh is adapted to the numerically computed flow during the simulation, as in [4]. The greatest eigenvalue of the elevation field's Hessian matrix is used as an *a priori* error estimator, since with linear elements, the error is dominated by the quadratic component of the solution. We define a reference edge length field δ as:

$$\delta(x, y) = \sqrt{\frac{\int_\Omega e(x', y')\mathrm{d}x'\mathrm{d}y'}{e(x, y)}} \tag{41}$$

where $e(x, y)$ is the norm of the greatest eigenvalue of the Hessian matrix of the elevation field. The meshes are generated using Gmsh [36], where we use $h\delta$ as edge-length field, with h as constant over the domain. The generated meshes have therefore about $1/(ah^2)$ elements, with $a \approx 0.8$ the typical area of a triangle whose edges have unit length. Such meshes are designed optimally for schemes giving second-order accuracy. However, the mesh need not be optimally adapted to observe the right convergence behavior. If it is suitably adapted, asymptotic convergence will occur with fewer elements. In Figure 3, we show the reference edge-length field δ and five of the corresponding meshes for the nonlinear Munk test case. The 9th finest mesh of each family, made of about 2500 triangles, is shown in Figures 5–9. Reference solutions are obtained using highly accurate P_3^{DG}–P_2^{DG} scheme for Stokes problem and P_3^{DG}–P_3^{DG} scheme for all other problems, using the same discrete formulation and time-stepping algorithm on the finest mesh used for the convergence tests.

4.2. Description of the 8 test cases

In realistic applications, a process, i.e. advection, geostrophy, diffusion, etc., can be the leading phenomena in some areas while being almost negligible in other areas for a single computation.

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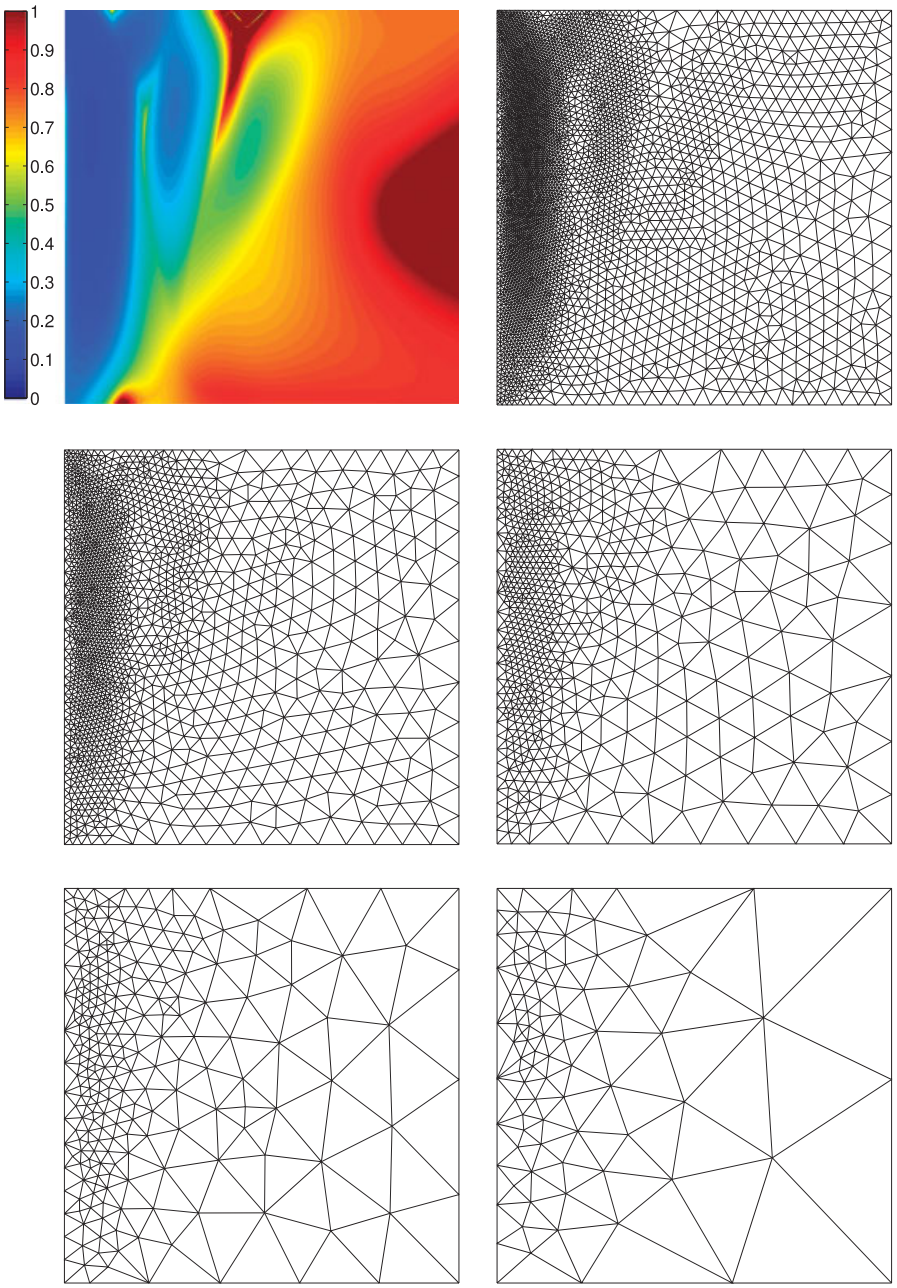

Figure 3. Sketch of the edge-length field δ and five corresponding meshes for the nonlinear Munk test case.

Therefore, the limit cases including or not including this phenomenon have both to be solved accurately. Unfortunately, it is not the case for some schemes that would appear to be attractive otherwise.

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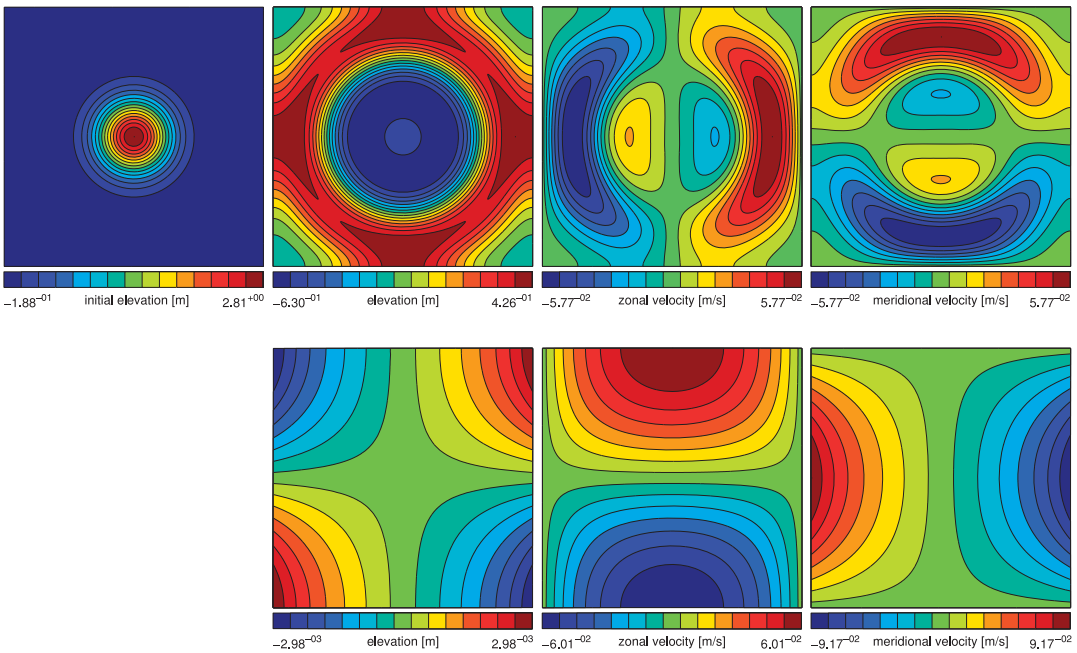

Figure 4. Sketch of the elevation and velocity fields for the unsteady (top, after 1 h of physical time) and steady (bottom) wave test cases.

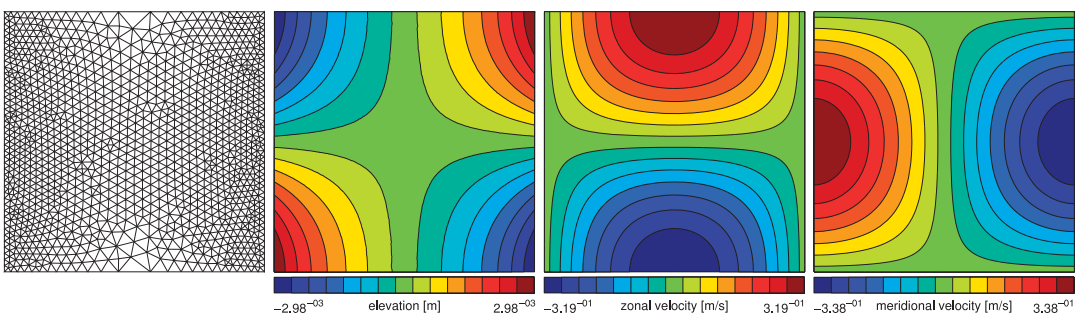

Figure 5. Typical mesh and sketch of the elevation and velocity fields for the Stokes test case.

Considering typical oceanic and coastal flows, we define a series of test cases, with the corresponding relevant meshes, detailed in Figures 4–9. The objective is to fairly compare the proposed finite element pair. Three limit flow states of the shallow water system, namely geostrophy, wave propagation and viscosity, are tested separately, and then the complexity of the problem is increased towards more realistic computations. Each flow develops in a square basin of 1000×1000 km.

Some of the test cases use a zonal wind stress, defined as:

$$\boldsymbol{\tau}^s = 0.1 \times \sin\left(\pi \frac{y}{L}\right) \mathbf{e}_x \tag{42}$$

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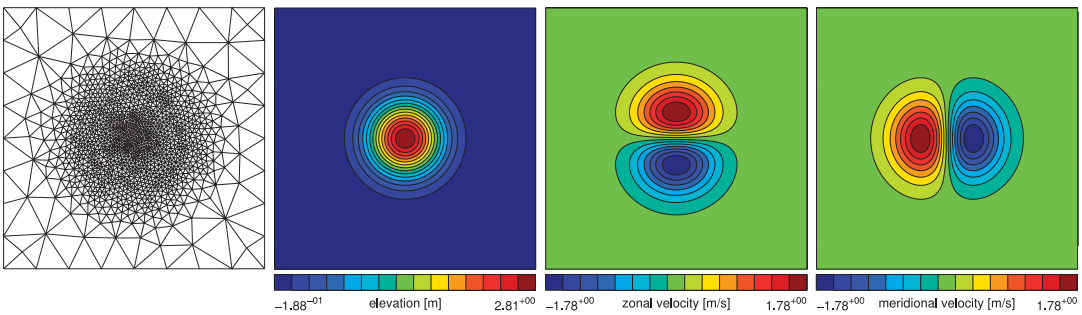

Figure 6. Typical mesh and sketch of the elevation and velocity fields for the geostrophic equilibrium test case.

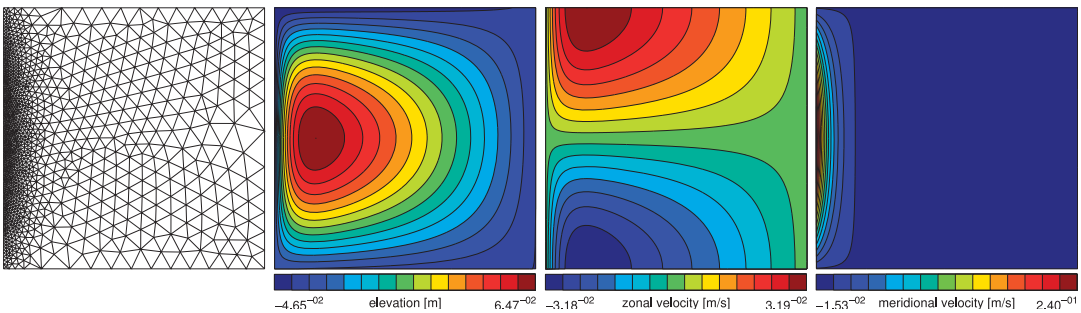

Figure 7. Typical mesh and sketch of the elevation and velocity fields for the Stommel gyre test case.

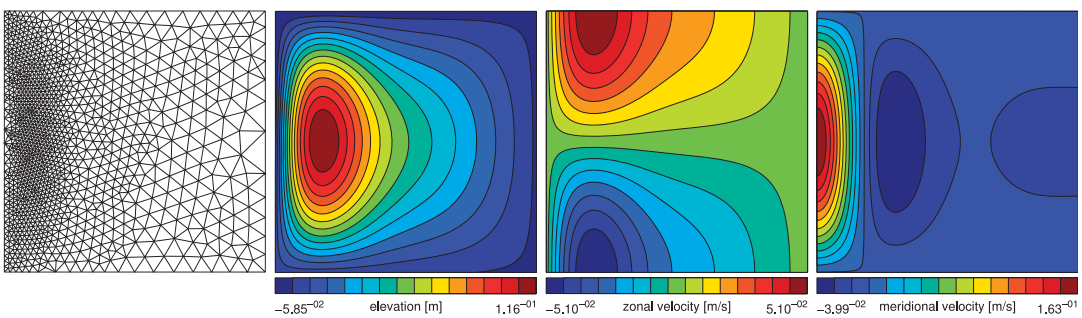

Figure 8. Typical mesh and sketch of the elevation and velocity fields for the Munk gyre test case.

inducing a clockwise circulation, and a linear dissipation term defined as:

$$\boldsymbol{\tau}^b = -\rho h \gamma \mathbf{u} \tag{43}$$

For all the test cases, we use slipping coasts. The test cases with viscosity need a second boundary condition, so we cancel out the normal flux of tangential velocity, and we compute the

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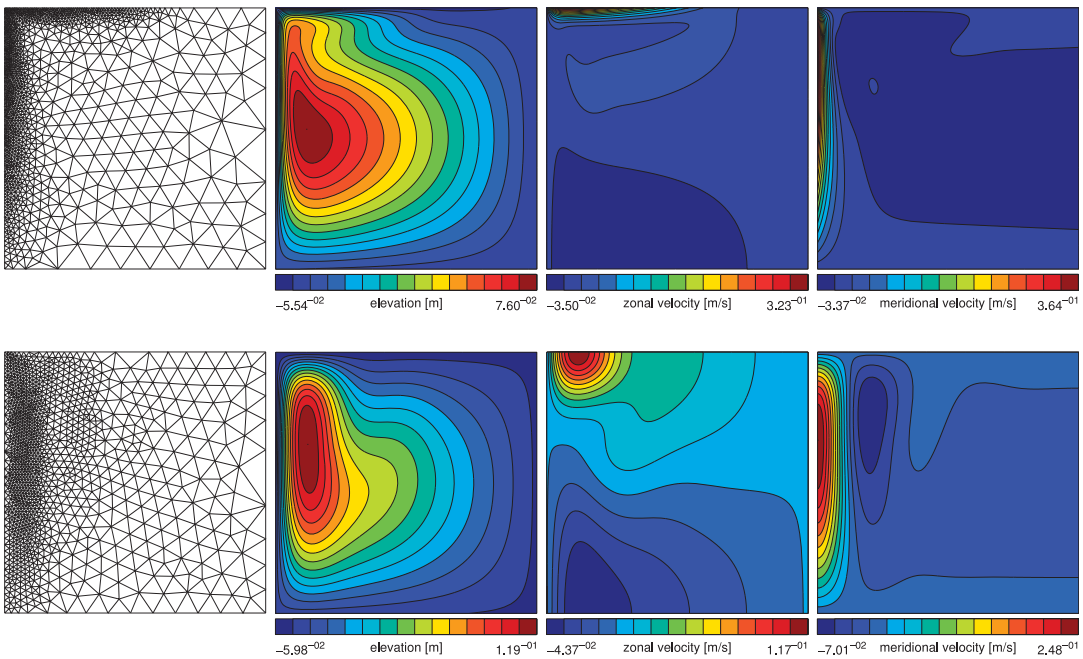

Figure 9. Typical meshes and sketch of the elevation and velocity fields for the nonlinear Stommel (top) and Munk (bottom) gyres.

normal flux of normal velocity with the interior value of the velocity. Table I summarizes the physical parameters that define each test case.

4.3. Wave equation

As a first test case, we consider the linear wave equation:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \tag{44}$$

$$\frac{\partial \mathbf{u}}{\partial t} + g\nabla \eta = 0 \tag{45}$$

It is the simplest approximation of the shallow water equations. Wave phenomena are the leading effects in small scale low Froude number flows. A Gaussian is given as initial condition for the elevation, and we observe the solution after 1 h, so that the wave crest has covered more than 350 km. A fourth-order explicit Runge–Kutta scheme is used to progress in time, with a time step corresponding to the CFL condition, ensuring that the solution is converged in time.

As the goal of this paper is to show which finite element pair may be unstable or exhibit a lack of convergence, a steady test case is much tougher. Indeed, the spurious modes that can appear in a finite element discretization are fully excited in steady solution, while they appear progressively

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Table I. Summary of physical parameters for each test case.

	L (m)	H (m)	g (ms^{-2})	f (s^{-1})	β ($m^{-1}s^{-1}$)	γ (s^{-1})	v (ms^{-2})	Nonlinear advection and free-surface terms	Wind stress
Unsteady wave	10^6	10^3	9.81	0	0	0	0	No	No
Steady wave	10^6	10^3	9.81	0	0	10^{-6}	0	No	Yes
Stokes	10^6	10^3	9.81	0	0	0	10^4	No	Yes
Geostrophic equilibrium	10^6	10^3	9.81	10^{-4}	0	0	0	No	No
Stommel gyre	10^6	10^3	9.81	10^{-4}	2×10^{-11}	10^{-6}	0	No	Yes
Munk gyre	10^6	10^3	9.81	10^{-4}	2×10^{-11}	0	10^4	No	Yes
Advective Stommel gyre	10^6	10^3	9.81	10^{-4}	2×10^{-11}	5×10^{-7}	0	Yes	Yes
Advection Munk gyre	10^6	10^3	9.81	10^{-4}	2×10^{-11}	0	3000	Yes	Yes

in a time-dependent problem. We then simulate a steady flow where wind forcing is balanced by linear dissipation:

$$\nabla\cdot(h\mathbf{u})=0 \tag{46}$$

$$g\nabla\eta=\frac{\boldsymbol{\tau}^s}{\rho h}-\gamma u \tag{47}$$

with $\gamma=10^{-6}\,s^{-1}$.

4.4. *Stokes flow*

The Stokes equations represent creeping flows, where inertial terms are negligible compared to viscous terms. This problem is difficult to solve numerically, because the incompressibility equation acts as a constraint on the velocity field. In order to obtain a mixed discrete formulation that defines a well-posed problem, it is mandatory to stabilize the discrete formulation or to define the mixed discretization space in such a way that the LBB condition is satisfied [37]. From a practical point of view, the discrete space for elevation/pressure must be small enough compared to the discrete space for velocities in a usual mixed formulation. The wind forcing now balances the viscous dissipation:

$$\nabla\cdot(h\mathbf{u})=0 \tag{48}$$

$$g\nabla\eta=\frac{\boldsymbol{\tau}^s}{\rho h}+\nabla\cdot(v\nabla\mathbf{u}) \tag{49}$$

with $v=10^4\,m\,s^{-2}$.

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4.5. Geostrophic equilibrium

Geophysical flows experience the Coriolis force due to the Earth's rotation. It is one of the leading terms in the large scale shallow water equations. We test the ability of the different methods to maintain a linear geostrophic equilibrium, where the Coriolis force is in balance with the elevation gradient. As there is no dissipation, a good numerical scheme should maintain this equilibrium for a long time. The elevation field is a Gaussian bell of 3 m in height. Coriolis parameter f is $10^{-4}\,\mathrm{s}^{-1}$ in the whole domain. A third-order implicit–explicit Runge–Kutta method is used to progress in time, with a time-step corresponding to the CFL criterion on advection, the terms related to gravity waves being treated implicitly. The flow satisfies the following equations:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \tag{50}$$

$$\frac{\partial \mathbf{u}}{\partial t} + f\mathbf{k} \times \mathbf{u} + g\nabla\eta = 0 \tag{51}$$

4.6. Stommel gyre

A time-dependent problem may not exhibit all the troubles that can be generated by the discretization. The steady counterpart to the geostrophic equilibrium is the Stommel gyre [38]. The Coriolis effect is taken into account using the β-plane approximation, $f = f_0 + \beta y$, with $f_0 = 10^{-4}\,\mathrm{s}^{-1}$ and $\beta = 2 \times 10^{-11}\,\mathrm{m}^{-1}\,\mathrm{s}^{-1}$, corresponding to a midlatitude domain in the northern hemisphere. The flow is forced by the wind stress defined at Equation (42), that induces a clockwise circulation, while a linear dissipation with coefficient $\gamma = 10^{-6}\,\mathrm{s}^{-1}$ balances the forcing. The variation of this Coriolis parameter induces Rossby waves that propagate westward and generate a strong boundary current. The flow satisfies the following equations:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \tag{52}$$

$$\frac{\partial \mathbf{u}}{\partial t} + f\mathbf{k} \times \mathbf{u} + g\nabla\eta = \frac{\boldsymbol{\tau}^s}{\rho h} - \gamma\mathbf{u} \tag{53}$$

4.7. Munk gyre

The Munk gyre test case is similar to the Stommel one, the difference is that now the wind forcing is balanced by viscous dissipation rather than linear damping [38]. The viscosity parameter is constant in space and taken as $\nu = 10^4\,\mathrm{m\,s}^{-2}$. The flow satisfies the following equations:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0 \tag{54}$$

$$\frac{\partial \mathbf{u}}{\partial t} + f\mathbf{k} \times \mathbf{u} + g\nabla\eta = \frac{\boldsymbol{\tau}^s}{\rho h} + \nabla \cdot (\nu \nabla \mathbf{u}) \tag{55}$$

This test case is often easier to solve by all numerical schemes. The viscous terms are typical elliptic contributions removing most of the troubles that may pollute the inviscid solution.

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4.8. Nonlinear problems

Finally, we incorporate the advection terms in both the Stommel and the Munk gyre problems. The first one is inviscid, satisfying the system:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot ((h+\eta)\mathbf{u}) = 0 \tag{56}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + f\mathbf{k} \times \mathbf{u} + g\nabla \eta = \frac{\boldsymbol{\tau}^s}{\rho H} - \gamma \mathbf{u} \tag{57}$$

with the same Coriolis factor as the two previous test cases and a linear dissipation of coefficient $\gamma = 5 \times 10^{-7}$. The second one is viscous, with viscosity $v = 3000\,\mathrm{m\,s^{-2}}$:

$$\frac{\partial \eta}{\partial t} + \nabla \cdot ((h+\eta)\mathbf{u}) = 0 \tag{58}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + f\mathbf{k} \times \mathbf{u} + g\nabla \eta = \frac{\boldsymbol{\tau}^s}{\rho H} + \frac{1}{H}\nabla \cdot (Hv\nabla \mathbf{u}) \tag{59}$$

The numerical handling of the advection term is not simple and requires a suitable numerical strategy. However, some difficulties appearing in the problems without advection terms are sometimes solved by the diffusion introduced within the discretization of those advection terms.

5. NUMERICAL RESULTS

To quantify the errors for all finite element pairs for each test case, convergence studies are given in Figures 10 and 11. The left panels show the diagrams for the elevation field, while the right panels show the diagrams for velocities. The dots represent the values of the L_2 norm of the discretization error normalized by the range of the field. The slopes of the linear mean-square regression, representing the orders of accuracy, are given in the legends. To further quantify the optimality of the method, the error of the best solution that can be obtained in the sense of the L_2 norm is traced in a continuous line. It is defined as the error in L_2 norm between the reference solution and the L_2 projection of this reference solution onto the finite element space defined with the current mesh.

A few conclusions may be drawn directly. The velocity fields of P_1^{NC}–P_1 and P_1^{DG}–P_1 pairs lack convergence in the absence of viscosity. The P_1^{NC}–P_1 pair was known to have such a behavior [26, 29]. This trouble is related to the wave component of the shallow water problem. The velocity field has too many degrees of freedom and a velocity noise can develop with little influence on the elevation field. This noise component is bounded, as we still observe convergence at a reduced rate. The boundedness of the noise implies that the noise is not an eigenvector lying in the nullspace of the discrete operator, hence this noise was not shown by the study in [27]. This mode depends on the structure of the mesh. With structured meshes made of squares divided in half, optimal convergence is observed for both fields [29]. The same observation has been made for dispersion and dissipation properties, where analytical considerations on structured grids give promising results [28, 39, 40], while numerical analysis on unstructured grids exhibits disappointing results [31]. Using structured meshes of squares divided in four where all triangles are

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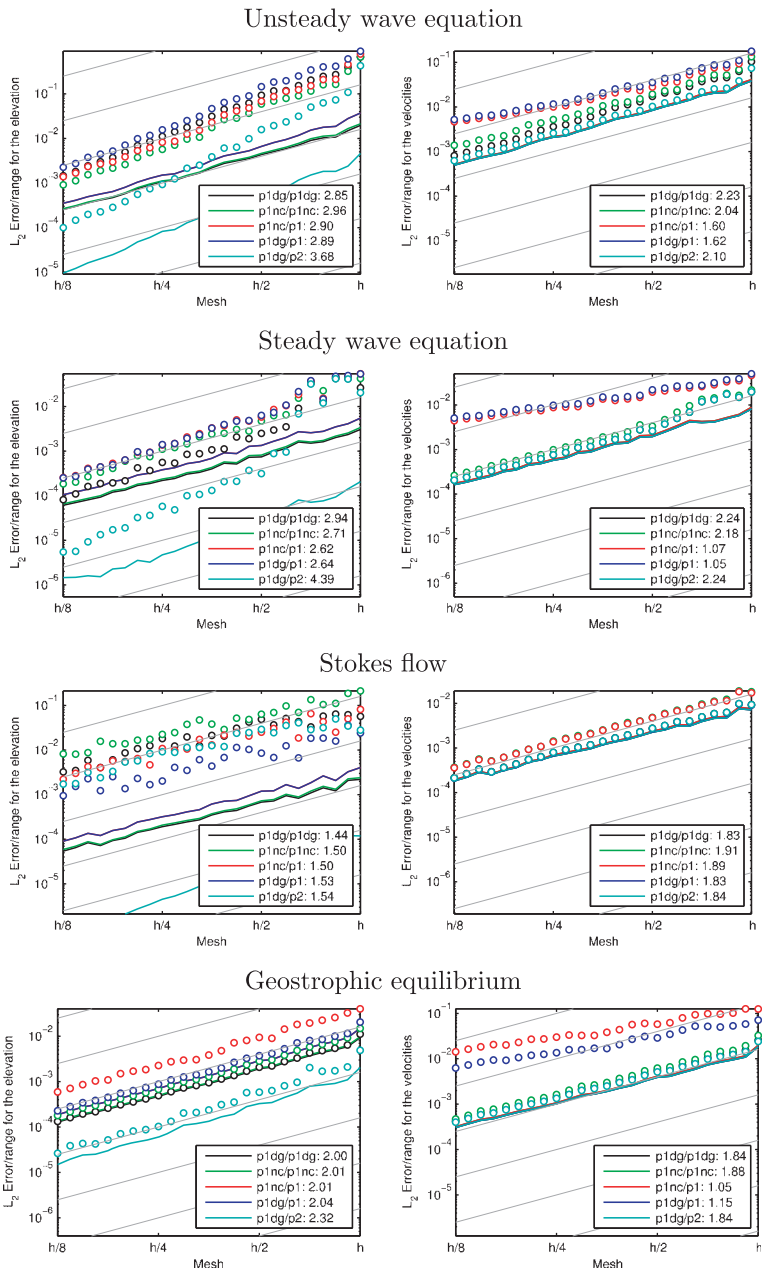

Figure 10. Convergence analysis. The circles denote the L_2 error, while continuous lines indicate the error of the L_2 projection of the reference solution onto the finite element space. The light gray lines indicate reference second-order convergence. The errors are plotted against the ratio h between the edge length and the reference size field. The number of elements scales as h^2.

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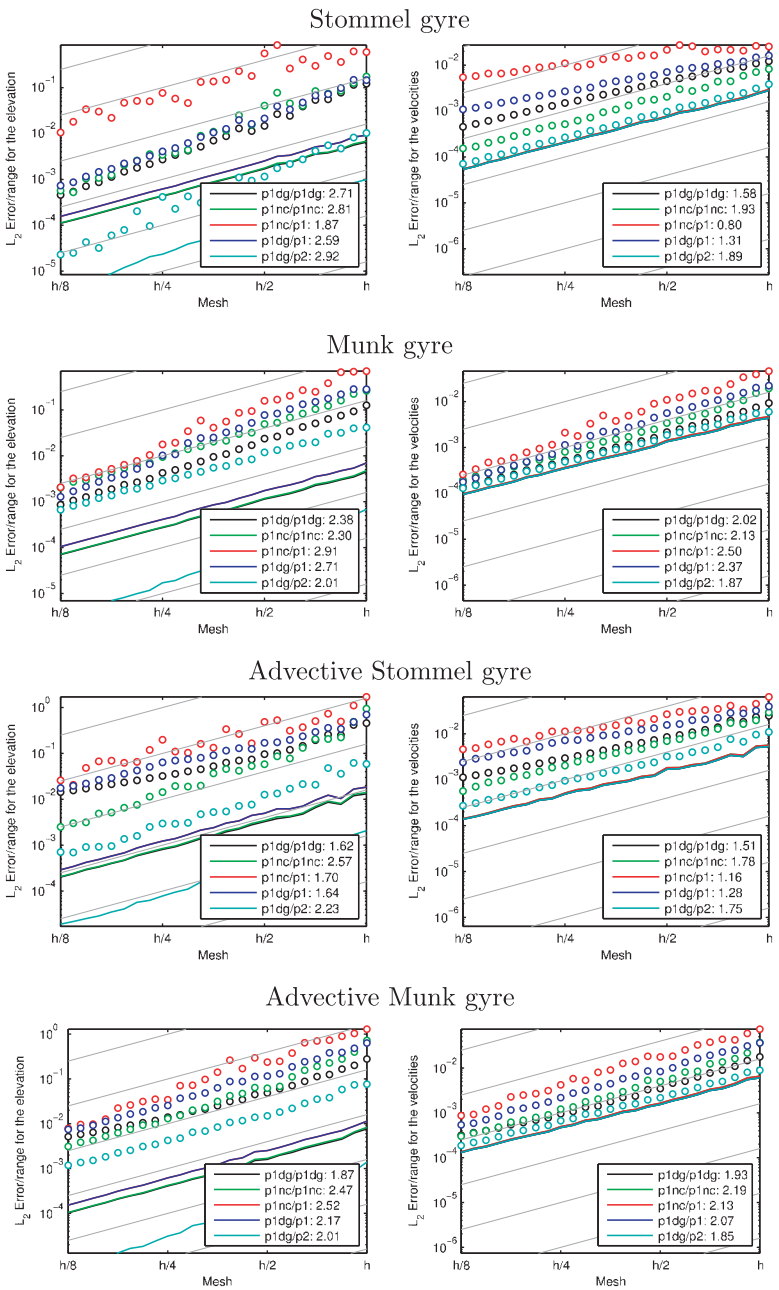

Figure 11. Convergence analysis. The circles denote the L_2 error, while continuous lines indicate the error of the L_2 projection of the reference solution onto the finite element space. The light gray lines indicate reference second-order convergence. The errors are plotted against the ratio h between the edge length and the reference size field. The number of elements scales as h^2.

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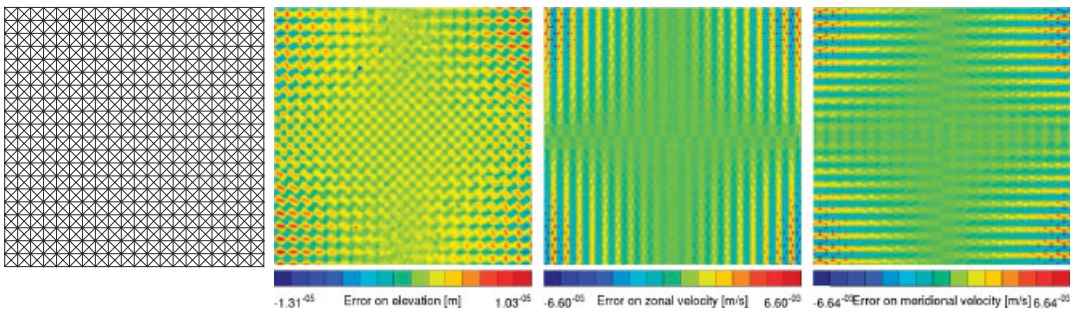

Figure 12. Sketch of the error for the steady wave problem, using P_1^{NC}–P_1 on the 'Union Jack' mesh.

not topologically identical, a relatively structured noise appears (see Figure 12). It is therefore possible to carry out spectral analysis as in [39, 40], to further characterize the behavior of this pair.

The $P_1^{\mathrm{DG}} - P_2$ pair demonstrates its very good properties in the vast majority of the test cases. An optimal rate of convergence for velocities is observed in all the test cases, and furthermore the solution is always quite close to the optimal solution for this element (i.e. close to the solid line in the right panels of Figures 10 and 11). Optimal convergence rate for elevation is obtained not only for the time-dependent test cases, where initial condition was third-order accurate, but also for the linear Stommel gyre. The latter can be explained as the functional spaces are optimally designed for geostrophy, as the gradient of the P_2 space exactly lies in the P_1^{DG} space. The nonlinearities seem to slightly deteriorate the accuracy of the solution to second order as the velocity and elevation fields are much more coupled.

For the Stokes flow, all the pairs exhibit second-order accuracy for velocities, and a 1.5 order of convergence for elevations. Our DG method applied to the Stokes equations must be related to the one from [41, 42], where interface fluxes are deduced from an artificial incompressibility Riemann problem. The time-dependent shallow water equations do not exhibit a solenoidal constraint for the velocity field, but in the steady limit, we recover an incompressibility constraint. Therefore, we use the surface gravity wave speed $\sqrt{gh}$ where an arbitrary wave velocity c is used in [41]. An additional difference is that the BRMPS method (referred as *Bassi et al.* [13] in the review [15]) is used to treat the diffusion terms, where we use an incomplete IP method (IIPG method in the book [17]). Still with DG, the same behavior is observed in [43], using LDG formulation, and proof that first- and second-order accuracies are expected for pressures and velocities, respectively, is given. All the finite element pairs do converge, but it cannot be excluded that some of them exhibit pressure modes on specific grids.

When Coriolis comes into play, the P_1^{DG}–P_1^{DG} pair lacks almost half an order of convergence for velocities. The velocity field in geostrophic equilibrium with a piecewise linear elevation field is piecewise constant. Then, interface terms are needed in the formulation to smooth the velocity field. Indeed, some flux terms exist for the normal velocity, but not for the tangent velocity. Therefore, some jumps on tangent velocities are allowed by the formulation, as shown in Figure 13 for the inviscid Stommel problem on a structured grid. The same half order of convergence is lost with second-order shape functions ($P_2^{\mathrm{DG}} - P_2^{\mathrm{DG}}$) on the same meshes.

The nonlinear advection terms do not significantly change the behavior of the different schemes. For the P_1^{DG}–P_1^{DG}, in the inviscid case, the lack of convergence on the velocity field is propagated

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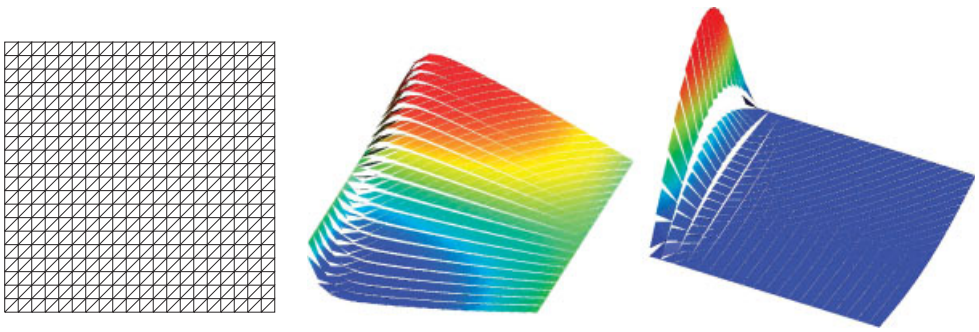

Figure 13. Zonal (center) and meridional (right) velocity field of the linear Stommel problem solved with the P_1^{DG}–P_1^{DG} pair on a structured mesh (left).

in the elevation field. The P_1^{NC}–P_1 and P_1^{DG}–P_1 velocity solutions are slightly smoothened by the numerical dissipation associated with the handling of the advective term, but the optimal convergence rates are not recovered. High Froude numbers are needed for the interface dissipation to be large enough to smooth the solution and recover the optimal behavior. Indeed, the Gulf of Mexico test case from [26] corresponds to a maximum Froude number of more than $\frac{1}{4}$, and the Williamson's test cases on the sphere, that were solved with optimal convergence rate in [44], are also advection dominated, with Froude numbers as high as $\frac{1}{10}$.

The P_1^{NC}–P_1^{NC} pair has overall quite an encouraging behavior. The pair shows optimal convergence rate in all the test cases, except the Stokes flow. Those rates are never lower than the rates observed with the P_1^{DG}–P_2 pair. The error values are slightly higher than those for P_1^{DG}–P_2 or P_1^{DG}–P_1^{DG} (when optimal rates are observed), but it must be noticed that it only requires half the number of degrees of freedom of the DG method. Moreover, the P_1^{NC} element naturally treats diffusion terms, while P_1^{DG} requires the IP method.

6. CONCLUSIONS

We provide a unified framework to define finite element formulations of the shallow water equations with continuous, discontinuous or partially discontinuous discretizations. We then perform a systematic numerical comparison of five relevant finite element pairs used in oceanic and coastal flows. In short, the following facts are observed:

- Large physical viscosity is required to obtain optimal order of convergence for P_1^{NC}–P_1 and P_1^{DG}–P_1 pairs.
- The accuracy of DG discretization of Coriolis-dominated flows is deteriorated by the lack of control on the jumps of tangent velocity.
- P_1^{DG}–P_2 gives accurate results in all ranges of flow, at the expense of second-order shape function for elevation, hence higher-order quadrature rules.
- P_1^{NC}–P_1^{NC} appears to behave optimally in all ranges of flow with a reasonable number of degrees of freedom. The diffusion terms are naturally handled by the discrete space.

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In terms of CPU efficiency, sharp conclusions are difficult to draw, as these are strongly implementation dependent. For explicit computations, using the same number of elements, P_1^{NC}–P_1^{NC} and P_1^{DG}–P_1^{DG} have truly similar cost per time step, as most of the CPU time is spent computing the finite element integrals, which require the same accuracy for both finite element pairs. The computation of spatial operators for P_1^{DG}–P_2 is more expensive as the higher order of the shape function for elevation requires more accurate quadrature rules. The DG pair has all the degrees of freedom associated with the triangles, giving a block structure that speeds up the assembling procedure. For implicit computations, the CPU time spent in the linear solver is important. The size of the system depends on the number of degree of freedom per element. The requirements of $P_1^{DG} - P_1^{DG}$ and $P_1^{DG} - P_2$ pairs are similar, with, respectively, 9 and 8 dof per element. $P_1^{NC} - P_1^{NC}$ behaves optimally in all our test cases, and uses only 4.5 degrees of freedom per element. Therefore, it is an interesting alternative that should be further studied to confirm its promising behavior.

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