

# A Verification Suite of Test Cases for the Barotropic Solver of Ocean Models

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## Abstract

The development of any atmosphere or ocean model warrants a suite of test cases to verify its spatial and temporal discretizations, order of accuracy, stability, reproducibility, portability, scalability, etc. In this paper, we present a suite of shallow water test cases designed to verify the barotropic solver of atmosphere and ocean models. These include the non-dispersive coastal Kelvin wave; the dispersive inertia-gravity wave; the dispersive planetary and topographic Rossby waves; the barotropic tide; and a non-linear manufactured solution. These test cases check the implementation of the linear pressure gradient term; the linear constant or variable-coefficient Coriolis and bathymetry terms; and the non-linear advection terms. Simulation results are presented for a variety of time-stepping methods as well as two spatial discretizations: a mimetic finite volume method based on the TRiSK scheme, and a high-order discontinuous Galerkin spectral element method. We explain the strategies that need to be adopted for specifying initial and non-periodic boundary conditions on hexagonal meshes. Convergence studies of every test case are conducted with refinement in both space and time, only in space, and only in time. The convergence slopes match the expected theoretical predictions.

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## Key Points:

- A suite of test cases is presented for the verification of barotropic dynamics of ocean models, with exact and manufactured solutions.
- Specifications are provided for the coastal Kelvin wave, the inertia-gravity wave, the planetary and topographic Rossby waves, the barotropic tide, and non-linear cases.
- Results are presented for a variety of time-stepping methods and two types of spatial discretizations: TRiSK and Discontinuous Galerkin Spectral Element Method.

**Abstract**

The development of any atmosphere or ocean model warrants a suite of test cases to verify its spatial and temporal discretizations, order of accuracy, stability, reproducibility, portability, scalability, etc. In this paper, we present a suite of shallow water test cases designed to verify the barotropic solver of atmosphere and ocean models. These include the non-dispersive coastal Kelvin wave; the dispersive inertia-gravity wave; the dispersive planetary and topographic Rossby waves; the barotropic tide; and a non-linear manufactured solution. These test cases check the implementation of the linear pressure gradient term; the linear constant or variable-coefficient Coriolis and bathymetry terms; and the non-linear advection terms. Simulation results are presented for a variety of time-stepping methods as well as two spatial discretizations: a mimetic finite volume method based on the TRiSK scheme, and a high-order discontinuous Galerkin spectral element method. The experimental procedure for conducting these numerical experiments is detailed. It underscores several key considerations that vary depending on the chosen spatial discretization method. Finally, convergence studies of every test case are conducted with refinement in both space and time, only in space, and only in time. The convergence slopes match the expected theoretical predictions.

**Plain Language Summary**

Before running an atmosphere, ocean, or a coupled climate simulation, every model developer should ensure the correct implementation of each term in the governing equations that drive the models forward in time. This motivates the development of idealized test cases, each of which verifies a subset of terms in the governing equations with different initial and boundary conditions. Here we present a suite of six test cases for the momentum equation and sea surface height equation for ocean models in a single-layer configuration. The computed results from the ocean model can be compared to exact solutions. The computed solution always has a small error, but is said to converge to the exact solution with reduction in grid cell size and time step. If the model converges at the expected rate, then we know that it is solving the governing equations correctly. We show results of convergence tests from two models, and share the full specifications of these test cases so that other ocean modelers may reproduce them.

**1 Introduction**

The verification of spatial and temporal discretizations is an important step in the development of any computational physics model based on partial differential equations (PDEs). Verification suites, with tests of increasing complexity that exercise a subset of terms, are particularly useful to identify problems as well as to compare discretization methods. Analysis metrics include the order of accuracy, stability, reproducibility, portability, computational performance, and scalability to large core counts. Atmosphere and ocean models are no different in this regard. Numerous test cases (TC) have been implemented in these models for benchmarking their results and performance against accepted standards (Bishnu et al., 2023). In this introduction, we provide an overview of the most influential test cases for geophysical fluids, and those that inspired the development of this paper. Additionally, we show that the shallow water test cases presented here satisfy a need in ocean model verification that is not provided in previous publications.

We start with the work of D. L. Williamson et al. (1992) that was published over three decades ago. They introduced a set of seven test cases for the discretized shallow water equations in a spherical geometry:

- (i) advection of a cosine bell with compact support around the sphere;
- (ii) a zonal geostrophically balanced flow, which is a steady state solution of the full non-linear shallow water equations;

- 66 (iii) a steady state non-linear zonal geostrophic flow, almost equivalent to (ii), except with  
67 a compactly supported non-zero wind field;
- 68 (iv) forced non-linear advection of a translating low pressure center superimposed on a jet  
69 stream that is symmetric about the equator;
- 70 (v) zonal flow impinging on an isolated mountain;
- 71 (vi) Rossby-Haurwitz waves, representing exact solutions to the non-linear nondivergent  
72 barotropic vorticity equation; and
- 73 (vii) a numerical experiment initialized from observed atmospheric states, with results  
74 compared to the finest possible resolution.

75 The Williamson test cases have been adopted as verification tools by numerous atmosphere  
76 and ocean models, including spectral element models in spherical geometries (Taylor et al.,  
77 1997; Thomas & Loft, 2002) and continuous Galerkin spectral element dynamical core in  
78 the Community Atmosphere Model (CAM) version 5 (Dennis et al., 2012), computational  
79 performance in CAM Evans et al. (2019), and others (Spotz et al., 2015). The Williamson  
80 cases are so frequently used that they are the canonical set of tests for new geophysical  
81 fluid dynamical cores (Walko & Avissar, 2008; T. D. Ringler et al., 2010). Our group  
82 has recently used Williamson test cases to verify local time-stepping schemes (Capodaglio  
83 & Petersen, 2022) and to measure improvements in stability and accuracy in the TRISK  
84 scheme (Calandrini et al., 2021).

85 The Aqua-Planet Experiment (APE) was first proposed by Neale and Hoskins (2000)  
86 as a benchmark for atmospheric general circulation models (AGCMs), and its aims were  
87 summarized by Blackburn and Hoskins (2013). The model setup consists of an idealised  
88 ocean-covered Earth, thereby eliminating the effect of topography and land on atmospheric  
89 flow. Surface forcing is provided by sea surface temperature varying only in latitude. Such  
90 an intermediate APE is more complex than a dry dynamical core experiment, but simpler  
91 than a full-climate simulation coupled to active land, ocean, and ice models. Therefore, the  
92 APE bridges the gap between realistic simulation and conceptual models of atmospheric  
93 phenomena in the existing modeling hierarchy. Despite these simplifications, APEs have  
94 produced realistic climate features like transient high and low pressure systems, convectively  
95 coupled equatorial waves, and tropical cyclones. Blackburn et al. (2013) compared climate  
96 simulations with 16 atmospheric general circulation models (AGCMs) on an aquaplanet,  
97 with the idealised configuration designed to expose differences in the circulation simulated by  
98 these models. APEs were performed with the variable-resolution spectral element dynamical  
99 core of CAM by Zarzycki et al. (2014), and the fundamental characteristics of the aquaplanet  
100 climate simulated by CAM5.3 are described in Medeiros et al. (2016). Chavas and Reed  
101 (2019) employed APEs under uniform thermal forcing and variable global dynamical forcing  
102 to test existing hypotheses regarding tropical cyclone genesis and size, whereas Merlis and  
103 Held (2019) provided a nice review of tropical cyclone simulations with APEs. Möbis  
104 and Stevens (2012) determined the factors controlling the position of the Intertropical  
105 Convergence Zone (ITCZ) on an aquaplanet. Although the Aquaplanet Experiment (APE)  
106 is predominantly tailored for atmospheric models, when integrated with a global ocean  
107 model, it sheds light on ocean-atmosphere dynamics without the influence of land-sea  
108 disparities and topographical intricacies. For instance, Donohoe et al. (2014) delved into the  
109 impact of the ocean mixed layer depth on climate using a series of slab ocean aquaplanet  
110 simulations.

111 The prominent test cases employed by ocean models to quantify mixing and diapycnal  
112 transport are:

- 113 (i) the lock exchange or dam break test case to measure mixing in the simplest possible  
114 configuration (D.-P. Wang (1984), Haidvogel and Beckmann (1999), Jankowski (1999),  
115 Ilıcak et al. (2012), Kärnä et al. (2013), Petersen et al. (2015), Gibson et al. (2017),  
116 Kärnä et al. (2018));

- 117 (ii) the overflow test case to investigate the impact of topography on spurious mixing  
118 (Haidvogel and Beckmann (1999), Ilıcak et al. (2012), Petersen et al. (2015));
- 119 (iii) the Dynamics of Overflow Mixing and Entrainment (DOME) test case to study the  
120 model’s ability to simulate density-driven overflows (Ezer and Mellor (2004), Legg  
121 et al. (2006), Q. Wang et al. (2008), Burchard and Rennau (2008), Reckinger et al.  
122 (2015), Gibson et al. (2017), Kärnä et al. (2018));
- 123 (iv) the internal wave test case to examine spurious diapycnal mixing associated with  
124 the adjustment of an internal gravity wave in a vertically stratified fluid (Ilıcak et al.  
125 (2012), Petersen et al. (2015), Gibson et al. (2017));
- 126 (v) the three-dimensional mesoscale baroclinic eddies test case at eddy-permitting grid  
127 resolution in the presence of rotation, to measure mixing under conditions closer to  
128 a realistic high-resolution global ocean models (Ilıcak et al. (2012), Petersen et al.  
129 (2015), Gibson et al. (2017), Kärnä et al. (2018)); and
- 130 (vi) the spin-down of a global ocean climate model at non-eddy and eddy permitting  
131 grid resolutions (Ilıcak et al. (2012), Petersen et al. (2015)).

132 The COmmunity MODelling Ocean (COMODO) project was funded by the French  
133 National Agency for Research to benchmark and improve existing ocean models and methods,  
134 and guide their future evolution. It consisted of the following test cases:

- 135 (i) Stommel gyre test case of Hecht et al. (2000) for testing the conservation of tracers;
- 136 (ii) Adapted Smolarkeiwicz test case for testing the terrain-following coordinate;
- 137 (iii) Lock exchange test case for testing the tracer advection scheme and diapycnal mixing;
- 138 (iv) Barotropic vortex test case for testing the tracer and momentum advection schemes,  
139 and the time-stepping method;
- 140 (v) Baroclinic vortex test case for testing the tracer and momentum advection-diffusion  
141 schemes, the time-stepping method, and the vertical coordinate;
- 142 (vi) Baroclinic jet test case for testing the effective resolution, the tracer and momentum  
143 advection-diffusion schemes, the time-stepping method, and the vertical coordinate;
- 144 (vii) Thacker’s bowl test case for testing the wetting and drying phenomenon, the pressure  
145 gradient term, and the vertical coordinate;
- 146 (viii) Two-dimensional vertical upwelling test case for testing the time-stepping method,  
147 the vertical coordinate, and the bottom boundary conditions;
- 148 (ix) Internal tide test case for testing the vertical coordinate, the tracer and momentum  
149 advection-diffusion schemes, and the pressure gradient term;
- 150 (x) Sea mount test case for testing the tracer and momentum advection-diffusion schemes,  
151 the lateral boundary conditions, and the current-topography interactions.

152 The COMODO project paved the way to the successful COMMODORE workshops on the  
153 numerical solution techniques of PDEs that govern ocean circulation from global to coastal  
154 scales.

155 Two simplified linear models of the stationary quasi-geostrophic equations, namely the  
156 Stommel (Stommel, 1948) and Stommel–Munk (Munk & Carrier, 1950) models, have been  
157 employed as verification tools by numerous shallow water and barotropic ocean models. The  
158 Stommel model can be used to test the ability of an ocean model to reproduce the western  
159 intensification phenomenon. The Stommel–Munk model, on the other hand, focuses on  
160 the wind-driven gyres and the Ekman spiral, and can be used to test the representation of  
161 wind-driven circulation and the response of the ocean surface layer to wind stress. Foster  
162 et al. (2013) and Kim et al. (2015) presented conforming finite-element methods of the  
163 streamfunction formulation of the stationary one-layer quasi-geostrophic equations for the  
164 study of the large scale wind-driven ocean circulation. The finite element discretization in  
165 Foster et al. (2013) employed Argyris elements, whereas Kim et al. (2015) used a B-spline  
166 basis. Rotundo et al. (2016) presented the error analysis of the method in Kim et al. (2015),  
167 and Jiang and Kim (2016) generalized the method to domains with arbitrary shaped coastal  
168 boundaries. Myers and Weaver (1995) presented a diagnostic barotropic finite-element ocean

169 circulation model in Cartesian and spherical coordinates, and tested it against the linear  
 170 Stommel and Munk models, as well as the barotropic circulation in the North Atlantic  
 171 Ocean in the presence of realistic lateral boundaries and topography. Comblen et al.  
 172 (2010) considered continuous, discontinuous, as well as partially discontinuous finite element  
 173 formulations for the non-conservative shallow water equations, that are second-order accurate  
 174 in space. In addition to the linear and non-linear versions of the Stommel and Munk gyres,  
 175 the numerical solution was benchmarked against unsteady and steady wave equations, Stokes  
 176 flow, and the geostrophic equilibrium. Düben et al. (2012) studied the applicability of a new  
 177 finite element in atmosphere and ocean modeling that combines a second-order continuous  
 178 representation for the scalar field with a first-order discontinuous representation for the  
 179 velocity field. Q. Chen and Ju (2018) proposed conservative finite-volume schemes for solving  
 180 the inviscid and viscous quasi-geostrophic equations on coastal-conforming unstructured  
 181 primal–dual meshes. They also performed numerical experiments with a freely evolving  
 182 circular flow, and the intensified western boundary current. Beel et al. (2019) introduced a  
 183 novel strong form-based meshfree collocation method to directly discretize the second-order  
 184 Stommel model and the fourth-order Stommel–Munk model for the large-scale wind-driven  
 185 ocean circulation simulations.

186 We mention the relevant limited area, coastal, and tidal test cases in the ocean modeling  
 187 literature, starting with Drago and Iovenitti (2000). They introduced a three-dimensional  
 188 finite-difference model for coastal oceans and evaluated its performance against various  
 189 scenarios, including a wind-driven current, a wind and Coriolis force balance, an Ekman  
 190 spiral, tidal circulation, tidal flood and ebb on a beach, and a coastal jet influenced by a  
 191 long-shore wind. Fringer et al. (2006) discussed the fundamental hydrodynamic kernel of the  
 192 Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier–Stokes Simulator  
 193 (SUNTANS), a finite-volume, unstructured-grid, nonhydrostatic, parallel, coastal-ocean  
 194 solver. They tested it against a non-hydrostatic lock exchange test case, a non-hydrostatic  
 195 internal seiche test case, and the generation of internal waves in the Monterey Bay region.  
 196 Santilli and Scotti (2015) presented the Stratified Ocean Model with Adaptive Refinement  
 197 (SOMAR), a computational framework for the evolution of non-hydrostatic, baroclinic  
 198 flows encountered in regional and coastal ocean simulations. It combines the flexibility  
 199 of Adaptive Mesh Refinement with a set of numerical tools specifically developed to address  
 200 the high degree of anisotropy of oceanic flows and the accompanying numerical challenges.  
 201 The modeling framework was applied to (1) the lock exchange test case; (2) the beam  
 202 generation test case following Jalali et al. (2014) to analyze the generation of internal  
 203 waves; and (3) the Dubreil–Jacotin–Long (DJL) solution, which is an exact solution of  
 204 the Euler equations. Garcia et al. (2019) validated the nonhydrostatic General Curvilinear  
 205 Coastal Ocean Model (GCCOM) for stratified flows against the lock exchange test case; a  
 206 three dimensional internal seiche test case; and a field-scale internal wave beams test case,  
 207 following the experimental setup of Vitousek and Fringer (2014). Herzfeld et al. (2011)  
 208 reviewed some realistic test cases for limited area ocean modelling, including a coastal shelf  
 209 model application used for down-scaling; tidal response of a gulf with one open boundary  
 210 across the mouth of the gulf; and the response of a coastal region to the passage of a tropical  
 211 cyclone.

212 Many atmosphere, ocean and climate models are equipped with test suite creation and  
 213 verification infrastructure, in addition to the forward time-stepping core. For example, test  
 214 cases for MPAS-Ocean (T. Ringler et al., 2013) are available in the Configuration of Model  
 215 for Prediction Across Scales Setups (COMPASS) repository (Asay-Davis et al., 2024) and  
 216 more recently the Polaris repository (Asay-Davis & Begeman, 2024). The test cases are often  
 217 contained within a separate directory of the model itself, and tutorials for a subset of the test  
 218 cases are available on the online manual e.g. MITgcm (Marshall et al., 1997), MOM (Griffies  
 219 et al., 2005), SUNTANS (Fringer et al., 2006), or the README file of the Github repository  
 220 of the model e.g. Oceananigans (Ramadhan et al., 2020), NEMO (Madec et al., 2023), or  
 221 a Wikipedia page e.g. ROMS (Shchepetkin & McWilliams, 2005). Standardized test cases  
 222 provide a method to compare the solution quality and computational speed between models,

and even between different languages and architectures. For example, Bishnu et al. (2023) uses the coastal Kelvin wave and inertia-gravity wave cases to compare Fortran-MPI against Julia-MPI on CPUs and GPUs.

## 1.1 Contributions of this work

The majority of test cases mentioned in the introduction of our study are primarily used for validation, rather than verification. Verification, in simplest terms, investigates ‘if we are solving the equations right,’ contrasting with validation, which scrutinizes ‘if we are solving the right equations.’ Verification is a methodical process that quantifies simulation errors, displays the convergence of the numerical solution towards established benchmarks such as analytical and manufactured solutions with refinement in space and time, and ensures software quality. In contrast, code validation delves into whether the models themselves are representations of the right equations, aiming to assess how well a model mirrors the real world from the perspective of its intended application. The core objective of validation is to instill confidence in the model’s predictive capability by comparing it with observed and experimental data. As a best practice, verification should precede validation to facilitate precise assessments.

Our work with MPAS-Ocean and interactions with fellow ocean modelers has enlightened us to the dangers of overlooking essential verification steps in favor of more advanced validation exercises. For instance, bypassing proper verification can inadvertently allow subtle software bugs to slip through, that are challenging to detect later on. As an illustrative example, consider a scenario where an implementation error in the spatial discretization of the non-linear advection term in the continuity equation compromises the spatial order of accuracy of an ocean model under development. The model remains stable due to the diffusion terms in the governing equations and the inherent diffusion within the numerical scheme. It performs satisfactorily against standard validation exercises, thereby arousing no suspicion. If this ocean model’s predictive capability falls short compared to a more mature model, one might contemplate enhancing specific attributes like the discretization scheme, parametrizations, topographic representation, open boundary conditions, or coupling with other Earth system model components. While some of these modifications may still be necessary, without definitive evidence, we might completely overlook the possibility of incorrect implementation of the non-linear advection term. Its cumulative effect over long simulation times is far from negligible, and rectifying it may significantly improve the model’s predictive capability. This highlights the imperative of extensive verification exercises—the primary subject of this paper—before proceeding with model validation. Such meticulous scrutiny could have exposed the non-linear advection term’s bug early in the model’s developmental phase, thereby saving valuable time for the developers. Moreover, the creation of a verification suite, although a one-time investment, can be integrated within an automated nightly regression suite. This allows for regular examination every time a substantial modification is introduced into the model, promoting a robust and consistent development process.

In this paper, we present a verification suite of shallow water test cases consisting of the non-dispersive coastal Kelvin wave, the dispersive inertia-gravity wave, the dispersive planetary and topographic Rossby waves, the barotropic tide, and a non-linear manufactured solution specifically designed for the barotropic mode. Our primary motivation for selecting these shallow water test cases stems from their routine usage in evaluating the dynamical core of atmosphere and ocean models. Moreover, many of these models are equipped with a barotropic-baroclinic time-splitting operation. This technique advances the fast, two-dimensional, depth-independent external gravity waves explicitly with a small barotropic time step or implicitly with a large one. The residual three-dimensional subsystem, which models slower internal gravity waves and ocean currents, is advanced using a large baroclinic time step. This splitting approach substantially enhances the computational efficiency of the models, often by orders of magnitude, when compared to employing a small time step for

275 the full three-dimensional equations, as dictated by the CFL condition for the fastest wave.  
276 Notably, within this framework, the barotropic equations adopt the form of inhomogeneous  
277 rotating shallow water equations, with the source term represented by the barotropic average  
278 of a subset of terms within the baroclinic momentum equation. As a result, our carefully  
279 chosen shallow water test cases can also serve as verification tools for the barotropic solver  
280 integrated within these models.

281 A secondary, yet substantial motivation for this research is to furnish model developers  
282 with a method to critically assess their code designed to numerically solve fluid dynamics  
283 problems, such as those pertaining to the shallow water equations or the hydrostatic primitive  
284 equations. Our methodology initiates with a set of governing equations, upon which we  
285 apply spatial and temporal discretizations. We then implement this discretized formulation  
286 into the code. Our approach leverages fundamental knowledge of classical geophysical  
287 phenomena such as non-dispersive and dispersive geophysical waves, which can be modeled  
288 by the code. So, we devise straightforward test cases, beginning with linear ones, and then  
289 progressing to non-linear ones. This ensures that we accurately capture the behaviors of  
290 these geophysical phenomena. After all, correctly modeling basic problems is foundational to  
291 successful oceanic modeling, not to mention the development of general circulation models  
292 (GCMs). However, securing the correct answer using a fixed spatial grid and time step  
293 size is insufficient. It is essential to perform refinement in spatial grid size and time step  
294 to demonstrate the attainment of the appropriate convergence rate. In essence, this not  
295 only verifies that the correct solution is achieved but also assures that it is achieved for the  
296 correct underlying reasons. If the correct convergence rate is not obtained, the numerical  
297 method or its implementation may be flawed, and any successful result could be coincidental  
298 rather than systematic. Our robust set of test cases is therefore an invaluable resource  
299 for anyone engaged in the development of a GCM. At some stage in the development  
300 process, the accurate resolution of the shallow water equations is almost inevitably required.  
301 Moreover, the present work elucidates a comprehensive process for evaluating both the  
302 physical and numerical correctness of the code. Through carefully chosen examples, this  
303 paper aims to demonstrate not only the methodology but also the underlying principles,  
304 thereby contributing a vital tool for future developments in the field of ocean modeling.

305 Equally pivotal, and forming the third cornerstone of our paper's objectives, is its  
306 pedagogical value, particularly in enriching the curriculum of geophysical fluid dynamics  
307 courses. This work extends beyond theoretical concepts, providing a practical, hands-on  
308 approach to learning. By integrating the physical characteristics of various geophysical  
309 waves (Sections 2.5, 2.6, 2.7, and 2.8), including equatorial waves (Section A2), with their  
310 numerical simulations, this work bridges the gap between theory and practice. Students can  
311 visualize and appreciate the dynamic evolution of these waves, enhancing their understanding  
312 of these complex geophysical phenomena. Moreover, the paper equips students with the  
313 tools and knowledge to critically evaluate the accuracy of numerical ocean models, or even  
314 a basic code they develop for visualizing geophysical waves. They can verify the correctness  
315 of the discretized equations of motion implemented in these models, by ensuring that the  
316 numerical solution convergences at the expected theoretical rate based on the spatial and  
317 temporal orders of accuracy.

318 Among the cited literature, the seven cases of D. L. Williamson et al. (1992), the  
319 Stommel and Stommel-Munk test cases, and the COMODO barotropic vortex test case are  
320 specifically designed for shallow water equations. Only test cases (i)–(iv) of D. L. Williamson  
321 et al. (1992), the Stommel, and Stommel-Munk test cases are equipped with exact solutions.  
322 However, the exact solution of the fluid layer depth of test case (iii) and the exact solution  
323 of all the prognostic variables of test case (iv) of D. L. Williamson et al. (1992) consists  
324 of an integral which is difficult to evaluate analytically, and is computed using numerical  
325 quadrature. The exact solutions of test cases (ii) and (iii) of D. L. Williamson et al. (1992)  
326 as well as the Stommel and Stommel-Munk test cases are steady-state solutions. The  
327 remaining test cases, meant for validation rather than verification, investigate anomalous

328 mixing, coastal processes, etc., but not the accuracy of the barotropic solver in a split  
 329 baroclinic-barotropic time stepping scheme. To properly test the accuracy of the barotropic  
 330 solver, the existence of analytical time-dependent solutions is crucial. They serve as a  
 331 benchmark, towards which the numerical solutions are expected to converge, when refined  
 332 simultaneously in both space and time. The creation of our test cases arose from these  
 333 practical needs during the development and improvement of MPAS-Ocean. Although the  
 334 exact solutions of some of these test cases are provided in standard geophysical fluid dynamics  
 335 textbooks e.g. Cushman-Roisin and Beckers (2011), this work contributes to the development  
 336 of a standard verification suite by providing specific details of the initial and boundary  
 337 conditions, error plots, and rates of convergence, that will be useful for comparison with  
 338 other ocean models.

339 The structure of this paper is organized as follows: Section 2 provides the essential  
 340 theoretical foundation on the shallow water equations and offers a concise overview of the test  
 341 cases, which encompass geophysical waves, barotropic tide, and a non-linear manufactured  
 342 solution. In Section 3, we discuss the spatial and temporal discretizations applied to  
 343 the prognostic equations. Our study employs two types of spatial discretizations: (1) a  
 344 mimetic finite volume based on the TRiSK scheme and used in MPAS-Ocean; and (2) a  
 345 high-order Discontinuous Galerkin Spectral Element Method implemented in the Spectral  
 346 Element Library in Fortran (SELF). The prognostic equations are advanced using a variety  
 347 of time-stepping methods. Section 6 presents the numerical results, including time evolution  
 348 of the error as well as convergence plots with refinement in both space and time, only  
 349 in space, and only in time. Conclusions are drawn in Section 7. Appendix A outlines  
 350 an additional suite of shallow water test cases with exact solutions, consisting of a plane  
 351 wave, diffusion, advection-diffusion, a moving shock, as well as non-dispersive and dispersive  
 352 equatorial waves. Appendix B underscores the relevance of the shallow water test cases in the  
 353 context of baroclinic-barotropic splitting in oceanic models, illustrating how the barotropic  
 354 equations align with the form of inhomogeneous rotating shallow water equations. Finally,  
 355 Appendix C delves into nuanced aspects of the numerical implementation, including the  
 356 specification of initial and boundary conditions on hexagonal meshes, and the interpolation  
 357 of the numerical solution or the error to the coarsest mesh for refinement only in space.

## 358 **2 A Verification Suite of Shallow Water Test Cases**

359 We have developed a verification suite for shallow water cases, starting with linear  
 360 test cases before advancing to non-linear ones. With each test case, we incrementally  
 361 introduce a new layer of complexity, enabling us to verify the implementation of every  
 362 term in the equations governing barotropic motion and the shallow water core in ocean  
 363 models. The linear test cases, consisting of the linear geophysical waves and the barotropic  
 364 tide, are tailored to verify the pressure gradient, Coriolis, and linearized advection terms.  
 365 Conversely, the non-linear test cases, encompassing the non-linear planetary and topographic  
 366 Rossby waves, along with the manufactured solution, prove instrumental for examining the  
 367 non-linear advection terms. The source term in the manufactured solutions can exemplify  
 368 the barotropic average of the baroclinic terms found on the right-hand side of the barotropic  
 369 equations.

370 Although lacking exact solutions, we have incorporated the Rossby waves into our  
 371 verification suite for several compelling reasons. First, these comprehensive test cases, in  
 372 their non-linear form, verify the implementation of each and every term in the non-linear  
 373 shallow water equations. Second, they feature non-trivial variations in the meridional  
 374 gradient of the Coriolis parameter and the bottom topography (Section 2.4). Third, Rossby  
 375 wave test cases illustrate that exact solutions are not a prerequisite for verifying the model's  
 376 spatial and temporal orders of accuracy. This can be achieved by plotting the norm of  
 377 the differences between numerical solutions over successive pairs of spatial and temporal  
 378 resolutions, refined at a constant ratio, instead of the actual error norm (Section 4.5).

379 Finally, these test cases significantly contribute to the educational aspect of our research  
 380 (Section 1.1).

381 Building on the rationale for including Rossby waves in our verification suite, it is  
 382 important to clarify that the second reason does not diminish the value of test cases with  
 383 exact solutions. In fact, the actual error norm of the numerical solution, defined only  
 384 for these test cases, converges under the simultaneous spatial and temporal refinement  
 385 (Section 4.3). Additionally, it is worth noting that for certain test cases and specific  
 386 resolution ranges, the norm of differences between numerical solutions over a pair of spatial  
 387 or temporal resolution, may be minimal and susceptible to overshadowing by round-off  
 388 errors. This scenario underscores the need for additional test cases, preferably those with  
 389 exact solutions, to ensure comprehensive verification (Section 6.1, bullet point 10).

390 Before delving into detailed descriptions of the various test cases, we provide a brief  
 391 theoretical overview of equations representing shallow water and barotropic flows.

## 392 2.1 The Shallow Water Equations

393 The non-linear rotating shallow water equations, representing the shallow water core  
 394 of ocean models, can be expressed compactly as

$$\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u} + f \mathbf{k} \times \mathbf{u} = -g \nabla(h + b) + \nu \nabla^2 \mathbf{u}, \quad (1a)$$

$$h_t + \nabla \cdot (h \mathbf{u}) = 0, \quad (1b)$$

395 where  $\mathbf{u}(x, y, t) = u(x, y, t)\mathbf{i} + v(x, y, t)\mathbf{j}$  is the velocity vector,  $h(x, y, t)$  is the shallow water  
 396 layer thickness above the bottom topography  $b(x, y)$  originating at  $z = 0$ ,  $\eta(x, y, t)$  is the  
 397 surface elevation,  $f$  is the Coriolis parameter,  $g$  is the acceleration due to gravity, and  $\nu$  is  
 398 the horizontal viscosity. The subscripts denote partial differentiation, and  $\mathbf{i}$ ,  $\mathbf{j}$ , and  $\mathbf{k}$  are  
 399 the unit vectors in the  $x$ ,  $y$  and  $z$  directions. If  $H$  represents the mean depth of the fluid at  
 400 rest, then the surface elevation  $\eta(x, y, t)$  at any point in time satisfies

$$\eta(x, y, t) = h(x, y, t) + b(x, y) - H, \quad (2)$$

401 Using (2) and replacing the non-linear advection term in (1a) with the right-hand side of  
 402 the vector identity

$$\mathbf{u} \cdot \nabla \mathbf{u} = (\nabla \times \mathbf{u}) \times \mathbf{u} + \nabla \frac{|\mathbf{u}|^2}{2} = \{\mathbf{k} \cdot (\nabla \times \mathbf{u})\} \mathbf{k} \times \mathbf{u} + \nabla \frac{|\mathbf{u}|^2}{2}, \quad (3)$$

403 we obtain the vector-invariant form of the momentum equation

$$\mathbf{u}_t + \nabla K + (\zeta + f) \mathbf{u}^\perp = -g \nabla \eta + \nu \nabla^2 \mathbf{u}. \quad (4)$$

404 Here  $\mathbf{u}^\perp = \mathbf{k} \times \mathbf{u}$ ,  $K = |\mathbf{u}|^2/2$  is the kinetic energy, and  $\zeta = \mathbf{k} \cdot (\nabla \times \mathbf{u})$  is the relative  
 405 vorticity.

## 406 2.2 The Barotropic Equations

407 The barotropic equations of an ocean model can be expressed in vector-invariant form

$$\bar{\mathbf{u}}_t + f \bar{\mathbf{u}}^\perp = -g \nabla \eta + \nu \nabla^2 \bar{\mathbf{u}} + \bar{\mathbf{G}}, \quad (5a)$$

$$\eta_t + \nabla \cdot (h_{\text{total}} \bar{\mathbf{u}}) = 0, \quad (5b)$$

408 where  $h_{\text{total}} = \sum_{k=1}^N h_k$  is the total depth equivalent to the sum of individual layer thicknesses  
 409  $h_k$ ,  $\bar{\mathbf{u}} = \left( \sum_{k=1}^N h_k \mathbf{u} \right) / h_{\text{total}}$  is the barotropic velocity, and  $\bar{\mathbf{G}}$  is the barotropic average  
 410 of specific baroclinic terms. Typically, the diffusion term  $\nu \nabla^2 \bar{\mathbf{u}}$  is encapsulated within  
 411  $\bar{\mathbf{G}}$ , and it does not explicitly feature in the barotropic momentum equation (5a), except  
 412 in some variants such as Blumberg and Mellor (1987). A comprehensive demonstration

of the barotropic-baroclinic splitting procedure, alongside a derivation of the barotropic equations of motion using MPAS-Ocean as a case study, can be found in Appendix B. In an analytical comparison against the shallow water equations (1), it becomes evident that the barotropic equations (5) essentially mirror the form of (1), albeit with some key differences: the exclusion of the non-linear advection term and the introduction of the source term  $\overline{\mathbf{G}}$  in the momentum equation, and the substitution of the shallow water velocity and layer thickness by the barotropic velocity  $\overline{\mathbf{u}}$  and the total depth  $h_{\text{total}}$  respectively.

The shallow water and barotropic equations can be succinctly expressed as the following set of equations:

$$u_t + \underbrace{\nabla K}_{(1)} + \underbrace{\zeta \mathbf{u}^\perp}_{(2)} + \underbrace{f_0 \mathbf{u}^\perp}_{(3)} + \underbrace{\beta_0 y \mathbf{u}^\perp}_{(4)} = - \underbrace{g \nabla \eta}_{(5)} + \underbrace{\nu \nabla^2 \mathbf{u}}_{(6)} + \underbrace{\overline{\mathbf{G}}}_{(7)}, \quad (6a)$$

$$\eta_t + \underbrace{\nabla \cdot (H \mathbf{u})}_{(8)} + \underbrace{\nabla \cdot (\eta \mathbf{u})}_{(9)} - \underbrace{\nabla \cdot (b \mathbf{u})}_{(10)} = 0, \quad (6b)$$

where the Coriolis parameter  $f$  has been decomposed into its leading-order components:  $f_0$ , the base Coriolis parameter at a reference latitude, and  $\beta_0 y$ , where  $\beta_0$  is the meridional gradient of  $f$ . The non-linear advection term in the continuity equation has been split into three parts using (2). Each term in (6), excluding the temporal derivatives, is labeled for convenient referencing in test cases that verify its numerical implementation.

### 2.3 Shallow Water Equations in Cartesian Coordinates

The inviscid rotating shallow water equations in Cartesian coordinates are

$$u_t + uu_x + vu_y - fv = -g(h+b)_x, \quad (7a)$$

$$v_t + uv_x + vv_y + fu = -g(h+b)_y, \quad (7b)$$

$$h_t + (hu)_x + (hv)_y = 0. \quad (7c)$$

Inserting (2) into (7), we obtain

$$u_t + uu_x + vu_y - fv = -g\eta_x, \quad (8a)$$

$$v_t + uv_x + vv_y + fu = -g\eta_y, \quad (8b)$$

$$\eta_t + (hu)_x + (hv)_y = 0. \quad (8c)$$

The geophysical waves consisting of the coastal Kelvin wave, the inertia-gravity wave, and the planetary and topographic Rossby waves are solutions to the linearized rotating inviscid shallow water equations, obtained by dropping the non-linear terms in (8) as

$$u_t - fv = -g\eta_x, \quad (9a)$$

$$v_t + fu = -g\eta_y, \quad (9b)$$

$$\eta_t + \{(H-b)u\}_x + \{(H-b)v\}_y = 0. \quad (9c)$$

In the case of a flat bottom,  $b(x, y) = 0$ ,  $h(x, y, t) = H + \eta(x, y, t)$ , and (9) reduces to

$$u_t - fv = -g\eta_x, \quad (10a)$$

$$v_t + fu = -g\eta_y, \quad (10b)$$

$$\eta_t + H(u_x + v_y) = 0. \quad (10c)$$

In the subsequent subsections, we review the exact solutions associated with the various test cases, which we have numbered 1–6 for convenient reference. The derivations of these exact solutions, particularly for some of the geophysical wave test cases, can be found in standard textbooks on geophysical fluid dynamics (GFD), such as those by Vallis (2017), Cushman-Roisin and Beckers (2011), Pedlosky (1987), and Gill (2016).

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## 2.4 Summary of Shallow Water Test Cases

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The test cases presented in the following sections, summarized in Table 1, assess the numerical implementation of various terms within the rotating shallow water equations. Each of them incorporates the Coriolis force, which imparts rotation to the shallow water. The Coriolis term is constant, rendering the domain of motion to be an *f-plane* for all but the planetary Rossby wave test case, where the Coriolis term is a linear function of  $y$  and the domain of wave motion is a *beta-plane*. The topographic Rossby wave test case uniquely features a sloping bottom as a linear function of  $y$ , while others possess a flat bottom. With the meridional gradient of the Coriolis parameter and the bottom topography being non-trivial for the planetary and the topographic Rossby waves respectively, the shallow water systems for these solutions are variable-coefficient. In contrast, the systems for other test cases remain constant-coefficient. The non-linear planetary and topographic Rossby waves, along with the manufactured solution test case verify the implementation of the non-linear advection terms. In fact, the non-linear Rossby wave test cases check every term in the non-linear homogeneous shallow water equations. On the other hand, the coastal Kelvin wave, inertia-gravity wave, linear Rossby waves, and the barotropic tide are solutions to the linearized form of these equations, thus their governing PDEs are stripped of non-linear terms. Table 1 concisely captures the assumptions underpinning the geophysical waves, the barotropic tide, and the non-linear manufactured solution. This table details the nature of the simplified PDEs for the shallow water equations, applied boundary conditions, and the specific terms from (6) that are tested. In the context of convergence studies, where extensive simulation times are unnecessary, the diffusion terms for the non-linear Rossby wave test cases are discretionary and are denoted with an asterisk.

**Table 1.** Summary of assumptions for the geophysical waves, barotropic tide, and non-linear manufactured solution, detailing the nature of the corresponding simplified PDEs for the shallow water equations, their applied boundary conditions, and the specific terms tested from (6), with optional ones indicated by an asterisk.

	Coriolis Parameter	Bottom Topography	Numerical PDE	Boundary Conditions	Terms Verified in Equation (6)
1. Coastal Kelvin Wave	Constant ( <i>f-plane</i> )	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Non-Periodic in $x$ Periodic in $y$	(3), (5), (8)
2. Inertia-Gravity Wave	Constant ( <i>f-plane</i> )	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Periodic in $x$ Periodic in $y$	(3), (5), (8)
3a. Planetary Rossby Wave	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	Linear, Homogeneous, Variable-Coefficient	Radiation or No-Normal Flow	(3), (4), (5), (8)
3b. Planetary Rossby Wave (NL)	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	<b>Non-Linear</b> , Homogeneous, Variable-Coefficient	Radiation or No-Normal Flow	(1), (2), (3), (4), (5), (6)*, (8), (9)
4a. Topographic Rossby Wave	Constant ( <i>f-plane</i> )	Linear in $y$ , Sloping Bottom	Linear, Homogeneous, Variable-Coefficient	Radiation or No-Normal Flow	(3), (5), (8), (10)
4b. Topographic Rossby Wave (NL)	Constant ( <i>f-plane</i> )	Linear in $y$ , Sloping Bottom	<b>Non-Linear</b> , Homogeneous, Variable-Coefficient	Radiation or No-Normal Flow	(1), (2), (3), (5), (6)*, (8), (9), (10)
5. Barotropic Tide	Constant ( <i>f-plane</i> )	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Non-Periodic in $x$ , Non-Periodic in $y$	(3), (5) (8)
6. Manufactured Solution	Constant ( <i>f-plane</i> )	Flat Bottom	Non-Linear, Inhomogeneous, Constant-Coefficient	Periodic in $x$ , Periodic in $y$	(1), (2), (3), (5), (7), (8), (9)

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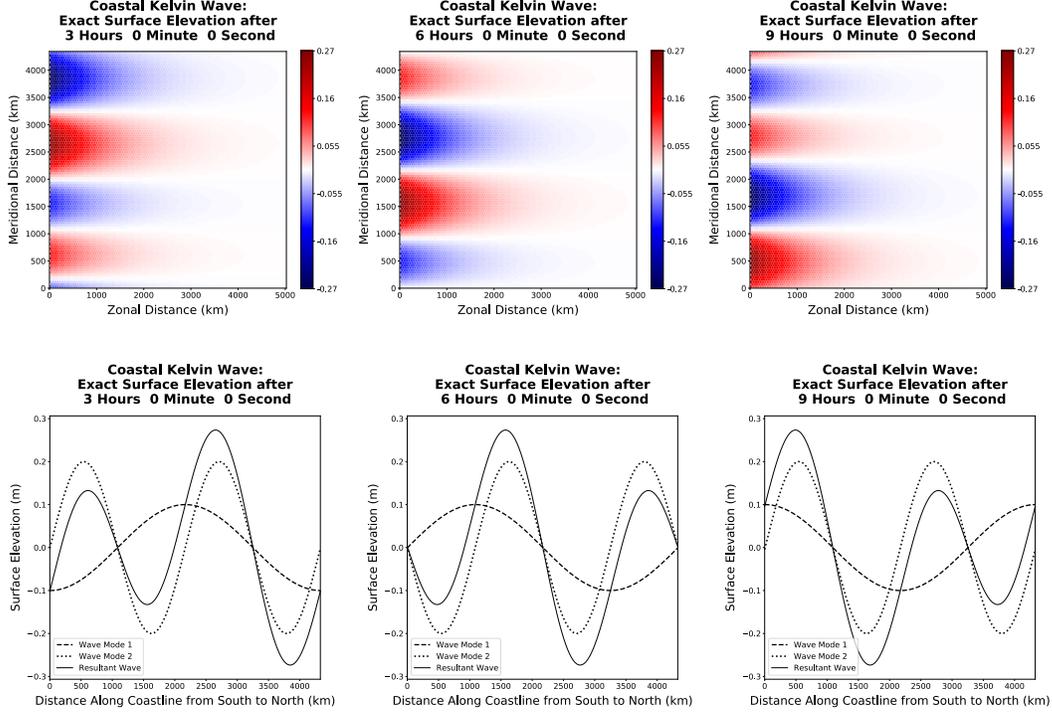
## 2.5 Test Case 1: Coastal Kelvin Wave

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A Kelvin wave is a lateral disturbance that requires the presence of a topographic boundary e.g. the oceanic coast or a waveguide e.g. the equator. As the name implies, the coastal Kelvin wave belongs to the topographic boundary category and is therefore a



**Figure 1.** Time evolution of the exact surface elevation of TC1, the non-dispersive coastal Kelvin wave, in the entire domain (first row), and along the coastline (second row), with dashed and dotted lines representing component wave modes, and the solid line representing the resultant wave.

466 common phenomenon along coastlines. It travels with the coast on its right in the Northern  
 467 Hemisphere and with the coast on its left in the Southern Hemisphere. Its amplitude  
 468 decreases exponentially away from the coast with a decay scale equal to the barotropic  
 469 Rossby radius of deformation. This is why the coastal Kelvin wave appears to be ‘trapped’  
 470 near the coast. It is non-dispersive which causes the coastal Kelvin wave to preserve its  
 471 initial profile as it propagates in the alongshore direction over time.

472 Following the derivation in Cushman-Roisin and Beckers (2011), if the coastline is  
 473 aligned along the  $y$ -axis ( $x = 0$ ) and we specify  $u = 0$  throughout the domain, we arrive at  
 474 the physically feasible general solution

$$u = 0, \tag{11}$$

$$v = \sqrt{gH}F(y + ct)e^{-x/R}, \tag{12}$$

$$\eta = -HF(y + ct)e^{-x/R}. \tag{13}$$

475 Here  $R = c/f = \sqrt{gH}/f$  is the barotropic Rossby radius of deformation, a length scale where  
 476 rotational effects are considered important. From (12) and (13), we observe that  $R$  is also a  
 477 measure of the trapping distance of the Kelvin wave from the coast. The dispersion relation  
 478 of a coastal Kelvin wave mode with angular frequency  $\omega$  and meridional wavenumber  $k_y$   
 479 is  $\omega = ck_y$ , where the wave speed  $c = \sqrt{gH}$  is independent of  $k_y$ , a characteristic of  
 480 non-dispersive waves.

481 In our numerical simulations, we choose a sinusoidal meridional profile defined by  
 482  $F(y) = \hat{\eta} \sin(k_y y)$ . In addition, we designate the exact solution to be a superposition  
 483 of two wave modes, with the second mode having twice the amplitude and wavenumber  
 484 components compared to the first, i.e.,  $\hat{\eta}^{(2)} = 2\hat{\eta}^{(1)}$  and  $k_y^{(2)} = 2k_y^{(1)}$ . Here,  $\hat{\eta}^{(1)} = 10^{-4}$

485 m,  $k_y^{(1)} = 2\pi/L_y$ , and  $L_y$  denotes the meridional extent of the domain. For this test case  
 486 and subsequent ones, we set  $f_0 = 10^{-4} \text{ s}^{-1}$ ,  $g = 10 \text{ m s}^{-2}$  and  $H = 10^3 \text{ m}$ , yielding  
 487  $c = \sqrt{gH} = 100 \text{ m s}^{-1}$  and  $R = c/f_0 = 10^6 \text{ m}$ . As elaborated in Section 2.7,  $f_0$  is identical  
 488 to the Coriolis parameter  $f$  on an  $f$ -plane, but corresponds to its leading-order component  
 489 on a  $\beta$ -plane. The zonal extent is specified as  $L_x = 5R = 5 \times 10^6 \text{ m}$ , ensuring the wave  
 490 amplitude diminishes to virtually zero just west of the open eastern boundary. For all test  
 491 cases, the meridional extent is set as  $L_y = \sqrt{3}/2L_x$  when modeled with the TRiSK-based  
 492 finite volume method, and as  $L_y = L_x$  when discretized with the discontinuous Galerkin  
 493 spectral element method (DGSEM). Figure 1 presents the temporal evolution of the exact  
 494 surface elevation of the coastal Kelvin wave. The first row illustrates the surface elevation  
 495 throughout the entire domain, while the second row depicts the surface elevation along the  
 496 coastline. Here, dashed and dotted lines denote the component wave modes, with the solid  
 497 line indicating the resultant wave. Both component wave modes propagate at identical  
 498 phase speeds, a fact that can be confirmed by tracking the crest or trough of the first wave  
 499 mode and one crest or trough of the second wave mode, and observing that their relative  
 500 positions do not vary over time. This phenomenon leads to the maintenance of the original  
 501 resultant profile without distortion, a characteristic anticipated for a non-dispersive wave.

## 502 2.6 Test Case 2: Inertia-Gravity Wave

503 As discussed in Cushman-Roisin and Beckers (2011), by eliminating the requirement of  
 504 a lateral boundary and the constraint  $u = 0$ , we can assume a Fourier series solution to (10)  
 505 of the form

$$\begin{bmatrix} \eta \\ u \\ v \end{bmatrix} = \text{Re} \left\{ \begin{bmatrix} \hat{\eta} \\ \hat{u} \\ \hat{v} \end{bmatrix} e^{i(k_x x + k_y y - \omega t)} \right\}, \quad (14)$$

506 and arrive at the dispersion relation

$$\omega \{ \omega^2 - (c^2 k^2 + f^2) \} = 0, \quad (15)$$

507 where  $k = \sqrt{k_x^2 + k_y^2}$ . The root  $\omega = 0$  corresponds to the steady geostrophic state and the  
 508 remaining two roots  $\omega = \pm \hat{\omega}$ , where  $\hat{\omega} = \sqrt{c^2 k^2 + f^2}$ , correspond to oppositely-travelling  
 509 inertia-gravity waves with super-inertial frequency ( $\omega > f$ ). Since the zonal and meridional  
 510 phase speeds, given by  $c_x = \omega/k_x$  and  $c_y = \omega/k_y$ , are functions of the wavenumber  
 511 components  $k_x$  and  $k_y$ , the inertia-gravity wave is dispersive. To arrive at a particular  
 512 solution consisting of only the inertia-gravity wave mode  $\hat{\omega}$ , we replace  $\omega$  by  $\hat{\omega}$  and insert  
 513 (14) in (10), which results in

$$-i\hat{\omega}\hat{u} - f\hat{v} = -ik_x g\hat{\eta}, \quad (16a)$$

$$-i\hat{\omega}\hat{v} + f\hat{u} = -ik_y g\hat{\eta}, \quad (16b)$$

$$-i\hat{\omega}\hat{\eta} + iH(k_x\hat{u} + k_y\hat{v}) = 0. \quad (16c)$$

514 We can now solve any two equations of (16) to obtain

$$\hat{u} = \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} (\hat{\omega}k_x + ifk_y), \quad (17)$$

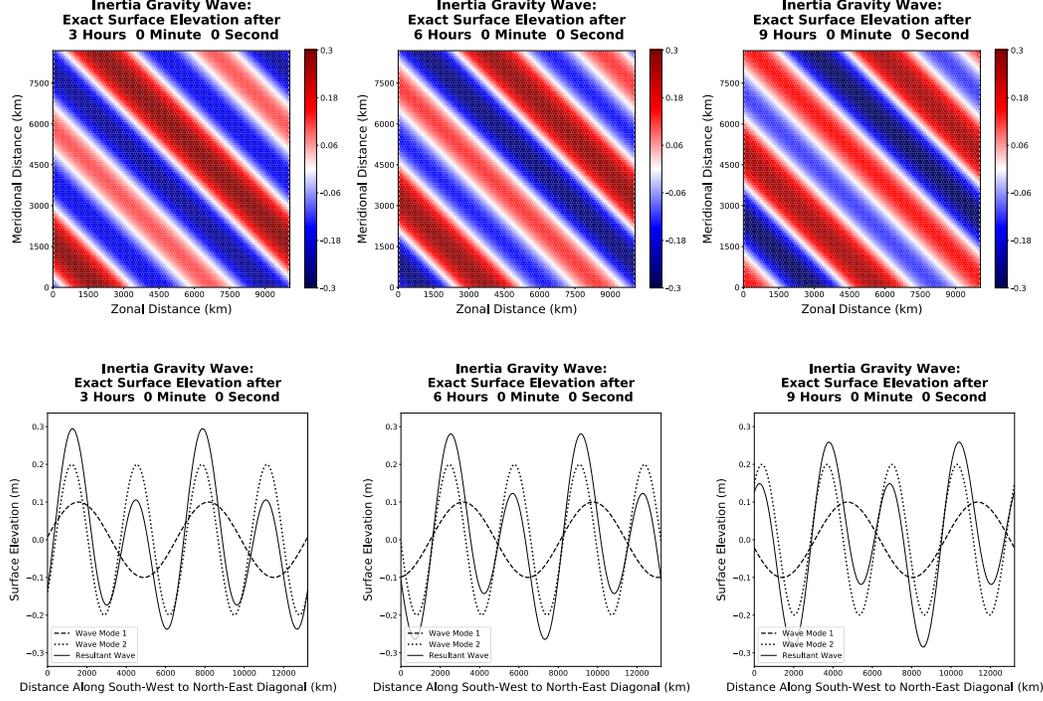
$$\hat{v} = \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} (\hat{\omega}k_y - ifk_x), \quad (18)$$

515 and demonstrate that these values of  $\hat{u}$  and  $\hat{v}$  satisfy the third equation as well. Therefore,  
 516 the particular solution consisting of only the inertia-gravity wave mode  $\hat{\omega}$  is

$$\eta = \text{Re} \left\{ \hat{\eta} e^{i(k_x x + k_y y - \hat{\omega} t)} \right\}, \quad (19)$$

$$u = \text{Re} \left\{ \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} (\hat{\omega}k_x + ifk_y) e^{i(k_x x + k_y y - \hat{\omega} t)} \right\}, \quad (20)$$

$$v = \text{Re} \left\{ \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} (\hat{\omega}k_y - ifk_x) e^{i(k_x x + k_y y - \hat{\omega} t)} \right\}, \quad (21)$$



**Figure 2.** Same as Figure 1, but for TC2, the high-frequency dispersive inertia-gravity wave, with the second row depicting the time evolution of the exact surface elevation and its component wave modes (represented by solid, dashed, and dotted lines respectively) along the south-west to north-east diagonal of the domain.

517 which simplifies to

$$\eta = \hat{\eta} \cos(k_x x + k_y y - \hat{\omega} t), \quad (22)$$

$$u = \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} \{ \hat{\omega} k_x \cos(k_x x + k_y y - \hat{\omega} t) - f k_y \sin(k_x x + k_y y - \hat{\omega} t) \}, \quad (23)$$

$$v = \frac{g\hat{\eta}}{\hat{\omega}^2 - f^2} \{ \hat{\omega} k_y \cos(k_x x + k_y y - \hat{\omega} t) + f k_x \sin(k_x x + k_y y - \hat{\omega} t) \}. \quad (24)$$

518 We once again specify the exact solution in our numerical simulations to be the sum  
 519 of two wave modes, whose amplitudes and wavenumbers satisfy  $\hat{\eta}^{(2)} = 2\hat{\eta}^{(1)}$ ,  $k_x^{(2)} = 2k_x^{(1)}$ ,  
 520 and  $k_y^{(2)} = 2k_y^{(1)}$ , where  $\hat{\eta}^{(1)} = 0.1$  m,  $L_x = 10^7$  m,  $k_x^{(1)} = 2\pi/L_x$ , and  $k_y^{(1)} = 2\pi/L_y$ . The  
 521 domain extents  $L_x$  and  $L_y$  are chosen carefully to ensure that the ratio  $f/ck$  ranges between  
 522 0.5 and 1.0 for these wave modes, so that both the gravity and the rotational forces play  
 523 important roles in their generation. The first row of Figure 2 exhibits the surface elevation  
 524 in the entire domain, and the second row depicts the surface elevation along the south-west  
 525 to north-east diagonal. With the phase speed now being a function of the wavenumber,  
 526 the component wave modes represented by dashed and dotted lines propagate at different  
 527 phase speeds (as manifested by the temporal variation in the relative position of the crest or  
 528 trough of the first wave mode with respect to a crest or trough of the second wave mode).  
 529 This leads to modification of the resultant wave profile (represented by a solid line) with  
 530 time, a characteristic that aligns with the behavior of a dispersive wave.

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### 2.7 Test Case 3: Planetary Rossby Wave

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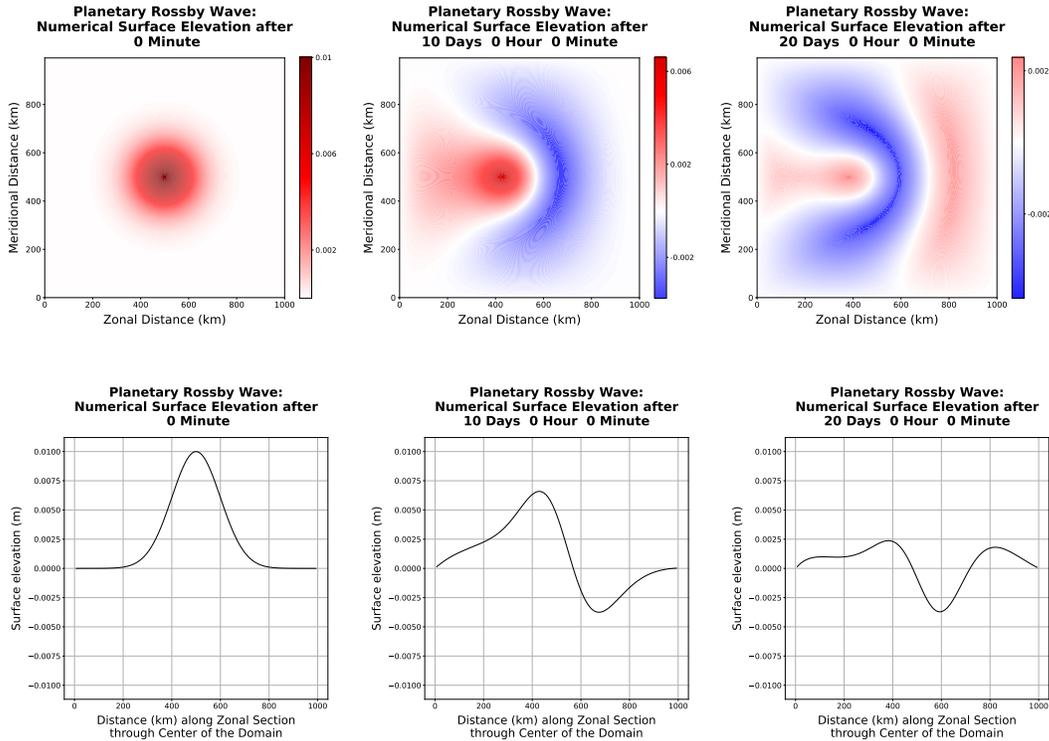
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Planetary Rossby waves are low-frequency dispersive waves that feel the rotation of the Earth. They owe their existence to the variation of the Coriolis parameter  $f = 2\Omega \sin \theta$  with the latitude  $\theta$ , where  $\Omega$  denotes Earth's rotational rate. A Taylor expansion of  $f$  around a reference latitude  $\theta_0$ , limited to the first two terms, results in  $f = f_0 + \beta_0 y$ . Here,  $f_0 = 2\Omega \sin \theta_0$ ,  $\beta_0 = 2(\Omega/a) \cos \theta_0$ , and  $a$  represents Earth's radius. A geophysical wave motion's domain is termed a *beta-plane* if the  $\beta$  term is included, and an *f-plane* if not. The *beta-plane* approximation is applicable when  $\beta_0 y \ll f_0$  across the domain, implying  $\beta = \beta_0 L \ll f_0$ , where  $L$  indicates the meridional extent of the domain and  $\beta$  is a dimensionless planetary number. For Earth's mid-latitudes, typical values are  $f_0 \approx 10^{-4} \text{ s}^{-1}$  and  $\beta_0 \approx 2 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ , which we adopt in our numerical simulations as well.



**Figure 3.** Time evolution of the numerical surface elevation of TC3, the low-frequency dispersive planetary Rossby wave, in the entire domain (first row) and along the zonal section through the domain center (second row), advanced with Williamson's low-storage third-order Runge-Kutta time-stepping method, and spatially discretized with DGSEM using 10 elements and polynomial basis functions of order 7 in each horizontal direction.

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Planetary Rossby waves represent a slow evolution of steady geostrophic flows, with the velocity field consisting of a leading-order geostrophic term and an ageostrophic perturbation term. Following the derivation in Cushman-Roisin and Beckers (2011), if the velocities are approximated solely by the geostrophic terms and inserted into the momentum equations, a first-order velocity approximation is obtained. Applying these velocities to the continuity equation (10c) yields a constant-coefficient equation, the Fourier series solution of which results in the dispersion relation

$$\omega = -\frac{\beta_0 R^2 k_x}{1 + R^2 (k_x^2 + k_y^2)}. \quad (25)$$

549 For shorter waves, where the length scale  $L(\sim 1/k_x \sim 1/k_y) \lesssim R$ , we find  $\omega \sim \beta_0 L$ .  
 550 Longer waves, with  $L(\sim 1/k_x \sim 1/k_y) \gtrsim R$ , yield  $\omega \sim \beta_0 R^2/L \lesssim \beta_0 L$ . In both cases,  
 551 under the assumption  $\beta_0 L \ll f_0$ , we obtain  $\omega \ll f_0$ , affirming the subinertial nature of the  
 552 planetary Rossby wave. The zonal and meridional phase speeds, represented by  $c_x = \omega/k_x$   
 553 and  $c_y = \omega/k_y$ , are clearly functions of the wavenumber components  $k_x$  and  $k_y$ , thereby  
 554 attributing to the wave's dispersive nature. Moreover, the zonal phase speed is invariably  
 555 negative, with higher potential vorticity on the right of the propagation direction, resulting  
 556 in a phase propagation in westward, northwestward, or southwestward directions.

557 Our attempt to simulate the planetary Rossby wave using the shallow water equations  
 558 presents a unique challenge. Since the shallow water equations admit a spectrum of wave  
 559 solutions, it is impossible to only extract the low-frequency planetary Rossby waves as a  
 560 numerical solution. To simulate the low-frequency planetary Rossby waves, we numerically  
 561 solve the linear but variable-coefficient shallow water equations on a *beta-plane*. We specify  
 562 the initial surface elevation as a Gaussian blob at the center of the domain, and obtain the  
 563 initial velocities using the pressure gradient force and geostrophic balance:

$$\eta(x, y, t = 0) = \hat{\eta} e^{-\{(x-x_0)^2/(2R_x^2) + (y-y_0)^2/(2R_y^2)\}}, \quad (26)$$

$$u(x, y, t = 0) = \frac{g}{f_0 R_y^2} (y - y_0) \hat{\eta} e^{-\{(x-x_0)^2/(2R_x^2) + (y-y_0)^2/(2R_y^2)\}}, \quad (27)$$

$$v(x, y, t = 0) = -\frac{g}{f_0 R_x^2} (x - x_0) \hat{\eta} e^{-\{(x-x_0)^2/(2R_x^2) + (y-y_0)^2/(2R_y^2)\}}. \quad (28)$$

564 Here  $\hat{\eta} = 0.01$  m represents the surface elevation amplitude,  $(x_0, y_0)$  represents the center  
 565 of the domain with zonal extent  $L_x = 10^6$  m, and the decay scales  $R_x$  and  $R_y$  amount to  
 566 10% of the zonal and meridional extents of the domain. Time integration results in the  
 567 evolution of this ‘geostrophic’ monopole on the *beta-plane*. Since we are not equipped with  
 568 the time-dependent exact solutions, we demonstrate high-resolution numerical solutions in  
 569 Figure 3 obtained using (a) a high-order discontinuous Galerkin spectral element method  
 570 (DGSEM) in space with 10 elements and polynomial basis functions of order 7 in each  
 571 horizontal direction, resulting in seventh-order spatial accuracy, and (b) the low-storage  
 572 third-order Runge-Kutta method of J. Williamson (1980) in time. The first row illustrates  
 573 the time evolution of the numerical surface elevation in the entire domain, and the second  
 574 row depicts the same along the zonal section through the domain center. Right after  
 575 initialization, some gravity waves radiate out of the monopole towards the domain boundaries.  
 576 We impose radiation boundary conditions by setting the external state to a motionless  
 577 fluid with no free surface height variation ( $u = v = 0, \eta = 0$ ), leading to the eventual  
 578 propagation of the gravity waves out of the domain. Alternatively, if solid wall or no-normal  
 579 flow boundary conditions were applied, these gravity waves would continue propagating  
 580 along the domain boundaries as coastal Kelvin waves. On a much slower time scale on  
 581 the order of the diurnal motion of the Earth, we observe the monopole itself propagating  
 582 in the direction of the planetary Rossby waves, with increasing potential vorticity to the  
 583 right of the propagation direction. The monopole can be considered to be a superposition  
 584 of infinite wave modes with different wavelengths, each of which propagates according to  
 585 the dispersion relation (25). Due to the dispersive nature of the planetary Rossby wave, the  
 586 wave modes with different wavelengths propagate with different phase speeds, resulting in  
 587 a distortion of the initial Gaussian profile of the monopole with time (as observed in the  
 588 plots of Figure 3).

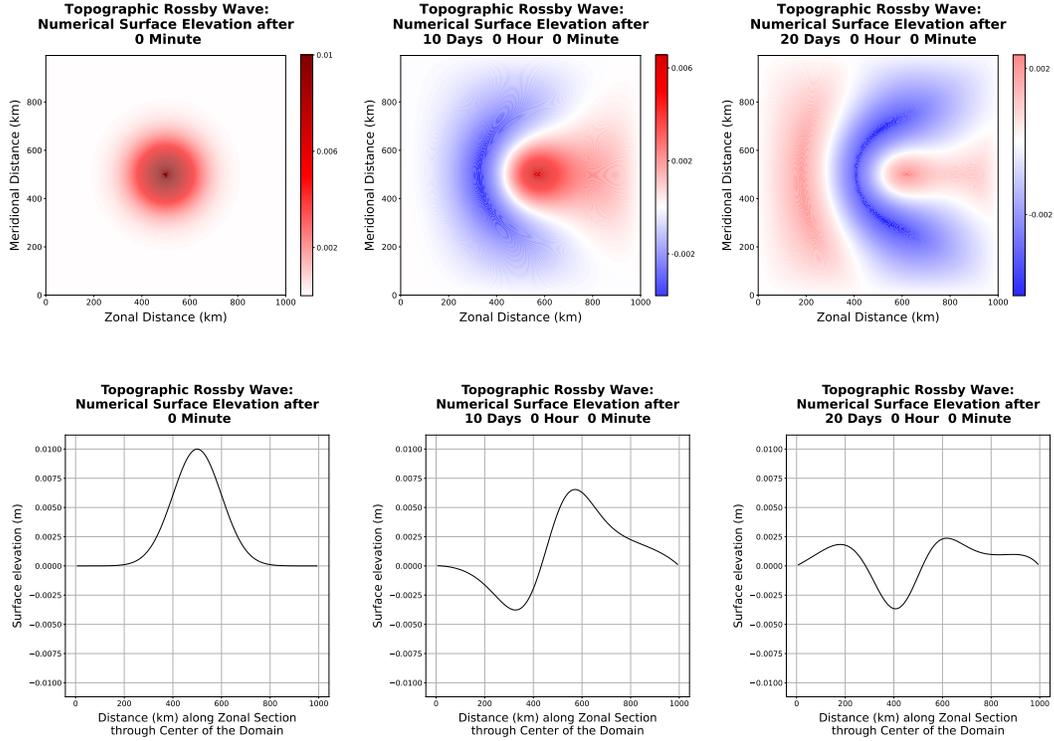
589 The non-linear advection terms can also be turned on, along with appropriate diffusion  
 590 terms to ensure a stable solution over prolonged simulation times. It is worth mentioning  
 591 that the inclusion of non-linear and diffusion terms verifies the implementation of every term  
 592 in the non-linear homogeneous shallow water equations. While we present the numerical  
 593 solution for the linear version of the planetary Rossby wave test case, the non-linear solutions  
 594 have also been thoroughly examined. In our convergence analyses, aimed at verifying the  
 595 spatial and temporal orders of accuracy, both the linear and non-linear versions of the

596 planetary Rossby wave were solved. As extensive simulation times are not required for  
 597 these convergence studies, the activation of diffusion terms is optional for this purpose.

598 **2.8 Test Case 4: Topographic Rossby Wave**

599 The topographic Rossby wave arises because of variations of the bottom topography.  
 600 Following the derivation in Cushman-Roisin and Beckers (2011), we only consider a bottom  
 601 topography with a small slope of constant magnitude in the meridional direction. If  $\alpha_0$   
 602 denotes the bottom slope, the topography is  $b(x, y) = -\alpha_0 y$ . Using (2), the thickness of the  
 603 shallow water layer at any point in time is

$$h(x, y, t) = H + \eta(x, y, t) - b(x, y) = H + \alpha_0 y + \eta(x, y, t). \quad (29)$$



**Figure 4.** Same as Figure 3, but for TC4, the topographic Rossby wave.

604 The requirement of a gentle bottom slope implies  $\alpha = \alpha_0 L/H \ll 1$ , where  $\alpha$  is a  
 605 dimensionless parameter similar to the planetary number, and  $L$  is the horizontal length  
 606 scale of motion. Just like the planetary Rossby waves, the velocity field of their topographic  
 607 analogues consist of a leading-order geostrophic term, and a much smaller ageostrophic  
 608 correction term. The ageostrophic terms, driving the motion of these waves, are  $\mathcal{O}(\alpha)$   
 609 relative to the geostrophic ones, resulting in subinertial wave frequencies  $\omega \sim \alpha f \ll f$ .

610 Again, assuming the velocities to consist entirely of the geostrophic terms and inserting  
 611 them into the momentum equations, we arrive at a first-order approximation of the velocities,  
 612 which upon insertion into the continuity equation results in a constant-coefficient equation,  
 613 the Fourier series solution of which results in the dispersion relation

$$\omega = \frac{\alpha_0 g k_x}{f \{1 + R^2 (k_x^2 + k_y^2)\}}. \quad (30)$$

614 The zonal and meridional phase speeds, given by  $c_x = \omega/k_x$  and  $c_y = \omega/k_y$ , depend on the  
 615 wavenumber, rendering the topographic Rossby waves dispersive. Since  $c_x$  has the same sign  
 616 as  $\alpha_0 f$ , in the northern hemisphere (where  $f > 0$ ), the topographic Rossby waves propagate  
 617 with the shallower side on their right. Similar to planetary Rossby waves, the potential  
 618 vorticity increases towards the right of the direction of the zonal phase propagation.

619 Figure 4 illustrates high-resolution numerical solutions for the topographic Rossby wave,  
 620 modeled using DGSEM and RK3. The horizontal domain extents, the spatial and temporal  
 621 resolutions, as well as the initial and boundary conditions have been configured to match  
 622 their counterparts for the planetary Rossby wave test case (Section 2.7). The bottom slope  
 623 is chosen to be  $\alpha_0 = \beta_0 H_0 / f_0$ , with  $\beta_0 = 2 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$ ,  $f_0 = 10^{-4} \text{ s}^{-1}$  and  $H_0 = 1000$   
 624 m. As a result, the depth increases northward, and the different modes of the dispersive  
 625 topographic Rossby wave, each associated with a unique wavenumber, exhibit the same  
 626 phase speeds as their planetary analogues, though they travel in the opposite direction, i.e.,  
 627 eastward. Due to the variation of phase speed with wavenumber, the initial profile is no  
 628 longer maintained, as evidenced by the plots in Figure 4. Just like the planetary Rossby wave  
 629 test case, our presentation focuses on the linear solution. However, we have also explored  
 630 the non-linear solution, which effectively tests every term in the homogeneous non-linear  
 631 shallow water equations. During our convergence studies, we address both variants of the  
 632 topographic Rossby wave.

## 633 2.9 Test Case 5: Barotropic Tide

634 Following the analysis of barotropic tides in Clarke and Battisti (1981) and Clarke  
 635 (1991), we consider a simple model of the continental shelf, with constant depth  $h$  from the  
 636 coast at  $x = 0$  to the edge of the shelf at  $x = L$ , where the depth abruptly increases to  $H$   
 637 and remains so in the deep sea. By combining equations (10a), (10b) and (10c), we arrive  
 638 at the single equation

$$\nabla^2 \eta_t - \frac{1}{c^2} (\eta_{ttt} + f^2 \eta_t) = 0, \quad (31)$$

639 for modeling sinusoidal barotropic tides with  $c^2 = gh$  on the continental shelf and  $c^2 = gH$   
 640 on the coast. Assuming the continental shelf is long and straight, and applying scaling  
 641 analysis and no-normal flow boundary condition at the coast, we arrive at the complete  
 642 solution

$$\eta = \hat{\eta} \cos(kx) \cos(\omega t), \quad (32)$$

$$u = \frac{\hat{\eta} g \omega k}{\omega^2 - f_0^2} \sin(kx) \sin(\omega t), \quad (33)$$

$$v = \frac{\hat{\eta} g f_0 k}{\omega^2 - f_0^2} \sin(kx) \cos(\omega t), \quad (34)$$

643 where  $\omega = \sqrt{ghk^2 + f_0^2}$ . Rewriting (32) as

$$\eta = \frac{1}{2} \hat{\eta} \cos(kx - \omega t) + \frac{1}{2} \hat{\eta} \cos(kx + \omega t), \quad (35)$$

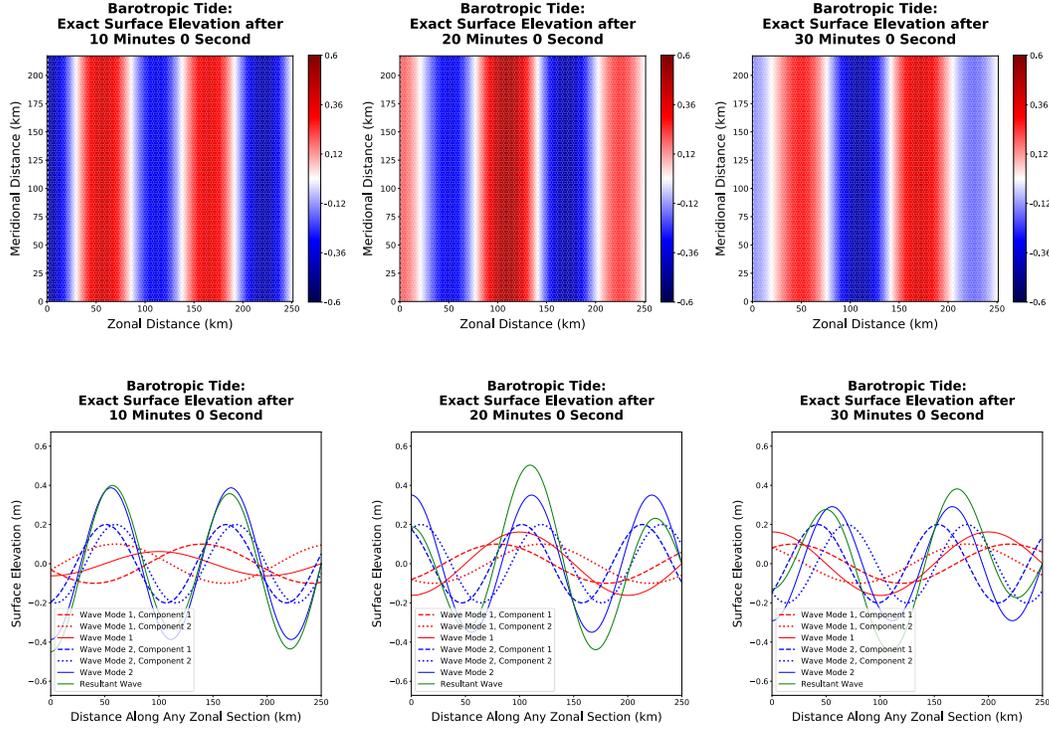
644 we can interpret the surface elevation as the sum of two waves perpendicular to the coast  
 645 but travelling in opposite directions. Tidal resonance occurs when the ratio of coastal to  
 646 deep sea level is infinite, i.e. when

$$\frac{\eta(0)}{\eta(L)} = \frac{1}{\cos(kL)} = \pm\infty, \quad (36)$$

647 which occurs when

$$L = \left(m + \frac{1}{2}\right) \frac{\pi}{k} = \left(m + \frac{1}{2}\right) \pi \sqrt{\frac{gh}{\omega^2 - f^2}}, \quad (37)$$

648 for a non-negative integer  $m$ .

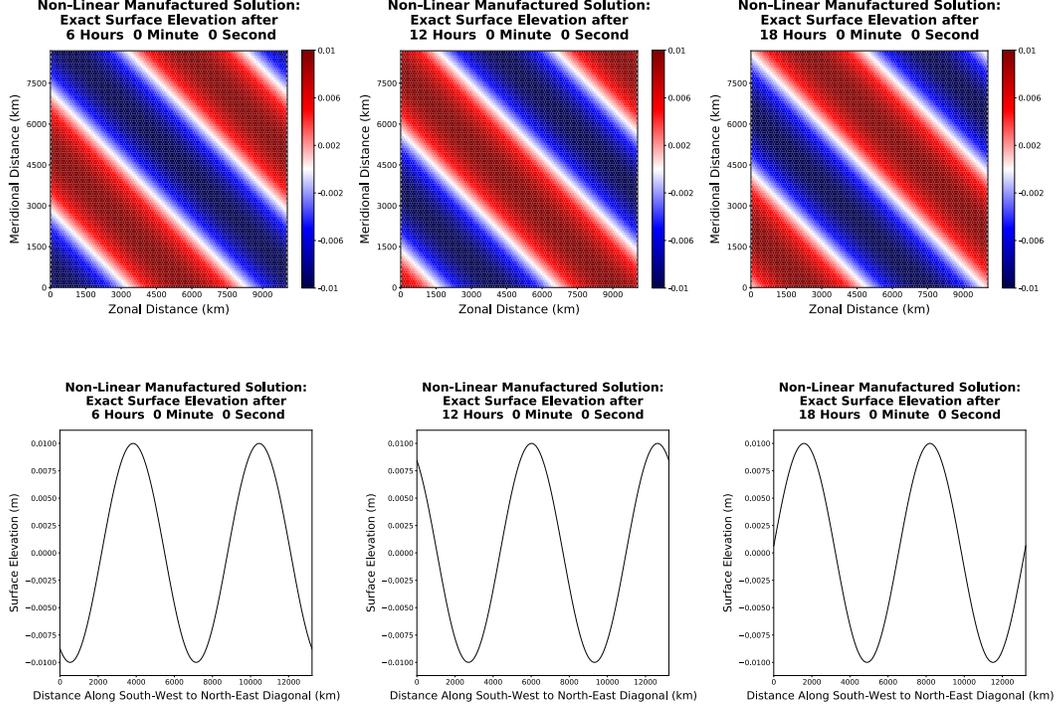


**Figure 5.** Time evolution of the exact surface elevation of TC5, the barotropic tide, in the entire domain (first row), and along any zonal section (second row).

649 Figure 5 depicts the time evolution of the barotropic tide in the entire domain (first  
 650 row) with zonal extent  $L_x = 2.5 \times 10^5$  m, and along any zonal section (second row). The  
 651 exact surface elevation is chosen to be a superposition of two standing wave modes, each of  
 652 which is the sum of two wave modes of equal amplitude and phase speed but traveling in  
 653 opposite directions. Each of these component modes is uniform in the meridional direction.  
 654 Their wavelengths,  $\lambda^{(1)} = 2\pi/k^{(1)}$  and  $\lambda^{(2)} = 2\pi/k^{(2)}$ , amount to 4/5-th and 4/9-th of the  
 655 zonal extents of the domain, which satisfy the conditions for tidal resonance. The surface  
 656 elevation amplitudes are designated as  $\hat{\eta}^{(1)} = 0.2$  m and  $\hat{\eta}^{(2)} = 2\hat{\eta}^{(1)}$ . The second row  
 657 of Figure 5 shows the resultant barotropic tide as a solid green line, while its underlying  
 658 standing wave modes are indicated by solid red and blue lines. The individual components  
 659 of each standing wave mode are represented by dashed and dotted lines of the same color.

## 660 2.10 Test Case 6: Non-linear Manufactured Solution

661 The method of manufactured solutions (MMS) has been applied to a wide variety of  
 662 scientific and engineering codes involving the numerical solution of linear and non-linear  
 663 PDEs. MMS can be used to generate PDEs with exact solutions so that the order of  
 664 accuracy of numerical methods can be investigated. The basic idea of MMS is to choose  
 665 such an exact solution,  $u = u_e$ , and insert it in the left-hand side of the governing PDE  
 666  $\mathcal{L}(u) = 0$ , where  $u$  represents the dependent variable. This gives rise to a source term  
 667  $f = \mathcal{L}(u_e)$ , which is only a function of space and time, and the coefficients appearing in  
 668 the PDE. The modified PDE  $\mathcal{L}(u) = f$  is then discretized as  $\mathcal{L}_\Delta(u_\Delta) = f_\Delta$ , and solved to  
 669 obtain the numerical solution  $u_\Delta$ , where the subscript  $\Delta$  represents the set of discretization  
 670 parameters.



**Figure 6.** Same as Figure 5, but for TC6, the non-linear manufactured solution, with the second row depicting the time evolution of the exact surface elevation along the south-west to north-east diagonal of the domain.

671 Detailed investigations of MMS against benchmark solutions with sufficiently complex  
 672 structure were conducted by Salari and Knupp (2000) and Roache (2002). Within the  
 673 geophysical literature, test case (iv) of D. L. Williamson et al. (1992) belongs to the  
 674 category of MMS. More recently, Kärnä et al. (2018) presented a steady-state baroclinic  
 675 manufactured solution in one vertical and one horizontal dimension. In contrast, we propose  
 676 a time-dependent barotropic manufactured solution in the horizontal plane,

$$u = \hat{\eta} \cos(k_x x + k_y y - \omega t), \quad (38a)$$

$$v = 0, \quad (38b)$$

$$\eta = \hat{\eta} \sin(k_x x + k_y y - \omega t), \quad (38c)$$

677 which solves the non-linear rotating inviscid shallow water equations

$$u_t + uu_x + vu_y - fv = -g\eta_x + s^u, \quad (39a)$$

$$v_t + uv_x + vv_y + fu = -g\eta_y + s^v, \quad (39b)$$

$$\eta_t + \{(H + \eta)u\}_x + \{(H + \eta)v\}_y = s^\eta. \quad (39c)$$

678 Inserting the exact solution (38) into the left-hand side of (39), we obtain the source terms

$$s^u = \hat{\eta} \{(-f + gk_x) \cos \phi + \omega \sin \phi - \hat{\eta}(k_x + k_y) \sin(2\phi)/2\}, \quad (40a)$$

$$s^v = \hat{\eta} \{(f + gk_y) \cos \phi + \omega \sin \phi - \hat{\eta}(k_x + k_y) \sin(2\phi)/2\}, \quad (40b)$$

$$s^\eta = \hat{\eta} \{-H(k_x + k_y) \sin \phi - \omega \cos \phi + \hat{\eta}(k_x + k_y) \cos(2\phi)\}, \quad (40c)$$

679 where the phase  $\phi = k_x x + k_y y - \omega t$ . As expected, the source terms undergo modification if  
 680 the governing equations being discretized assume a different form. For instance, if we employ

681 the discontinuous Galerkin Spectral Element Method (DGSEM), outlined in Section 3.2, for  
 682 spatial discretization, one option is to start out with the conservative form of the non-linear  
 683 rotating shallow water equations. The conservative form can be obtained by adding the  
 684 depth-multiplied momentum equations (7a) and (7b) to the continuity equation (7c). The  
 685 resulting equations are

$$(hu)_t + (hu^2 + gh^2/2)_x + (huv)_y - fhv = -ghb_x, \quad (41a)$$

$$(hv)_t + (huv)_x + (hv^2 + gh^2/2)_y + fhu = -ghb_y, \quad (41b)$$

$$h_t + (hu)_x + (hv)_y = 0. \quad (41c)$$

686 The source terms transition to

$$\begin{aligned} s^{hu} = & \hat{\eta}H \{ (gk_x - f) \cos \phi + \omega \sin \phi \} \\ & + \hat{\eta}^2 [\sin(2\phi) \{ -H(k_x + k_y) + (gk_x - f)/2 \} - \omega \cos(2\phi)] \\ & + \hat{\eta}^3 (k_x + k_y) \{ -\sin(2\phi) \sin \phi + \cos^3 \phi \}, \end{aligned} \quad (42a)$$

$$\begin{aligned} s^{hv} = & \hat{\eta}H \{ (gk_y + f) \cos \phi + \omega \sin \phi \} \\ & + \hat{\eta}^2 [\sin(2\phi) \{ -H(k_x + k_y) + (gk_y + f)/2 \} - \omega \cos(2\phi)] \\ & + \hat{\eta}^3 (k_x + k_y) \{ -\sin(2\phi) \sin \phi + \cos^3 \phi \}, \end{aligned} \quad (42b)$$

$$s^h = \hat{\eta} \{ -H(k_x + k_y) \sin \phi - \omega \cos \phi + \hat{\eta}(k_x + k_y) \cos(2\phi) \}, \quad (42c)$$

687 where the water depth is simplified to  $h(x, y, t) = H + \eta(x, y)$ , and the right-hand side of  
 688 (41a) and (41b) is reduced to zero due to the presence of a flat bottom ( $b = 0$ ). Figure 6  
 689 depicts the time evolution of the manufactured solution across the entire domain (first row)  
 690 and along the south-west to north-east diagonal (second row). The relevant parameters are  
 691  $L_x = 10^7$  m and  $\hat{\eta} = 0.01$  m. The wavenumbers are defined by  $k_x = 2\pi/L_x$  and  $k_y = 2\pi/L_y$ .  
 692 The angular frequency is  $\omega = c\sqrt{k_x^2 + k_y^2}$ , with  $c = \sqrt{gH} = 100$  m s<sup>-1</sup> representing the speed  
 693 of shallow water gravity waves.

694 While we have utilized (38) to ‘manufacture’ our solution for this non-linear test case,  
 695 any smooth solution in space and time can serve the purpose, provided that the source  
 696 terms are accurately defined. For instance, the exact solutions of the coastal Kelvin wave,  
 697 inertia-gravity wave, and the barotropic tide, which solve the linearized homogeneous form  
 698 of (39), can be employed to ‘manufacture’ our solution and verify the implementation of  
 699 non-linear terms. In these cases, the source terms are essentially the non-linear terms of (39)  
 700 computed with the exact solutions, and can be expressed as:

$$s^u = [uu_x + vu_y]_{\text{exact}}, \quad (43a)$$

$$s^v = [uv_x + vv_y]_{\text{exact}}, \quad (43b)$$

$$s^\eta = [(\eta u)_x + (\eta v)_y]_{\text{exact}}. \quad (43c)$$

### 701 3 Spatial and Temporal Discretizations

702 To generate the numerical solutions, we have developed a rotating shallow water solver  
 703 in an object-oriented Python environment (Bishnu, 2024a). This tool employs two forms of  
 704 spatial discretizations: first, a mimetic finite volume method based on the TRiSK framework  
 705 (Thuburn et al., 2009; T. D. Ringler et al., 2010), and second, a high-order discontinuous  
 706 Galerkin spectral element method (DGSEM). The primary motivation for selecting these two  
 707 spatial discretization methods originates from their widespread application in operational  
 708 ocean models. These models generally adopt

- 709 (a) finite volume methods (LeVeque, 2002; Eymard et al., 2003; Versteeg & Malalasekera,  
 710 2007; Patankar, 2018); or
- 711 (b) finite element (Zienkiewicz et al., 2005; Bathe, 2006; Hughes, 2012; D. L. Logan, 2022)  
 712 or spectral element (Patera, 1984; Maday & Patera, 1989; Karniadakis & Sherwin,  
 713 2005; D. A. Kopriva, 2009) methods.

714 Finite volume methods (FVMs) serve as a highly efficient method for solving PDEs.  
 715 By partitioning the computational domain into a finite set of control volumes, FVMs  
 716 approximate the integral form of the governing equations over these volumes. This method’s  
 717 distinct advantage lies in its conservation of quantities of interest, making it a preferred  
 718 choice for problems bound by conservation laws, typical in fields such as fluid dynamics and  
 719 heat transfer. Many ocean models like Oceananigans (Ramadhan et al., 2020), MITgcm  
 720 (Marshall et al., 1997), MOM (Griffies et al., 2005), ROMS (Shchepetkin & McWilliams,  
 721 2005), NEMO (Madec et al., 2023), FVCOM (C. Chen et al., 2006), and MPAS-Ocean  
 722 (T. Ringler et al., 2013) utilize FVMs for spatial discretization.

723 The finite element method (FEM), on the other hand, offers a versatile solution to tackle  
 724 complex problems, often formulated as PDEs in engineering and mathematical physics.  
 725 The computational domain, divided into a mesh of simpler elements (like 2D triangles  
 726 or 3D tetrahedra), forms the foundation of FEM. The methodology hinges on computing  
 727 approximate solutions at the element nodes, thereby minimizing an associated error function.  
 728 This results in highly accurate solutions within the approximations’ constraints, making  
 729 FEM particularly useful for problems involving structural analysis, heat transfer, fluid flow,  
 730 mass transport, and electromagnetic fields.

731 A specialized class of the FEMs is the spectral element method (SEM), discussed in  
 732 detail in Section 3.2. In contrast to the classical FEMs that predominantly use low, fixed  
 733 order polynomials (typically linear or quadratic) as basis functions, SEMs leverage the  
 734 flexibility of adjustable polynomial order, enabling exponential convergence rates in smooth  
 735 problems. SEMs, typically using quadrilateral (2D) or hexahedral (3D) elements, are adept  
 736 at managing complex geometries. The numerical solution derived using SEM parallels those  
 737 produced by FEM, facilitating comparable methods for conducting convergence studies and  
 738 interpreting the resulting plots. This is especially true if the underpinning method is a  
 739 discontinuous Galerkin (DG) method (Hesthaven & Warburton, 2007). The DG method  
 740 allows for the solution to be discontinuous between elements, thereby making it particularly  
 741 effective for problems characterized by sharp gradients or shocks, as encountered in fluid  
 742 dynamics or electromagnetism. Software based on SEM showcases excellent compatibility  
 743 with GPU-accelerated hardware, a technology that is now dominant in the world’s fastest  
 744 supercomputers (Strohmaier & Dongarra, 2023). Therefore, we anticipate a surge in the  
 745 development of high-order methods like SEMs in research software in the years to come.  
 746 Currently, among functional ocean models, FESOM (Danilov et al., 2004; Q. Wang et al.,  
 747 2014) and NUMO (Kopera et al., 2018, 2023) employ FEM and SEM respectively for spatial  
 748 discretization.

749 We discuss in subsequent sections a few key considerations depending on the spatial  
 750 discretization technique in use. For instance, in Section 6, we explore the significance of  
 751 conducting self-refinement convergence tests only in space and only in time, the underlying  
 752 reasons for which may vary between FVMs and SEMs. Moreover, we delve into numerical  
 753 implementation details in Appendix C, some of which are pertinent to FVMs and some  
 754 to SEMs. Regardless of these disparities, we demonstrate the robustness of our numerical  
 755 recipe in verifying the spatial and temporal orders of accuracy across both types of spatial  
 756 discretization.

757 We now provide a brief description of the TRiSK-based FVM and DGSEM used in our  
 758 numerical experiments.

### 759 3.1 TRiSK-Based Mimetic Finite Volume Method

760 The mimetic finite volume spatial discretization based on the TRiSK scheme was first  
 761 proposed by Thuburn et al. (2009) to ensure that geostrophic modes remain stationary and  
 762 Coriolis terms remain energy conserving on arbitrarily structured C-grids. It was then  
 763 generalized by T. D. Ringler et al. (2010) to model the non-linear rotating shallow water  
 764 equations while guaranteeing the evolution of mass, velocity, and potential vorticity in a

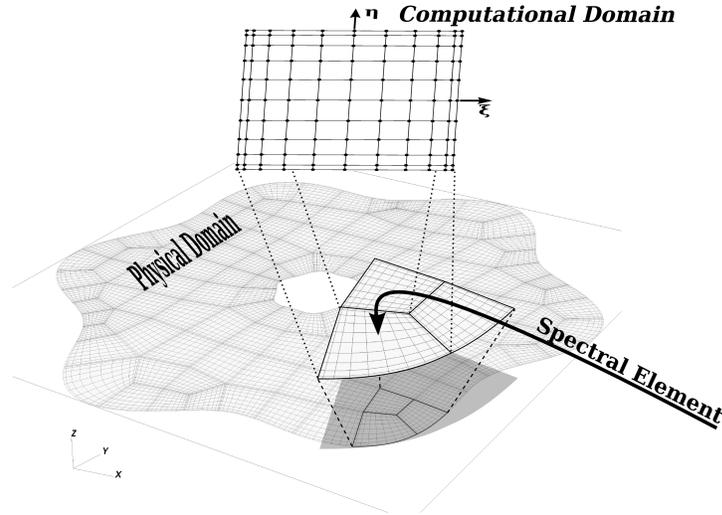
765 consistent and compatible manner, and the conservation of total energy within the time  
 766 truncation error. This mimetic finite volume method was chosen to horizontally discretize  
 767 the primitive equations of MPAS-Ocean while invoking the hydrostatic, incompressible,  
 768 and Boussinesq approximations on a staggered C-grid. Even though the grid cells of  
 769 MPAS-Ocean are near hexagons consisting of five or more sides, the MPAS framework  
 770 supports cells with any number of sides with the algorithm and code remaining identical for  
 771 cells of all shapes and sizes. Since this horizontal discretization guarantees conservation of  
 772 mass, potential vorticity, and energy, it makes MPAS-Ocean a suitable candidate to simulate  
 773 mesoscale eddies.

774 The spatial domain is assumed to be tessellated by two meshes, a primal mesh and a  
 775 dual mesh. Each corner of a primary mesh cell is uniquely associated with a center of a dual  
 776 mesh cell and vice versa. For a regular hexagonal mesh, each corner of a primary mesh cell  
 777 coincides with a vertex of a dual mesh cell and vice versa. A line segment connecting two  
 778 primal mesh cell centers is uniquely associated with a line segment connecting two dual mesh  
 779 cell centers. In case of a regular hexagonal mesh, these two line segments are perpendicular  
 780 bisectors of each other. In case of an irregular hexagonal mesh, these two line segments can  
 781 still intersect orthogonally, but not necessarily at their midpoints. As mentioned before, the  
 782 two prognostic variables for the rotating shallow water equations are the surface elevation,  
 783  $\eta$ , defined at the primal cell centers, and the normal velocity  $\mathbf{u}_e$  defined at the primal cell  
 784 edges. The divergence of a two-dimensional vector quantity is defined at the position of  
 785  $\eta$ , while the two-dimensional gradient of a scalar quantity is defined at the position of  $\mathbf{u}_e$   
 786 and oriented along its direction. The curl of a vector quantity is defined at the vertices of  
 787 the primal cells. Finally, the tangential velocity  $\mathbf{u}_e^\perp$  along a primal cell edge is computed  
 788 diagnostically using a flux mapping operator from primal to dual mesh, which essentially  
 789 takes a weighted average of the normal velocities on the edges of the cells sharing that edge.  
 790 Interested readers may refer to Thuburn et al. (2009) and T. D. Ringler et al. (2010) for an  
 791 extensive discussion on the mesh specifications, the elements of the discrete system along  
 792 with their positioning and their connectivities, and the formulation of the discrete spatial  
 793 and flux-mapping operators.

### 794 3.2 Discontinuous Galerkin Spectral Element Method

795 Spectral element methods belong to the category of multidomain spectral methods.  
 796 In spectral element methods, the physical domain is divided into smaller, non-overlapping  
 797 elements, as illustrated in Figure 7. Within each element, functions are approximated by  
 798 Lagrange interpolating polynomials. The interpolation knots are Gauss-type Quadrature,  
 799 often Legendre-Gauss or Legendre-Gauss-Lobatto (D. A. Kopriva, 2009; D. Kopriva &  
 800 Gassner, 2010; Gassner et al., 2016). Each element is mapped to a reference element,  
 801 and the mapping and metric terms are also approximated by Lagrange interpolation.

802 With Discontinuous Galerkin Spectral Element Methods, the weak form of the equations  
 803 are solved within each element. As explained in standard finite and spectral element  
 804 textbooks like Donea and Huerta (2003), Hughes (2012), Zienkiewicz et al. (2005), Bathe  
 805 (2006), Reddy (2019), D. L. Logan (2022), Karniadakis and Sherwin (2005), Canuto et al.  
 806 (2007b), and D. A. Kopriva (2009), the weak form is obtained by multiplying the original  
 807 “strong form” of the PDE by a test function and then integrating over the domain. In this  
 808 context, a test function is a mathematical tool that facilitates the derivation of the weak  
 809 form of the PDE. This weak form requires the solution to be differentiable to a lower order  
 810 compared to the strong form, and is generally easier to solve numerically. The test function  
 811 is chosen to have certain properties, such as being zero on the boundaries of the domain  
 812 or being part of a certain function space. Integration by parts is subsequently applied to  
 813 the product of the PDE and the test function to reduce the order of the derivatives. This  
 814 process transitions the problem into an integral representation wherein the solution satisfies  
 815 the PDE in an averaged “weak” sense rather than at every single point, as mandated by  
 816 the strong form. In case of DGSEM, the test functions are specified as each of the Lagrange



**Figure 7.** Depiction of a physical domain divided into elements that are then each mapped to a reference computational element. Within each element, solution variables and the coordinate mapping are approximated by Lagrange interpolating polynomials.

817 interpolating polynomials. Additionally, continuous integrals in the weak formulation are  
 818 replaced by discrete quadrature. For computational efficiency, the quadrature points are  
 819 chosen to match the interpolation points which also provides spectral accuracy. To couple  
 820 neighboring elements, approximate Riemann solvers are used to exchange properties, such  
 821 as mass and momentum. For hyperbolic systems, like the shallow water equations, the  
 822 Riemann solver is chosen to be consistent with the underlying equations while also providing  
 823 dissipation to stabilize the numerical method (Gassner et al., 2016; Ranocha, 2016). To  
 824 exchange momentum and mass fluxes between neighboring elements and approximate the  
 825 numerical flux at the element boundaries, we employ the upwind local Lax-Friedrichs Riemann  
 826 solver of Rusanov (1961).

827 DGSEM allows for spatial refinement through two distinct approaches: increasing the  
 828 polynomial order while keeping the number of elements constant, known as  $p$ -refinement, or  
 829 alternatively, increasing the number of elements with a constant polynomial order, termed  
 830  $h$ -refinement. In Section 6.2, the leading order error terms of DGSEM are employed to  
 831 illustrate how  $p$ -refinement achieves exponential convergence, while  $h$ -refinement effectively  
 832 captures the spatial order of accuracy.

833 For the linear test cases, the weak form of the linear constant- or variable-coefficient  
 834 shallow water equations (9c) is solved in Cartesian coordinates. However, for non-linear test  
 835 cases, including the manufactured solution, and the non-linear planetary and topographic  
 836 Rossby waves, we start with the conservative form (41) of the non-linear shallow water  
 837 equations (7), and then solve the weak form of these equations.

### 838 3.3 Time-Stepping Methods

839 We advance the numerical solution using the following set of time-stepping methods:

840 **List 1.** *Standard predictor-corrector and multistep time-stepping methods*

841 RK2: explicit midpoint method, belonging to the second-order Runge-Kutta family

842 RK3: low-storage third-order Runge-Kutta method of J. Williamson (1980)

843 RK4: low-storage fourth-order Runge-Kutta method of Carpenter and Kennedy (1994)

844 AB2: second-order Adams-Bashforth method  
 845 AB3: third-order Adams-Bashforth method  
 846 AB4: fourth-order Adams-Bashforth method

847 **List 2.** *Time-stepping methods popular in ocean modeling*

848 FB: forward-backward or Implicit Euler method  
 849 LF\_TR: leapfrog trapezoidal method  
 850 LF\_AM3: leapfrog Adams-Moulton method  
 851 FB\_RK2: forward-backward method with RK2 feedback  
 852 GenFB\_AB2-AM3: generalized forward-backward method with AB2-AM3 step  
 853 GenFB\_AB3-AM4: generalized forward-backward method with AB3-AM4 step

854 Shchepetkin and McWilliams (2005) perform a detailed stability analysis of each of the  
 855 time-stepping methods of List 2. The parameters of all of these methods can be optimized to  
 856 attain a specific order of accuracy, maximize the stability range, and minimize the magnitude  
 857 of the local truncation error. By considering all variations of these parameters discussed in  
 858 Shchepetkin and McWilliams (2005), the total number of time-stepping methods of List 2  
 859 exceeds 20. Even though we have tested the numerical solution against all of these methods,  
 860 we present the convergence plots for only the methods of List 1.

861 **4 A Primer on Truncation Error and Order of Accuracy**

862 We furnish the necessary background on truncation error and how it is related to the  
 863 numerical solution's spatial and temporal orders of accuracy. We consider situations where  
 864 the orders of accuracy of the local truncation error and the global error agree, as encountered  
 865 in a wide variety of computational physics domains including atmosphere and ocean models.

866 When solving PDEs, especially in the context of physics and engineering, it is often  
 867 impossible or highly impractical to obtain an analytical solution. Instead, numerical methods  
 868 are employed, and this involves discretizing the domain of the problem, i.e., breaking it down  
 869 into small discrete segments or elements. The process of discretization inherently introduces  
 870 approximations, primarily due to the omission of higher-order derivative terms, culminating  
 871 in truncation errors. For time-dependent PDEs that model transient phenomena, like the  
 872 unsteady heat conduction or fluid flow, both spatial and temporal discretizations are used,  
 873 resulting in truncation errors associated with both space and time approximations. As  
 874 the simulation progresses, these errors accumulate, leading to an increasingly pronounced  
 875 divergence between the numerical and exact solutions.

876 The order of accuracy of the truncation error corresponds to the rate at which this error  
 877 diminishes relative to the size of the discretization. A higher order signifies a more rapid  
 878 shrinkage of error with finer discretization. For example, a second-order accurate method  
 879 in space anticipates an error reduction by  $n^2$  for every refinement of the spatial grid by a  
 880 factor of  $n$ .

881 Truncation errors play a pivotal role in determining the accuracy of a numerical solution.  
 882 Striking the right balance is essential: one must pick a method or grid resolution that offers  
 883 adequate accuracy without overburdening computational resources. While refining the grid  
 884 often curtails truncation errors, it simultaneously escalates the computational demands and  
 885 may exacerbate other anomalies, such as round-off errors. In the world of numerical PDE  
 886 solutions, a deep comprehension of truncation errors, their origins, and their ramifications  
 887 is indispensable. This knowledge guides the choice of optimal methods, grid scales, and  
 888 bolsters confidence in the accuracy of derived solutions.

#### 4.1 Truncation Error, Consistency, Stability, and Convergence

The local truncation error,  $\tau$ , is the residual after substituting the exact solution into the difference equation, obtained by discretizing the original differential equation. For time-marching or initial value problems involving ordinary differential equations (ODEs), hyperbolic and parabolic PDEs, some textbooks define the local truncation error as the error incurred in a single time step  $\Delta t$  starting with the exact solution at the beginning of the time step. If  $\hat{\tau}$  represents the local truncation error based on this definition, it is straightforward to demonstrate that  $\tau = \hat{\tau}/\Delta t$  (Bishnu, 2021).

A numerical method is called consistent if the local truncation error,  $\tau$ , over a single time step, reduces to zero with the refinement of the spatial and temporal grids, sometimes under additional constraints. Mathematically,

$$\lim_{\Delta \rightarrow 0} \tau = \lim_{\Delta \rightarrow 0} \frac{\hat{\tau}}{\Delta t} = 0, \quad (44)$$

where  $\Delta$  represents the set of discretization parameters for the spatial and temporal grids.

Numerical stability in the context of solving time-marching ODEs and PDEs involves analyzing how various types of errors—those from initial conditions, boundary conditions, round-off errors, and notably discretization or truncation errors—propagate in space and time as the numerical method is employed. In the realm of ODEs, the stability of a method largely depends on the chosen time step size, with the objective being to prevent errors from growing exponentially or becoming unbounded as time progresses. This concept extends to PDEs as well, but with an added layer of complexity. Here, stability is influenced not just by the time step size, but also by its relationship with spatial step sizes. This relationship is often scrutinized using the Courant-Friedrichs-Lewy (CFL) condition, a crucial criterion in the stability analysis of numerical methods for hyperbolic PDEs. The Von Neumann stability analysis emerges as another pivotal technique, particularly adept at determining the stability of numerical schemes applied to linear PDEs. By assessing the growth of Fourier modes in the numerical solution, this method provides a deeper understanding of how errors might amplify over iterations. The stability of a numerical method is crucial to ensure that the computed solution remains reliable and bounded over time. An unstable method can lead to solutions that diverge dramatically from the exact solution, even if the method is consistent, rendering the numerical approach ineffective for practical applications.

The numerical solution is said to converge to the exact solution if the global truncation error, or simply the global error,  $\hat{\tau}_G$ , defined as the difference between the exact and numerical solutions at a time horizon, reduces to zero with the refinement of the spatial and temporal grids. If the time horizon is specified as  $T = n\Delta t$ ,  $\hat{\tau}_G$  encapsulates the cumulative effect of  $\hat{\tau}$  over  $n$  time steps. For a broad spectrum of numerically stable methods, barring exceptions like superconvergent and subconvergent ones (Levine, 1985; Ferreira & Grigorieff, 1998; Barbeiro et al., 2005),  $\hat{\tau}_G$  is typically one order of  $\Delta t$  smaller than  $\hat{\tau}$  and of the same order of accuracy as  $\tau$ . So, if (44) holds for a stable numerical scheme, it is indicative of convergence. This concept aligns with the first half of the Lax Equivalence Theorem (Lax & Richtmyer, 1956), asserting that a consistent finite difference method for a linear initial value problem converges if and only if it is stable. For numerical methods such as finite volume, finite and spectral element methods, the Lax Equivalence Theorem does not directly apply in its classical form, as these methods have different formulations compared to finite difference methods. However, the underlying principles of consistency, stability, and convergence are still crucial in these methods.

#### 4.2 Truncation Error of Hyperbolic and Parabolic PDEs

In Bishnu (2021), we determined the full expression for the local truncation error of numerical solutions of hyperbolic and parabolic PDEs advanced with Method of Lines time integrators. These integrators are characterized by their separate treatment of space and

937 time discretizations: they initially discretize the spatial variables to reduce the PDE to  
 938 a system of ODEs, which are then solved using standard ODE integration techniques.  
 939 By employing theoretical analysis and symbolic algebra computations, we obtained exact  
 940 expressions for the coefficients of the generic local truncation error

$$\tau = \mathcal{O}(\Delta x^\alpha) + \Delta t \mathcal{O}(\Delta x^\alpha) + \Delta t^2 \mathcal{O}(\Delta x^\alpha) + \dots + \Delta t^{\beta-1} \mathcal{O}(\Delta x^\alpha) + \mathcal{O}(\Delta t^\beta), \quad (45)$$

941 where  $\Delta x$  and  $\Delta t$  denote the cell width and time step size, and  $\alpha$  and  $\beta$  represent the  
 942 spatial and temporal orders of accuracy. The right-hand side of (45) is applicable not  
 943 only to the numerical solution of hyperbolic and parabolic PDEs in one spatial dimension,  
 944 but also extends to higher-dimensional cases, provided a uniform grid is employed. This  
 945 is exemplified in Section 6.2, where, in the context of a two-dimensional hexagonal mesh,  
 946 the two primary grid scales are identified: the distance  $\Delta x$  between adjacent cell centers,  
 947 and the side length  $\Delta y$  of a hexagonal cell. In a uniform hexagonal mesh,  $\Delta x$  and  $\Delta y$   
 948 remain constant, and exhibit a proportional relationship, which paves the way for the local  
 949 truncation error to assume the form (45).

950 The derivation of (45) is replete with mathematical complexities. While we forgo  
 951 a detailed breakdown here, interested readers can refer to Bishnu (2021) which provides  
 952 thorough explanations and numerous illustrative examples. Nevertheless, we will touch  
 953 upon the core rationale behind this specific form of the local truncation error. Delving  
 954 into the steps of any Method of Lines time integrator, we note that time derivatives or  
 955 tendency terms are evaluated either at fractional time steps in the case of predictor-corrector  
 956 methods or at prior time levels for multistep methods. For an ODE (or a PDE with no  
 957 spatial discretization error), these tendencies are exact. However, for a general PDE, these  
 958 tendencies accrue spatial discretization errors of  $\mathcal{O}(\Delta x^\alpha)$ , which manifest as coefficients of  
 959 the various powers of  $\Delta t$ .

960 The coefficients of  $\Delta x^\alpha$  in the terms  $\Delta t \mathcal{O}(\Delta x^\alpha)$ ,  $\Delta t^2 \mathcal{O}(\Delta x^\alpha)$ ,  $\dots$ ,  $\Delta t^{\beta-1} \mathcal{O}(\Delta x^\alpha)$  of  
 961 (45) contain higher order spatial derivatives of the solution, coefficients of the PDE and  
 962 source terms (Bishnu, 2021). Consequently, the terms  $\Delta t^k \mathcal{O}(\Delta x^\alpha)$  for  $k = 1, 2, \dots, \beta - 1$   
 963 are typically much smaller in magnitude compared to the first and last terms of (45),  
 964 assuming forms  $\mathcal{O}(\Delta x^\alpha)$  and  $\mathcal{O}(\Delta t^\beta)$ , and representing the leading-order spatial and  
 965 temporal discretization errors. This disparity enables us to succinctly approximate (45)  
 966 as

$$\tau = \mathcal{O}(\Delta x^\alpha) + \mathcal{O}(\Delta t^\beta). \quad (46)$$

967 It is worth emphasizing that (45) and (46) hold true for a broad spectrum of hyperbolic  
 968 or parabolic PDEs, irrespective of whether they are linear or non-linear. This applicability  
 969 spans various spatial discretizations and time-stepping techniques within the Method of  
 970 Lines framework. To bring these theoretical assertions to life, we undertook convergence  
 971 studies on both linear and non-linear advection equations, as well as diffusion equations,  
 972 detailed in Bishnu (2021). These studies employed finite difference and finite volume spatial  
 973 discretizations, coupled with predictor-corrector and multistep time-stepping methods. In  
 974 the present paper, we solidify our findings, showcasing convergence plots for linear and  
 975 non-linear shallow water test cases using the TRiSK-based mimetic finite volume and  
 976 high-order discontinuous Galerkin spectral element methods.

### 977 4.3 Convergence at Constant Ratio of Time Step to Cell Width

978 Assume that our numerical scheme is stable, and the global error,  $\hat{\tau}_G$ , is of the same  
 979 order of accuracy as the local truncation error,  $\tau$ , conforming to the form (46). Then a  
 980 simultaneous refinement in space and time, maintaining a constant ratio of  $\gamma = \Delta t/\Delta x$ ,  
 981 simplifies the global error to

$$\hat{\tau}_G = \mathcal{O}(\Delta x^\alpha) + \mathcal{O}(\gamma^\beta \Delta x^\beta) = \mathcal{O}(\Delta x^\alpha) + \mathcal{O}(\Delta x^\beta) \approx \mathcal{O}(\Delta x^{\min(\alpha, \beta)}), \quad (47)$$

982 in the asymptotic regime, where the error is dominated by the larger of  $\Delta x^\alpha$  and  $\Delta t^\beta$ , rather  
 983 than their coefficients. Given a spatial discretization of order  $\alpha$ , the asymptotic convergence  
 984 rate clearly cannot exceed  $\alpha$ . To attain this convergence rate, we need a time-stepping  
 985 method of order  $\beta$  such that  $\beta \geq \alpha$ . For optimal computational efficiency within a given  
 986 family of time-stepping methods, the preferred choice would be  $\beta = \alpha$ .

#### 987 4.4 Refinement Only in Space or Only in Time

988 If refinement is performed only in space while employing a stable numerical scheme,  
 989 convergence of the global error cannot be guaranteed due to the presence of the  $\mathcal{O}(\Delta t^\beta)$   
 990 term. A similar situation arises with refinement only in time, where the  $\mathcal{O}(\Delta x^\alpha)$  term acts  
 991 as an impediment to the convergence of the global error. In other words, under only spatial  
 992 or temporal refinement, the local truncation error does not necessarily reduce to zero. As  
 993 a result, our numerical solution may not even be consistent. In such situations, in light of  
 994 the Lax Equivalence Theorem (Lax & Richtmyer, 1956), convergence becomes impossible.

#### 995 4.5 Verification of the Spatial or Temporal Order of Accuracy

996 While asymptotic convergence may not be achievable with only spatial or temporal  
 997 refinement, we can still verify the spatial and temporal orders of accuracy. For refinement  
 998 only in space at constant  $\Delta t$ , the global error at a specific time horizon and a spatial location  
 999  $x_j$  can be expressed as

$$(\hat{\tau}_G)_j = \mathcal{O}(\Delta x^\alpha) + \mathcal{O}(\Delta t^\beta) = \zeta \Delta x^\alpha + \zeta_{\beta+1} \Delta t^\beta, \quad (48)$$

1000 where the coefficients  $\zeta$  and  $\zeta_{\beta+1}$  are independent of  $\Delta x$ . If  $\zeta \Delta x^\alpha \gg \zeta_{\beta+1} \Delta t^\beta$ , we can  
 1001 calculate the spatial order of convergence by refining  $\Delta x$  with  $\Delta t$  held constant. For a  
 1002 general setting, however, we need to use an alternate method. This is achieved by comparing  
 1003 two uniform meshes with cell widths  $\Delta x_i$  and  $\Delta x_{i+1}$ , with  $\Delta x_{i+1} < \Delta x_i$ . Then we can write

$$(\hat{\tau}_{G_i^x})_j \approx \zeta \Delta x_i^\alpha + \zeta_{\beta+1} \Delta t^\beta, \quad (49a)$$

$$(\hat{\tau}_{G_{i+1}^x})_j \approx \zeta \Delta x_{i+1}^\alpha + \zeta_{\beta+1} \Delta t^\beta. \quad (49b)$$

1004 Assuming  $(\hat{\tau}_{G_{i+1}^x})_j < (\hat{\tau}_{G_i^x})_j$ , we define

$$\begin{aligned} (\Delta \hat{\tau}_{G_{i,i+1}^x})_j &\equiv (\hat{\tau}_{G_i^x})_j - (\hat{\tau}_{G_{i+1}^x})_j = \zeta (\Delta x_i^\alpha - \Delta x_{i+1}^\alpha) \\ &= \zeta \Delta x_{i+1}^\alpha \left\{ \left( \frac{\Delta x_i}{\Delta x_{i+1}} \right)^\alpha - 1 \right\} > 0. \end{aligned} \quad (50)$$

1005 Defining  $p = \Delta x_{i+1}/\Delta x_i < 1$  to be the ratio between the two mesh sizes, we can write

$$(\Delta \hat{\tau}_{G_{i,i+1}^x})_j = \zeta \Delta x_{i+1}^\alpha (p^{-\alpha} - 1). \quad (51)$$

1006 Upon taking the logarithm of both sides, we obtain

$$\log \left( (\Delta \hat{\tau}_{G_{i,i+1}^x})_j \right) = \theta + \alpha \log (\Delta x_{i+1}), \quad (52)$$

1007 where  $\theta = \log \{ \zeta (p^{-\alpha} - 1) \}$  is constant. To compute the spatial order of accuracy, we first  
 1008 choose a sequence of  $M$  grids with  $\Delta x_{i+1}/\Delta x_i = p$  for  $i = 1, 2, \dots, M-1$ , and all satisfying  
 1009 a CFL condition. After interpolating the error to the coarsest mesh with spacing  $\Delta x_1$ , we  
 1010 plot the norm of the difference between successive global errors  $(\Delta \hat{\tau}_{G_{i,i+1}^x})_{\text{norm}}$  against the  
 1011 cell width  $\Delta x_{i+1}$  on a log-log scale, for  $i = 1, 2, \dots, M-1$ . The slope of the best-fit line  
 1012 gives us the spatial order of accuracy.

1013 Proceeding in a similar fashion, we can ascertain the temporal order of accuracy.  
 1014 Specifically, we refine the time step while preserving the spatial resolution and plot the  
 1015 norm of the difference between successive global errors. Since the spatial resolution remains  
 1016 unchanged, there is no need for the interpolation step.

1017 It is worth noting that the exact solution is independent of both the spatial resolution  
 1018 and the time step. So, for refinement only in time, if  $u_j^{n+1}$  represents the solutions at time  
 1019 level  $t^{n+1}$ , and  $(\hat{u}_i)_j^{n+1}$  represents its numerical counterpart obtained with time step  $\Delta t_i$ ,  
 1020 we can write

$$\begin{aligned} \left(\Delta \hat{\tau}_{G_{i,i+1}^t}\right)_j^{n+1} &\equiv \left(\hat{\tau}_{G_i^t}\right)_j^{n+1} - \left(\hat{\tau}_{G_{i+1}^t}\right)_j^{n+1} = \left\{u_j^{n+1} - (\hat{u}_i)_j^{n+1}\right\} - \left\{u_j^{n+1} - (\hat{u}_{i+1})_j^{n+1}\right\} \\ &= (\hat{u}_{i+1})_j^{n+1} - (\hat{u}_i)_j^{n+1} \equiv (\Delta \hat{u}_{i,i+1})_j^{n+1}. \end{aligned} \quad (53)$$

1021 Therefore, if we calculate the difference  $(\Delta \hat{u}_{i,i+1})_j^{n+1}$  between numerical solutions  $(\hat{u}_i)_j^{n+1}$   
 1022 and  $(\hat{u}_{i+1})_j^{n+1}$  obtained with time steps  $\Delta t_i$  and  $\Delta t_{i+1}$  for  $i = 1, 2, \dots, M-1$ , at every mesh  
 1023 point  $x_j$  and time level  $t^{n+1}$ , and then compute its norm  $(\Delta \hat{u}_{i,i+1})_{\text{norm}}^{n+1}$  and plot it against  
 1024  $\Delta t_{i+1}$ , we can achieve convergence at a rate matching the temporal order of accuracy. In the  
 1025 event of performing only a spatial refinement, it is necessary to first interpolate the numerical  
 1026 solution to the coarsest mesh. Subsequently, the same steps can be followed to achieve  
 1027 convergence aligned with the spatial order of accuracy. This methodology offers a practical  
 1028 advantage by eliminating the need to engage with exact or manufactured solutions, thereby  
 1029 streamlining the process and enhancing its applicability. In our own numerical experiments,  
 1030 we adopt this approach for verifying the spatial and temporal orders of accuracy for the  
 1031 planetary and topographic Rossby wave test cases, which are not equipped with exact  
 1032 solutions.

1033 One should recognize that these unconventional convergence exercises primarily aim  
 1034 to verify the correct implementation of the spatial and temporal discretizations. The error  
 1035 norm of the numerical solution under only spatial or temporal refinement is not expected to  
 1036 converge in the asymptotic regime. It is only when the time step and the cell width undergo  
 1037 simultaneous refinement, while maintaining their ratio, that we can expect convergence of  
 1038 the global error norm.

#### 1039 4.6 Beyond Method of Lines Time Integrators

1040 We reiterate that the full expression (45) for the local truncation error was specifically  
 1041 derived for Method of Lines time integrators in Bishnu (2021). This formulation does  
 1042 not universally apply to time integrators that concurrently handle spatial and temporal  
 1043 discretizations, and are applicable exclusively to PDEs. Notable exceptions, such as the  
 1044 Lax-Wendroff method, do exist. Nevertheless, if the specific form of the local truncation  
 1045 error is known beforehand, the principles, methodologies, and anticipated outcomes for  
 1046 performing space-time, space-only, or time-only convergence studies, as discussed in Sections  
 1047 4.3 to 4.5, may be extended to time integrators beyond Method of Lines, with appropriate  
 1048 adjustments.

### 1049 5 Numerical Dispersion, Numerical Dissipation, and Spurious Oscillations

1050 Numerical dispersion and numerical dissipation are intrinsic challenges that arise when  
 1051 approximating PDEs using numerical methods. These phenomena are particularly impactful  
 1052 in wave-propagation problems, with dispersion errors influencing the propagation speed of  
 1053 disturbances and dissipation errors impacting the strength.

1054 Numerical dispersion commonly manifest in conservation laws when the dominant  
 1055 truncation error stems from odd-order derivatives, causing a misrepresentation of the wave's  
 1056 phase speed. Dispersion errors are observed not only in finite difference and finite volume

1057 methods, but also in high-order methods like single- and multi-domain SEMs. It is crucial  
 1058 to underscore that even though high-order methods like DGSEM boast increased accuracy,  
 1059 they are not immune to dispersion, especially at element boundaries with discontinuous  
 1060 solutions. Here, the choice of basis functions and the employed Riemann solver play pivotal  
 1061 roles. Even with high-order polynomial approximations, phase errors may arise as waves  
 1062 cross multiple elements.

1063 Numerical dissipation or diffusion, usually linked with even-order derivatives in the  
 1064 truncation error, signifies the artificial attenuation of the solution introduced by numerical  
 1065 methods. For example, first-order upwind schemes inherently dampen waves. So, while  
 1066 physically a wave might maintain its amplitude, numerically it could wane over time due  
 1067 to this effect. In the context of DGSEM, the primary source of artificial damping is the  
 1068 Riemann solvers at element boundaries. While the polynomial representation within an  
 1069 element may be non-dissipative, the Riemann solvers, which facilitate information exchange  
 1070 between elements, can introduce dissipation. This can lead to a slight reduction in amplitude  
 1071 over extended simulation times. As detailed in Section 5.1 with the local Lax-Friedrichs  
 1072 Riemann solver as an example, such damping effects, although vital for maintaining numerical  
 1073 stability, do not necessarily compromise the spatial order of accuracy. The terms “numerical  
 1074 dissipation” and “numerical diffusion” are often used interchangeably to address this damping  
 1075 effect, especially when dealing with sharp gradients or discontinuities. However, “numerical  
 1076 dissipation” typically emphasizes the removal of high-frequency components, especially in  
 1077 the context of stabilizing a numerical solution. In contrast, “numerical diffusion” underscores  
 1078 the artificial smoothing of particular features in the solution.

1079 Spurious oscillations represent another significant challenge in the numerical simulation  
 1080 of physical phenomena, particularly when the mathematical models involve discontinuities  
 1081 or steep gradients. These non-physical oscillations are most noticeable as “wiggles” or  
 1082 “overshoots” in the vicinity of abrupt changes, such as shock waves or material interfaces,  
 1083 and are indicative of the numerical method struggling to reconcile the sharp variations  
 1084 in the solution’s profile. High-order numerical methods like SEMs, while offering enhanced  
 1085 accuracy over smoother parts of the solution, are particularly susceptible to this phenomenon,  
 1086 a manifestation of the well-documented “Gibbs phenomenon”. Spurious oscillations are  
 1087 especially troublesome as they do not dissipate over time. Instead, they may intensify if  
 1088 the numerical scheme lacks the necessary stability features, potentially compromising the  
 1089 entire solution. However, the numerical community has developed several strategies to  
 1090 suppress these oscillations, thus enhancing the fidelity of simulations. The introduction of  
 1091 numerical dissipation, for example, can help to damp out these oscillations by smoothing the  
 1092 solution in a controlled manner. Artificial viscosity is another effective tool, subtly altering  
 1093 the equations to increase the physical diffusion, which helps to eliminate non-physical  
 1094 fluctuations. Moreover, the implementation of carefully designed limiters can specifically  
 1095 target and neutralize spurious oscillations without significantly distorting the true solution.

## 1096 **5.1 The Dissipative Local Lax-Friedrichs Riemann Solver and the Spatial** 1097 **Order of Accuracy of DGSEM**

1098 The numerical flux obtained using the local Lax-Friedrichs (LLF) Riemann solver can  
 1099 be expressed as

$$F_{LLF} = \frac{1}{2} \{f(U_L) + f(U_R)\} - \frac{|\lambda|}{2} (U_L - U_R). \quad (54)$$

1100 Here,  $U_L$  and  $U_R$  represent the left and right states, respectively. The parameter  $|\lambda|$  signifies  
 1101 the maximum characteristic speed of the Riemann problem, commonly estimated as the  
 1102 magnitude of the maximum eigenvalue or wave speed across  $U_L$  and  $U_R$ . The central flux  
 1103  $\frac{1}{2} \{f(U_L) + f(U_R)\}$  is essentially the average of the fluxes from the left and right. On its  
 1104 own, it is a second-order central scheme, prone to spurious oscillations near discontinuities.  
 1105 The dissipative term  $\frac{|\lambda|}{2} (U_L - U_R)$  acts to dampen those oscillations. It is proportional to

1106 the jump in the solution, so it is stronger (more dissipative) where the solution has steep  
1107 gradients or discontinuities.

1108 In spectral element methods including DGSEM, the solution within each element is  
1109 approximated by high-order polynomials. Hence, flux computation at boundaries does not  
1110 solely rely on boundary values, as seen in many lower-order finite volume methods. Instead,  
1111 the polynomial approximation of the internal solution is interpolated to the boundaries,  
1112 ensuring high-order accuracy right up to the edge. Fluxes are then computed using these  
1113 interpolated values from neighboring elements, with the LLF Riemann solver subsequently  
1114 applied. It is crucial to note that the LLF solver’s primary role in this context is not flux  
1115 computation but determining the upwind direction based on eigenvalues and introducing the  
1116 necessary dissipation for numerical stability. The high-order accuracy of the spectral element  
1117 method stems from its polynomial representation, not the Riemann solver. In simpler terms,  
1118 the LLF Riemann solver does not cause first-order accuracy in finite volume methods. It is  
1119 the low-order approximations of the left and right states,  $U_L$  and  $U_R$ , used as inputs. With  
1120 DGSEM, both  $U_L$  and  $U_R$  are spectrally accurate, resulting in much smaller jumps. As  
1121 such, while the Lax-Friedrichs method is intrinsically first order, the LLF Riemann solver  
1122 does not degrade the DGSEM’s overall accuracy.

1123 Numerous works, such as Hussaini and Zang (1987), Boyd (1988), Cockburn and Shu  
1124 (1989), Cockburn and Shu (1998), Hesthaven and Warburton (2007), Canuto et al. (2007b),  
1125 Canuto et al. (2007a), and D. A. Kopriva et al. (2017) extensively explore spectral methods  
1126 and their synergy with Riemann solvers. These studies imply that various Riemann solvers  
1127 can integrate with spectral methods without compromising their inherent accuracy. Our  
1128 convergence plots demonstrate that even with the LLF Riemann solver, we achieve the  
1129 anticipated high-order accuracy typical of spectral element methods. Nonetheless, while the  
1130 LLF Riemann solver might not diminish the accuracy order, it is known to introduce more  
1131 dissipation than other Riemann solvers, potentially impacting the quality of the solution in  
1132 terms of sharpness of features or the preservation of certain scales.

## 1133 6 Numerical Experiments

1134 We first outline the experimental procedure used to conduct these numerical experiments  
1135 and verify the spatial and temporal orders of accuracy of the barotropic solver or the  
1136 dynamical core of ocean models. We believe that this recipe will serve as a valuable resource  
1137 to ocean modelers by ensuring that their respective ocean models actually converge at the  
1138 expected order of accuracy. We proceed by plotting the time evolution of numerical errors,  
1139 studying their nature, and creating convergence plots for each test case, with refinement in  
1140 both space and time, only in space, and only in time.

1141 This comprehensive approach, involving three flavors of convergence tests, may seem  
1142 overly detailed at first glance. However, it is chosen for a number of reasons. Consider  
1143 an ocean model employing a low-order finite volume method for spatial discretization.  
1144 The standard practice in ocean modeling is to conduct convergence studies by refining  
1145 in both space and time, i.e., by simultaneously reducing the time step and cell width while  
1146 maintaining their ratio (and the Courant number) constant. However, if a time-stepping  
1147 method of order higher than the spatial discretization is used, a convergence plot with  
1148 refinement in both space and time will always converge at the spatial order of accuracy in  
1149 the asymptotic regime, thereby hindering the verification of the temporal order of accuracy.  
1150 This is further compounded by the fact that the leading-order spatial error term’s coefficient  
1151 is typically a few orders of magnitude larger than that of the leading-order temporal error  
1152 term, a phenomenon we will refer to as leading-order coefficient discrepancy from here  
1153 onward. Consequently, order reduction is seldom observed before reaching the asymptotic  
1154 regime, and the convergence rate invariably mirrors the (low) spatial order of accuracy.  
1155 Moreover, ocean models being typically characterized by their spatial discretization, may  
1156 allow users to choose from multiple time-stepping methods. During the integration of a

1157 novel time-stepping method into a fully functional ocean model, a developer might want to  
 1158 verify solely its order of accuracy, underscoring the necessity for self-refinement tests only  
 1159 in time.

1160 In contrast, consider an ocean model where the spatial order of accuracy far surpasses  
 1161 its temporal counterpart. With refinement in both space and time, order reduction may  
 1162 be observed as the numerical solution error is expected to progress through three distinct  
 1163 regimes: spatial discretization error dominance (first regime), temporal discretization error  
 1164 dominance (second regime which overlaps with the beginning of the asymptotic regime  
 1165 where  $\Delta x^\alpha$  and  $\Delta t^\beta$  in (46) exert dominance over their respective coefficients), and finally,  
 1166 round-off error dominance (third regime). However, in practice, for the selected sets of  
 1167 discretization parameters  $\Delta x$  and  $\Delta t$ , the error might not traverse all three regimes. If  
 1168 the round-off error takes over before the time integration error, verification of the temporal  
 1169 accuracy order becomes impossible. Similarly, if the leading-order coefficient discrepancy is  
 1170 insufficient, the first regime may be bypassed in favor of the second and third regimes even  
 1171 at relatively low resolutions, preventing the verification of the spatial order of accuracy. This  
 1172 demonstrates the necessity for self-refinement tests in both space and time. To mitigate the  
 1173 impact of round-off errors in spectral element discretizations, it is crucial to avoid excessively  
 1174 high polynomial orders during convergence studies. Last but not the least, self-refinement  
 1175 tests in space can ensure that code modifications, such as incorporating a new time-stepping  
 1176 method, do not inadvertently introduce bugs that detrimentally affect the spatial order of  
 1177 accuracy.

1178 We now outline the experimental procedure for numerical experiments and convergence  
 1179 studies below. After addressing the initial steps for spatial operators and their convergence,  
 1180 which are common to all test cases, the procedure for individual test cases remains consistent.

## 1181 6.1 Experimental Procedure

- 1182 1. Construct the mesh for discretizing the numerical solution. This mesh will also be  
 1183 used for visualization of the exact and numerical solutions, and the associated error.  
 1184 Create a set of meshes with different spatial resolutions for conducting convergence  
 1185 studies in both space and time, and only in space. For convergence studies only in  
 1186 time, a single spatial mesh suffices.
- 1187 2. Specify a smooth function in space, which can be selected from the initial condition of  
 1188 a test case. Evaluate both the exact and numerical spatial operators of this function  
 1189 on the mesh, then plot these operators alongside their error. Ensure that the error  
 1190 norm is considerably smaller than the operator norm, by at least several orders of  
 1191 magnitude for high-order spectral element methods and a few orders for low-order  
 1192 finite volume methods. Conduct convergence tests of these spatial operators with  
 1193 spatial refinement to confirm that their convergence slopes align with the expected  
 1194 spatial order of accuracy.
- 1195 3. Identify an exact or manufactured solution if applicable, keeping in mind that for finite  
 1196 volume methods, the exact solutions pertain to cell- and edge-averaged quantities  
 1197 rather than cell- or edge-centered ones. Consult Section C1 in Appendix C for  
 1198 an insightful explanation on initializing these quantities on non-rectilinear meshes,  
 1199 utilizing the hexagonal meshes of MPAS-Ocean as an illustrative example.
- 1200 4. Given a characteristic wave speed, choose an appropriate Courant number that is  
 1201 consistent with the CFL condition for both the spatial and temporal discretizations.  
 1202 Regarding the specification of the characteristic wave speed, consider the following  
 1203 examples. For the coastal Kelvin and inertia-gravity wave test cases, define the  
 1204 characteristic wave speed as the phase speed of the faster wave mode. For the  
 1205 Rossby wave test cases, set the characteristic wave speed as the phase speed of the  
 1206 fastest gravity waves emitted by the initially Gaussian monopole. For explicit time  
 1207 integration methods, the CFL condition mandates that the Courant number must be  
 1208 less than one to ensure stability. This requirement becomes even more stringent with

1209 explicit multistep time-integration methods, such as Adams-Bashforth, where the  
 1210 region of absolute stability narrows with higher orders, necessitating an even smaller  
 1211 Courant number. Based on this choice, determine the time step. Initialize the model  
 1212 using the exact solution at  $t = 0$ . Implement boundary conditions that mirror the  
 1213 exact solution over time. Likewise, define space- and time-dependent source terms  
 1214 for manufactured solutions. For detailed guidelines on setting boundary conditions  
 1215 and source terms on non-rectilinear meshes, refer to Sections C1 and C2 in Appendix  
 1216 C, again using the hexagonal meshes of MPAS-Ocean as a reference. Run the model  
 1217 forward in time to obtain the numerical solution. At intervals equivalent to integral  
 1218 multiples of the time step, print and plot both the exact and numerical solutions,  
 1219 along with the associated error, to study their temporal evolution.

1220 5. Employ visual inspection (sometimes humorously referred to as the ‘eyeball norm’)  
 1221 to assess the numerical solution for approximate physical and numerical accuracy,  
 1222 examining, for instance, whether geophysical waves propagate at their theoretically  
 1223 expected phase speeds. If errors significantly amplify along the boundaries compared  
 1224 to the domain’s interior, reevaluate the implementation of boundary conditions or the  
 1225 plotting of boundary values. As with the spatial operators, the error norm should  
 1226 be substantially smaller than the solution norm, with the difference being more  
 1227 pronounced for high-order spectral element methods than low-order finite volume  
 1228 methods.

1229 6. After achieving satisfactory preliminary results, initiate comprehensive convergence  
 1230 studies, with refinements in both space and time, only in space, and only in time.  
 1231 Revisit the beginning of this section for the underlying reasoning behind these different  
 1232 flavors of convergence tests and specific strategies tailored for low- and high-order  
 1233 spatial discretizations. For refinement in both space and time, adjust the time step in  
 1234 direct proportion to the cell width, ensuring that their ratio and the Courant number  
 1235 remain constant. When refining only in space, determine the time step for the finest  
 1236 mesh using the Courant number. Employ this stringent time step across all spatial  
 1237 resolutions. For convergence tests with refinement only in time, calculate the largest  
 1238 time step based on the Courant number for the singular spatial mesh in use.

1239 7. The refinement ratio between successive pairs of spatial or temporal resolutions does  
 1240 not necessarily need to be an integer. This flexibility is particularly advantageous for  
 1241 convergence tests only in space, the most computationally intensive type. Following  
 1242 that in computational demand is the convergence test in both space and time, and  
 1243 finally the convergence test only in time. The error norm in a convergence test is  
 1244 calculated at a specific time horizon. This horizon is always reached if:

- 1245 (a) refinement is performed only in space, implying a constant time step value;
- 1246 (b) the time horizon equates to an integral number of the largest time step, and the  
 1247 refinement ratio is integral e.g doubling each time.

1248 This may not hold true for convergence tests with refinement in both space and time  
 1249 or only in time when the refinement ratio is not an integer. Nonetheless, a clever  
 1250 approach can circumvent this issue. By selecting a rational refinement ratio,  $r = p/q$   
 1251 for  $p > q$  and  $p, q \in \mathbb{Z}^+$ , and denoting  $s$  as the number of different resolution sets, we  
 1252 can define the time horizon as  $T = N\Delta t_{\text{largest}}$ , with  $N = q^t$ ,  $t \in \mathbb{Z}^+$  and  $t \geq s$ . As  
 1253 lengthy simulation times are generally unnecessary for convergence tests,  $t$  does not  
 1254 need to greatly exceed  $s$ . For example, with  $r = 3/2$  and  $s = 5$ , we can choose  $N$  to  
 1255 be powers of 2 equal to or greater than 32. This ensures that the time horizon aligns  
 1256 with integral multiples of every time step used in the study, obviating the need for  
 1257 adjustments that could lead to errors.

1258 8. For refinement in both space and time, employ a test case with either an exact or a  
 1259 manufactured solution, and plot the actual error norm at a designated time horizon  
 1260 against either the cell width or the total number of cells. For refinement only in space  
 1261 or only in time, plot the norm of the difference between

- 1262 (a) the numerical solutions; or
- 1263 (b) the error (for test cases equipped with exact solutions);

1264 against the cell width (or number of cells) or the time step (or number of time steps)  
 1265 for successive pairs of spatial and temporal resolutions.

1266 9. Analyze whether the convergence slope:

- 1267 (a) aligns with the spatial or temporal order of accuracy when refining only in space  
 1268 or only in time;
- 1269 (b) corresponds to the lesser of the spatial and temporal orders of accuracy when  
 1270 refining in both space and time.

1271 If the above observations hold true, our results are satisfactory. However, deviations  
 1272 from these patterns may point to issues such as:

- 1273 (a) a bug within the numerical implementation of spatial or temporal discretizations;
- 1274 (b) the asymptotic regime not yet reached by the spatial and temporal resolutions,  
 1275 suggesting a need for broader resolution sets in convergence studies.
- 1276 (c) the dominance of round-off errors, a common issue in high-order spectral element  
 1277 methods, which can be remedied by reducing the polynomial order.

1278 10. In scenarios where machine precision constraints may preclude reaching the asymptotic  
 1279 regime, separate spatial and temporal convergence tests are crucial. It is also vital to  
 1280 diversify test cases, given that error magnitudes can vary based on the exact solution  
 1281 and its gradients.

1282 The above procedure sets the stage for a rigorous numerical study that can adapt to different  
 1283 scenarios, accounting for the particularities and complexities inherent to both finite volume  
 1284 and spectral element methods, and offering flexibility in convergence testing and verification.

## 1285 6.2 Numerical Solutions and Convergence Plots

1286 Based on our experimental procedure, we begin by testing the convergence of the various  
 1287 spatial operators. For the TRiSK-based mimetic finite volume method, these encompass the  
 1288 gradient, divergence, curl, kinetic energy, and Laplacian operators as well as the interpolation  
 1289 or flux-mapping operator. This last operator is used to obtain the tangential velocity on  
 1290 an edge from the normal velocities on the edges of the cells sharing that edge. In contrast,  
 1291 for DGSEM, the only pertinent spatial operators are the zonal and meridional gradient  
 1292 operators.

1293 We opt for a smooth spatial test function, which, along with its gradient and Laplacian,  
 1294 is expressed as:

$$\eta = \hat{\eta} \sin\left(\frac{2\pi x}{L_x}\right) \sin\left(\frac{2\pi y}{L_y}\right), \quad (55a)$$

$$\begin{aligned} \nabla\eta &= \eta_x \mathbf{i} + \eta_y \mathbf{j} \\ &= 2\pi\hat{\eta} \left\{ \frac{1}{L_x} \cos\left(\frac{2\pi x}{L_x}\right) \sin\left(\frac{2\pi y}{L_y}\right) \mathbf{i} + \frac{1}{L_y} \sin\left(\frac{2\pi x}{L_x}\right) \cos\left(\frac{2\pi y}{L_y}\right) \mathbf{j} \right\}, \end{aligned} \quad (55b)$$

$$\nabla^2\eta = \nabla \cdot \nabla\eta = - \left\{ \left(\frac{2\pi}{L_x}\right)^2 + \left(\frac{2\pi}{L_y}\right)^2 \right\} \eta. \quad (55c)$$

1295 By defining the surface elevation via (55a), the components of the geostrophic velocity field  
 1296 emerge as  $u = -g/f\eta_y$  and  $v = g/f\eta_x$ , where  $g = 10 \text{ m s}^{-2}$  and  $f = 10^{-4} \text{ s}^{-1}$ . If an  
 1297 edge's normal forms an angle  $\theta$  with the positive direction of the zonal axis, the velocity  
 1298 field components in the normal ( $\mathbf{n}$ ) and tangential ( $\mathbf{t} = \mathbf{k} \times \mathbf{n}$ ) directions are represented  
 1299 as  $\mathbf{u}^n = \mathcal{N}\mathbf{u} = u \cos\theta + v \sin\theta$  and  $\mathbf{u}^t = \mathcal{T}\mathbf{u} = v \cos\theta - u \sin\theta$ . The vertical component of  
 1300 the curl of the velocity field, the kinetic energy, and the Laplacian of the normal velocity at

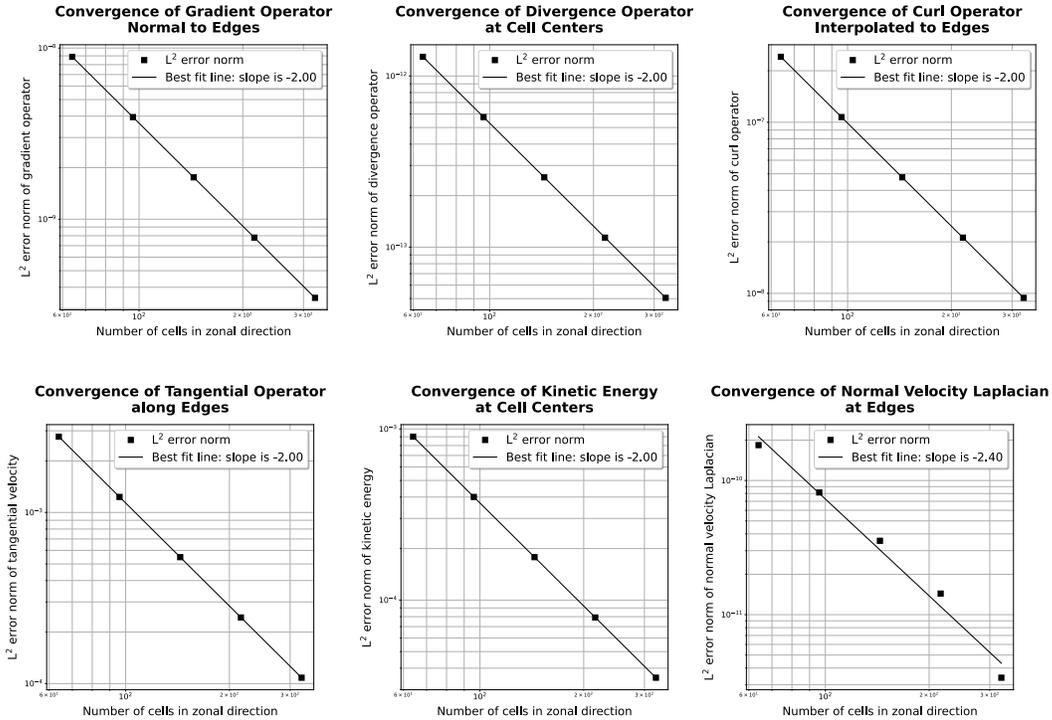
1301 the edges are defined as

$$\zeta = \mathbf{k} \cdot \nabla \times \mathbf{u} = \mathbf{k} \cdot \nabla \times (u\mathbf{i} + v\mathbf{j}) = v_x - u_y = \frac{g}{f} \nabla^2 \eta, \quad (56a)$$

$$K = \frac{1}{2} |\mathbf{u}|^2 = \frac{1}{2} (u^2 + v^2) = \frac{g^2}{2f^2} (\eta_x^2 + \eta_y^2), \quad (56b)$$

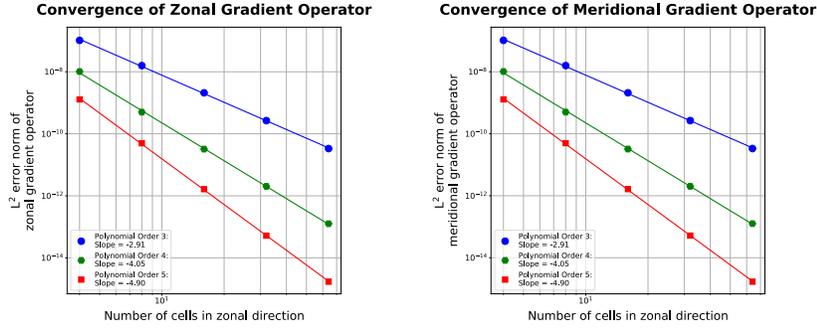
$$\nabla^2 \mathbf{u}^n = \frac{g}{f} \nabla^2 (-\eta_y \cos \theta + \eta_x \sin \theta) = -\frac{g}{f} \nabla^2 \mathcal{T} \nabla \eta = \frac{g}{f} \left\{ \left( \frac{2\pi}{L_x} \right)^2 + \left( \frac{2\pi}{L_y} \right)^2 \right\} \mathcal{T} \nabla \eta. \quad (56c)$$

1302 It is worth noting that although our test function was defined by (55), any function exhibiting  
 1303 smooth spatial variation in both zonal and meridional directions, such as the initial conditions  
 1304 for the geophysical waves or the manufactured solution, would have served the purpose.



**Figure 8.** Convergence of TRiSK-based spatial and flux-mapping operators applied to the test function (55) on a uniform MPAS-Ocean mesh.

1305 Figure 8 displays the convergence plots for the TRiSK-based spatial operators, which  
 1306 are all second-order accurate as expected. These studies were carried out on uniform planar  
 1307 hexagonal MPAS-Ocean meshes. These meshes have an equal number of cells, say  $N$ , in  
 1308 both zonal and meridional directions. Each row is offset by half a cell width, and the  
 1309 configuration ensures that the regular hexagons' parallel sides align with the meridional  
 1310 direction. Given that  $\Delta x$  denotes the distance between cell centers, the side length of these  
 1311 hexagonal cells is  $1/\sqrt{3}\Delta x$ . Consequently, the leading-order spatial discretization error term  
 1312 for the second-order TRiSK scheme can be represented as  $\mathcal{O}(\Delta x^2)$ . With the zonal domain  
 1313 extent set to  $L_x = N\Delta x$ , maintaining a constant  $L_x$  while increasing  $N$  means a log-log  
 1314 plot of the error norm against  $N$  will display a slope identical in magnitude to that against  
 1315  $\Delta x$ . Hence, in our plots, we designate the  $x$ -axis as the cell count  $N$ , a choice enhancing  
 1316 visualization as refinement progresses in the positive  $x$ -direction.



**Figure 9.** Convergence of weak forms of the zonal and meridional gradient operators of DGSEM applied to the test function (55) for polynomial orders 3, 4, and 5.

1317 Figure 9 displays the convergence plots for the weak forms of DGSEM’s zonal and  
 1318 meridional gradient operators, utilizing the Bassi-Rebay method (Bassi & Rebay, 1997) to  
 1319 approximate functions at the element boundaries. Notably, the convergence slopes align  
 1320 with the orders of the polynomial basis functions. Although not depicted here, additional  
 1321 convergence tests were performed on the strong form of these gradient operators, yielding  
 1322 identical results. In our spectral element meshes, we specified the number of elements  $N$ ,  
 1323 the length of each element  $\Delta x$ , and the order of the polynomial basis functions  $p$  to be the  
 1324 same in both the zonal and meridional directions. For complete functions, the leading-order  
 1325 spatial error term for our DGSEM solution takes the form

$$\varepsilon = k_1 \exp(-k_2 p) \Delta x^p, \quad (57)$$

1326 where  $k_1$  and  $k_2$  are constants. Equation (57) follows from the in-depth error analysis of  
 1327 DGSEMs in spectral element textbooks by Karniadakis and Sherwin (2005), Hesthaven and  
 1328 Warburton (2007), and Canuto et al. (2007b). Taking the logarithm of both sides of (57)  
 1329 gives

$$\ln \varepsilon = \ln k_1 - k_2 p + p \ln \Delta x = k_3 - p(k_2 - \ln \Delta x). \quad (58)$$

1330 We recall from Section 3.2 that a spatial refinement in DGSEM can be performed in  
 1331 two ways: by increasing  $p$  while maintaining a constant  $N$  ( $p$ -refinement), or vice versa  
 1332 ( $h$ -refinement, where  $h$  denotes the cell width  $\Delta x$ ). Equation (58) shows that  $p$ -refinement  
 1333 is expected to yield a straight line with negative slope of magnitude  $k_2 - \ln \Delta x$  on a log-log  
 1334 graph, demonstrating exponential convergence. In contrast, an  $h$ -refinement should render  
 1335 a straight line with a slope of magnitude  $p$ , akin to finite difference or finite volume methods.  
 1336 Moreover,  $p$ -refinement is not applicable in the context of the TRiSK-based finite volume  
 1337 method, for which the effective polynomial order remains fixed at second order. To ensure  
 1338 a consistent and clear presentation, we have chosen to display the spatial convergence plots,  
 1339 employing  $h$ -refinement, for both DGSEM and TRiSK in a sequential and organized manner.

1340 The Courant number, critical for the stability of numerical simulations, can be defined  
 1341 for two-dimensional advective problems as

$$C = \Delta t \left( \frac{c_x}{\Delta x} + \frac{c_y}{\Delta y} \right), \quad (59)$$

1342 where  $c_x$  and  $c_y$  are wave speeds, while  $\Delta x$  and  $\Delta y$  denote grid scales in the zonal and  
 1343 meridional directions respectively. For DGSEM, employing rectangular elements with side  
 1344 lengths  $\Delta x$  and  $\Delta y$ , the Courant number modifies to

$$C = \Delta t \left( \frac{c_x}{\frac{\Delta x}{P_x^2}} + \frac{c_y}{\frac{\Delta y}{P_y^2}} \right) = \Delta t \left( P_x^2 \frac{c_x}{\Delta x} + P_y^2 \frac{c_y}{\Delta y} \right), \quad (60)$$

1345 where  $P_x$  and  $P_y$  represent the orders of the polynomial basis function in the zonal and  
 1346 meridional directions respectively. Given that the internal grid of each spectral element has  
 1347 higher density towards the edges, the measures  $\Delta x/P_x^2$  and  $\Delta y/P_y^2$  offer close estimates for  
 1348 the smallest internal grid spacings adjacent to these edges. In uniform planar hexagonal  
 1349 MPAS-Ocean meshes, where  $\Delta x$  indicates the distance between neighboring cell centers,  
 1350 and in DGSEM meshes using spectral elements with side lengths  $\Delta x$  and polynomial order  
 1351  $P$  in both horizontal directions, the CFL condition can be concisely represented as

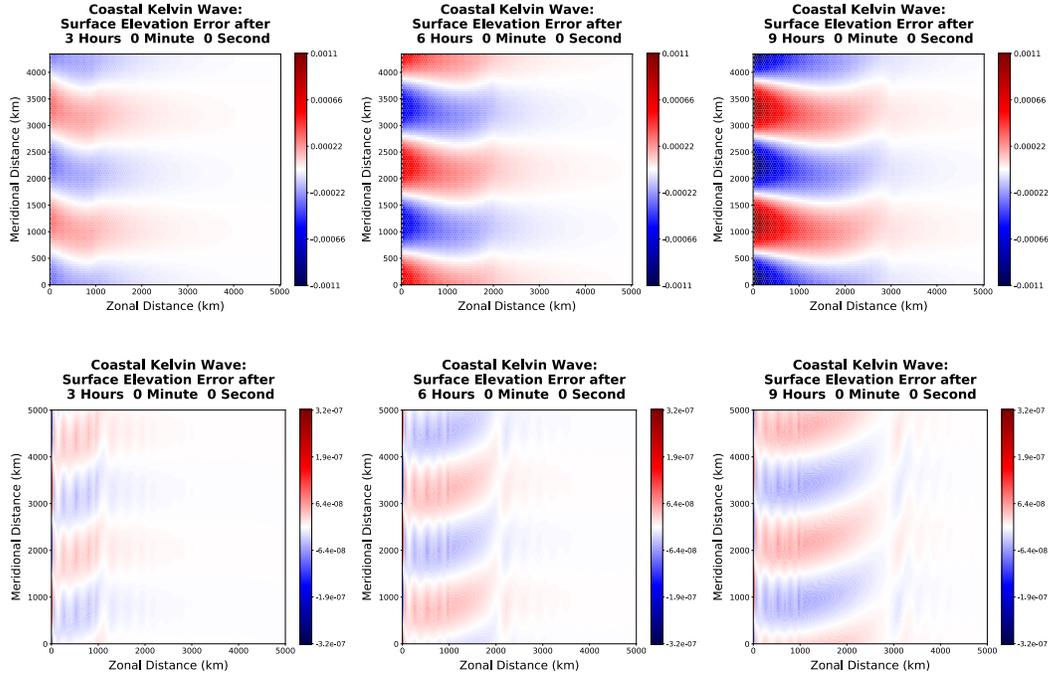
$$C = \lambda \Delta t / \Delta x, \text{ where } \lambda = \begin{cases} c_x + \frac{2}{\sqrt{3}} c_y & \text{for TRiSK,} \\ c_x + c_y & \text{for DGSEM.} \end{cases} \quad (61)$$

1352 In our simulations, we specify  $c_x$  and  $c_y$  to be the zonal and meridional components of the  
 1353 phase speed for the manufactured wave solution; the phase speed of the faster wave mode  
 1354 for the coastal Kelvin and inertia-gravity waves; and the phase speed of the component  
 1355 waves of the standing wave mode with faster components for the barotropic tide.

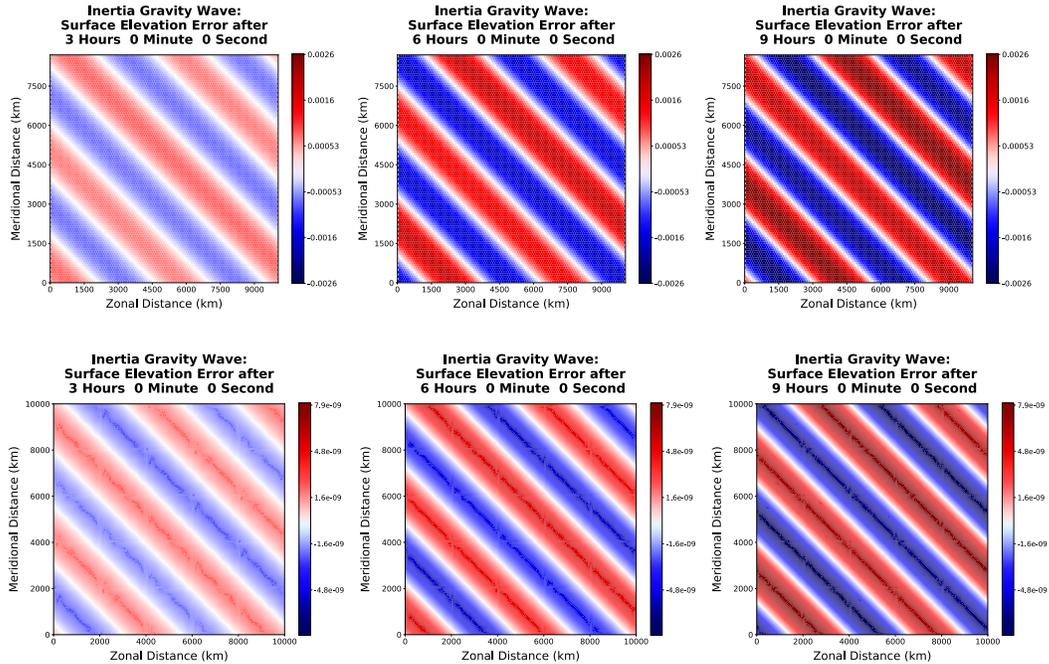
1356 In each horizontal direction, let  $N$  represent the number of hexagonal cells for TRiSK  
 1357 and the count of spectral elements for DGSEM. Additionally, let  $P$  symbolize the polynomial  
 1358 order in each direction for DGSEM. For the TRiSK-based approach, we utilize a structured  
 1359 planar hexagonal MPAS-Ocean mesh with  $N = 100$ . The spectral element mesh for DGSEM  
 1360 is defined by  $N = 5$  and  $P = 10$  in all test cases except for the Rossby waves, resulting in  
 1361  $10^{\text{th}}$  order spatial accuracy. For the Rossby wave test cases, we specify  $N = 10$  and  $P = 7$ ,  
 1362 yielding a  $7^{\text{th}}$  order spatial accuracy. The zonal domain extent,  $L_x$  is specified as  $5 \times 10^6$  m,  
 1363  $10^7$  m,  $10^6$  m,  $2.5 \times 10^5$  m, and  $10^7$  m for the coastal Kelvin wave, the inertia-gravity wave,  
 1364 the Rossby waves, the barotropic tide and the manufactured solution test cases respectively.  
 1365 The distance between the adjacent hexagonal cell centers for TRiSK, as well as the side  
 1366 lengths of the spectral elements for DGSEM are given by  $\Delta x = L_x/N$ . For DGSEM, the  
 1367 smallest grid spacings near element boundaries are approximately  $\Delta x/P^2$ . The meridional  
 1368 domain extent  $L_y$  is set to  $\sqrt{3}/2L_x$  for TRiSK, resulting in a “measure” for the meridional  
 1369 grid scale  $\Delta y = L_y/N = \sqrt{3}/2\Delta x$ . For DGSEM,  $L_y$ ,  $\Delta y$ , and the meridional grid spacings  
 1370 mirror their zonal counterparts. By leveraging (61) to maintain the Courant number,  $C$ ,  
 1371 near 0.5, we specify the time step,  $\Delta t$ , in the coastal Kelvin wave, inertia-gravity wave,  
 1372 barotropic tide, and manufactured solution test cases to be 200 s, 100 s, 10 s, and 180  
 1373 s respectively for TRiSK, and 50 s, 25 s, 2.5 s, and 30 s respectively for DGSEM. For  
 1374 the Rossby wave test cases, a particularly small  $\Delta t = 0.5$  s is selected for both TRiSK  
 1375 and DGSEM to meet the CFL condition for the fastest gravity waves, ensuring numerical  
 1376 stability.

1377 The numerical solutions being visually indistinguishable from their exact counterparts,  
 1378 we limit our presentation to the time evolution of surface elevation errors for the coastal  
 1379 Kelvin wave, inertia-gravity wave, barotropic tide, and the non-linear manufactured solution,  
 1380 as shown in Figures 10, 11, 12, and 13. These solutions are advanced with Williamson’s  
 1381 low-storage third-order Runge-Kutta time-stepping method, and spatially discretized with  
 1382 TRiSK and DGSEM. The error stemming from these two types of spatial discretizations is  
 1383 depicted in the first and second rows of Figures 10–13. At first glance, we notice that the  
 1384 TRiSK error is three orders of magnitude less than the solution magnitude for the linear  
 1385 coastal Kelvin wave, inertia-gravity wave, and barotropic tide test cases. It is two orders of  
 1386 magnitude less for the non-linear manufactured solution test case. Conversely, the DGSEM  
 1387 error is six orders of magnitude less than the solution error for the coastal Kelvin wave and  
 1388 barotropic tide test cases, and eight orders of magnitude less for the inertia-gravity wave  
 1389 and manufactured solution test cases.

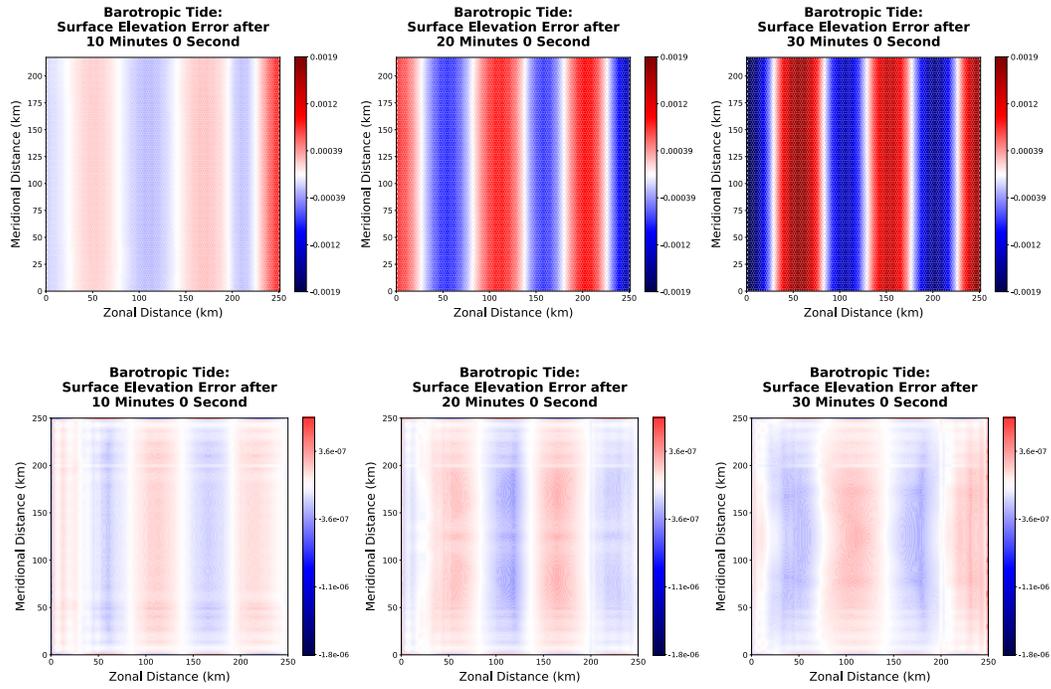
1390 In our analysis of the temporal evolution of the coastal Kelvin wave error for both  
 1391 TRiSK and DGSEM (Figure 10), it is evident that the error modes propagate not only  
 1392 meridionally from north to south in line with the wave direction, but also zonally from west  
 1393 to east. Even though the exact tendency of the zonal velocity in the linear rotating shallow  
 1394 water equations (10) is zero, due to a balance between the exact Coriolis and pressure



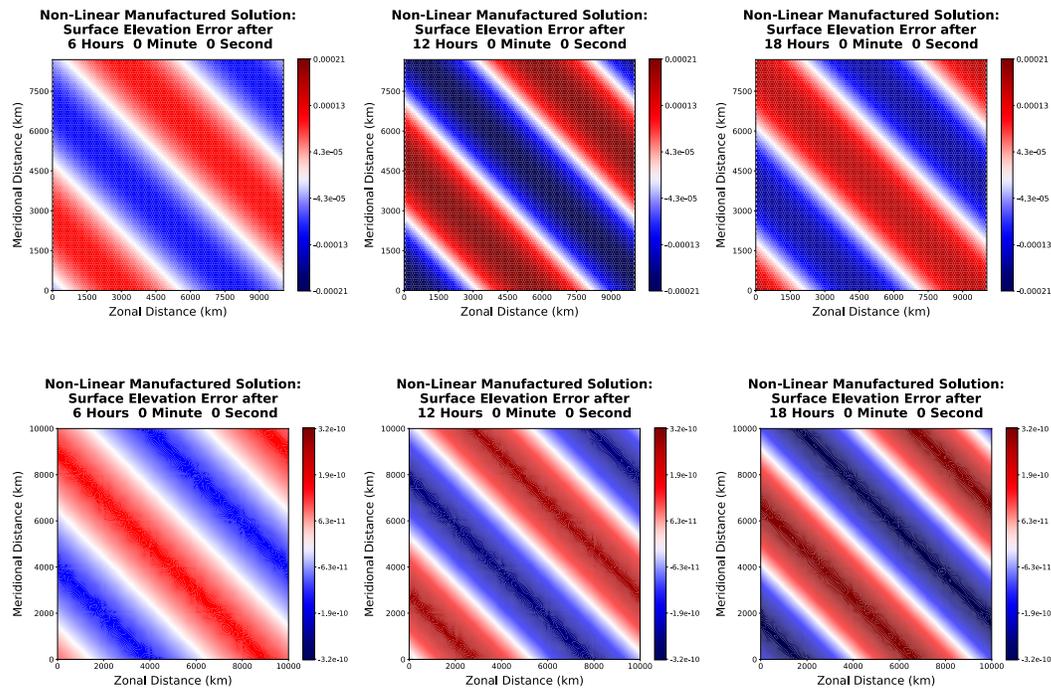
**Figure 10.** Time evolution of the surface elevation error of TC1, the coastal Kelvin wave, spatially discretized with the TRiSK-based mimetic finite volume method (first row), and DGSEM using 5 elements and polynomial basis functions of order 10 in each horizontal direction (second row).



**Figure 11.** Same as Figure 10, but for TC2, the high-frequency dispersive inertia-gravity wave, showing error for TRiSK (first row), and DGSEM (second row).



**Figure 12.** Same as Figure 10, but for TC5, the barotropic tide test case, showing error for TRiSK (first row), and DGSEM (second row).



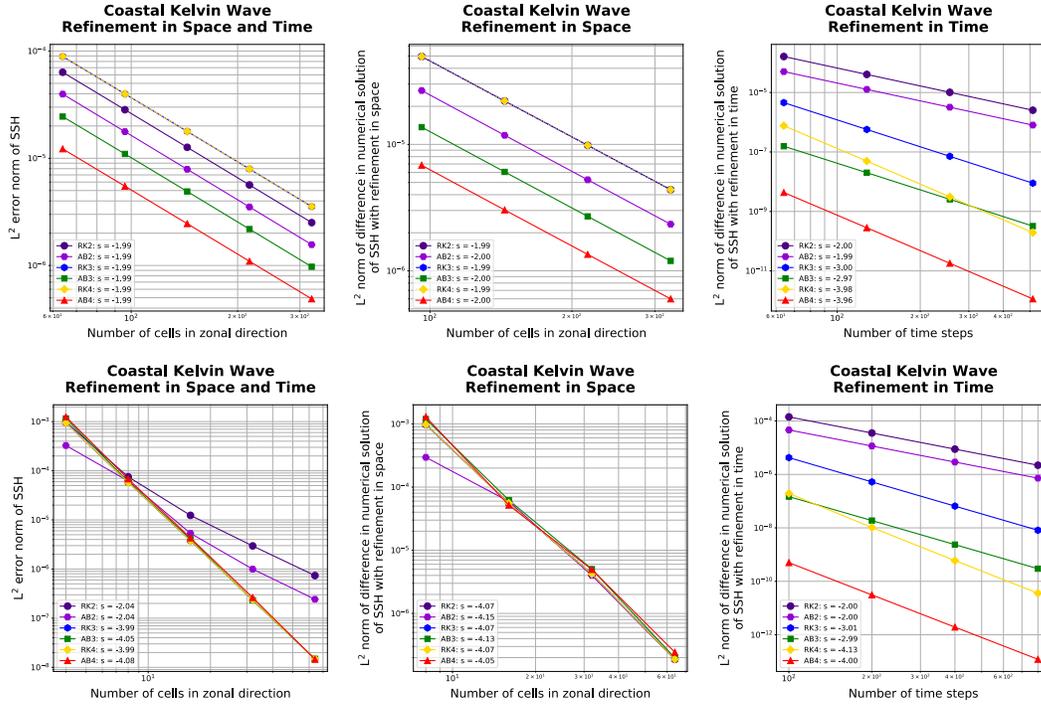
**Figure 13.** Same as Figure 10, but for TC6, the non-linear manufactured solution test case, showing error for TRiSK (first row), and DGSEM (second row).

1395 gradient terms in (10a), its numerical counterpart is not. Referring to our discussion in  
 1396 Section 4.2, the spatial discretization error in the pressure gradient term of (10a) is of order  
 1397  $\mathcal{O}(\Delta x^\alpha)$ . This non-zero error gives rise to a discernible numerical zonal velocity, serving  
 1398 as a catalyst for the error modes to propagate in both zonal and meridional directions.  
 1399 Moreover, the western boundary, characterized by high gradients and the imposition of a  
 1400 no-normal flow condition, act as an incubator for error. As the simulation progresses, the  
 1401 errors originating from this boundary permeate the interior domain. Notably, these error  
 1402 modes propagate at speeds identical to the shallow water gravity wave speed, a reflection  
 1403 of the system’s inherent physics. Interested readers may consult Figure A1 in Appendix A,  
 1404 which depicts the exact solution plots for a plane wave test case traveling at the gravity wave  
 1405 speed. They will observe a notable similarity between these plots and the aforementioned  
 1406 error modes. Such behavior underscores the principle that errors in numerical simulations  
 1407 tend to mirror the dynamics of the governing equations. This, in conjunction with the zonal  
 1408 error propagation, may account for the prominent west-to-east movement of errors observed.  
 1409 A distinctive front-like feature is observed migrating from west to east. Our interpretation  
 1410 suggests that this front represents the initial “boundary layer” of error, emanating from the  
 1411 western boundary. As this layer advances eastward, it collides with the pre-existing errors,  
 1412 predominantly moving southward. This intricate dance between the boundary-induced and  
 1413 interior error modes gives birth to the observed “front”.

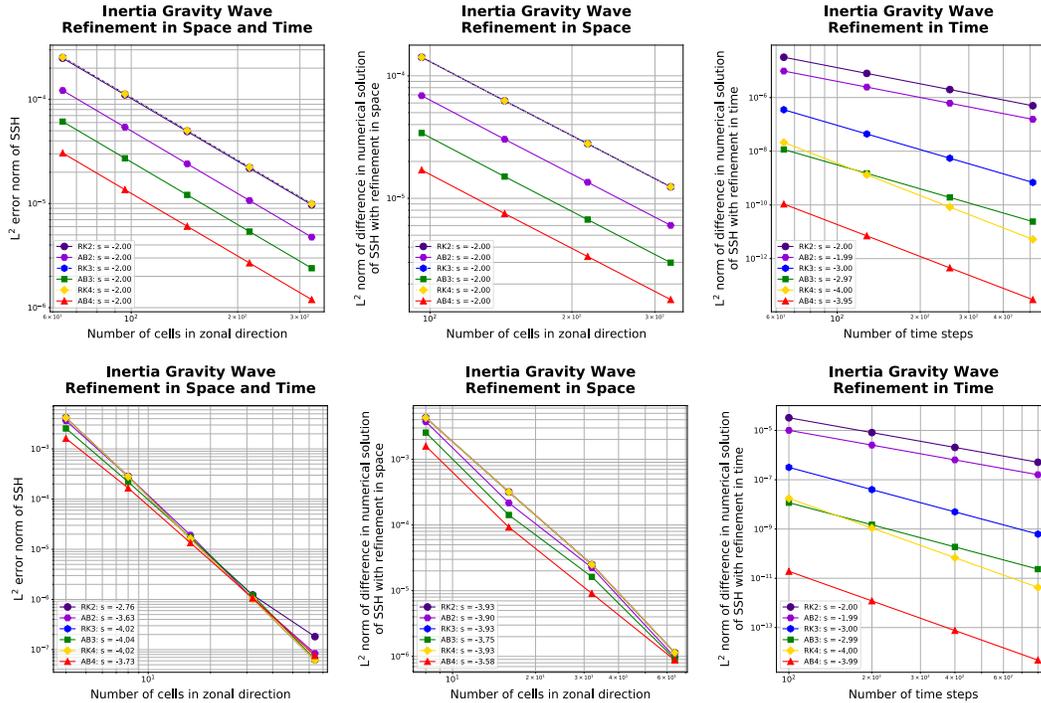
1414 We recall that the prescribed exact solutions for both the coastal and inertia-gravity  
 1415 waves are constructed as a superposition of two wave modes. The second mode possesses  
 1416 twice the amplitude and wavenumber relative to the first. Owing to the inherently dispersive  
 1417 nature of the inertia-gravity wave, these modes propagate with different phase speeds. This  
 1418 disparity in propagation speeds is manifested by the temporal variation of the solution’s  
 1419 amplitude and the width of its positive and negative “bands” (Figure 2). Intriguingly,  
 1420 the error exhibits analogous behavior. Given the absence of physical boundaries combined  
 1421 with the imposition of periodic boundary conditions, the error advances coherently in the  
 1422 direction of the solution (Figure 11). This observation again underscores that the system’s  
 1423 underlying physics significantly shapes the error’s dynamics, mirroring the solutions of the  
 1424 governing equations.

1425 The barotropic tide test case serves as a benchmark for evaluating an ocean model’s  
 1426 proficiency in simulating standing waves, a critical feature for coastal applications. While  
 1427 an initial assessment based on error magnitude (Figure 12) and convergence rate (Figure 18)  
 1428 suggests promising results for both TRiSK and DGSEM, a closer examination of the DGSEM  
 1429 error plots uncovers patterns that could be attributed to either spurious oscillations or  
 1430 numerical dispersion. On the other hand, the inherent dissipation of TRiSK damp outs  
 1431 potential oscillations and dispersive errors that the more accurate DGSEM tends to pick  
 1432 up. It is worth noting that despite these subtle numerical artifacts observed in DGSEM,  
 1433 which were discernible only upon meticulous examination, the error magnitude for DGSEM  
 1434 remains significantly lower than that of TRiSK at equivalent or even lower spatial resolution.

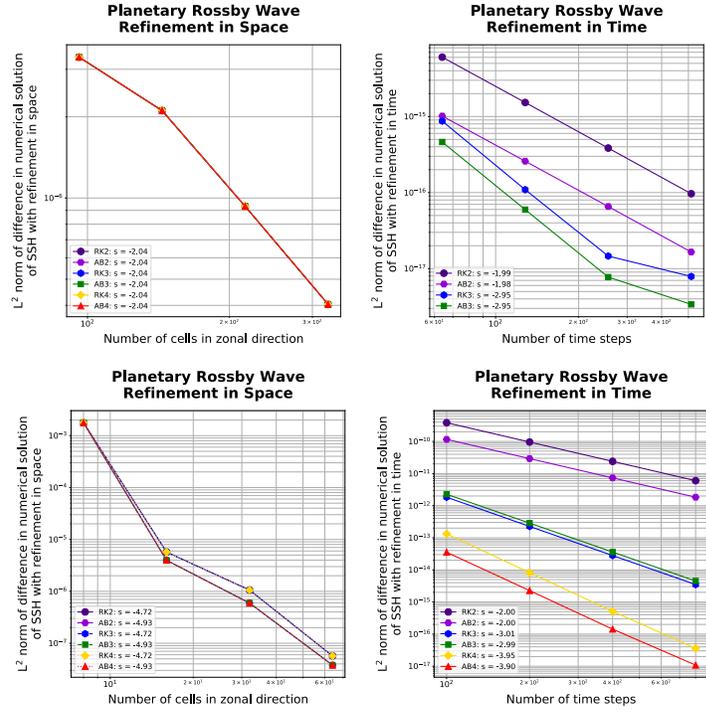
1435 Finally, interpreting the error dynamics of the non-linear manufactured solution test  
 1436 case (Figure 13) can be notably challenging. Nonlinearities inherently introduce a range of  
 1437 complex interactions and dependencies between different solution features. While in linear  
 1438 settings numerical artifacts like dispersion and oscillations may have predictable patterns, in  
 1439 non-linear contexts these patterns can be distorted, merged, or even amplified in unexpected  
 1440 ways. The intricacies of non-linear interactions can often cloak or overshadow the typical  
 1441 behaviors we associate with numerical errors. As a result, even when we observe smooth  
 1442 error fields as in Figure 13, these might be the consequence of numerous intertwined effects  
 1443 which, in isolation, would appear differently. This complexity not only complicates our  
 1444 ability to decipher the source or nature of errors but also underscores the importance  
 1445 of supplementing visual error assessments with quantitative tools like convergence plots  
 1446 (Figure 19) in non-linear scenarios.



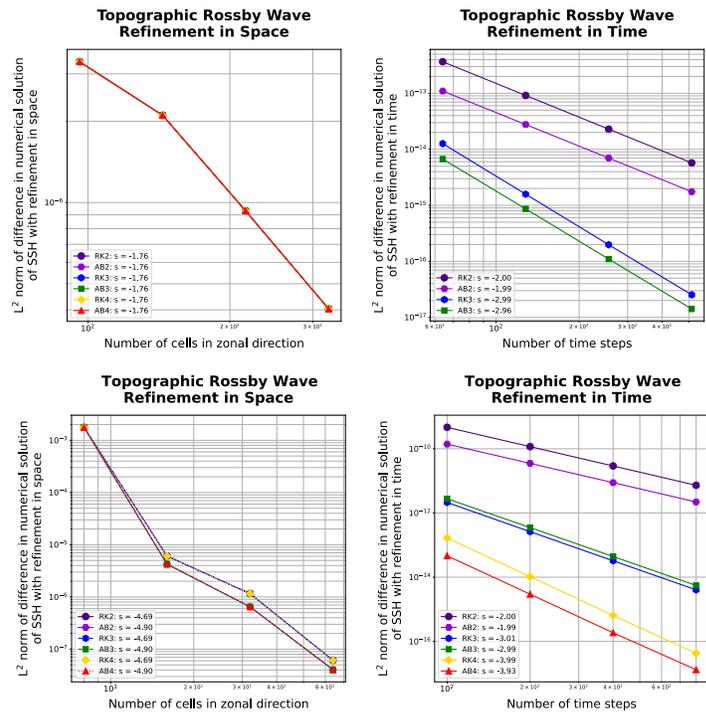
**Figure 14.** Convergence plots of TC1, the non-dispersive coastal Kelvin wave, discretized with TRiSK (first row) and DGSEM (second row), for refinement in space and time (first column), refinement in space (second column), and refinement in time (third column). The slope of the best-fit line,  $s$ , is shown in each legend.



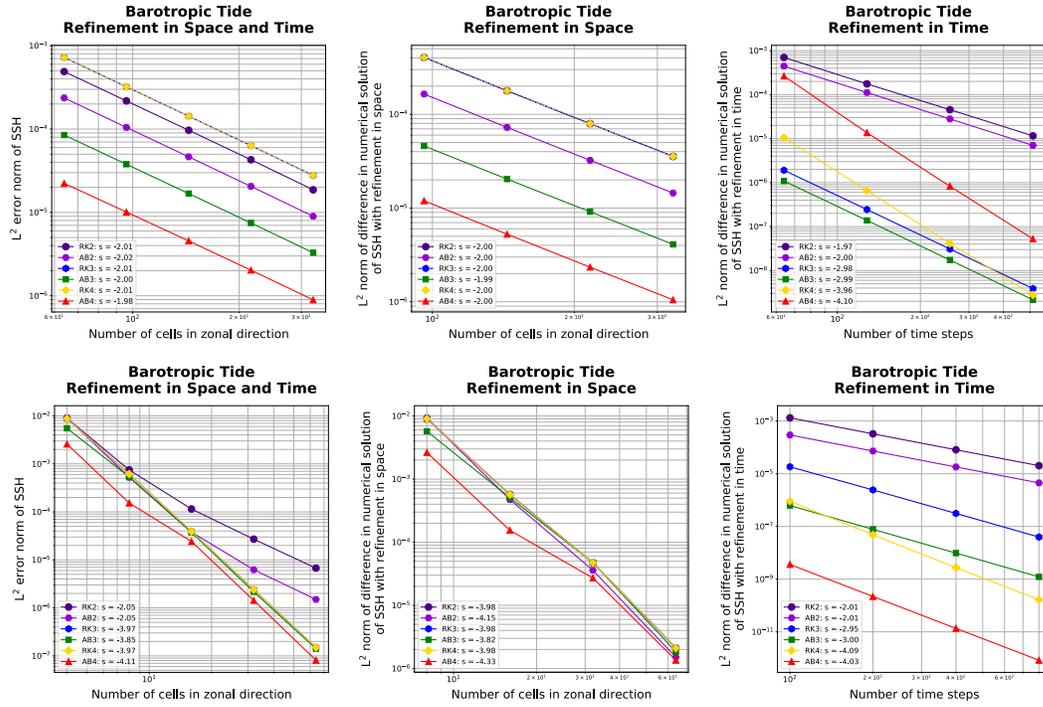
**Figure 15.** Same as Figure 14, but for TC2, the dispersive inertia-gravity wave.



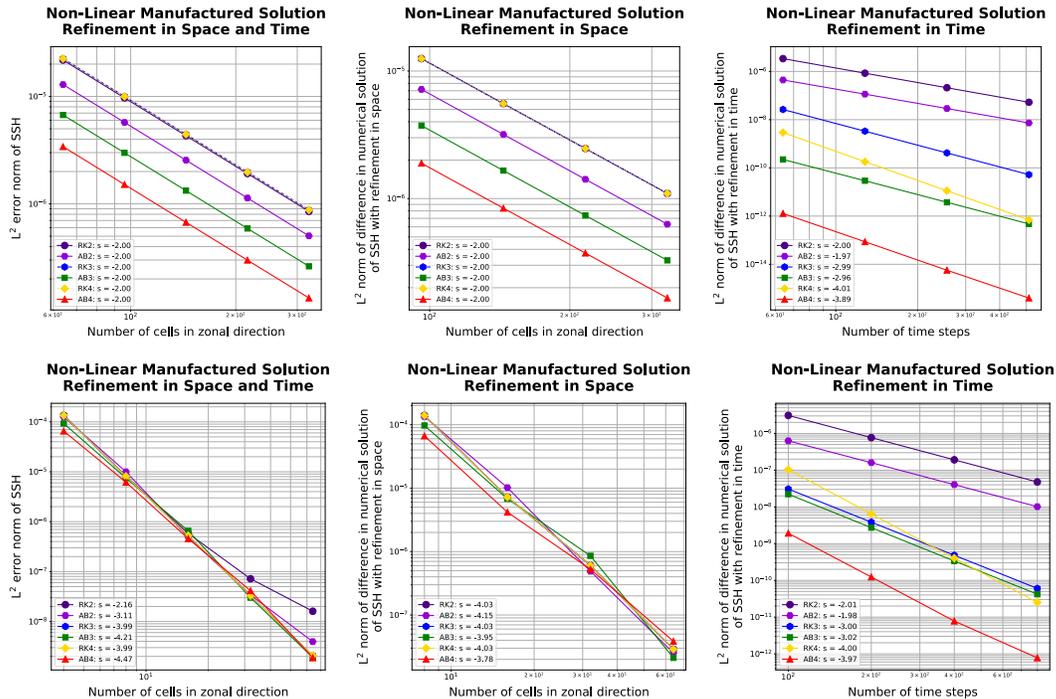
**Figure 16.** Convergence plots of the solution difference norm of TC3a, the linear dispersive planetary Rossby wave, discretized with TRiSK (first row) and DGSEM (second row), for refinement in space (first column), and refinement in time (second column). The slope of the best-fit line,  $s$ , is shown in each legend.



**Figure 17.** Same as Figure 16, but for TC4a, the linear dispersive topographic Rossby wave.



**Figure 18.** Convergence plots of TC5, the barotropic tide, discretized with TRiSK (first row) and DGSEM (second row), for refinement in space and time (first column), refinement in space (second column), and refinement in time (third column).



**Figure 19.** Same as Figure 18, but for TC6, the non-linear manufactured solution.

1447 We have examined the plots produced by DGSEM on low-resolution spectral element  
 1448 meshes. Coarsening was executed by diminishing the polynomial order ( $p$ -coarsening) as  
 1449 well as the number of elements ( $h$ -coarsening). To maintain brevity, we have opted not to  
 1450 include these results in this paper. However, interested readers can download the output  
 1451 files for each test case detailed in the main paper and in Appendix A from Bishnu (2024a),  
 1452 and review the low  $p$ - and  $h$ -resolution plots in the designated subdirectories of the DGSEM  
 1453 output directory. These subdirectories exist for all test cases equipped with exact solutions,  
 1454 and contain the numerical solution and error plots. The spectral element mesh used in the  
 1455 low  $p$ -resolution simulations was configured with 5 elements and polynomial basis functions  
 1456 of order 4 in each horizontal direction. In contrast, the mesh for the low  $h$ -resolution  
 1457 simulations was designed with 2 elements and polynomial basis functions of order 10 in each  
 1458 direction. The low-resolution plots reveal an increase in numerical dispersion and dissipation  
 1459 effects (Section 5). Notably, numerical dispersion often becomes more pronounced in coarser  
 1460 meshes, where the fidelity of the physical phenomena’s representation is compromised due  
 1461 to the lower resolution. This manifests as significant alterations in wave speeds and wave  
 1462 shapes, leading to attenuation of the signal in some parts of the domain and amplification  
 1463 in others. While these dispersive effects are imperceptible in the high-resolution DGSEM  
 1464 solution of the physically non-dispersive Kelvin wave, they become conspicuous in the low  
 1465 resolution solution, particularly with lower than three elements and third-order polynomial  
 1466 basis functions in each direction. It alters the phase speed of the component waves of  
 1467 different wavelengths, thereby distorting the resultant wave’s initial profile as the simulation  
 1468 progresses. Concurrently, the utilization of the LLF Riemann solver—implemented to  
 1469 dampen spurious oscillations at the spectral elements’ boundaries—introduces its own brand  
 1470 of error, that of a dissipative nature. A coarser mesh exacerbates this error, as there are  
 1471 fewer elements to absorb the impact of these dissipative effects. It is manifested by the  
 1472 errors assuming predominantly higher magnitudes along the element boundaries.

1473 Figures 14, 15, 18, and 19 show the convergence plots of the surface elevation error for  
 1474 the coastal Kelvin wave, the inertia-gravity wave, the barotropic tide, and the non-linear  
 1475 manufactured solution, respectively. The refinement is performed by keeping  $\Delta t \propto \Delta x$   
 1476 (first column), only refining in space (second column), and only refining in time (third  
 1477 column). The numerical solutions in the first rows of these figures have been discretized  
 1478 with the TRiSK-based mimetic finite volume method, while the ones in the second row  
 1479 have been discretized with DGSEM. Given the absence of exact solutions for the planetary  
 1480 and topographic Rossby wave test cases, we cannot ascertain their error, which is essential  
 1481 for convergence studies with both spatial and temporal refinement. Consequently, we plot  
 1482 the norm of the differences between numerical solutions over successive pairs of spatial and  
 1483 temporal resolutions, refined at a constant ratio, to verify the spatial and temporal orders of  
 1484 accuracy (Section 4.5). Figures 16 and 17 showcase these convergence plots for the planetary  
 1485 and topographic Rossby waves respectively, discretized with TRiSK (first row) and DGSEM  
 1486 (second row), for refinement only in space (first column) and only in time (second column).  
 1487 For refinement in both space and time, we utilize the Courant number formulation in (61)  
 1488 to first determine the time step  $\Delta t$  on the coarsest mesh, and then reduce this maximum  $\Delta t$   
 1489 proportional to  $\Delta x$  for the remaining meshes. Similarly, by leveraging (61), we determine  
 1490 (a) the largest  $\Delta t$  at a fixed spatial resolution for refinement only in time, and (b) the  $\Delta t$   
 1491 on the finest mesh for refinement only in space, ensuring it meets the CFL condition for  
 1492 the remaining meshes where it is also implemented. The time horizon is specified using  
 1493 the largest  $\Delta t$  as stipulated in point 7 of the experimental procedure of Section 6.1. The  
 1494 actual time-stepping methods corresponding to their abbreviated notations in the legends  
 1495 of the convergence plots can be obtained from List 1. The slope of the best fit line for each  
 1496 time-stepping method is denoted by  $s$ .

1497 The convergence slopes agree with the theoretical predictions in Bishnu (2021). As  
 1498 highlighted in point 9(c) of the experimental procedure outlined in Section 6.1, employing  
 1499 an exceedingly high-order DGSEM for convergence studies may not be optimal. This is  
 1500 attributed to the prevalence of round-off errors during spatial refinement, which manifest

1501 before the resolutions attain the asymptotic regime. To mitigate this, we only utilize  
 1502 fourth-order polynomial basis functions. The observed convergence slopes of approximately  
 1503 four in the spatial-only refinement plots for DGSEM confirm their fourth-order spatial  
 1504 accuracy. When refining in both space and time, we note that the asymptotic order of  
 1505 convergence matches the minimum of the spatial and temporal orders of accuracy. Since  
 1506 asymptotic convergence is observed with the second-order TRiSK scheme for refinement  
 1507 in both space and time, third- and fourth-order Runge-Kutta and Adams-Bashforth time  
 1508 integrators do not result in higher than second-order convergence rates. For this reason,  
 1509 it is imperative to perform convergence studies only in space and only in time, and plot  
 1510 the differences in the numerical solution or the error between successive pairs of spatial  
 1511 and temporal resolutions to capture the true spatial and temporal orders of accuracy. The  
 1512 second and third columns of Figures 14, 15, 18, and 19 can attest to this statement. The  
 1513 slope  $s$  is reported at resolutions where asymptotic convergence is observed. For example,  
 1514 for the coastal Kelvin wave test case discretized in space with a fourth-order DGSEM  
 1515 and advanced with the second-order accurate time stepping methods RK2 and AB2, only  
 1516 second-order accuracy is observed in the asymptotic regime. Similarly, as errors approach  
 1517 machine precision, which often happens with high-order methods, these errors near machine  
 1518 epsilon are excluded from the slope calculations. Finally, we note that when refining in  
 1519 both space and time, the convergence often appears faster than the theoretical asymptotic  
 1520 convergence rate—this occurs, for example, with the coastal Kelvin wave test. In these  
 1521 examples, even though the time stepping methods RK3 and AB3 are third-order accurate,  
 1522 the fourth-order accuracy is observed because the resolutions do not reach the asymptotic  
 1523 regime, and the spatial error dominates at the chosen time step sizes. This underscores yet  
 1524 another important reason for conducting the self-refinement convergence tests only in space  
 1525 and only in time to verify the spatial and temporal orders of accuracy. It is worth noting that  
 1526 for temporal refinement using TRiSK and fourth-order Runge-Kutta and Adams-Bashforth  
 1527 methods, round-off errors overshadow the norm of the solution difference. As such, we  
 1528 have excluded these particular convergence plots from our presentation. Finally, we obtain  
 1529 expected convergence rates with the non-linear planetary and topographic Rossby waves  
 1530 (test cases 3b and 4b), so we do not present these results here.

## 1531 7 Conclusion and Future Work

1532 We have designed a verification suite of shallow water test cases for ocean model  
 1533 development. Each of these test cases verifies the implementation of a subset of terms  
 1534 in the prognostic momentum and continuity equations e.g. the linear pressure gradient  
 1535 term, the linear constant- or variable-coefficient Coriolis and bathymetry terms, and the  
 1536 non-linear advection terms. The test cases constitute standard geophysical waves including  
 1537 the non-dispersive coastal Kelvin wave, the high-frequency dispersive inertia-gravity wave,  
 1538 the low-frequency dispersive planetary and topographic Rossby waves, the barotropic tide,  
 1539 and a non-linear manufactured solution. Appendix A includes the non-dispersive equatorial  
 1540 Kelvin wave and the dispersive equatorial Yanai, Rossby and inertia-gravity waves, as well  
 1541 as four non-geophysical test cases: the plane Gaussian wave, the diffusion equation, the  
 1542 advection-diffusion equation, and the viscous Burgers' equation.

1543 We have developed a shallow water solver in object-oriented Python (Bishnu, 2024a),  
 1544 employing two types of spatial discretizations—TRiSK representing low-order mimetic finite  
 1545 volume methods (FVMs), and DGSEM epitomizing high-order finite or spectral element  
 1546 methods (SEMs)—and numerous time-stepping methods. It was used as a platform to  
 1547 run the shallow water test cases, and conduct convergence studies for each test case with  
 1548 refinement in both space and time, only in space, and only in time. The observed convergence  
 1549 rates align with the theoretical predictions in Bishnu (2021).

1550 We utilized TRiSK and DGSEM, representing the finite volume and high-order spectral  
 1551 element methods, based on their prevalence in operational ocean models. In our discussion,  
 1552 we highlight key considerations associated with each spatial discretization technique. For

1553 example, we investigate the importance of conducting self-refinement convergence tests only  
 1554 in space and only in time, noting that the rationale might differ between FVMs and SEMs.  
 1555 We further delve into the nuances of numerical implementation, with certain details specific  
 1556 to either FVMs or SEMs. Despite the differences between TRiSK and DGSEM, our study  
 1557 underscores the robustness of our numerical approach in verifying the spatial and temporal  
 1558 orders of accuracy across both discretization methods.

1559 In our analysis of numerical solutions, we discerned that the temporal evolution of  
 1560 errors in both TRiSK and DGSEM closely mirrors the intrinsic physics of the system being  
 1561 modeled. The DGSEM approach, characterized by its use of high-order polynomial basis  
 1562 functions, is more prone to spurious oscillations near steep gradients or discontinuities, a  
 1563 trait commonly dubbed as the ‘‘Gibbs phenomenon’’. Employing Legendre-Gauss nodes in  
 1564 conjunction with the local Lax Friedrichs (LLF) Riemann solver significantly alleviates these  
 1565 oscillations. However, the LLF solver is not without its trade-offs, as it introduces its own  
 1566 flavor of dissipative error. In coarser meshes with fewer elements to absorb these errors,  
 1567 their impact becomes more pronounced, especially at element boundaries. Additionally,  
 1568 DGSEM’s susceptibility to numerical dispersion errors is heightened in these coarser meshes  
 1569 due to the physical phenomena being represented with less fidelity. In contrast, the TRiSK  
 1570 scheme, with its inherent dissipation properties, effectively dampens both spurious oscillations  
 1571 and dispersion errors. However, this comes at the expense of overall solution accuracy. In  
 1572 fact, TRiSK’s error turns out to be several orders of magnitude larger than DGSEM’s at  
 1573 comparable spatial resolution. This is despite the presence of the aforementioned numerical  
 1574 artifacts in DGSEM, which become evident only upon close scrutiny.

1575 It is our hope that the exact solutions and numerical results presented here will be useful  
 1576 to other developers of atmosphere and ocean dynamical cores. Shallow water equation  
 1577 test cases may be applied to ocean layered primitive equation models with the vertical  
 1578 advection and diffusion terms turned off, as well as the barotropic mode in split time-stepping  
 1579 schemes. The suite was designed to include a progressive sequence of added complexity in the  
 1580 terms tested, topography, and boundary conditions. Test cases with exact or manufactured  
 1581 solutions can verify model functionality without resorting to high resolutions and a large  
 1582 number time steps common in global simulations. Moreover, for convergence studies aimed  
 1583 at verifying the spatial and temporal orders of accuracy, the simulation time can be further  
 1584 reduced, leading to an even smaller number of time steps. Such attributes render these  
 1585 test cases ideal for automated nightly regression testing and as a prerequisite for code pull  
 1586 requests. Verification suites with thorough coverage of code functionality have proven to be  
 1587 indispensable in our own development work. In E3SM, we have developed an automated  
 1588 test harness called Polaris that creates the initial conditions, runs the ocean model, and then  
 1589 reports the error and order of convergence for verification test cases (Asay-Davis & Begeman,  
 1590 2024). Our ongoing and future work include designing further verification exercises with  
 1591 complexity in between the barotropic equations and the primitive equations; stratification  
 1592 and complex bathymetry; the ability to test both the barotropic and baroclinic components  
 1593 separately, and the coupling between these modes.

## 1594 **Appendix A An Additional Suite of Test Cases**

1595 We present an additional suite of test cases with exact solutions, summarized in Table  
 1596 A1. Test cases 1–6 in the main text encompass the largest variety of configurations—from  
 1597 linear to non-linear, solid and periodic boundaries, flat and sloping bathymetries, and  $f$ - and  
 1598  $\beta$ -plane domains. Though test cases 7–14 expand the suite, they exhibit more repetition  
 1599 in their configurations. The plane wave test case examines the most basic form of the linear  
 1600 shallow water equations, excluding the Coriolis terms. The diffusion, advection-diffusion,  
 1601 and viscous Burgers test cases do not offer solutions to the shallow water equations used  
 1602 to simulate geophysical fluid dynamics. However, the advection-diffusion test case verifies  
 1603 the implementation of the linear advection term, and in conjunction with the diffusion test  
 1604 case, it verifies the implementation of the diffusion term ensuring the numerical stability

1605 of the non-linear shallow water equations. The viscous Burgers test case not only verifies  
 1606 the implementations of the non-linear advection and diffusion terms, it also assesses the  
 1607 resilience of numerical methods against problems with low regularity. Lastly, the equatorial  
 1608 wave test cases (TC 10–13) may appear repetitive in their testing scope, but they hold merit  
 1609 for pedagogical purposes, elucidating the dynamics and visualization of equatorial waves in  
 1610 simplified configurations.

**Table A1.** Summary of test cases in Appendix A, continuing the case numbering from Table 1 in the main text. The last column refers to terms in the shallow water equations (6).

	Coriolis Parameter	Bottom Topography	Numerical PDE	Boundary Conditions	Terms Verified in Equation (6)
7. Plane Gaussian Wave	Zero (no Coriolis)	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Non-Periodic in $x$ Non-Periodic in $y$	(5), (8)
8. Diffusion Eqn	Zero (no Coriolis)	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Periodic in $x$ Periodic in $y$	(6)
9. Advection Diffusion Eqn	Zero (no Coriolis)	Flat Bottom	Linear, Homogeneous, Constant-Coefficient	Non-Periodic in $x$ Non-Periodic in $y$	(6), (8)
10. Viscous Burgers Equation	Zero (no Coriolis)	Flat Bottom	Non-Linear, Homogeneous, Constant-Coefficient	Non-Periodic in $x$ Non-Periodic in $y$	(1), (2), (6)
11. Equatorial Kelvin Wave	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	Linear, Homogeneous, Variable-Coefficient	Periodic in $x$ Non-Periodic in $y$	(4), (5), (8)
12. Equatorial Yanai Wave	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	Linear, Homogeneous, Variable-Coefficient	Periodic in $x$ Non-Periodic in $y$	(4), (5), (8)
13. Equatorial Rossby Wave	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	Linear, Homogeneous, Variable-Coefficient	Periodic in $x$ Non-Periodic in $y$	(4), (5), (8)
14. Equatorial Inertia Gravity Wave	Linear in $y$ ( <i>beta-plane</i> )	Flat Bottom	Linear, Homogeneous, Variable-Coefficient	Periodic in $x$ Non-Periodic in $y$	(4), (5), (8)

1611 **A1 Plane Wave, Diffusion, Advection-Diffusion and Viscous Burgers Test**  
 1612 **Cases**

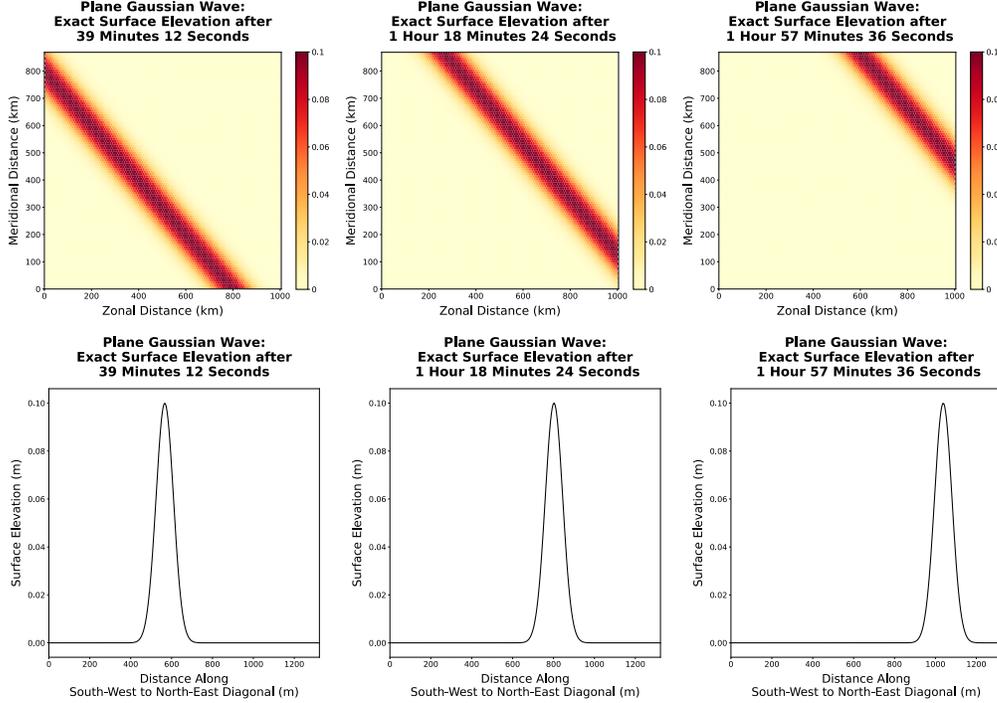
1613 We offer a concise overview of the plane wave, diffusion, advection-diffusion, and viscous  
 1614 Burgers test cases, accompanied by visual representations of the exact solutions' temporal  
 1615 evolution.

1616 **A11 Test Case 7: Plane Wave**

1617 The plane wave is a solution of the linear homogeneous non-rotating shallow water  
 1618 equations, obtained by specifying  $f = 0$  in (10). It only tests the implementation of the  
 1619 linear pressure gradient term in the momentum equations and the linear advection term in  
 1620 the continuity equation. This is the first test case against which the linear shallow water  
 1621 equations should be verified. In a domain with zonal and meridional extents denoted by  $L_x$   
 1622 and  $L_y$ , the exact solution for the plane wave can be characterized as a Gaussian, given by

$$\begin{bmatrix} u \\ v \\ \eta \end{bmatrix} = \begin{bmatrix} 1/k_x \\ 1/k_y \\ 1/g \end{bmatrix} \exp \left[ - \left\{ \frac{k_x(x - x_0) + k_y(y - y_0) - ct}{\sqrt{2}R_0} \right\}^2 \right], \quad (\text{A1})$$

1623 where  $(x_0, y_0)$  are the initial coordinates of the Gaussian peak,  $(k_x, k_y)$  are the wavenumber  
 1624 components,  $R_0$  is the RMS width of the Gaussian peak, and  $c = \sqrt{gH}$  is the propagation  
 1625 speed of this plane Gaussian wave, equivalent to the shallow water gravity wave speed. For  
 1626 the parameters, we have chosen  $L_x = 10^6$  m,  $x_0 = 0.25L_x$ ,  $k_x = k_y = 1/\sqrt{2}$  m<sup>-1</sup>,  $g = 10$



**Figure A1.** Time evolution of TC7, the plane Gaussian wave, showing the exact surface elevation (first row), and cross-section of the exact surface elevation along the south-west to north-east diagonal (second row).

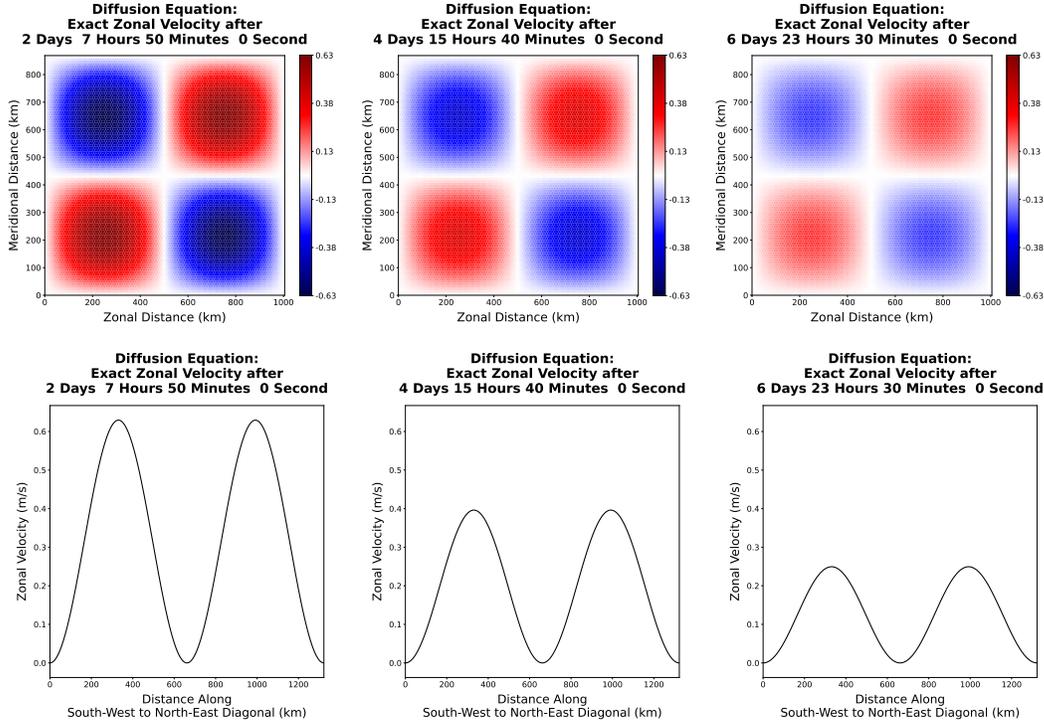
1627  $\text{m s}^{-2}$ ,  $H = 1000 \text{ m}$  (yielding  $c = 100 \text{ m s}^{-1}$ ), and  $R_0 = w/(2\sqrt{2\ln 2})$ , where  $w = 10^5 \text{ m}$   
 1628 denotes the full width at half maximum. For the spectral element mesh,  $y_0 = x_0$ , and for  
 1629 the MPAS-Ocean mesh,  $y_0 = \sqrt{3}/2x_0$ . Figure A1 depicts the time evolution of the surface  
 1630 elevation of this plane wave in the entire domain (first row) and along the south-west to  
 1631 north-east diagonal (second row). The error patterns of the non-dispersive Kelvin wave,  
 1632 depicted in Figure 10 of the main paper, resemble this plane wave, as they all travel at the  
 1633 shallow water gravity wave speed.

1634 **A12 Test Case 8: Diffusion Equation**

1635 The heat or diffusion equation is a fundamental equation in the study of heat transfer  
 1636 and diffusion processes. It describes how a quantity, such as temperature or concentration of  
 1637 a substance, spreads out over time inside a specified region. In two dimensions, the equation  
 1638 is expressed as

$$\varphi_t = \nu \nabla^2 \varphi, \tag{A2}$$

1639 where  $\varphi$  represents the diffusing quantity, and  $\nu$  is the diffusion coefficient, a measure  
 1640 of the rate at which diffusion occurs. Based on Fick's laws of diffusion, (A2) assumes a  
 1641 homogeneous and isotropic medium, meaning the properties of the medium do not change  
 1642 with direction or position. It essentially states that the rate of change of the scalar field,  
 1643  $\varphi$ , at any point in space is proportional to the curvature of  $\varphi$  at that point. This reflects  
 1644 the physical principle that diffusion acts to smooth out variations in the scalar field over  
 1645 time. Mathematically, (A2) is an example of a parabolic partial differential equation,  
 1646 and is derived under the assumption of a constant diffusion coefficient and the absence  
 1647 of any sources or sinks within the domain. Standard texts on partial differential equations  
 1648 and numerical analysis, including works by Strauss (2007), J. D. Logan (2014), Farlow



**Figure A2.** Same as Figure A1 but for TC8, the diffusion equation, showing the exact solution (first row), and cross-section of the exact solution along the south-west to north-east diagonal (second row).

1649 (1993), and Haberman (1998), offer in-depth explorations of this equation. Solving the  
 1650 diffusion equation while employing the spatial discretization of an ocean model verifies the  
 1651 implementation of the Laplacian operator. In our numerical simulations, we employ the  
 1652 exact solution

$$\varphi(x, y, t) = \sin(k_x x) \sin(k_y y) e^{-\kappa t}, \quad (\text{A3})$$

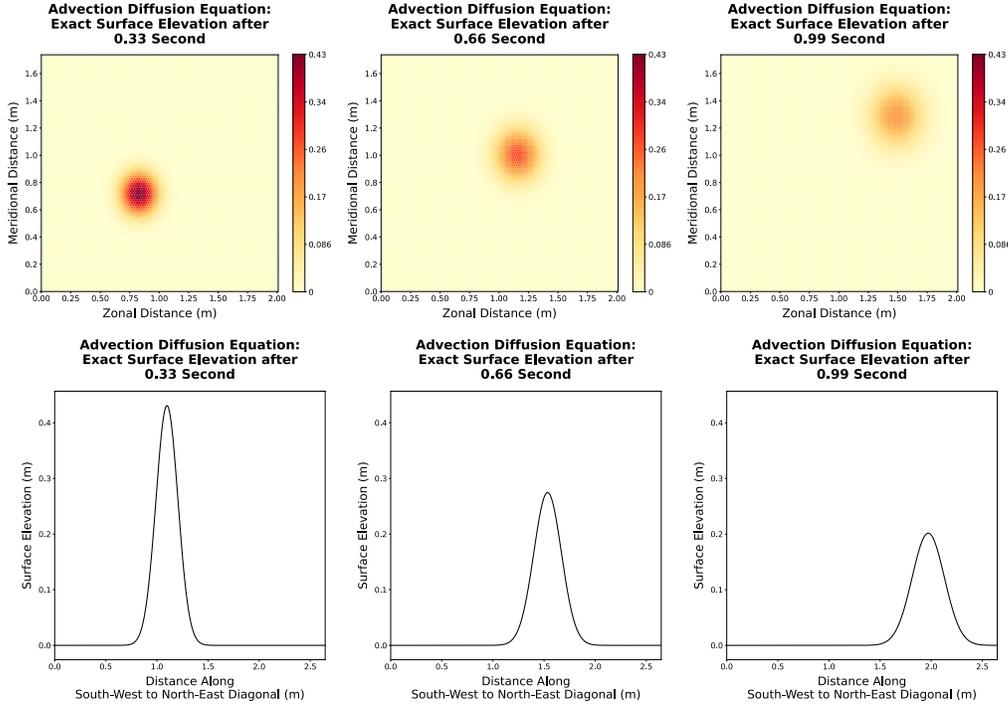
1653 to set the initial and boundary conditions. The diffusivity,  $\kappa = \nu (k_x^2 + k_y^2)$ , represents the  
 1654 rate and pattern of diffusion, factoring in the spatial variability of the system. In a domain  
 1655 with a zonal extent of  $L_x = 10^6$  m, key parameters include  $k_x = 2\pi/L_x$ ,  $k_y = 2\pi/L_y$ , and  
 1656  $\nu = 25000 \text{ m}^2 \text{ s}^{-1}$ . The exact solution's visualization, depicted in Figure A2, showcases  
 1657 the diffusion phenomenon across the entire domain (first row) and along the south-west to  
 1658 north-east diagonal (second row).

### 1659 *A13 Test Case 9: Advection-Diffusion Equation*

1660 The advection-diffusion equation models the combined effect of advection and diffusion  
 1661 on a scalar field,  $\varphi$ , such as concentration of a substance or temperature. This equation plays  
 1662 a pivotal role in fields including fluid dynamics, heat transfer, and environmental sciences.  
 1663 Mathematically, the equation is formulated as

$$\varphi_t + \mathbf{u}_0 \cdot \nabla \varphi \equiv \varphi_t + \nabla \cdot (\varphi \mathbf{u}_0) = \nu \nabla^2 \varphi. \quad (\text{A4})$$

1664 Here,  $\varphi$  is the scalar quantity of interest,  $\mathbf{u}_0 = u_0 \mathbf{i} + v_0 \mathbf{j}$  is the velocity field causing  
 1665 advection, and  $\nu$  is the diffusion coefficient. Comprehensive derivations and solutions of the  
 1666 advection-diffusion equation can be gleaned from standard PDE and numerical analysis  
 1667 texts, such as those by Strauss (2007), Smith (1985), Donea and Huerta (2003), and



**Figure A3.** Same as Figure A1 but for TC9, the advection-diffusion equation, showing the exact solution (first row), and cross-section of the exact solution along the south-west to north-east diagonal (second row).

1668 D. A. Kopriva (2009). When the advection-diffusion equation is solved using the spatial  
 1669 discretization of an ocean model, the implementation of the divergence and Laplacian  
 1670 operators can be verified. In our numerical simulations, we employ the exact solution

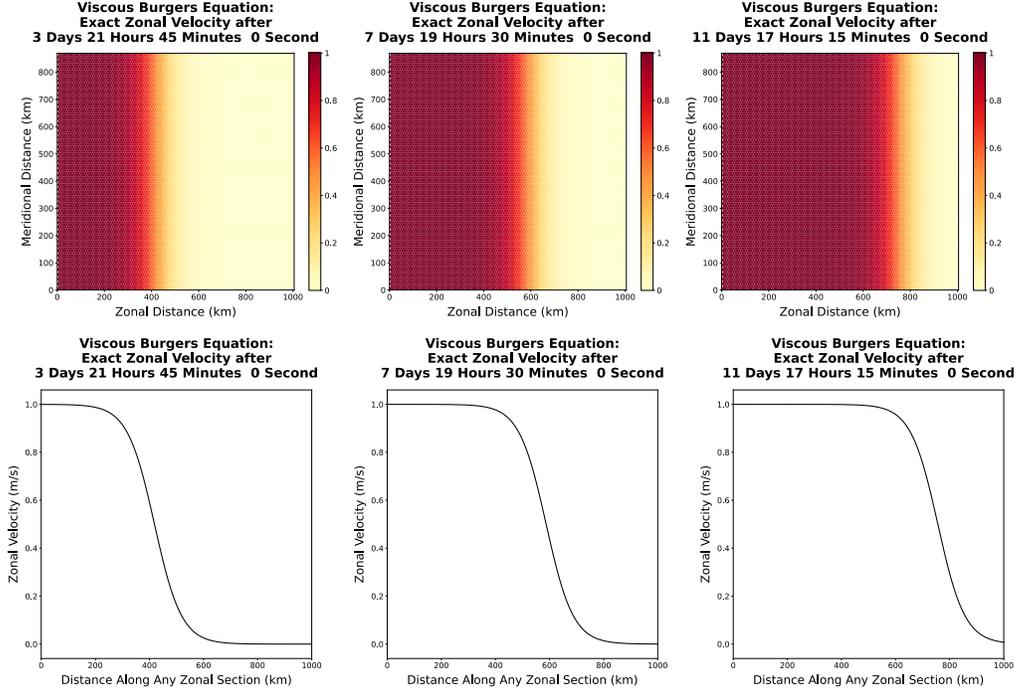
$$\varphi(x, y, t) = \frac{1}{4t + 1} \exp \left[ -\frac{\left\{ (x - x_0 - u_0 t)^2 + (y - y_0 - v_0 t)^2 \right\}}{\nu(4t + 1)} \right], \quad (\text{A5})$$

1671 to specify the initial and boundary conditions. This solution depicts a two-dimensional  
 1672 Gaussian patch with a time-dependent amplitude of  $1/(4t + 1)$  and a radial RMS width of  
 1673  $\sqrt{\nu(4t + 1)}/2$ . This patch is advected by the velocity  $\mathbf{u}_0$  while undergoing diffusion at a rate  
 1674 of  $\nu$ . The Gaussian’s peak is initially located at coordinates  $(x_0, y_0)$ . In a domain with a  
 1675 zonal extent of  $L_x = 2$  m, the parameters are chosen as  $x_0 = 0.25L_x = 0.5$  m,  $u_0 = 1$  m s<sup>-1</sup>,  
 1676 and  $\nu = 0.01$  m<sup>2</sup> s<sup>-1</sup>. For the spectral element mesh, the parameters  $y_0$ , and  $v_0$  mirror their  
 1677 zonal counterparts. In contrast, on the MPAS-Ocean mesh, these parameters are scaled by  
 1678 a factor of  $\sqrt{3}/2$  relative to their zonal values. Figure A3 illustrates the exact solution of  
 1679 the advection-diffusion equation with the aforementioned parameters, in the entire domain  
 1680 (first row) and along the south-west to north-east diagonal (second row).

1681 **A14 Test Case 10: Viscous Burgers’ Equation**

1682 The study of hyperbolic PDEs such as the Burgers’ equation requires understanding  
 1683 the notion of “characteristics”. In the context of the simpler linear advection equation,  
 1684  $u_t + au_x = 0$ , the solution is given by  $u(x, t) = u_0(x - at)$ , where  $u_0(x)$  represents the  
 1685 initial condition and  $a$  is the advection speed. For this equation,  $x - at = c$  (where  $c$  takes  
 1686 different values) represents straight lines in the  $x - t$  plane called characteristics. Along  
 1687 these characteristics, the solution remains unchanged, effectively signifying that information

1688 propagates without alteration. Transitioning to the inviscid Burgers' equation, the situation  
 1689 becomes non-linear and significantly more complex. Here, the equation reads  $u_t + uu_x = 0$   
 1690 or  $u_t + (f(u))_x = 0$ , where  $f(u) = u^2/2$ . A crucial difference is noticed: while in the  
 1691 linear advection equation, the advection speed is constant, in the Burgers' equation, it is  
 1692 dependent on the solution magnitude  $u$  itself. This means the characteristics are determined  
 1693 by the local value of the solution, causing them to curve in the  $x-t$  plane rather than being  
 1694 straight lines. As the local advection speed  $u$  varies across the domain, characteristics either  
 1695 converge or diverge.



**Figure A4.** Same as Figure A1 but for TC10, the viscous Burgers' shock wave, showing the exact solution (first row) and cross-section of the exact solution (second row).

1696 The Riemann problem, taken as an example, features a step-like initial condition:

$$u_0(x) = \begin{cases} u_l & \text{if } x < 0, \\ u_r & \text{if } x \geq 0, \end{cases} \quad (\text{A6})$$

1697 where  $u_l$  and  $u_r$  are constants. Due to the step-like variation, different advection speeds,  
 1698  $u_l$  and  $u_r$ , respectively, are possessed by the left and right sides. Characteristics are either  
 1699 caused to converge (if  $u_l > u_r$ ) resulting in a shock wave, or to diverge (if  $u_l < u_r$ ) leading  
 1700 to a rarefaction wave. With a smooth initial condition like a Gaussian  $u(x, 0) = \exp(-x^2)$ ,  
 1701 the solution is continuously varying, and so is the local advection speed. Initially, the  
 1702 solution remains single-valued for every  $x$ . However, due to the higher magnitude (and thus  
 1703 higher advection speed) at the Gaussian's peak, it starts overtaking its leading edge, causing  
 1704 characteristics to converge. A triple-valued solution at certain  $x$  values is encountered,  
 1705 marking the breaking time. Replacing the multi-valued region with a discontinuity by the  
 1706 equal area rule ensures the conservation of the integral of  $u$  and sets the shock's position.  
 1707 Meanwhile, at the trailing (left) edge of the Gaussian bump, the characteristics diverge due  
 1708 to a lower advection speed, causing a rarefaction wave to form.

1709 When characteristics converge leading to a shock formation, numerically the solution  
 1710 can become multi-valued in standard discretization schemes. This multi-valuedness is not  
 1711 physically realizable and leads to ambiguity. Numerical methods typically are not designed  
 1712 to handle multi-valued solutions directly. Instead, when faced with a choice among several  
 1713 possible values, the method may inadvertently pick one, leading to an artificially steep  
 1714 gradient. These steep gradients can induce numerical instabilities, particularly in explicit  
 1715 time-stepping schemes, where high gradients can result in time step restrictions (due to  
 1716 the CFL condition) or even solution blow-up. In the case of a rarefaction wave, the  
 1717 characteristics spread apart. Numerically, when modeling a rarefaction wave, the solution  
 1718 remains single-valued and smoother compared to a shock. There is not the same challenge of  
 1719 handling multi-valued solutions. However, if not captured accurately, numerical diffusion, an  
 1720 artifact of many discretization schemes, can overly smooth the rarefaction, making it wider  
 1721 and less pronounced than it should be. This is a common issue, especially in first-order  
 1722 numerical schemes.

1723 We now transition to the viscous Burgers' equation,  $u_t + uu_x = \nu u_{xx}$ , where  $\nu$  represents  
 1724 the viscosity or diffusion coefficient. The introduction of this viscous term plays a pivotal  
 1725 role in smoothing out the discontinuities found in the inviscid case. For instance, in the  
 1726 Riemann problem, the introduction of viscosity transforms what would be a shock wave in  
 1727 the inviscid case into a smooth transition in space and time, given by

$$u(x, t) = s - \frac{u_l - u_r}{2} \tanh \left\{ \frac{(x - x_0 - st)(u_l - u_r)}{4\nu} \right\}, \quad (\text{A7})$$

1728 where  $s = (u_l + u_r)/2$  represents the shock speed, and  $x_0$  denotes the location of the initial  
 1729 discontinuity or transition in the solution. In the context of the inviscid Burgers' equation,  
 1730  $s$  can be derived using the Rankine-Hugoniot jump condition:

$$s = \frac{\text{jump in } f(u)}{\text{jump in } u} = \frac{f(u_l) - f(u_r)}{u_l - u_r} = \frac{u_l^2 - u_r^2}{2(u_l - u_r)} = \frac{u_l + u_r}{2}. \quad (\text{A8})$$

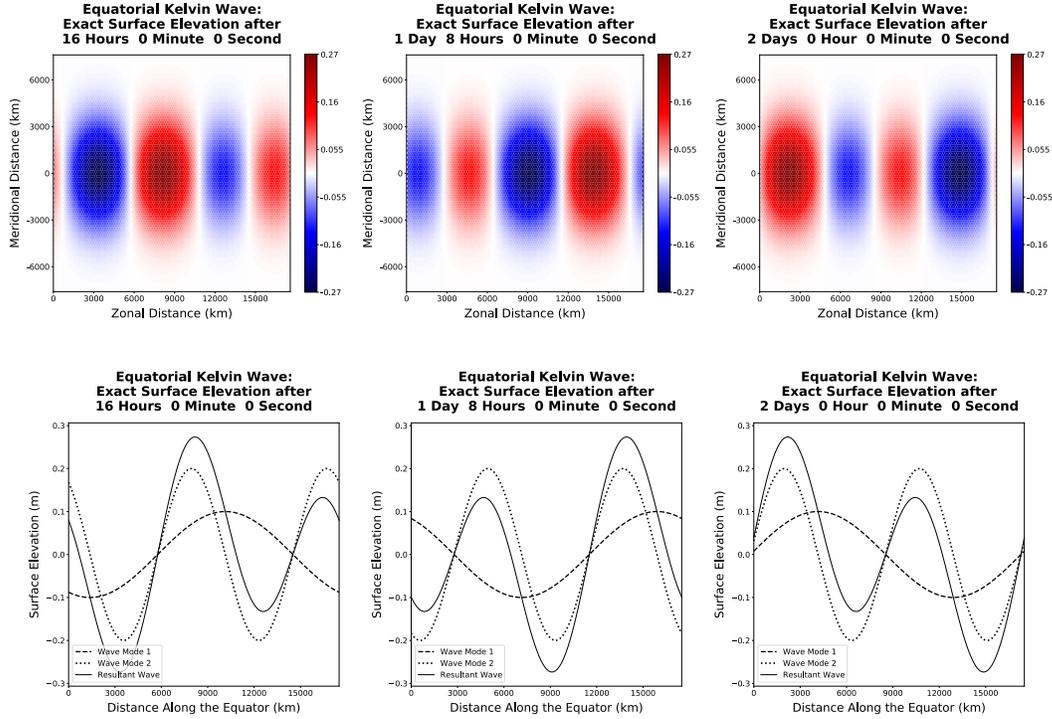
1731 As  $x \rightarrow +\infty$ , the hyperbolic tangent function asymptotically approaches 1, ensuring that  
 1732 the solution tends to  $u_r$ . Conversely, as  $x \rightarrow -\infty$ , the hyperbolic tangent function gravitates  
 1733 towards  $-1$ , and hence the solution aligns with  $u_l$ . The term  $(x - x_0 - st)(u_l - u_r)$  in the  
 1734 numerator ensures the solution progresses with the appropriate shock speed and correctly  
 1735 accounts for the position and magnitude of the initial discontinuity. When the viscosity  $\nu$   
 1736 is allowed to approach zero, the hyperbolic tangent function becomes increasingly sharp.  
 1737 In this limiting scenario, the solution of the viscous Burgers' equation converges to the  
 1738 step function solution that characterizes the inviscid Riemann problem, illustrating the  
 1739 connection between the viscous and inviscid formulations.

1740 Using the viscous Burgers' equation as a verification test for ocean models can be  
 1741 quite advantageous. Ocean models inherently do not encounter shock waves due to viscous  
 1742 terms and numerical diffusion. The viscous Burgers' equation allows these models to verify  
 1743 both their non-linear advection and viscous terms. Moreover, by adjusting the viscosity  
 1744 parameter, we can modulate the solution's regularity, allowing us to closely approach a  
 1745 discontinuous step function and thus robustly test our numerical methods.

1746 Figure A4 displays the exact solution of the viscous Burgers' equation in the entire  
 1747 domain (first row) and along any zonal section (second row). It is uniform in the meridional  
 1748 direction. In case of the TRiSK discretization, the normal velocity is the prognostic quantity  
 1749 of interest. So, we do not lose any generality by using a velocity field with zero meridional  
 1750 component as in this instance. Key parameters include  $L_x = 10^6$  m,  $x_0 = L_x/4 = 2.5 \times 10^5$   
 1751 m,  $u_l = 1$  m s<sup>-1</sup>,  $u_r = 0$ ,  $s = (u_l + u_r)/2 = 0.5$  m s<sup>-1</sup>, and  $\nu = 2.5 \times 10^4$  m<sup>2</sup> s<sup>-1</sup>.

## 1752 A2 Equatorial Waves

1753 Along the equator, the latitude  $\phi_0 = 0$ , and the Coriolis parameter  $f_0 = 2\Omega \sin \phi_0$   
 1754 vanishes. So, the equator is a dynamically special region. Therefore, in the vicinity of the



**Figure A5.** Time evolution of the TC11, the non-dispersive equatorial Kelvin wave, showing the exact surface elevation (first row) and cross-section of the exact surface elevation (second row).

1755 equator, certain geophysical waves develop unusually strong signals and contribute to the  
 1756 generation of the Quasi-Biennial Oscillation (QBO) in the atmosphere (Hell, 2020; Baldwin  
 1757 et al., 2001) and the El Niño Southern Oscillation (ENSO) phenomenon in the ocean and  
 1758 atmosphere (Clarke, 2008; Sarachik & Cane, 2010; Philander et al., 1989).

1759 The equatorial Kelvin, Yanai, Rossby, and inertia-gravity waves are solutions of the  
 1760 rotating shallow water equations

$$u_t - \beta_0 y v = -g \eta_x, \quad (\text{A9a})$$

$$v_t + \beta_0 y u = -g \eta_y, \quad (\text{A9b})$$

$$\eta_t + H(u_x + v_y) = 0, \quad (\text{A9c})$$

1761 where  $u$  and  $v$  are the zonal and meridional velocities,  $\eta$  is the surface elevation,  $H$  is the  
 1762 mean depth of the ocean with a flat bottom,  $\beta_0$  is the first-order meridional gradient of the  
 1763 Coriolis parameter, and  $g$  is the acceleration due to gravity. Equation (A9) is obtained by  
 1764 replacing  $f$  with  $\beta_0 y$  in equation (18) of the main paper. Detailed derivations of equatorial  
 1765 wave solutions are found in textbooks specializing in equatorial dynamics (Clarke, 2008)  
 1766 and many geophysical fluid dynamics textbooks (Vallis, 2017; Cushman-Roisin & Beckers,  
 1767 2011).

### 1768 **A21 Test Case 11: Equatorial Kelvin Wave**

1769 The equatorial Kelvin wave is a long gravity wave trapped along the equator with decay  
 1770 scale  $\sqrt{2}R_{eq} = (2c/\beta_0)^{1/2}$ , where  $c = \sqrt{gH}$  is the shallow water gravity wave speed, and  
 1771  $R_{eq}$  is the equatorial Rossby radius of deformation. The equatorial Kelvin wave has zero  
 1772 meridional velocity, and travels eastward at speed  $c$ . It is non-dispersive and assumes a

1773 solution of the form

$$\eta = HG(x - ct) \exp\left(-\frac{1}{2} \left(\frac{y}{R_{eq}}\right)^2\right), \quad (\text{A10})$$

$$u = cG(x - ct) \exp\left(-\frac{1}{2} \left(\frac{y}{R_{eq}}\right)^2\right). \quad (\text{A11})$$

1774 In our numerical simulations, we specify

$$G(x - ct) = \hat{\eta} \sin(k(x - ct)) = \hat{\eta} \sin(kx - \omega t) = \hat{\eta} \text{Im}\left(e^{i(kx - \omega t)}\right), \quad (\text{A12})$$

1775 where  $\hat{\eta}$  is the amplitude, and the phase speed  $\omega/k = c$  is a constant.

1776 Figure A5 displays the time evolution of the equatorial Kelvin wave's surface elevation  
 1777 across the entire domain (first row) with zonal extent  $L_x = 1.75 \times 10^7$  m, and along  
 1778 the equator (second row). Similar to our simulations of the coastal Kelvin wave and the  
 1779 inertia-gravity wave in the main paper, we specify the exact solutions to be a superposition  
 1780 of two wave components, where the second component possesses twice the amplitude and  
 1781 wavenumber of the first. Mathematically,  $\hat{\eta}^{(2)} = 2\hat{\eta}^{(1)}$  and  $k^{(2)} = 2k^{(1)}$ , where  $\hat{\eta}^{(1)} = 10^{-4}$   
 1782 m and  $k^{(1)} = 2\pi/L_x$ . Being non-dispersive in nature, both components, as well as the  
 1783 resultant wave, propagate at an identical phase speed, thereby preserving the initial profile  
 1784 of the resultant wave.

### 1785 ***A22 Test Cases 12, 13, and 14: Equatorial Yanai, Rossby, and Inertia-*** 1786 ***Gravity Waves***

1787 The equatorial Yanai, Rossby and inertia-gravity waves can be obtained from the  
 1788 non-dimensional form of (A9),

$$u'_{t'} - y'v' = -\eta'_{x'}, \quad (\text{A13a})$$

$$v'_{t'} + y'u' = -\eta'_{y'}, \quad (\text{A13b})$$

$$\eta'_{t'} + u'_{x'} + v'_{y'} = 0, \quad (\text{A13c})$$

1789 where  $u = cu'$ ,  $v = cv'$ ,  $\eta = H\eta'$ ,  $x = \sqrt{c/\beta_0}x'$ ,  $y = \sqrt{c/\beta_0}y'$ , and  $t = 1/\sqrt{\beta_0}ct'$ .  
 1790 Dropping the primes for notational convenience, the non-dimensional meridional velocity  
 1791 of the dispersive equatorial Yanai, Rossby and inertia-gravity waves can be expressed in  
 1792 modal form as

$$v = \text{Re}\left(e^{i(kx - \omega t)}\psi_m(y)\right) = \cos(kx - \omega t)\psi_m(y), \quad (\text{A14})$$

1793 where the Hermite function  $\psi_m(y)$  is

$$\psi_m(y) = \frac{e^{-y^2/2}H_m(y)}{\sqrt{2^m m! \sqrt{\pi}}}, \quad (\text{A15})$$

1794 with  $H_m(y)$  being the  $m^{\text{th}}$ -order Hermite polynomial. Since  $H_m(y)$  is an odd function of  $y$   
 1795 for odd  $m$  and an even function of  $y$  for even  $m$ , so is  $\psi_m(y)$ . The Hermite function  $\psi(y)$   
 1796 satisfies

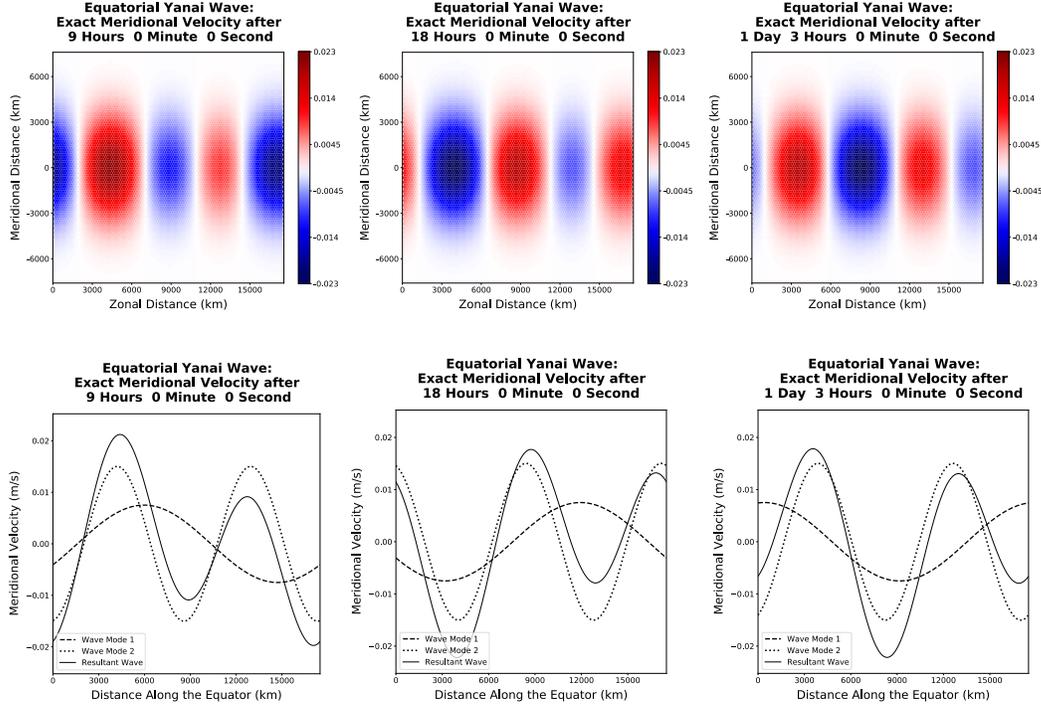
$$\frac{d^2\psi_m}{dy^2} + \left(\omega^2 - k^2 - \frac{k}{\omega} - y^2\right)\psi \equiv \frac{d^2\psi_m}{dy^2} + (2m + 1 - y^2)\psi = 0, \quad m = 0, 1, \dots, \quad (\text{A16})$$

1797 with the non-dimensional dispersion relation being

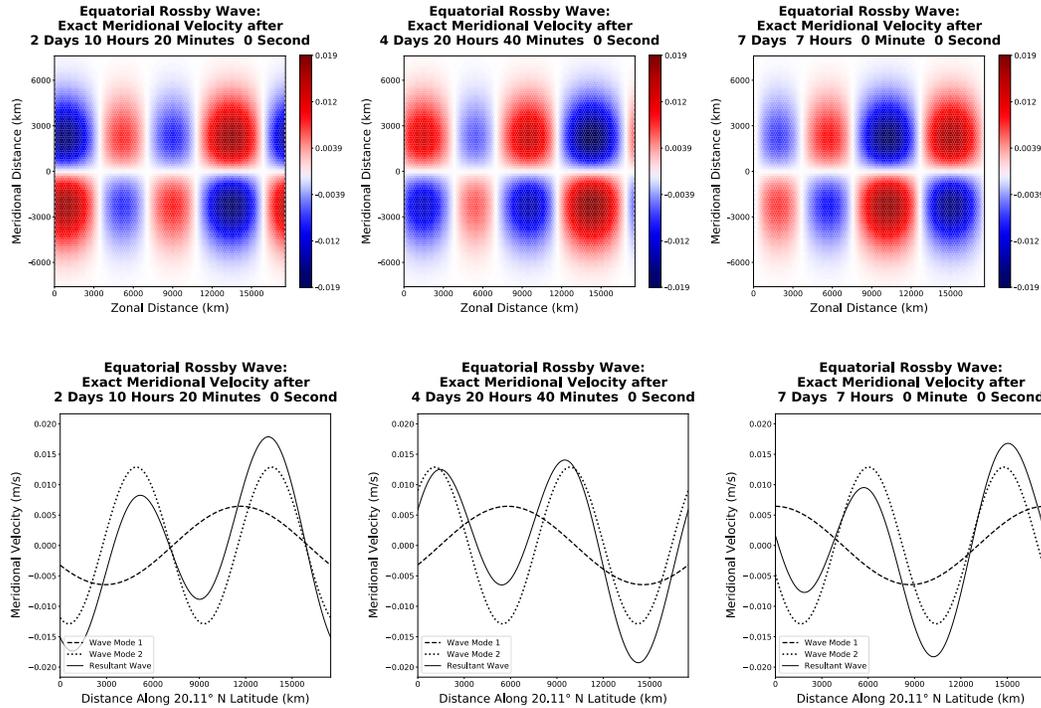
$$k^2 + \frac{k}{\omega} - \omega^2 + (2m + 1) = 0, \quad m = 0, 1, \dots \quad (\text{A17})$$

1798 From (A16), it can be seen that  $\psi_m(y)$  is oscillatory for  $|y| < \sqrt{2m + 1}$  and monotonically  
 1799 decaying for  $|y| > \sqrt{2m + 1}$ . Since the nature of  $\psi_m(y)$  changes at  $y = \sqrt{2m + 1}$ , it is  
 1800 referred to as the turning latitude for mode  $m$ . Solving the quadratic equation (A17) in  $k$ ,

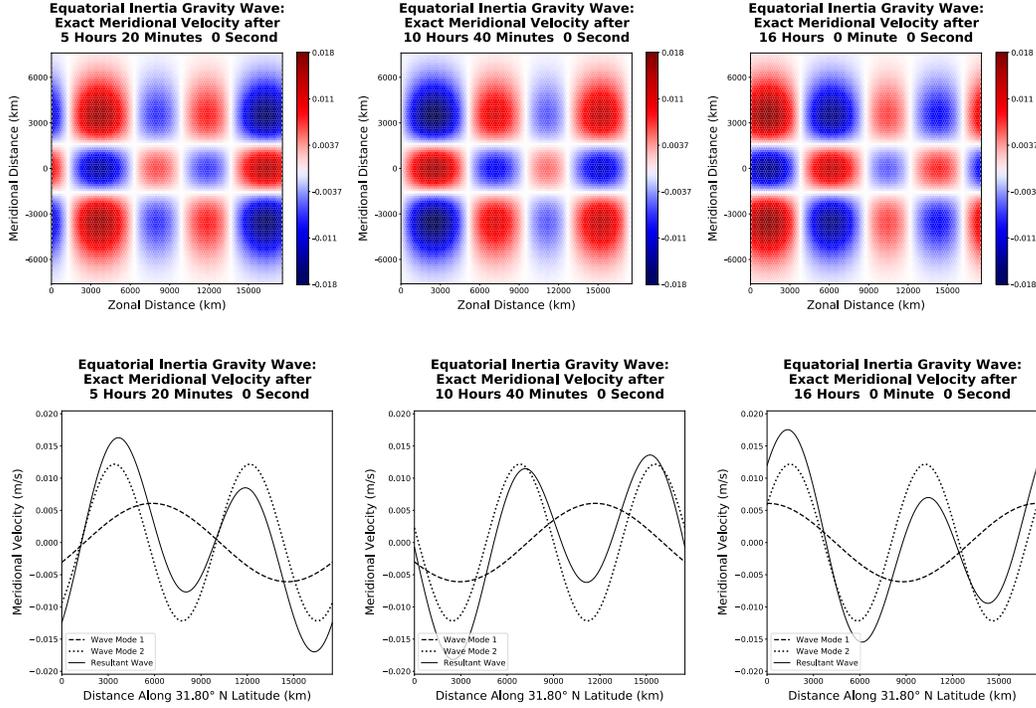
$$k = -\frac{1}{2\omega} \pm \sqrt{\omega^2 + \frac{1}{4\omega^2} - (2m + 1)}. \quad (\text{A18})$$



**Figure A6.** Time evolution of the TC12, the dispersive equatorial Yanai wave, showing the exact meridional velocity (first row) and cross-section of the exact meridional velocity along the equator (second row).



**Figure A7.** Time evolution of the TC13, the dispersive equatorial Rossby wave, showing the exact meridional velocity (first row) and cross-section of the exact meridional velocity along the 20.11°N latitude with maximum magnitude of the Hermite function  $\psi_1(y)$  (second row).



**Figure A8.** Time evolution of the TC14, the dispersive equatorial inertia-gravity wave, showing the exact meridional velocity (first row) and cross-section of the exact meridional velocity along the 31.80°N latitude with maximum magnitude of the Hermite function  $\psi_2(y)$  (second row).

1801 When  $m = 0$ , the roots are  $k = \omega - 1/\omega$  and  $k = -\omega$ , both of which are real. The  
 1802 root  $k = -\omega$  corresponds to a westward propagating Kelvin wave with unbounded velocity  
 1803 at large distances from the equator, and is therefore not a viable solution. The other root  
 1804  $k = \omega - 1/\omega$  gives rise to a Yanai or ‘mixed’ Rossby gravity wave with meridional velocity

$$v = \exp\left(i\left(\omega - \frac{1}{\omega}\right)x - \omega t\right)\psi_0(y). \quad (\text{A19})$$

1805 When the discriminant  $\omega^2 + 1/(4\omega^2) - (2m + 1) > 0$  and  $m \geq 1$ , both roots of (A18)  
 1806 are real and result in acceptable wave fields. But depending on the magnitude of  $\omega$ , these  
 1807 waves can belong to one of two categories: low-frequency Rossby waves for small  $\omega$ , or  
 1808 high-frequency inertia-gravity waves for large  $\omega$ .

1809 Equation (A18) expresses the wave number,  $k$ , in terms of the angular velocity,  $\omega$ .  
 1810 Alternatively, the angular velocity,  $\omega$ , corresponding to a particular wave number,  $k$ , can be  
 1811 determined by solving the non-linear equation

$$\mathcal{F}(\omega) \equiv \omega^3 - (k^2 + 2m + 1)\omega - k = 0, \quad (\text{A20})$$

1812 which is a variant of (A17). We use the Newton-Raphson method to solve (A20), and specify  
 1813 the magnitude of the initial guess for  $\omega$  to be close to zero for the low-frequency equatorial  
 1814 Rossby wave and greater than one for the high-frequency equatorial inertia-gravity wave.

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The non-dimensional zonal velocity and surface elevation are

$$u = \text{Re} \left( \frac{k \frac{d\psi_m}{dy} - \omega y \psi_m}{k^2 - \omega^2} i e^{i(kx - \omega t)} \right) = \frac{k \frac{d\psi_m}{dy} - \omega y \psi_m}{\omega^2 - k^2} \sin(kx - \omega t), \quad (\text{A21})$$

$$\eta = \text{Re} \left( \frac{\omega \frac{d\psi_m}{dy} - ky \psi_m}{k^2 - \omega^2} i e^{i(kx - \omega t)} \right) = \frac{\omega \frac{d\psi_m}{dy} - ky \psi_m}{\omega^2 - k^2} \sin(kx - \omega t). \quad (\text{A22})$$

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Figures A6 through A8 showcase the meridional velocity of the equatorial Yanai, Rossby, and inertia-gravity waves. As with previous demonstrations, we define the exact solutions for these equatorial waves as a combination of two wave components, wherein the second component possesses twice the amplitude and wavenumber of the first. Mathematically,  $\hat{\eta}^{(2)} = 2\hat{\eta}^{(1)}$  and  $k^{(2)} = 2k^{(1)}$ , where  $\hat{\eta}^{(1)} = 10^{-4}$  m,  $k^{(1)} = 2\pi/L_x$ , and  $L_x = 1.75 \times 10^7$  m. The first row of these figures portrays the equatorial wave across the entire domain, while the second row focuses on a segment of the resultant wave solution and its components along the latitude characterized by the peak magnitude of the Hermite function,  $\psi_m(y)$ . Due to the dispersive nature, these components propagate at different phase speeds causing the resultant wave profile to alter over time. For the equatorial Yanai wave (Figure A6) and inertia-gravity wave (Figure A8), we specify  $m = 0$  and  $m = 2$ , so that the Hermite functions  $\psi_0(y)$  and  $\psi_2(y)$  are even, and therefore the solution is symmetric across the equator. For the equatorial Rossby wave (Figure A7), we specify  $m = 1$ , so that the Hermite function  $\psi_1(y)$  is odd, and therefore the solution is antisymmetric across the equator. Moreover,  $\psi_0(y)$ ,  $\psi_1(y)$ , and  $\psi_2(y)$  attain their maximum magnitudes at  $y = 0$ ,  $y = \pm 1$ , and  $y = \pm \sqrt{2.5}$ . After multiplying by the length scale  $\sqrt{c/\beta_0}$ , and dividing by the radius of the Earth, these non-dimensional values of  $y$  correspond to the  $0^\circ$  latitude or the equator (second row of Figure A6), the  $20.11^\circ\text{N}$  and S latitudes (second row of Figure A7), and the  $31.80^\circ\text{N}$  and S latitudes (second row of Figure A8).

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### A3 Numerical Results

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We begin this section by addressing the time step limitations inherent to the numerical simulation of the diffusion, advection-diffusion and viscous Burgers' equations. The parabolic nature of these equations, resulting from the diffusion term, necessitates a more restrictive time step. Drawing from the Von Neumann stability analysis of the linear diffusion equation, we define the diffusive time step on a two-dimensional spatial domain as

$$\Delta t_{\text{diffusive}} = \begin{cases} \frac{1}{2\nu \left( \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right)} & \text{for TRiSK,} \\ \frac{1}{2\nu \left( \frac{P_x^2}{\Delta x^2} + \frac{P_y^2}{\Delta y^2} \right)} & \text{for DGSEM.} \end{cases} \quad (\text{A23})$$

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Here,  $\nu$  symbolizes the diffusion coefficient, while  $\Delta x$  and  $\Delta y$  represent the widths of the cell (or element). On a uniform TRiSK mesh with hexagonal cells, we can set  $\Delta y = \sqrt{3}/2\Delta x$ . In the context of DGSEM,  $P_x$  and  $P_y$  signify the polynomial orders in the two horizontal directions. Based on (59)–(61) in the main paper, we define the advective time step to be

$$\Delta t_{\text{advective}} = \begin{cases} \frac{C}{\frac{c_x}{\Delta x} + \frac{c_y}{\Delta y}} & \text{for TRiSK,} \\ \frac{C}{\frac{c_x P_x^2}{\Delta x} + \frac{c_y P_y^2}{\Delta y}} & \text{for DGSEM.} \end{cases} \quad (\text{A24})$$

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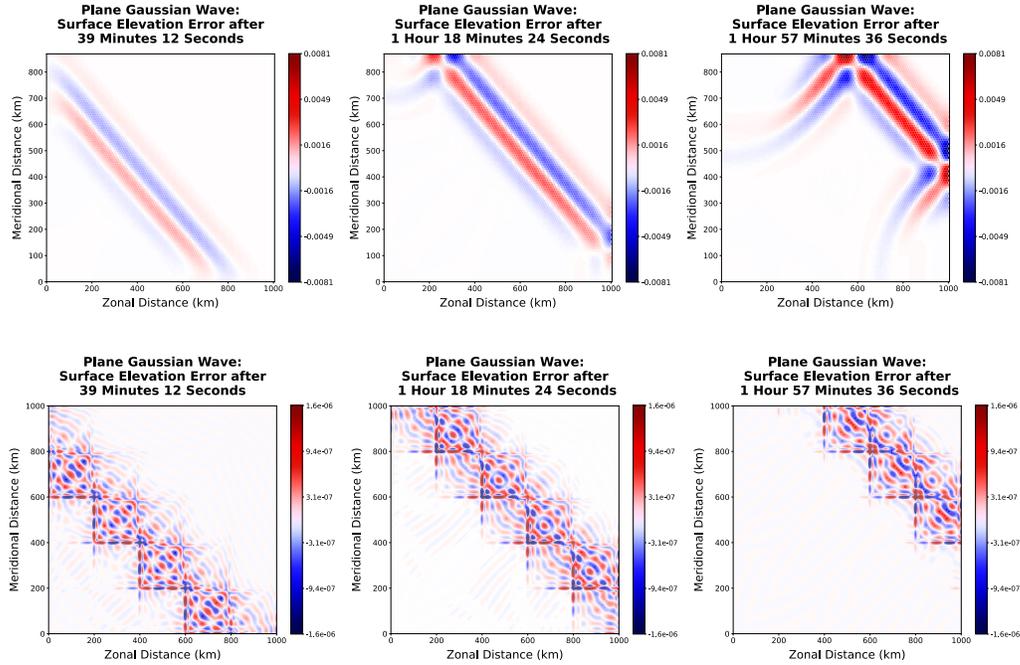
In the equations above,  $C$  represents the Courant number. For the advection-diffusion equation, we specify  $c_x = u_0$  and  $c_y = v_0$ . Similarly, for the viscous Burgers' equation, we set  $c_x = \max(|u_l|, |u_r|)$  and  $c_y = 0$ . The actual time step is specified as  $\Delta t = \Delta t_{\text{diffusive}}$  for

1848 the diffusion equation and  $\Delta t = \min(\Delta t_{\text{advective}}, \Delta t_{\text{diffusive}})$  for the advection-diffusion and  
 1849 viscous Burgers' equations.

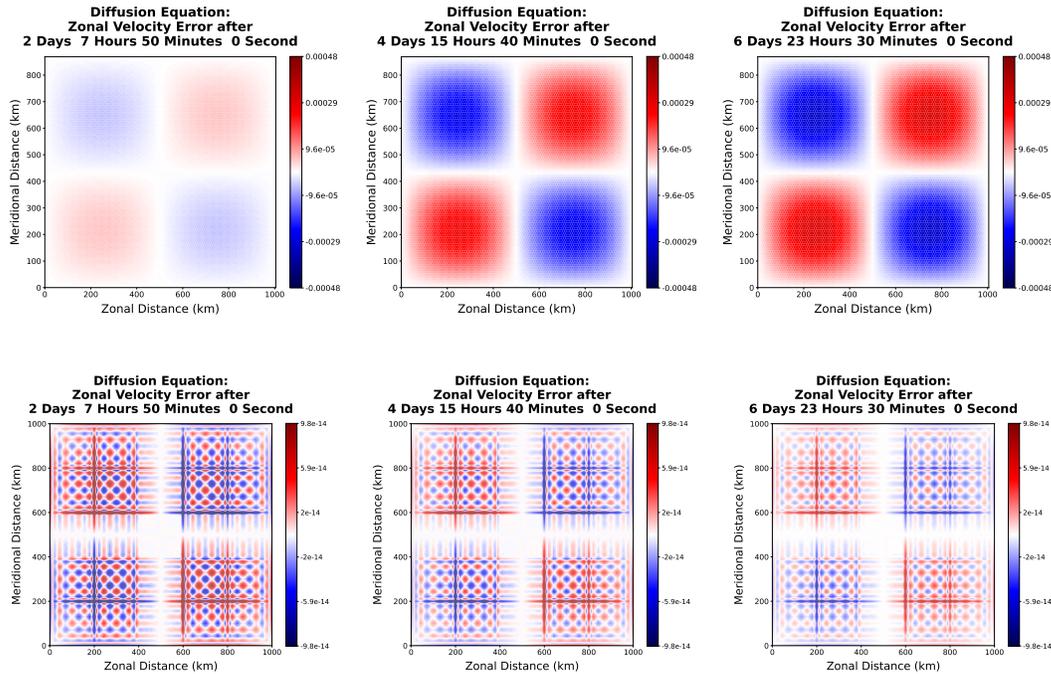
1850 We present the numerical results, showcasing error plots and their temporal evolution.  
 1851 Figures A9 to A12 display the surface elevation errors for the plane Gaussian wave, the  
 1852 diffusion and advection-diffusion equation solutions, and the zonal velocity error of the  
 1853 viscous Burgers shock wave. Subsequently, Figures A13 to A16 depict the temporal evolution  
 1854 of the surface elevation error of the equatorial Kelvin wave, as well as the meridional velocity  
 1855 error for equatorial Yanai, Rossby, and inertia-gravity waves. The zonal extent of the  
 1856 rectangular domain for each test case is specified as follows:  $L_x = 10^6$  m,  $10^6$  m, 2 m,  $10^6$  m,  
 1857 and  $1.75 \times 10^7$  m for the plane Gaussian wave, the diffusion equation, the advection-diffusion  
 1858 equation, the viscous Burgers' equation, and the equatorial waves respectively. As for the  
 1859 meridional extent, it is defined by  $L_y = \sqrt{3}/2L_x$  for TRiSK, and by  $L_y = L_x$  for DGSEM. In  
 1860 each horizontal direction, the planar hexagonal TRiSK mesh comprises  $N = 100$  cells, and  
 1861 the spectral element mesh consists of  $N = 5$  elements. The distance between the hexagonal  
 1862 cell centers of the TRiSK mesh, given by  $\Delta x = L_x/N$ , represents the zonal cell width,  
 1863 and  $\Delta y = \sqrt{3}/2\Delta x$  provides a measure for the meridional cell width. Meanwhile, for the  
 1864 spectral element mesh, the side lengths are equal in both directions:  $\Delta x = L_x/N$ . The  
 1865 smallest grid spacings near the element boundaries approximate to  $\Delta x/P^2$ , with  $P = 10$   
 1866 indicating the order of the polynomial basis functions and the spatial order of accuracy of  
 1867 our DGSEM. For all test cases, we target an advective Courant number close to 0.5. For  
 1868 the diffusion equation, we choose the diffusive time step, and for the advection-diffusion  
 1869 and viscous Burgers test cases, we select the minimum between the advective and diffusive  
 1870 time steps, as elaborated in the preceding paragraph. When modeled with TRiSK, this  
 1871 leads to time step sizes of  $\Delta t = 16$  s, 750 s,  $5 \times 10^{-3}$  s, 750 s, 900 s, 450 s, 1200 s, and  
 1872 300 s for the plane Gaussian wave, the diffusion equation, the advection-diffusion equation,  
 1873 the viscous Burgers' equation, and the equatorial Kelvin, Yanai, Rossby, and inertia-gravity  
 1874 waves respectively. With DGSEM, the respective time steps for these cases are set at 3.5 s,  
 1875 40 s,  $4 \times 10^{-4}$  s, 30 s, 180 s, 90 s, 240 s, and 60 s.

1876 The first row of Figures A9—A16 demonstrates the error yielded by the second-order  
 1877 accurate TRiSK-based finite volume method. In contrast, the second row illustrates the  
 1878 error from the 10<sup>th</sup>-order accurate DGSEM. As anticipated, the TRiSK error is a few orders  
 1879 of magnitude smaller, and the DGSEM error is several orders of magnitude smaller than the  
 1880 solution magnitude. As observed in our main paper's test case simulations, the error plots  
 1881 resonate with the intrinsic physics of the system. For example, the error associated with  
 1882 the plane wave propagates at the same phase speed as the solution, mirroring the speed of  
 1883 a shallow water gravity wave. In the TRiSK-based mimetic finite volume method, spurious  
 1884 reflections observed at domain boundaries are likely due to the implementation of Dirichlet  
 1885 boundary conditions that do not fully capture the characteristics of the incoming wave.  
 1886 The method involves updating the normal velocities at the boundary edges of the hexagonal  
 1887 mesh using exact solution values, whereas the normal velocities at the interior edges and the  
 1888 surface elevation at cell centers are updated prognostically through numerical gradient and  
 1889 divergence and formulations respectively. However, without direct boundary constraints on  
 1890 surface elevation, discrepancies can arise during wave-boundary interactions. In contrast,  
 1891 DGSEM updates zonal and meridional velocities as well as surface elevation at the interior  
 1892 Gauss quadrature points of each element, with tendencies computed from both interior fluxes  
 1893 at the quadrature points and numerical fluxes at the element's edges. Moreover, DGSEM  
 1894 applies the exact solution as the external state at boundary edges, offering a more accurate  
 1895 wave representation and minimizing reflections, aided by the dissipative properties of the  
 1896 LLF Riemann solver at these edges. This distinction in boundary treatment between the  
 1897 methods helps explain the observed differences in wave reflection.

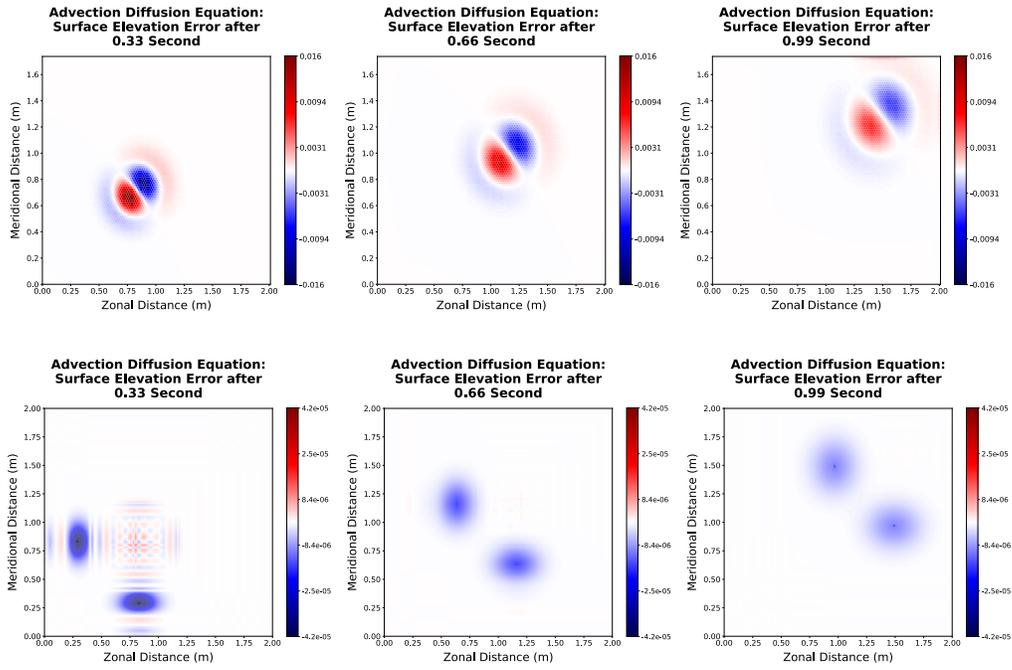
1898 Given that the error magnitude is contingent on the exact solution and its gradients,  
 1899 pronounced errors in regions characterized by high spatial gradients are unsurprising. This  
 1900 is most prominent for the plane Gaussian wave error (both TRiSK and DGSEM), and the



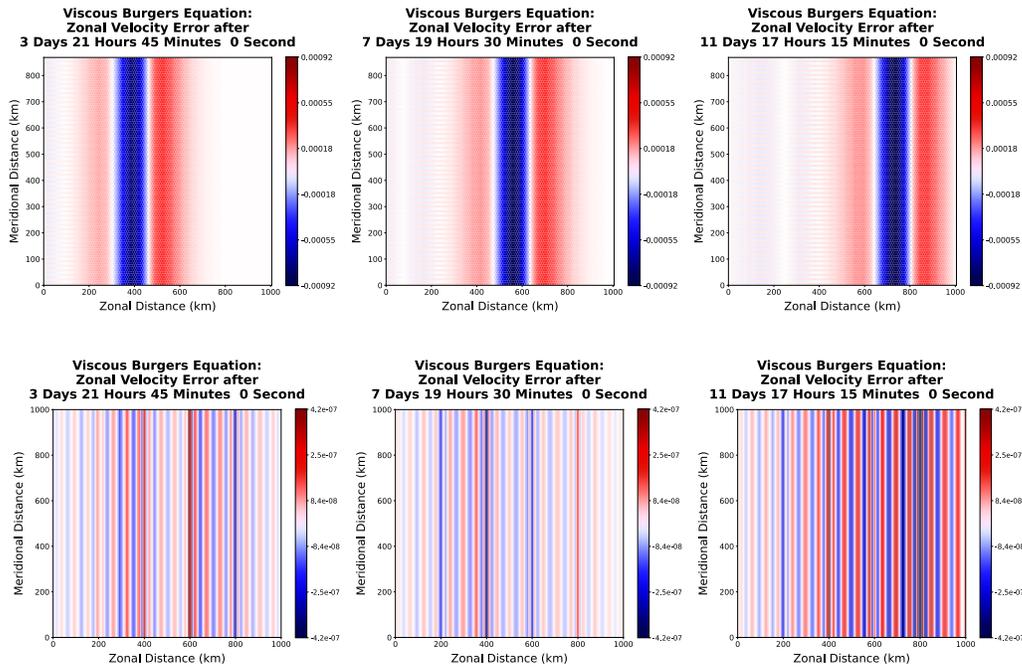
**Figure A9.** Time evolution of the surface elevation error of TC7, the plane Gaussian wave, spatially discretized with the TRiSK-based mimetic finite volume method (first row), and DGSEM using 5 elements and polynomial basis functions of order 10 in each horizontal direction (second row).



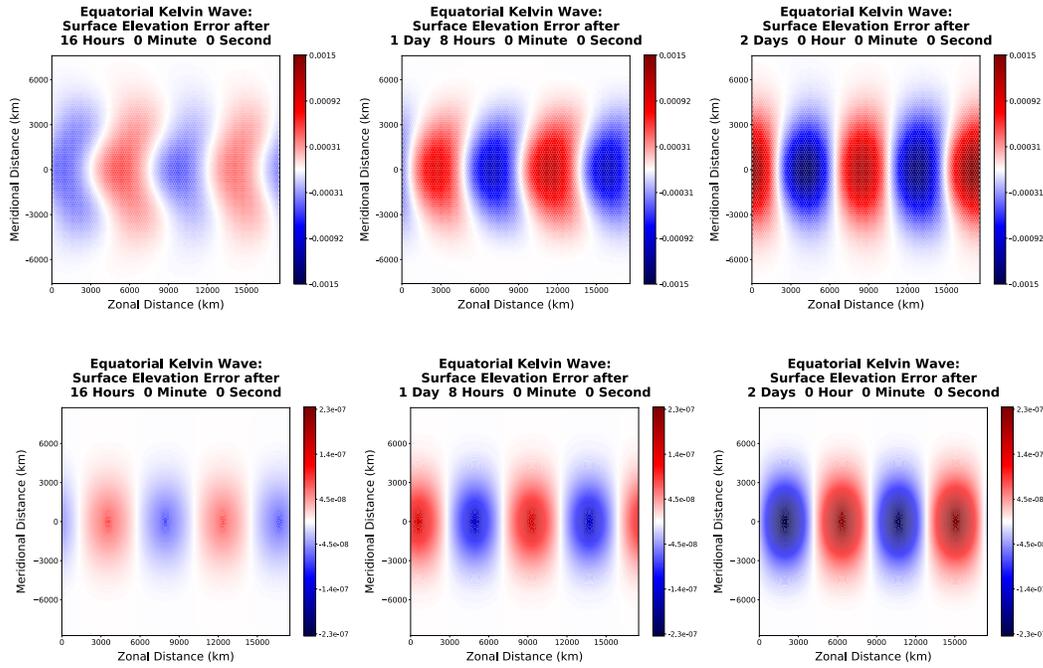
**Figure A10.** Same as Figure A9 but for TC8, the diffusion equation, showing error for TRiSK (first row) and DGSEM (second row).



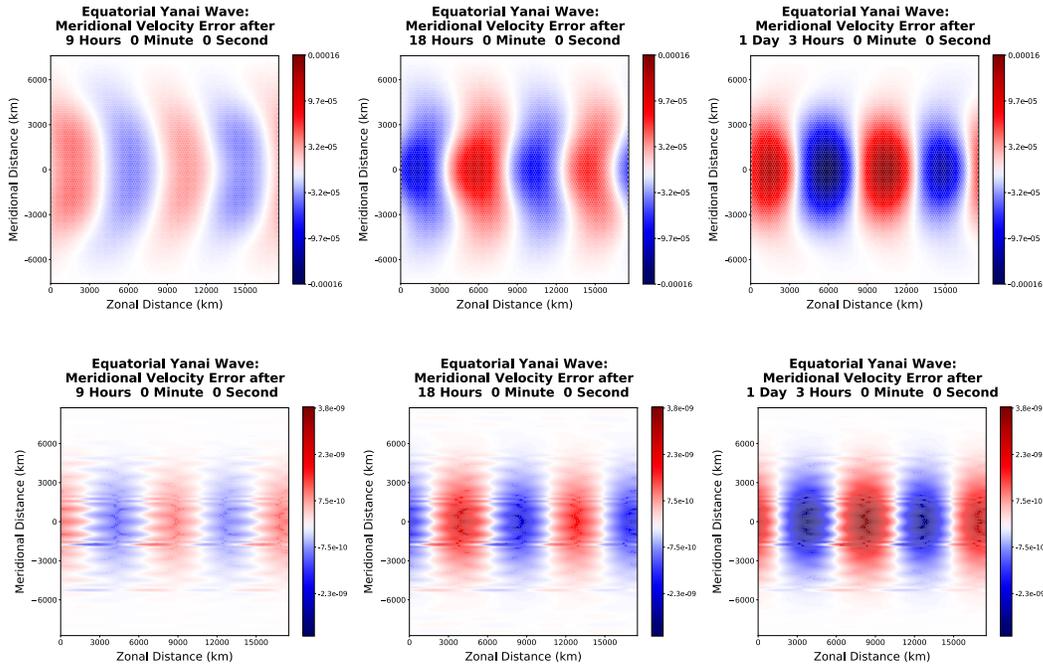
**Figure A11.** Same as Figure A9 but for TC9, the advection-diffusion equation, showing error for TRiSK (first row) and DGSEM (second row).



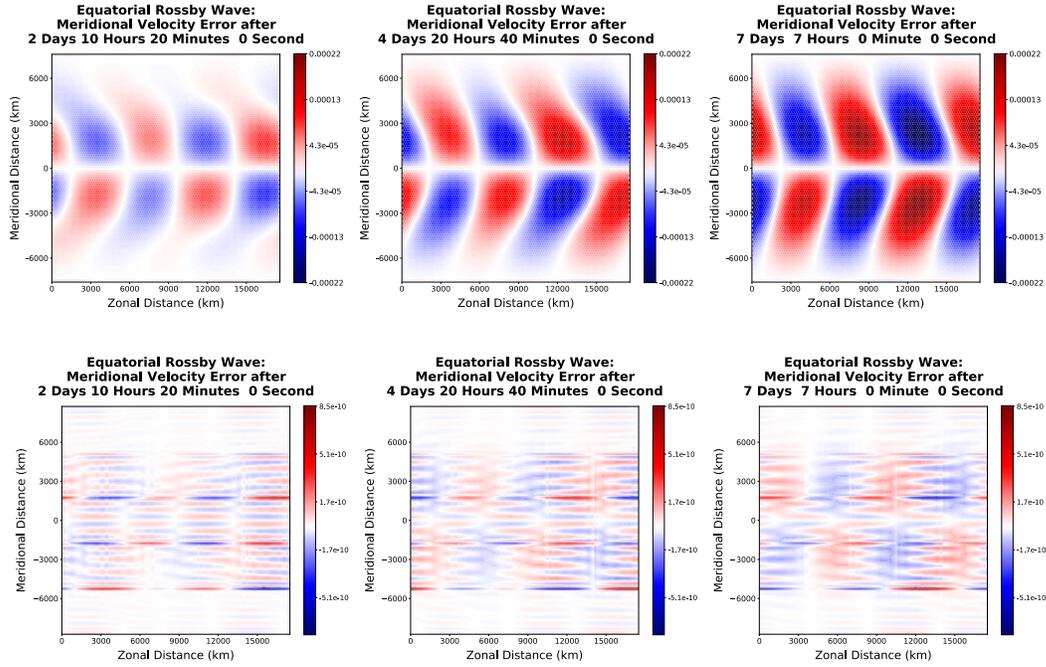
**Figure A12.** Same as Figure A9 but for TC10, the viscous Burgers shock wave, showing error for TRiSK (first row) and DGSEM (second row).



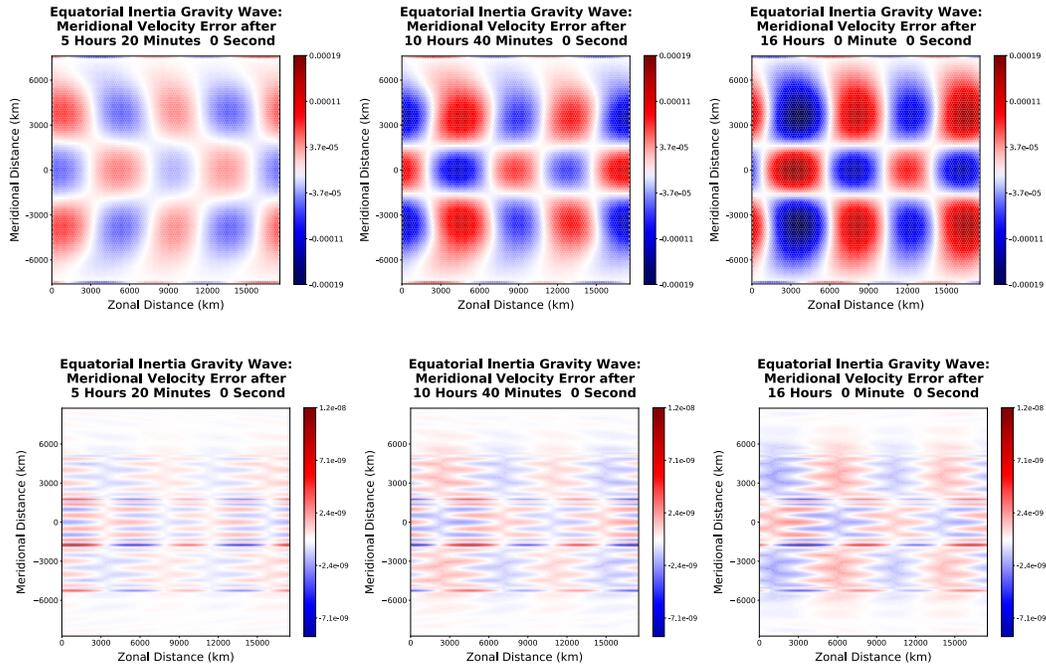
**Figure A13.** Time evolution of the surface elevation error of TC11, the non-dispersive equatorial Kelvin wave, spatially discretized with TRiSK (first row) and DGSEM (second row).



**Figure A14.** Same as Figure A13 but for TC12, the dispersive equatorial Yanai wave, showing the meridional velocity error for TRiSK (first row) and DGSEM (second row).



**Figure A15.** Same as Figure A13 but for TC13, the dispersive equatorial Rossby wave, showing the meridional velocity error for TRiSK (first row) and DGSEM (second row).



**Figure A16.** Same as Figure A13 but for TC14, the dispersive equatorial inertia-gravity wave, showing the meridional velocity error for TRiSK (first row) and DGSEM (second row).

1901 TRiSK error for the diffusion, advection-diffusion, and viscous Burgers' equations. The  
 1902 DGSEM errors manifest in various forms, including numerical dispersion and dissipation,  
 1903 and spurious oscillations (Section 5). The setup for the viscous Burgers' equation amplifies  
 1904 the numerical dispersion and spurious oscillations (Figure A12), especially when compared to  
 1905 linear test cases like the barotropic tide. The dispersive errors traverse element boundaries  
 1906 and exit the domain at velocities surpassing that of the shock wave. For the equatorial  
 1907 Kelvin, Yanai, Rossby, and inertia-gravity waves, the inherent dissipation of the mimetic  
 1908 TRiSK scheme largely curtails the dispersive error prevalent in the DGSEM error. We  
 1909 again encourage interested readers to access low  $p$ - and  $h$ -resolution DGSEM solution plots  
 1910 from Bishnu (2024a), which reveal increased numerical dispersion and dissipation, although  
 1911 spurious oscillations are not as prevalent. This observation is attributed to the deployment  
 1912 of the LLF Riemann solver, whose primary function is to suppress such oscillations at the  
 1913 edges of spectral elements. However, this solver introduces its own dissipative error, which  
 1914 becomes more noticeable in coarser meshes where fewer elements are available to absorb it,  
 1915 leading to visibly enhanced errors at element boundaries. Despite not affecting the spatial  
 1916 order of accuracy (Section 5.1), the global pattern of this dissipative error unveils the element  
 1917 boundaries, revealing the spectral elements' positions in the mesh. This, in conjunction with  
 1918 the linear scaling of the color bars, rendering any error of magnitude lower than the dominant  
 1919 error nearly invisible, can create the impression of mesh effects in the plots (Figures A9  
 1920 and A10). Numerical dispersion is accentuated in the coarser meshes due to less accurate  
 1921 representation of the physical phenomena at a given scale. For instance, the equatorial  
 1922 Kelvin wave, akin to its coastal counterpart, exhibits no physical dispersion. However,  
 1923 when simulated with less than three elements and third-order polynomial basis functions  
 1924 in each horizontal direction, numerical dispersion significantly alters the phase speed across  
 1925 varying wavelengths, which in turn, distort the shape of these physically non-dispersive  
 1926 Kelvin waves as the simulation unfolds.

## 1927 **Appendix B Problem of Multiple Time Scales and Barotropic-Baroclinic** 1928 **Splitting in Ocean Models**

1929 In this section, we highlight the applicability of shallow water test cases within the  
 1930 context of baroclinic-barotropic splitting in an ocean model. We initiate our discussion with  
 1931 the challenge of multiple time scales inherent in ocean models, elucidating how the splitting  
 1932 approach can effectively address this complication and boost computational efficiency. As  
 1933 a practical example of the splitting procedure, we derive the barotropic and baroclinic  
 1934 equations from the governing equations of MPAS-Ocean. We then demonstrate that the  
 1935 barotropic equations assume the form of inhomogeneous rotating shallow water equations.

1936 Numerical ocean circulation models typically admit motions varying on a wide range  
 1937 of time scales. For instance, the fast external gravity waves, approximately independent of  
 1938 depth, propagate at a speed of  $\mathcal{O}(100 \text{ ms}^{-1})$ . On the other hand, the major current systems  
 1939 and internal gravity waves exhibit velocities of  $\mathcal{O}(1 \text{ ms}^{-1})$  i.e. two orders of magnitude less.  
 1940 This vast disparity of time scales imposes a tremendous constraint on numerically modelling  
 1941 oceanic phenomena. For explicit time-stepping methods, the CFL condition states that, for  
 1942 a given Courant number, the maximum permissible time step of a hyperbolic system should  
 1943 be inversely proportional to the wave speed to attain a numerically stable solution (see,  
 1944 e.g. Griffies et al. (2005, Section 12.8). Therefore, the presence of external gravity waves  
 1945 forces the time step to be much smaller than what is required to resolve the internal gravity  
 1946 waves. Solving the full three-dimensional momentum equations with the smallest time  
 1947 step dictated by the CFL condition of the fastest waves is computationally impractical, as  
 1948 running a global simulation at high resolution (10 km grid cells or smaller) would require  
 1949 time steps on the order of minutes. While restrictions of the time step size can be addressed  
 1950 by using an implicit method, this would require solving a system of non-linear equations at  
 1951 every time step thereby compensating for the reduction in computational time achieved by  
 1952 increasing the time step size. A traditional alternative is to split the governing equations

1953 into two subsystems: a barotropic one for solving the fast depth independent motions and  
 1954 a baroclinic one for solving the much slower depth dependent motions, as described in  
 1955 Griffies et al. (2005); T. Ringler et al. (2013). Being independent of the vertical coordinate,  
 1956 the fast barotropic subsystem is two-dimensional and the computational cost involved in  
 1957 solving it, either explicitly using a small time step or implicitly using a large time step, is  
 1958 drastically reduced. The full three-dimensional baroclinic subsystem modeling the slower  
 1959 internal motions is solved explicitly using a much larger time step. Finally, if the baroclinic  
 1960 variables are advanced explicitly using a small time step, a time-averaging filter is applied  
 1961 over the barotropic solutions to minimize mode-splitting and aliasing errors (Shchepetkin  
 1962 & McWilliams, 2005). The resulting time-averaged barotropic solutions are then reconciled  
 1963 with their baroclinic counterparts to arrive at the total 3D states.

1964 As an illustrative example, we briefly discuss the barotropic-baroclinic splitting in  
 1965 MPAS-Ocean. The MPAS-Ocean  $z$ -level formulation solves the following equations for  
 1966 thickness, momentum, and tracers at layer  $k$ :

$$\frac{\partial h_k}{\partial t} + \nabla \cdot (h_k^{edge} \mathbf{u}_k) + \frac{\partial}{\partial z} (h_k w_k) = 0, \quad (B1)$$

$$\begin{aligned} \frac{\partial \mathbf{u}_k}{\partial t} + \frac{1}{2} \nabla |\mathbf{u}_k|^2 + (\mathbf{k} \cdot \nabla \times \mathbf{u}_k) \mathbf{u}_k^\perp + f \mathbf{u}_k^\perp + w_k^{edge} \frac{\partial \mathbf{u}_k}{\partial z} = & -\frac{1}{\rho_0} \nabla p_k + \nu_h \nabla^2 \mathbf{u}_k \\ & + \frac{\partial}{\partial z} \left( \nu_v \frac{\partial \mathbf{u}_k}{\partial z} \right), \end{aligned} \quad (B2)$$

$$\begin{aligned} \frac{\partial h_k \varphi_k}{\partial t} + \nabla \cdot (h_k^{edge} \varphi_k^{edge} \mathbf{u}_k) + \frac{\partial}{\partial z} (h_k \varphi_k w_k) = & \nabla \cdot (h_k^{edge} \kappa_h \nabla \varphi_k) \\ & + h_k \frac{\partial}{\partial z} \left( \kappa_v \frac{\partial \varphi_k}{\partial z} \right). \end{aligned} \quad (B3)$$

1967 The layer thickness  $h$ , vertical velocity  $w$ , pressure  $p$ , and tracer  $\varphi$ , are scalar quantities  
 1968 defined at the center of near-hexagonal cells of the primal MPAS-Ocean mesh. The horizontal  
 1969 velocity vector  $\mathbf{u}$  and the variables with *edge* superscript are defined at the edges of the  
 1970 cells. The gradient, divergence and curl operators are all defined on the horizontal plane.  
 1971 The barotropic and baroclinic velocities are

$$\bar{\mathbf{u}} = \frac{\sum_{k=1}^{N^{edge}} h_k^{edge} \mathbf{u}_k}{\sum_{k=1}^{N^{edge}} h_k^{edge}}, \quad (B4)$$

$$\mathbf{u}'_k = \mathbf{u}_k - \bar{\mathbf{u}}, \quad k = 1, 2, \dots, N. \quad (B5)$$

1972 If  $H$  is the mean depth in the absence of bottom topography,  $h_b(x, y)$  is the topographic  
 1973 height at  $(x, y)$ , and  $\eta$  is the surface elevation or the sea surface height (SSH),

$$\eta = \sum_{k=1}^{N^{edge}} h_k - \{H - h_b(x, y)\}. \quad (B6)$$

1974 Summing over all layers results in the barotropic surface elevation equation

$$\frac{\partial \eta}{\partial t} + \nabla \cdot \left( \bar{\mathbf{u}} \sum_{k=1}^{N^{edge}} h_k^{edge} \right) \equiv \frac{\partial \eta}{\partial t} + \nabla \cdot [\bar{\mathbf{u}} \{\eta + H - h_b(x, y)\}] = 0, \quad (B7)$$

1975 using the boundary conditions  $w_{\frac{1}{2}} = w_{N+\frac{1}{2}} = 0$ . Defining

$$\begin{aligned} \mathbf{T}(\mathbf{u}_k, w_k, p_k) = & -\frac{1}{2} \nabla |\mathbf{u}_k|^2 - (\mathbf{k} \cdot \nabla \times \mathbf{u}_k) \mathbf{u}_k^\perp - w_k^{edge} \frac{\partial \mathbf{u}_k}{\partial z} \\ & - \frac{1}{\rho_0} \nabla p_k + \nu_h \nabla^2 \mathbf{u}_k + \frac{\partial}{\partial z} \left( \nu_v \frac{\partial \mathbf{u}_k}{\partial z} \right), \end{aligned} \quad (B8)$$

1976 (B2) can be written in the more compact form

$$\frac{\partial \mathbf{u}_k}{\partial t} + f \mathbf{u}_k^\perp = \mathbf{T}(\mathbf{u}_k, w_k, p_k). \quad (\text{B9})$$

1977 Extracting the barotropic component of (B9),

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + f \bar{\mathbf{u}}^\perp = \bar{\mathbf{T}}(\mathbf{u}_k, w_k, p_k) \equiv -g \nabla \eta + \bar{\mathbf{G}}, \quad (\text{B10})$$

1978 where  $\bar{\mathbf{T}}$  is the barotropic average of  $\mathbf{T}_k = \mathbf{T}(\mathbf{u}_k, w_k, p_k)$  over all layers computed similar  
 1979 to  $\bar{\mathbf{u}}$  with  $\mathbf{u}_k$  replaced by  $\mathbf{T}_k$  in (B4), and  $\bar{\mathbf{G}}$  is defined as  $\bar{\mathbf{G}} = \bar{\mathbf{T}}(\mathbf{u}_k, w_k, p_k) + g \nabla \eta$ .  
 1980 Subtracting the barotropic equation (B10) from the total momentum equation (B9), we  
 1981 obtain the baroclinic momentum equation

$$\frac{\partial \mathbf{u}'_k}{\partial t} + f \mathbf{u}'_k{}^\perp = \mathbf{T}(\mathbf{u}_k, w_k, p_k) + g \nabla \eta - \bar{\mathbf{G}}. \quad (\text{B11})$$

1982 It is evident that the barotropic equations (B7) and (B10) exhibit a resemblance to  
 1983 the inviscid inhomogeneous rotating shallow water equations. However, this similarity is  
 1984 marked by two key differences: the omission of the non-linear advection term and the  
 1985 incorporation of a source term  $\bar{\mathbf{G}}$  within the barotropic momentum equation. This latter  
 1986 term,  $\bar{\mathbf{G}}$ , represents the barotropic average of  $\mathbf{T}(\mathbf{u}_k, w_k, p_k) + g \nabla \eta$ . The splitting procedure  
 1987 and the split equations may vary slightly among different ocean models. One variation, as  
 1988 observed in Blumberg and Mellor (1987), is to extract the diffusion of the barotropic velocity  
 1989 out of the  $\bar{\mathbf{G}}$  term so that the barotropic momentum equation becomes equivalent to the  
 1990 viscous inhomogeneous linear rotating shallow water momentum equation

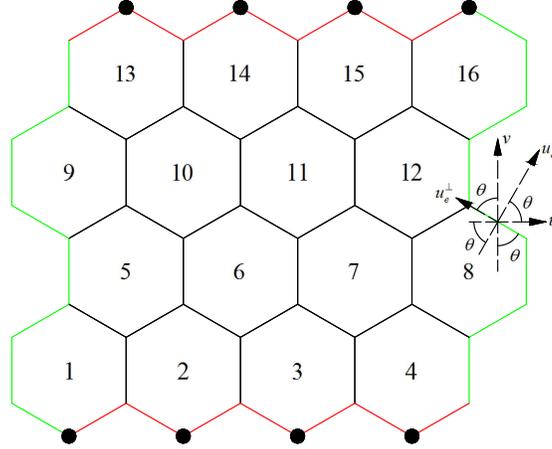
$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + f \bar{\mathbf{u}}^\perp = -g \nabla \eta + \nu_h \nabla^2 \bar{\mathbf{u}} + \bar{\mathbf{G}}. \quad (\text{B12})$$

## 1991 Appendix C Details of Numerical Implementation

1992 In this section, we discuss subtle details in the numerical implementation of the shallow  
 1993 water equations. Constructing the initial-boundary value problem to numerically obtain  
 1994 the solution of the various test cases necessitates careful attention, particularly in ensuring  
 1995 that the initial and boundary conditions are correctly applied on hexagonal meshes, and the  
 1996 source terms for the manufactured solutions are exact. We will methodically tackle these  
 1997 aspects, using a uniform MPAS-Ocean mesh with hexagonal primal cells and triangular  
 1998 dual cells as a case study. The discussion culminates with addressing the crucial process  
 1999 of interpolating the numerical solution or the error to the coarsest spatial mesh, before  
 2000 calculating the error norm, for refinement only in space.

### 2001 C1 Specifying Initial and Boundary Conditions on Hexagonal Meshes

2002 For MPAS-Ocean, the prognostic variables are the surface elevations defined at the  
 2003 centers of the primal cells and the normal velocities defined at the primal cell edges. The  
 2004 spatial discretization of MPAS-Ocean based on the TRiSK scheme belongs to the category of  
 2005 finite volume methods, which study the time evolution of cell- and edge-averaged quantities  
 2006 in two dimensions, as opposed to the cell- and edge-centered ones. So, for a test case, it is  
 2007 imperative to adopt an averaging procedure to determine the mean values of the prognostic  
 2008 variables within every cell and edge. Since the cell-averaged quantity is the cell-integrated  
 2009 quantity divided by the cell area, we need to first integrate the quantity over the area  
 2010 spanned by a hexagonal cell. If the quantity consists of a complex combination of polynomial,  
 2011 trigonometric, and exponential functions, performing the integration analytically may be a  
 2012 Herculean task if not impossible. So, we resort to numerical quadrature, which may not  
 2013 be exact but is definitely more accurate than the value at the cell center times the area of  
 2014 the cell. Rules for evaluating numerical quadrature on regular hexagons first appeared in



**Figure C1.** A  $4 \times 4$  MPAS-Ocean mesh with non-periodic zonal and periodic meridional boundaries, showing the components of zonal and meridional velocities normal and tangential to an edge.

2015 Stroud (1971) followed by Lyness and Monegato (1977). In all test cases, we employ Lyness’  
 2016 rule for integrating any scalar quantity over the hexagonal MPAS-Ocean cells. For exact  
 2017 evaluation of the integral of polynomials upto degree 15 over the unit hexagon inscribed  
 2018 within the unit circle centered at the origin, Table A.1 in Lyness and Monegato (1977) lists  
 2019 the number of quadrature points, their coordinates, and weights.

2020 We use the Gauss-Legendre quadrature method to specify the edge-averaged normal  
 2021 velocity at the midpoint of

- 2022 (a) every edge for the initial condition,
- 2023 (b) every edge along a non-periodic boundary for the boundary condition.

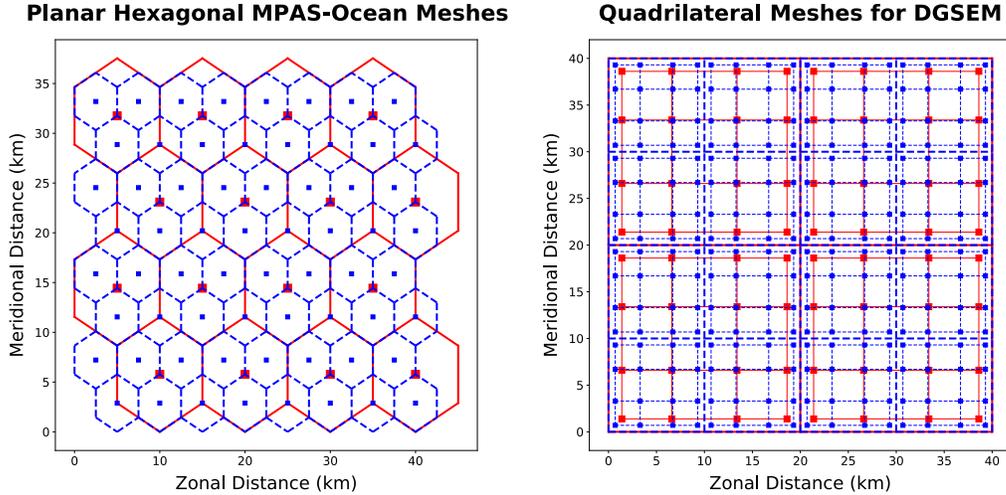
2024 Figure C1 is a schematic of a  $4 \times 4$  MPAS-Ocean mesh with periodic zonal and  
 2025 non-periodic meridional boundaries. It also shows the resolution of the zonal and meridional  
 2026 velocities in the normal and tangential directions of a non-periodic boundary edge. Since  
 2027 the prognostic variables include only the normal and not the tangential velocity, we do  
 2028 not lose any generality by conducting a test case with zero zonal velocity (e.g. the Coastal  
 2029 Kelvin wave) or one with zero meridional velocity (e.g. the non-linear manufactured solution)  
 2030 since the normal velocity on these hexagonal MPAS-Ocean meshes will, in general, remain  
 2031 non-zero in either case.

## 2032 C2 Specifying Source Terms for Manufactured Solutions

2033 The non-linear manufactured solution (38) satisfies inhomogeneous non-linear rotating  
 2034 inviscid shallow water equations (38) on a flat bottom. The source terms (40) are obtained by  
 2035 inserting the manufactured solution and its spatial and temporal gradients into the left-hand  
 2036 side of these equations. On a hexagonal MPAS-Ocean mesh, the source term for the normal  
 2037 velocity on an edge, where the normal makes an angle  $\theta$  with the positive direction of the  
 2038  $x$ -axis is

$$s^{u^n} = s^u \cos \theta + s^v \sin \theta. \quad (C1)$$

2039 The cell-averaged source term for the surface elevation and the edge-averaged one for the  
 2040 normal velocity can be obtained by following the same procedure outlined in Section C1 for  
 2041 computing the cell-averaged surface elevation and the edge-averaged normal velocity.



**Figure C2.** (a) A planar hexagonal MPAS-Ocean mesh consisting of 8 cells of width 5 km in each horizontal direction (in blue), superimposed on a coarser mesh consisting of 4 cells of width 10 km in each direction (in red) on the left. (b) A discontinuous Galerkin spectral element mesh (DGSEMesh) consisting of 4 elements of width 10 km and polynomial basis functions of order 4 in each horizontal direction (in blue) superimposed on a coarser mesh consisting of 2 elements of width 20 km and the same polynomial order in each direction (in red) on the right.

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### C3 Interpolation to the Coarsest Mesh

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As a final note, for refinement only in space, we need to interpolate the numerical solution (or the error) to the coarsest mesh before taking the difference in the numerical solution (or the error) for successive spatial resolutions and computing its norm. Figure C2 illustrates (a) a planar hexagonal MPAS-Ocean mesh consisting of 8 cells of width 5 km in each horizontal direction (in blue), superimposed on a coarser mesh consisting of 4 cells of width 10 km in each direction (in red); and (b) a discontinuous Galerkin spectral element mesh (DGSEMesh) consisting of 4 elements of width 10 km and polynomial basis functions of order 4 in each horizontal direction (in blue) superimposed on a coarser mesh consisting of 2 elements of width 20 km and the same polynomial order in each direction (in red). The cell centers of the MPAS-Ocean meshes and the quadrature nodes within each element of the DGSEMeshes are represented by square markers. In Figure C2(a), the numerical solution (or the error) on the finer mesh is interpolated to the coarser mesh with a bilinear interpolant (Vetterling & Press, 1992). In Figure C2(b), a Newton-Raphson method is used to determine the physical coordinates of the quadrature nodes of the coarser mesh with respect to the computational coordinates of the quadrature nodes of the finer mesh. Then, the polynomial representation of the solution (or the error) on the finer mesh is evaluated at these physical coordinates.

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### Open Research Section

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The model code and visualization scripts may be accessed from the GitHub repository at [https://github.com/siddharthabishnu/Rotating\\_Shallow\\_Water\\_Verification\\_Suite/tree/v1.2.5](https://github.com/siddharthabishnu/Rotating_Shallow_Water_Verification_Suite/tree/v1.2.5), and may also be downloaded from the Zenodo release (Bishnu, 2024a) at <https://doi.org/10.5281/zenodo.10460245>. The mesh files (Bishnu, 2023) used for initialization, may be obtained from <https://doi.org/10.5281/zenodo.10161055>, and

2066 the output files (Bishnu, 2024b) including the solution, error and convergence plots, may be  
2067 downloaded from <https://doi.org/10.5281/zenodo.10460252>.

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