Constructing and Comparing Two-Dimensional Anelastic Vector Vorticity Model (VVM) and Quasi-Compressible Model (QCM)

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Source Code & Derivation (Github)

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I. Introduction

The dynamical frameworks of cloud models nowadays can be generally classified into two categories: one is founded on the anelastic system of equations, in contrast to the other is based on the fully compressible system. These models do some approximations for some reasons like numerical instability or efficiency. This is a trade-off that we cannot ignore and use models without take them into consideration.

The purpose of this research is to compare the differences between two models under several initial fields. By doing so, we can get more acknowledgment about the pros and cons of the differences of them, and how we can apply them according to the situations.

II. Model description

Both models are two-dimensional models which are assumed diffusive, frictionless atmosphere on a flat, non-rotating planet. Note that the energy and mass conservation will not occur once physics is included. Quasi-compressible approximation is conducted on FCM and anelastic approximation is implemented on VVM.

a. Dynamical system

1. Quasi-Compressible Model (QCM)

QCM's dynamic process is to predict velocity (u, w) and non-dimensional pressure (π'). The reason we used π' rather than P is because we hope that the effects of sound waves are less.

2. Vector Vorticity Model (VVM)

VVM's dynamic process is to predict vorticity (ζ) and solve the 2-D Poisson's equation to get the velocity field. Rather than predict velocity, it is diagnosed by vorticity now. So VVM might get sharper velocity wind field.

b. Thermal Process & Moisture & Microphysics

The thermal dynamic equation in these two models is given by

$$\frac{\partial \theta'}{\partial t} = -\left(\frac{\partial (u\theta')}{\partial x} + \frac{1}{\rho_0}\frac{\partial(\rho_0 w\theta')}{\partial z}\right) - w\frac{d\bar{\theta}}{dz} + K_x\frac{\partial^2\theta'}{\partial x^2} + K_z\frac{\partial^2\theta'}{\partial z^2}$$

Once the moisture and microphysics are included, both dynamic and thermal systems should add some terms. In dynamic process, the buoyancy of different kinds of water need to be placed into the equation. In thermodynamic process, condensation, auto-conversion, accretion, and evaporation will be added to thermal equation and microphysics process.

III. Model Setup

a. Discretization & Grid Setup

Leapfrog scheme is implemented as the time-difference method and the second-order central difference method is served as the space-difference method on both two models. Fig1. shows the grid setup principles across the domain. The width of the models is 150 km and the height of them is 15 km. One grid size (dx = dz) is 250 m.

b. Model structure

These two models are constructed by C++ and we use objected-oriented programming (OOP) skills to make these programs work divisionally. By doing so, we can easily know the whole picture of the models and find what's wrong in the models more comfortably.

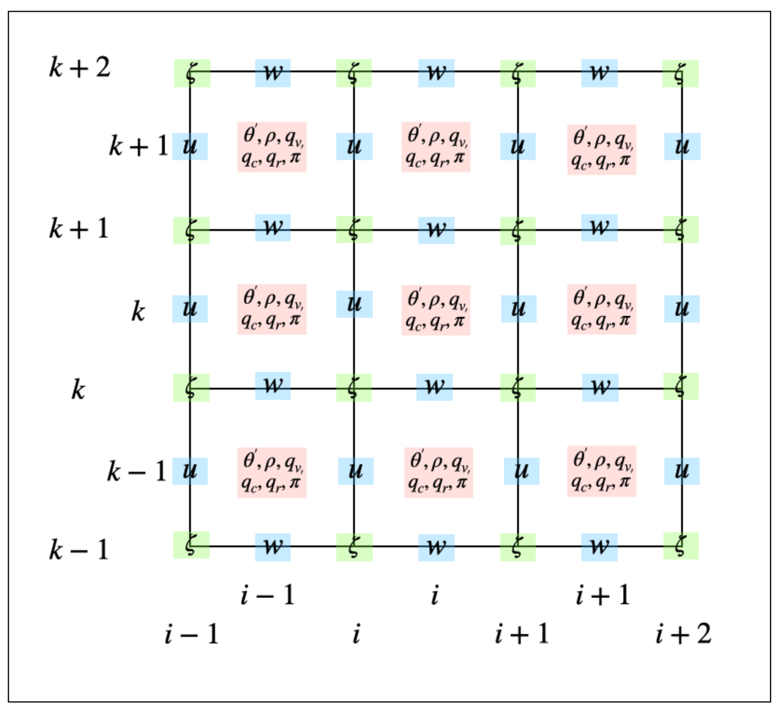


Fig1. A two-dimensional view of the model grids

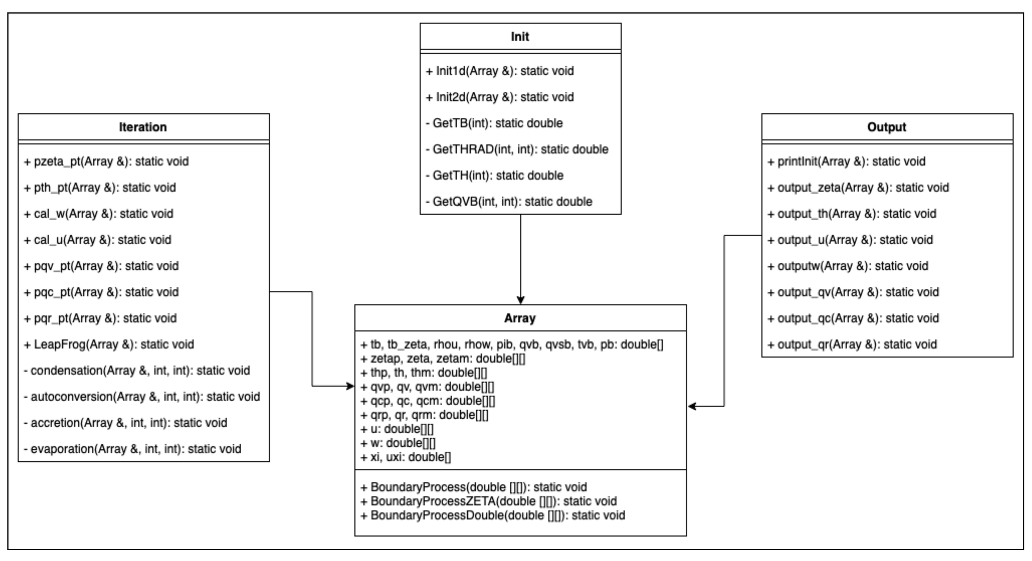
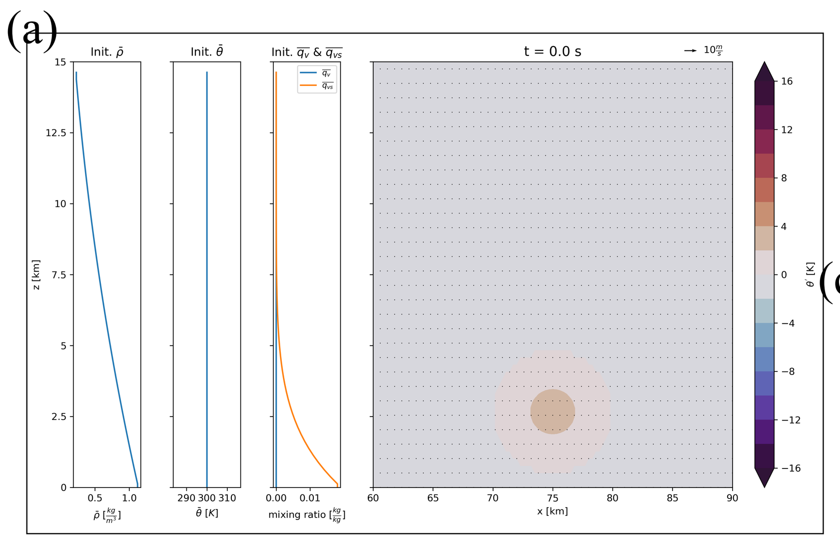


Fig2. UML graph of 2-D VVM

IV. Experiment

- EX1. Neutral and dry environment, diffusion is set to Kx=Kz=150. Initial wind field is zero, and the θ' (theta perturbation) maximum is 3 K.
- EX2. Stable environment, diffusion is set to Kx=Kz=1000. Moisture and microphysics are added into model. Initial wind field is zero, and the θ' (theta perturbation) maximum is 3 K.
- EX3. Stable environment, diffusion is set to Kx=Kz=1000. Moisture and microphysics are added into model. A horizontally uniform westerly wind (u_0) which linearly increases from -10 at the surface to 10 ms^{-1} at 5 km to 20 ms^{-1} at top (15 km) is added to the initial wind field.

EX1. Warm bubble



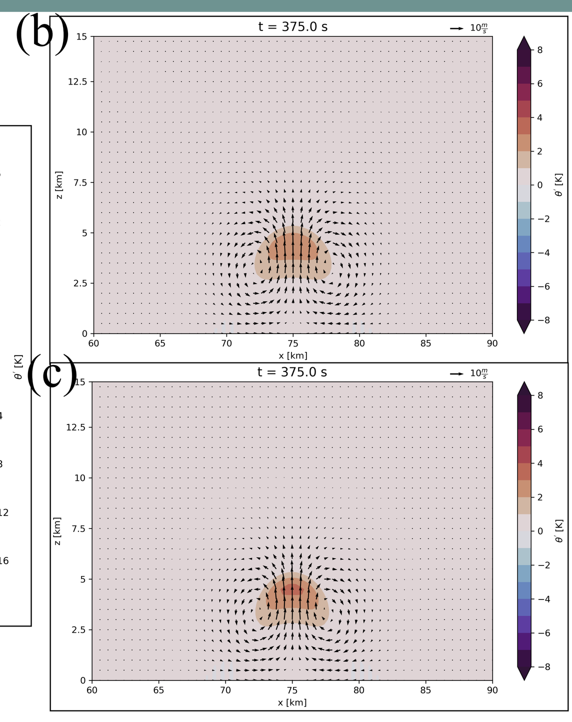


Fig3. (a) is the initial profile and fields of both models. (b) is QCM's result and (c) is VVM's result. In (b) and (c), wind and thermal field are generally same but VVM has higher peak.

EX2. Warm bubble + physics

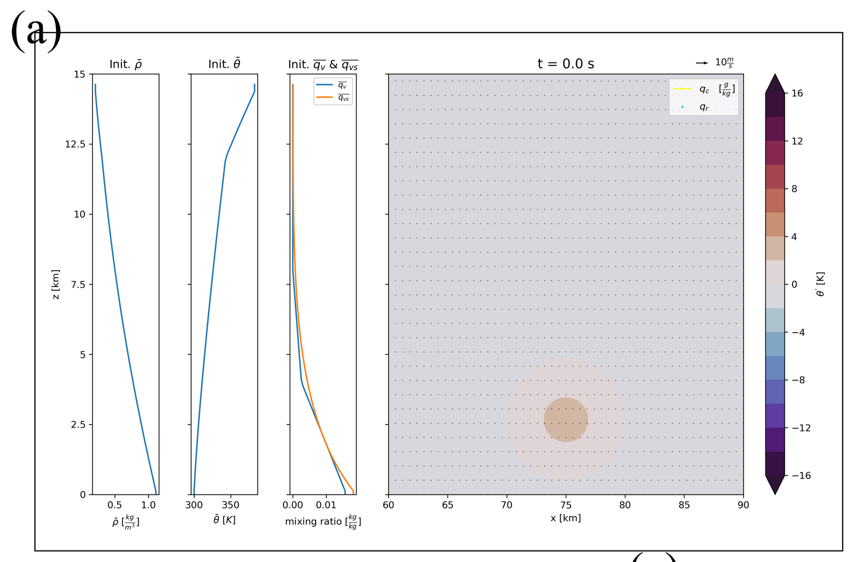
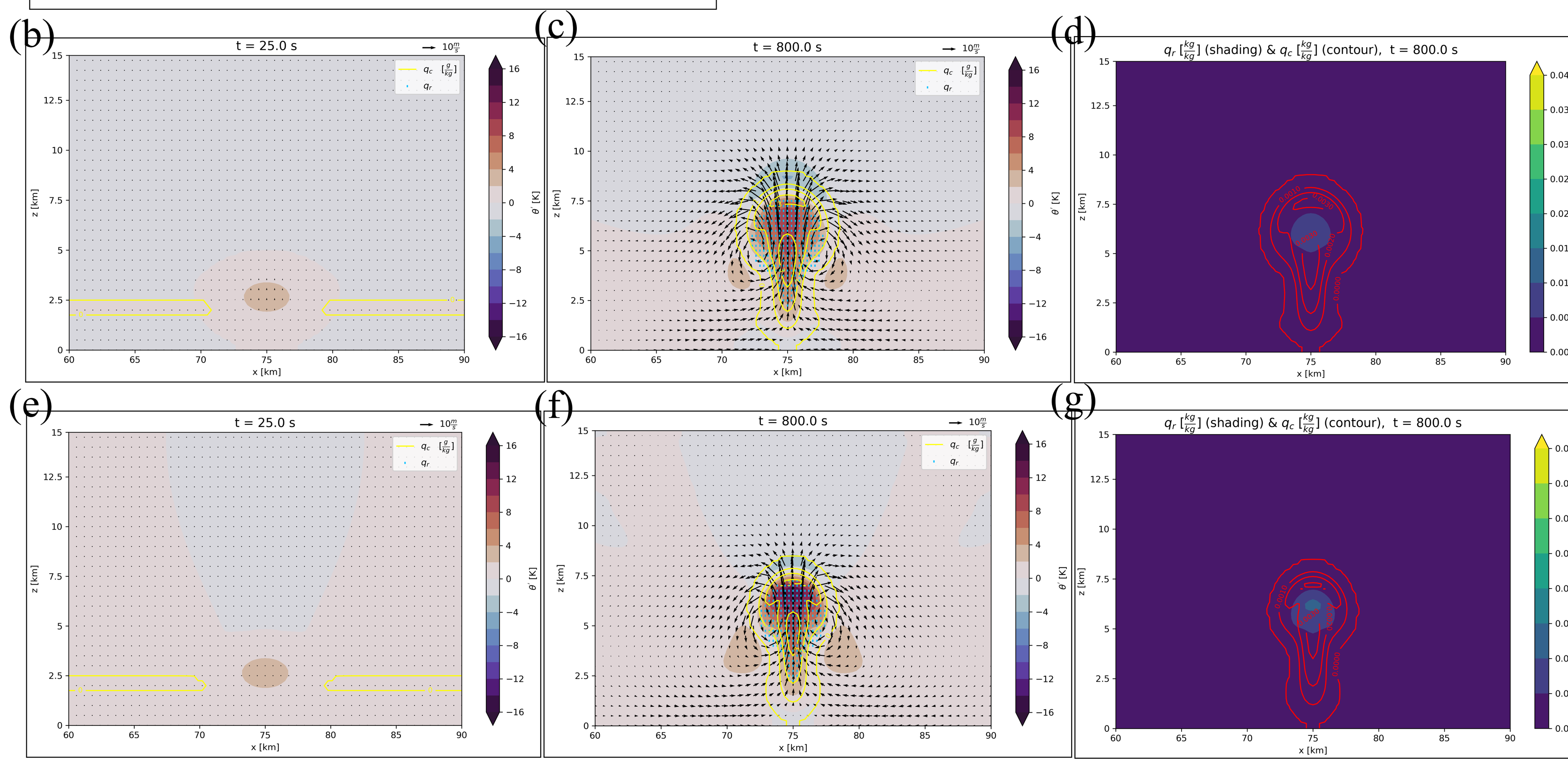


Fig4. (a) is the initial profile and fields of both models. (b)~(d) are QCM's results and (e)~(f) are VVM's results. In (b) and (e), the differences between the quasi-compressible and the anelastic approximation are clear. In (c), (d), (f), and (g), the influences of water seems to be strong.



EX3. Warm bubble + physics + shear

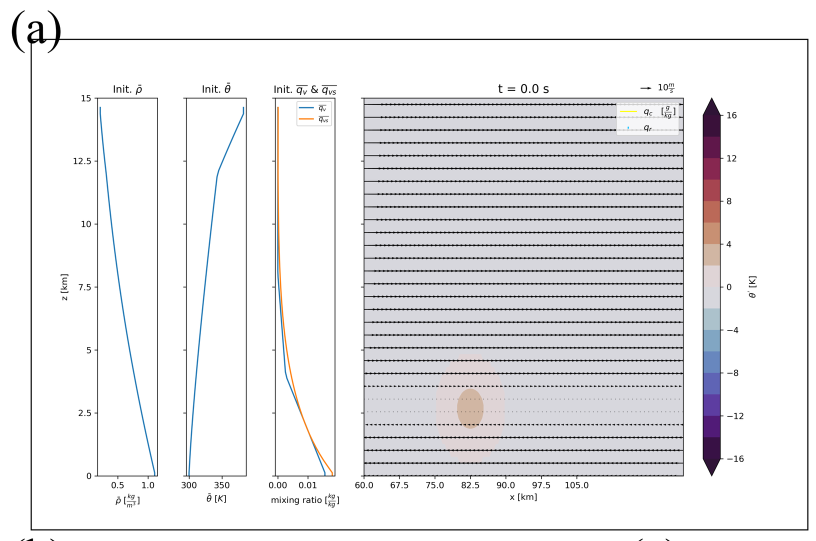
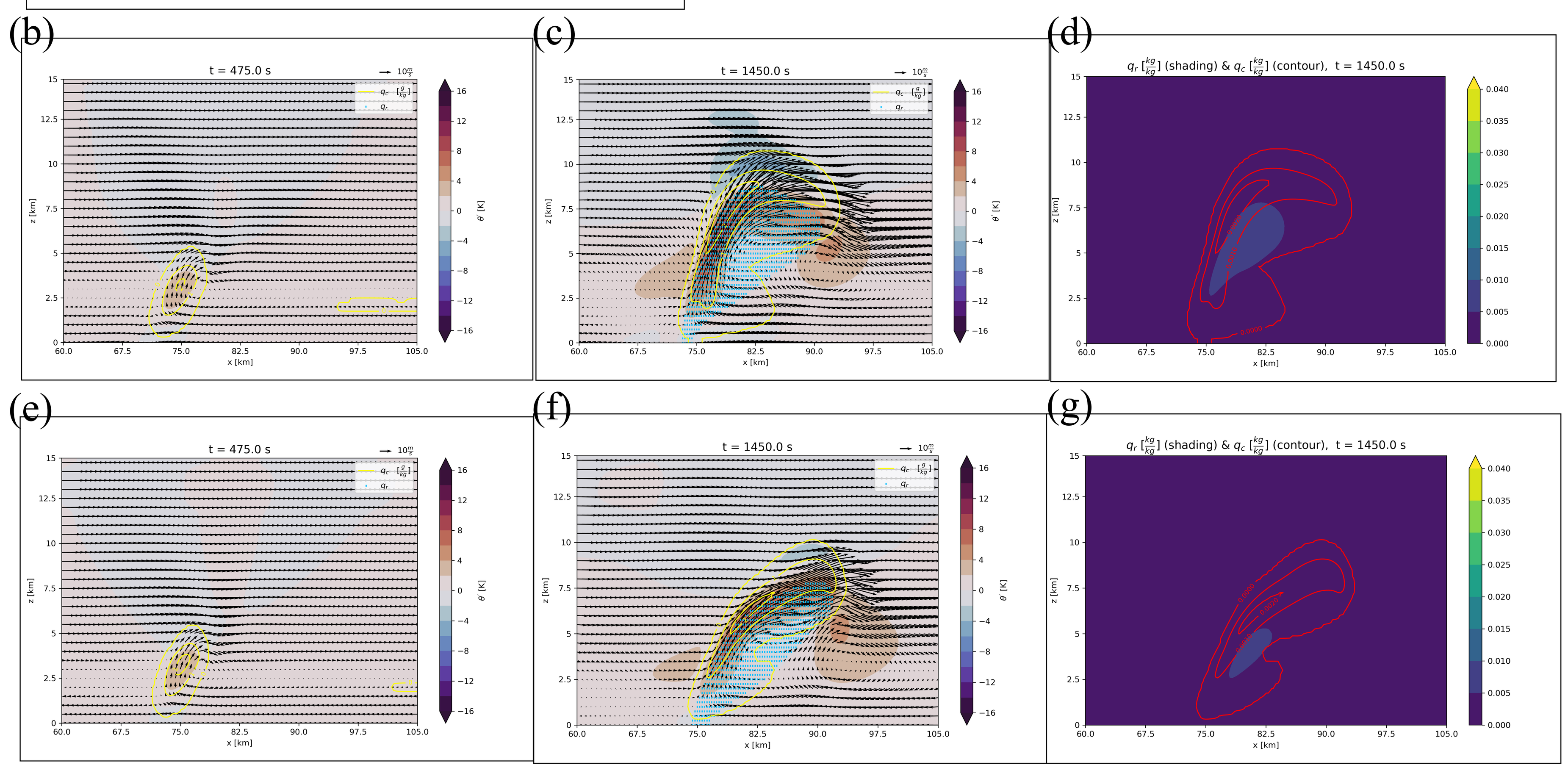


Fig5. (a) is the initial profile and fields of both models. (b)~(d) are QCM's results and (e)~(f) are VVM's results. In (b) and (e), it show the bubble before rain water appear. In (c), (d), (f), and (g), the wind shear and the rain drop affect the bubble. The sinking area and rising area are separated.



V. Discussion

- Diffusion has essential effects on the stability and results of models. Models are sensitive, it's a trade-off to do some artificially adjust.
- These two models have their own advantages, for the development of the models, we can take several choices like the microphysics process, the higher resolution model for the sake of diffusion processing, and sea-land breeze.

VI. Reference

- Robert G. Fovell (2017). ATM 562: Numerical modeling.
- Jung, J. H., & Arakawa, A. (2008). A three-dimensional anelastic model based on the vorticity equation. Monthly weather review, 136(1), 276-294.