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Geoscientific
Model Development
Discussions

Interactive comment on "A High-order Staggered Finite-Element Vertical Discretization for Non-Hydrostatic Atmospheric Models" *by* J. E. Guerra and P. A. Ullrich

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In the paper, and in their last reply to the second reviewer, the authors state that the code is able to preserve hydrostatic balance. However, they do not show any time evolution of the vertical velocity to demonstrate their statement. As the authors stress this point, a plot that shows the evolution of vertical velocity with time for a problem with zero initial velocity will be beneficial. An example is shown in the figure attached for a linear finite element solution.

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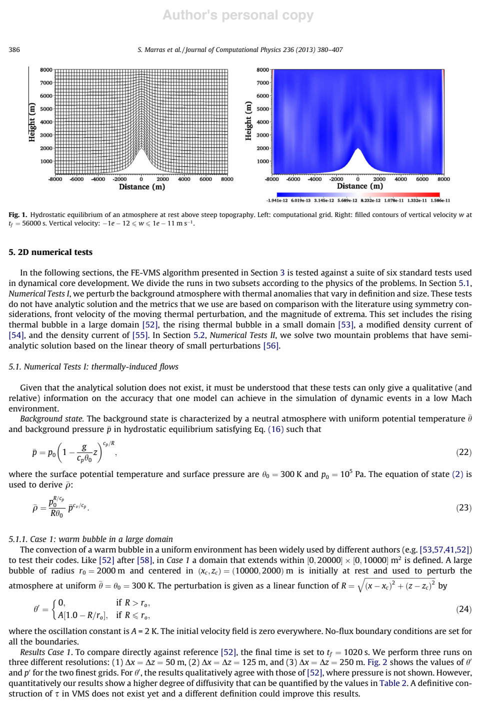

Fig. 1. Hydrostatic equilibrium of an atmosphere at rest above steep topography. Left: computational grid. Right: filled contours of vertical velocity w at $t_f = 56000$ s. Vertical velocity: $-1e-12 \leqslant w \leqslant 1e-11$ m s^{-1}.

5. 2D numerical tests

In the following sections, the FE-VMS algorithm presented in Section 3 is tested against a suite of six standard tests used in dynamical core development. We divide the runs in two subsets according to the physics of the problems. In Section 5.1, *Numerical Tests I*, we perturb the background atmosphere with thermal anomalies that vary in definition and size. These tests do not have analytic solution and the metrics that we use are based on comparison with the literature using symmetry considerations, front velocity of the moving thermal perturbation, and the magnitude of extrema. This set includes the rising thermal bubble in a large domain [52], the rising thermal bubble in a small domain [53], a modified density current of [54], and the density current of [55]. In Section 5.2, *Numerical Tests II*, we solve two mountain problems that have semi-analytic solution based on the linear theory of small perturbations [56].

5.1. Numerical Tests I: thermally-induced flows

Given that the analytical solution does not exist, it must be understood that these tests can only give a qualitative (and relative) information on the accuracy that one model can achieve in the simulation of dynamic events in a low Mach environment.

Background state. The background state is characterized by a neutral atmosphere with uniform potential temperature $\bar{\theta}$ and background pressure $\bar{p}$ in hydrostatic equilibrium satisfying Eq. (16) such that

$$\bar{p} = p_0\left(1 - \frac{g}{c_p\theta_0}z\right)^{c_p/R}, \tag{22}$$

where the surface potential temperature and surface pressure are $\theta_0 = 300$ K and $p_0 = 10^5$ Pa. The equation of state (2) is used to derive $\bar{\rho}$:

$$\bar{\rho} = \frac{p_0^{R/c_p}}{R\theta_0}\,\bar{p}^{c_v/c_p}. \tag{23}$$

5.1.1. Case 1: warm bubble in a large domain

The convection of a warm bubble in a uniform environment has been widely used by different authors (e.g. [53,57,41,52]) to test their codes. Like [52] after [58], in *Case 1* a domain that extends within $[0, 20000] \times [0, 10000]$ m^2 is defined. A large bubble of radius $r_0 = 2000$ m and centered in $(x_c, z_c) = (10000, 2000)$ m is initially at rest and used to perturb the atmosphere at uniform $\bar{\theta} = \theta_0 = 300$ K. The perturbation is given as a linear function of $R = \sqrt{(x-x_c)^2 + (z-z_c)^2}$ by

$$\theta' = \begin{cases} 0, & \text{if } R > r_o, \\ A[1.0 - R/r_o], & \text{if } R \leqslant r_o, \end{cases} \tag{24}$$

where the oscillation constant is $A = 2$ K. The initial velocity field is zero everywhere. No-flux boundary conditions are set for all the boundaries.

Results Case 1. To compare directly against reference [52], the final time is set to $t_f = 1020$ s. We perform three runs on three different resolutions: (1) $\Delta x = \Delta z = 50$ m, (2) $\Delta x = \Delta z = 125$ m, and (3) $\Delta x = \Delta z = 250$ m. Fig. 2 shows the values of θ' and p' for the two finest grids. For θ', the results qualitatively agree with those of [52], where pressure is not shown. However, quantitatively our results show a higher degree of diffusivity that can be quantified by the values in Table 2. A definitive construction of τ in VMS does not exist yet and a different definition could improve this results.

Fig. 1. vertical velocity