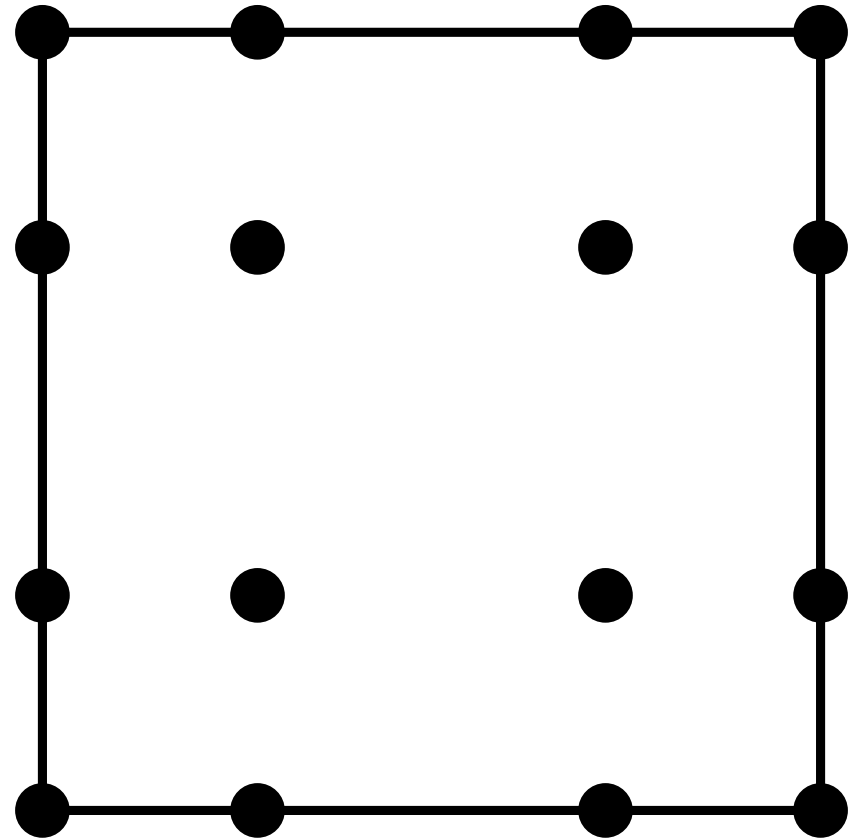


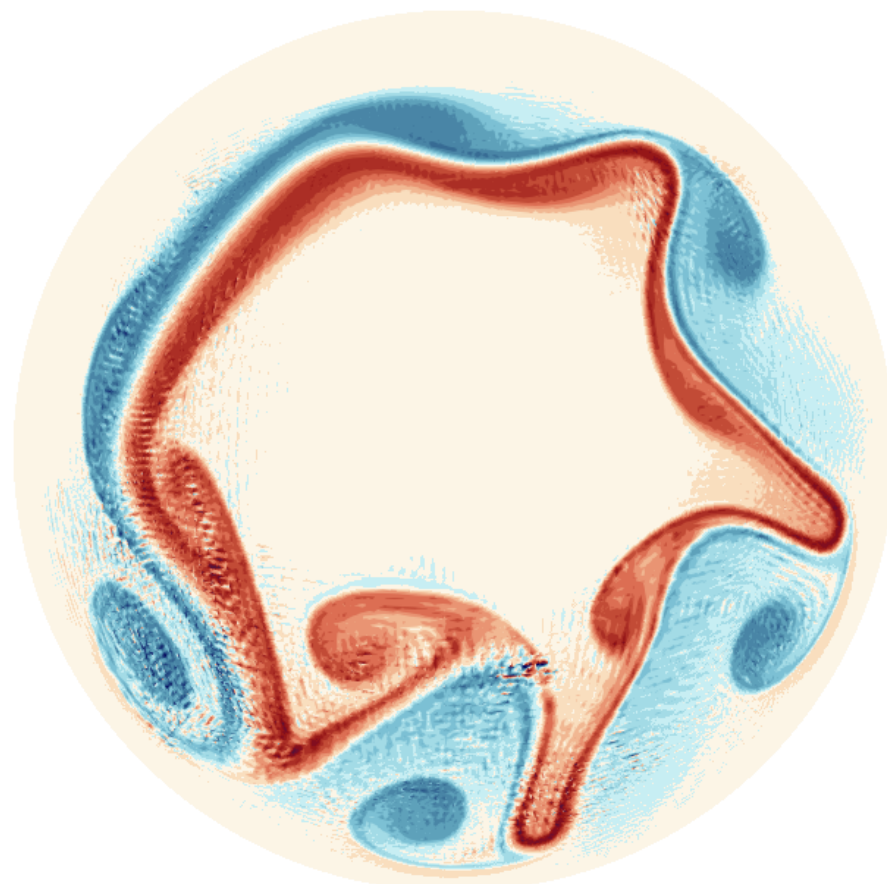
Unstructured quadrilateral grid on curved manifold



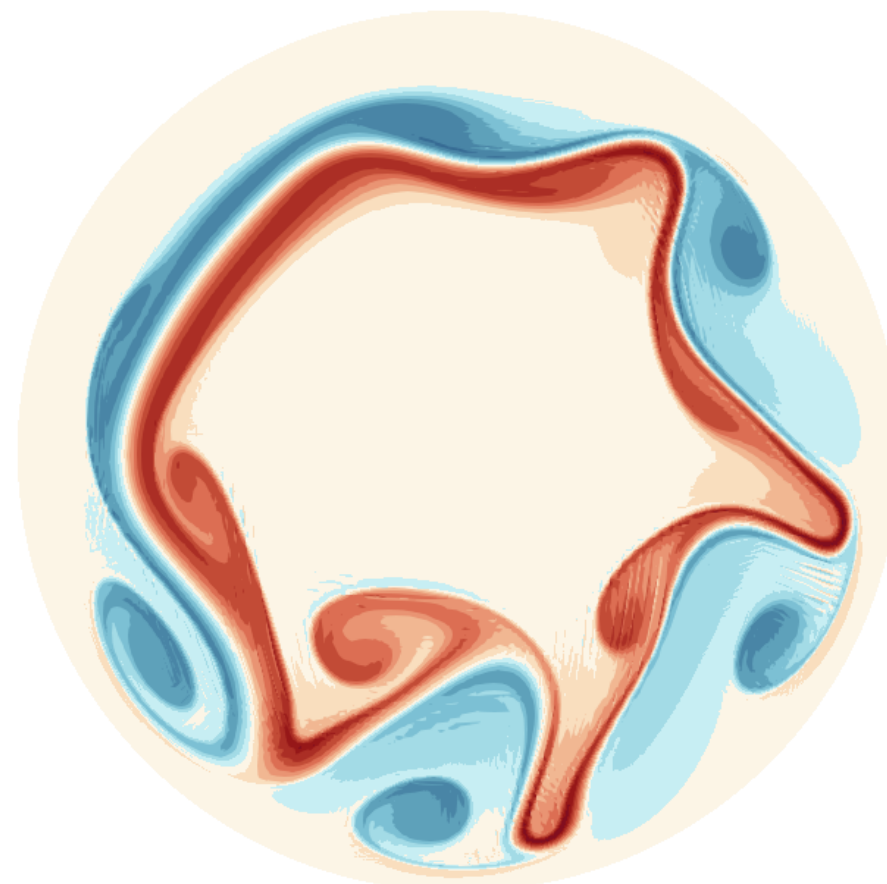
Tensor-product summation-by-parts operators on collocated Legendre–Gauss–Lobatto quadrature

$$\begin{aligned} \nabla_j \tau^{ij} = & \frac{1}{2J} \left(\partial_j (J h v^i v^j) + v^i \partial_j (J h v^j) + G^{ik} J h v^j \partial_j v_k \right) \\ & + g G^{ij} h \partial_j h + \frac{1}{2} \left(\Gamma_{jk}^i h v^j v^k - G^{ik} \Gamma_{jk}^l h v^j v_l \right) \end{aligned}$$

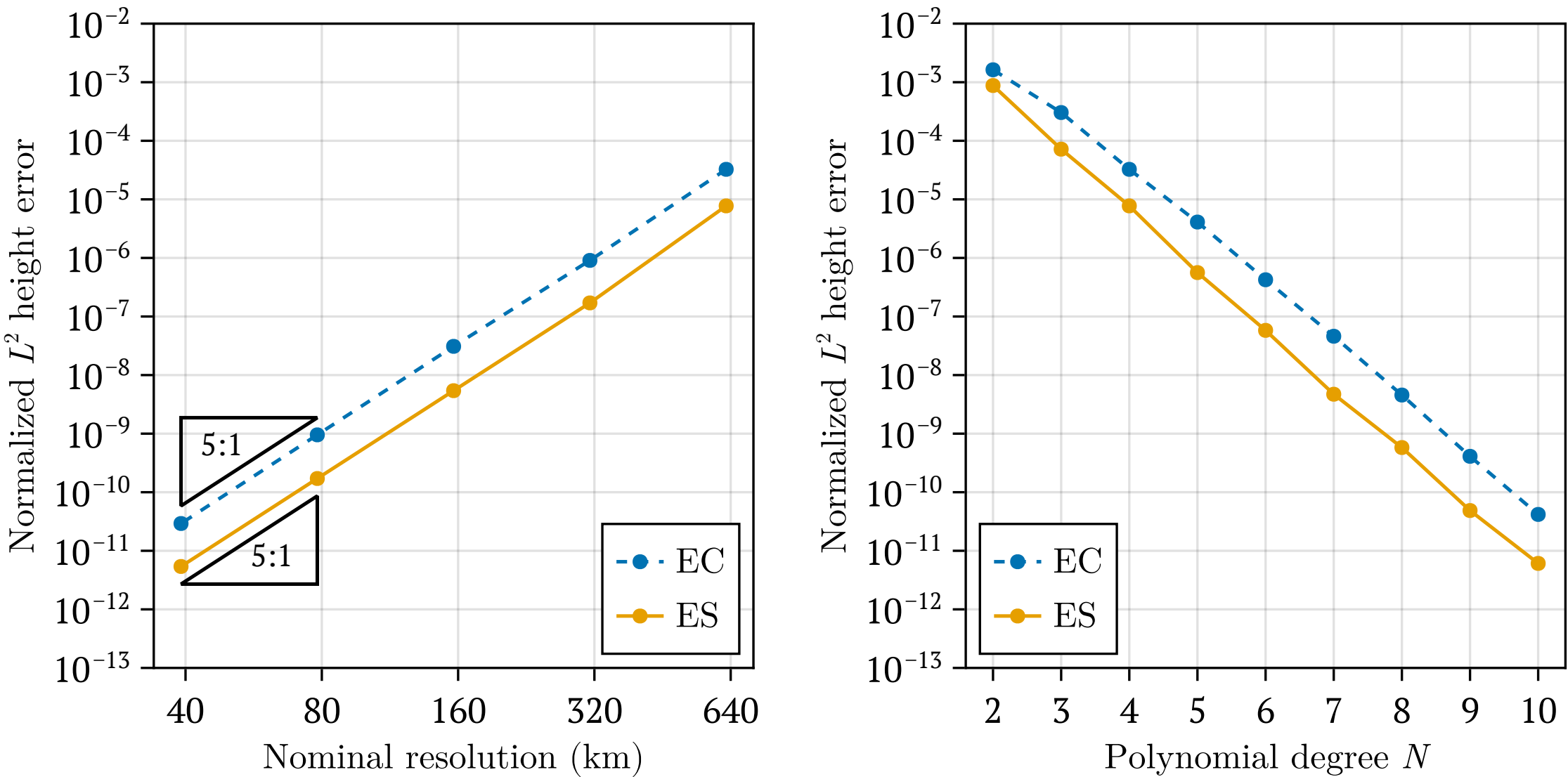
Covariant divergence in skew-symmetric form conserves total energy (mathematical entropy)



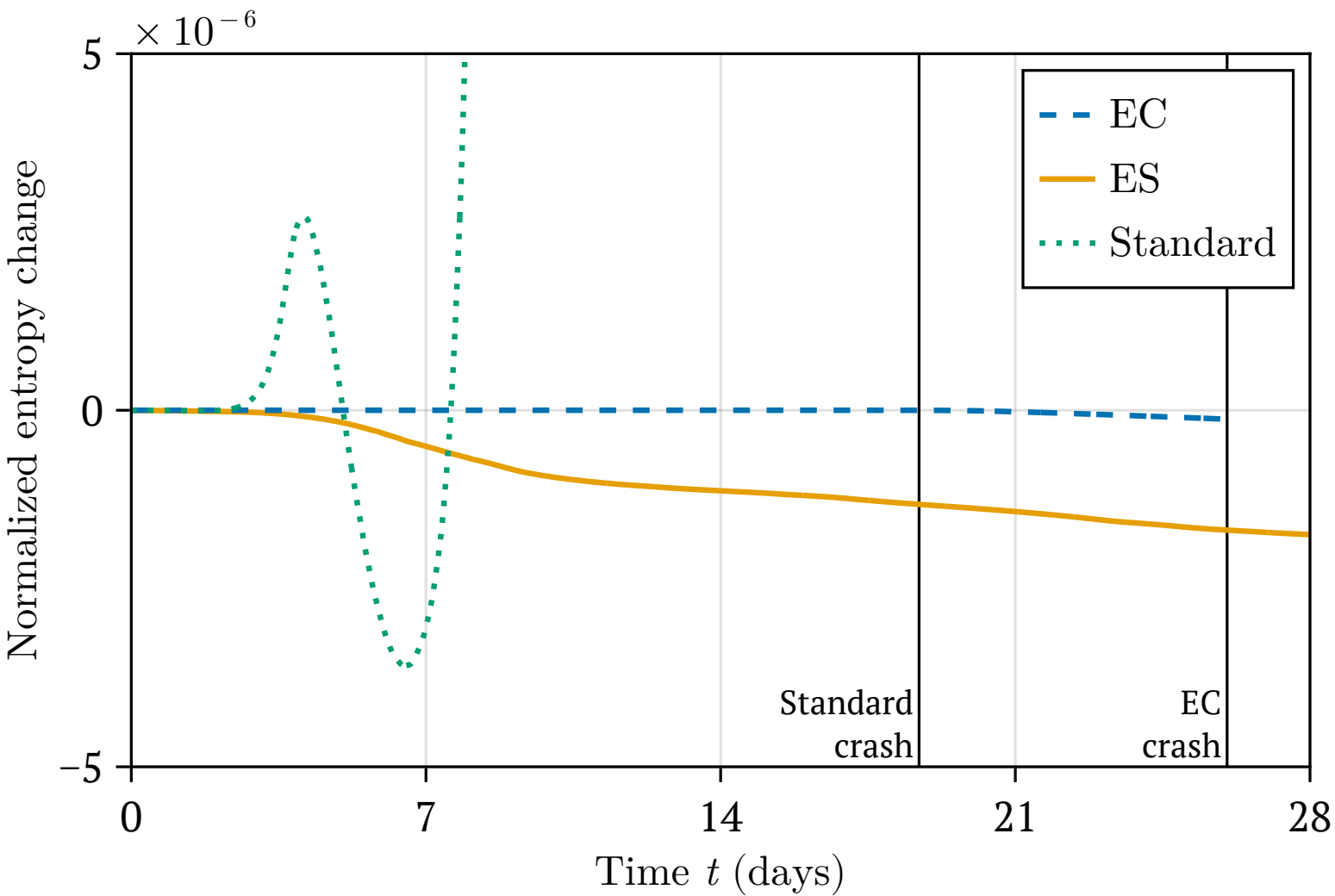
Entropy-conservative (EC) scheme, zero dissipation



Entropy-stable (ES) interface dissipation



Convergence with respect to mesh and polynomial degree



Improved robustness for Rossby–Haurwitz wave