

# **Model Development: Road to Global Cloud Resolving Model (GCRM)**

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and

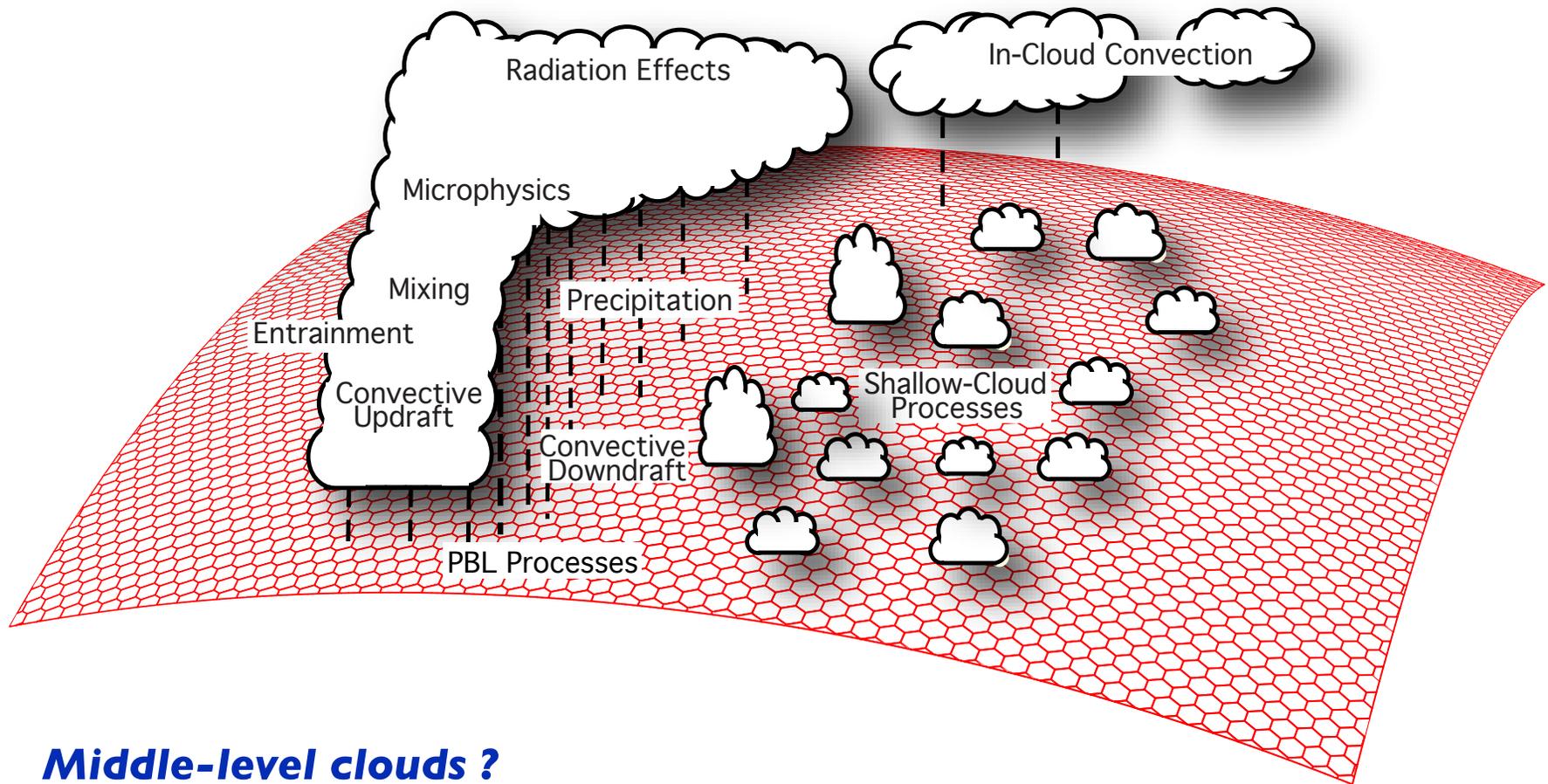
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**Our goal is to develop a GCRM with a grid-cell spacing of approximately 3 km or less, capable of resolving circulations associated with cloud ensembles and large individual clouds**



**Middle-level clouds ?**

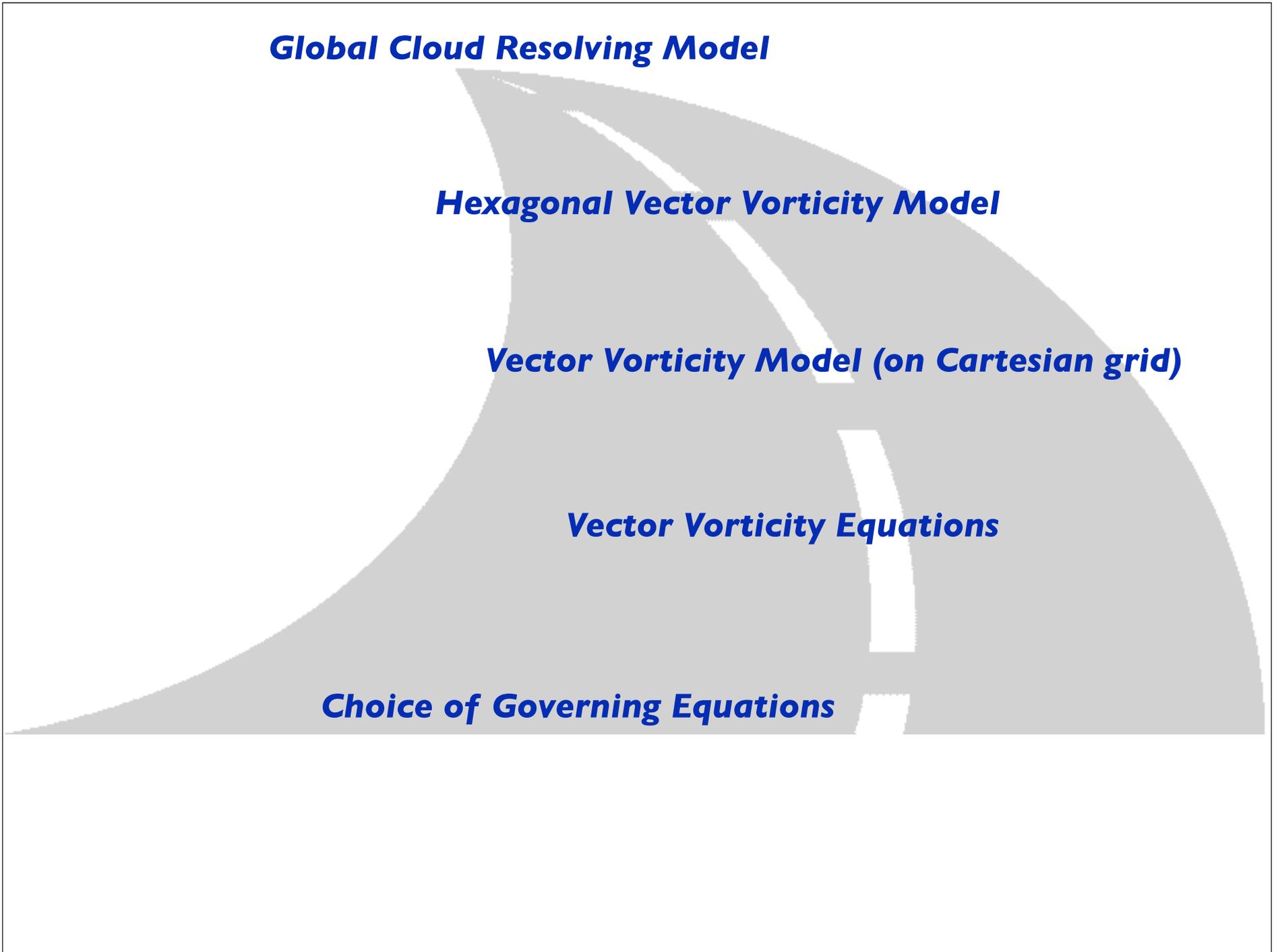
***Global Cloud Resolving Model***

***Hexagonal Vector Vorticity Model***

***Vector Vorticity Model (on Cartesian grid)***

***Vector Vorticity Equations***

***Choice of Governing Equations***



***Community's expectation from global  
cloud resolving models is very high***

***Change is difficult ...***

***We should not give up or sacrifice from any  
advantages of current global climate (and  
NWP) models***

# Choice of governing equations for global models

- Quasi-hydrostatic (same as hydrostatic) system of equations:
  - Used in most of the Global Climate (or General Circulation) Models (GCMs) for many years (*highly positive comfort factor*)
  - Mass, energy etc. are conserved.
  - Filter vertically propagating sound waves of all scales while retain compressibility for large-scale motion
  - Problems with governing small-scale motion (*Cannot be justified for cloud-scale motion*)

*If we really want to maintain the comfort of quasi-hydrostatic system in a cloud resolving model, we have to find a way to include non-hydrostatic effects with the quasi-hydrostatic system.*

# Choice of governing equations for global models (Cont.)

- Non-hydrostatic anelastic system of equations:
  - Used in many Cloud-Resolving Models (CRMs) with small domains for a long time but limited experience with global dynamical cores.
  - Filters sound waves of all scales. (*All scales of motion are incompressible*)
    - Since large-scale motion is incompressible, *cannot be justified for global applications.*
  - Problems with handling high stability. (*Cannot be justified for Stratospheric applications*)
  - Horizontally uniform basic state is needed.
  - Ambiguities in determining the mean nonhydrostatic pressure.
  - Ambiguities in prescribing the upper and lower boundary values of nonhydrostatic pressure.

# Choice of governing equations for global models (Cont.)

- Non-hydrostatic pseudo-incompressible system of equations:
  - Same as anelastic system (*filters sound waves of all scales*)
  - Density change due to temperature fluctuations is retained in some fashion. (*Can be justified for Stratospheric applications if a slight error is accepted*)
  - Large-scale motion is still incompressible. (*Cannot be justified for global applications. Yet, there are ad hoc methods applied in the discrete system to cure the problem*)
  - A mean state is needed

# Choice of governing equations for global models (Cont.)

- Fully-compressible system of equations:

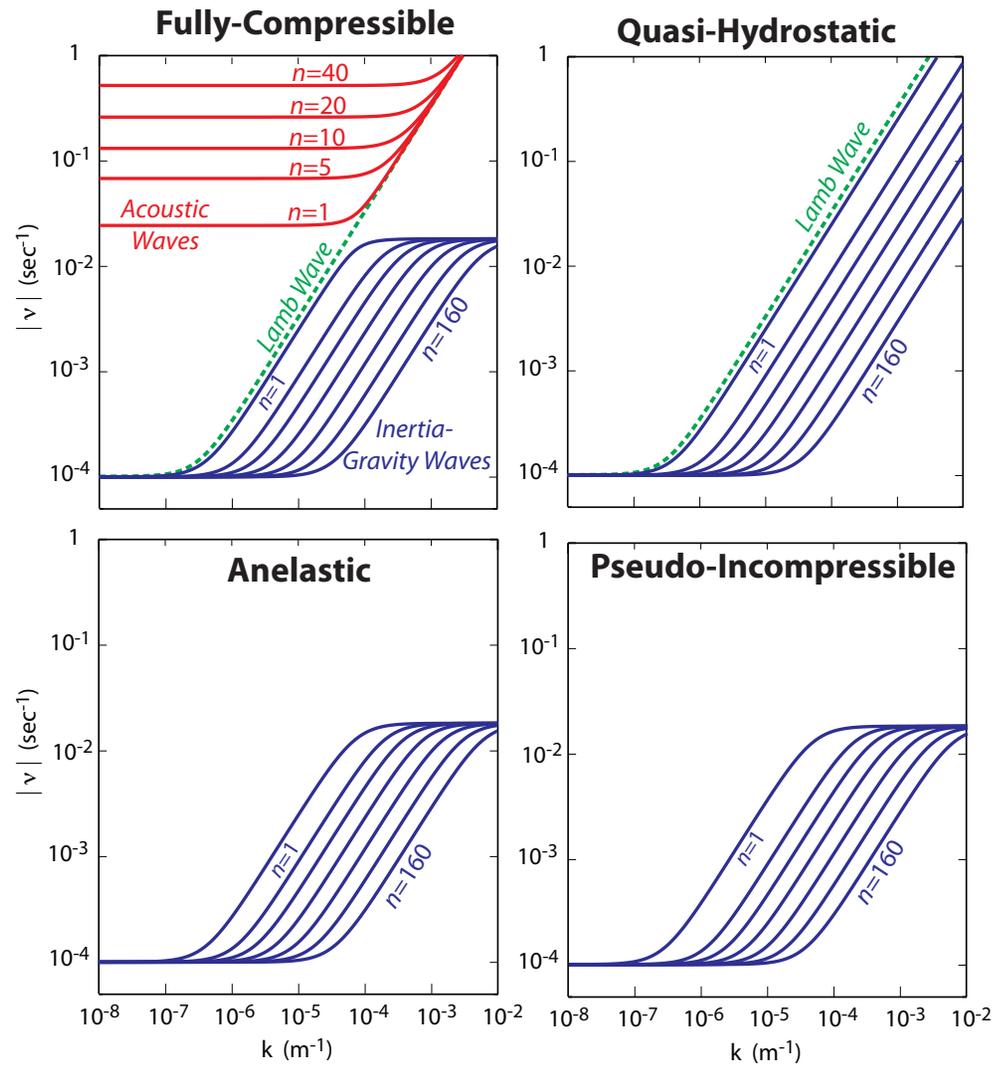
- Used in many Cloud-Resolving Models (CRMs) with small (regional) domains for a long time but limited experience with global models.
- Retains sound waves of all scales. (*Sound waves have to be dealt with in the discrete system*)

\* *There is a clear division in the community*

\* *Proponents of fully-compressible system claim that the anelastic system should not be used in neither operational numerical prediction nor climate simulation at any scale. They think that the pseudo-incompressible system is usable for NWP but only at short horizontal scales.*

# A normal mode analysis applied on an $f$ -plane

## Frequencies of normal modes vs. horizontal wavenumber

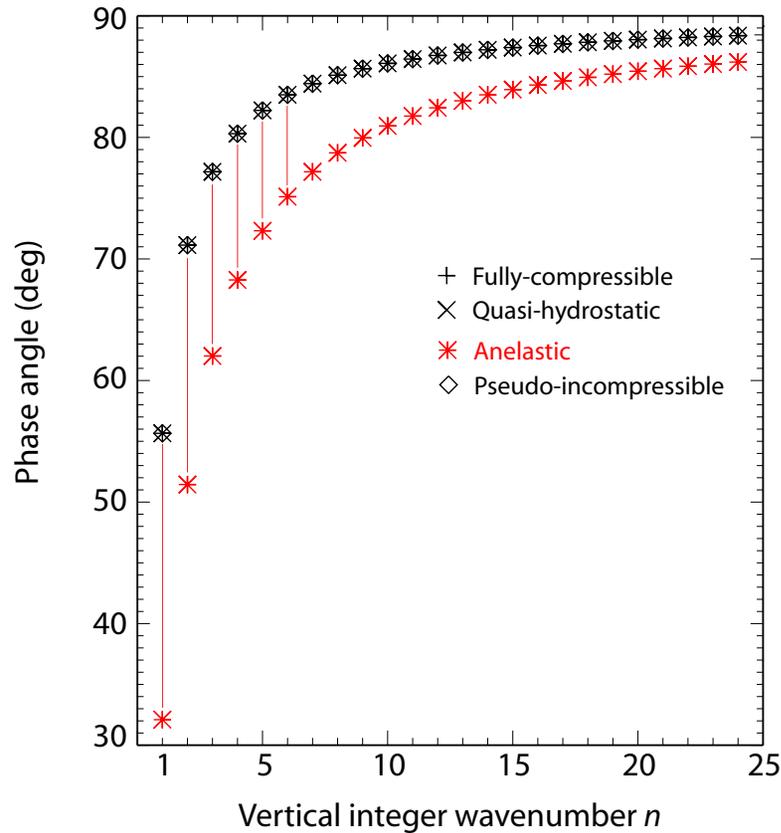


$n$  : Vertical (integer) wavenumber

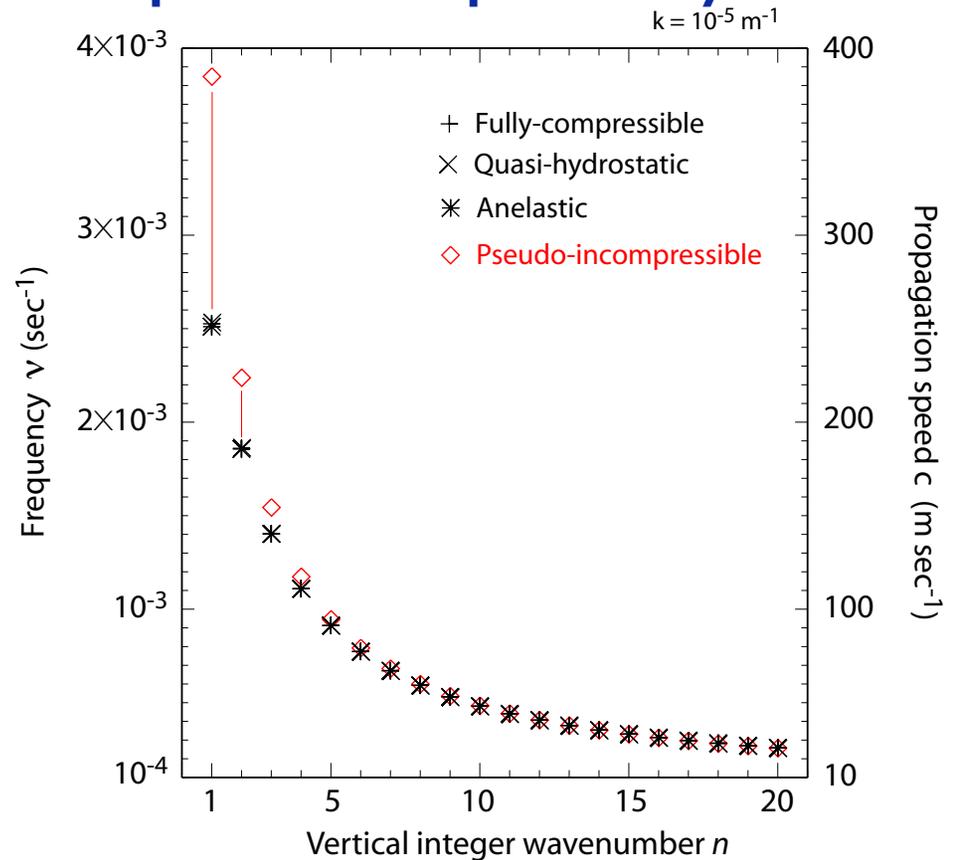
Arakawa and Konor (2008)

# A normal mode analysis applied on an $f$ -plane (Cont.)

## Vertical phase angle error with the anelastic system

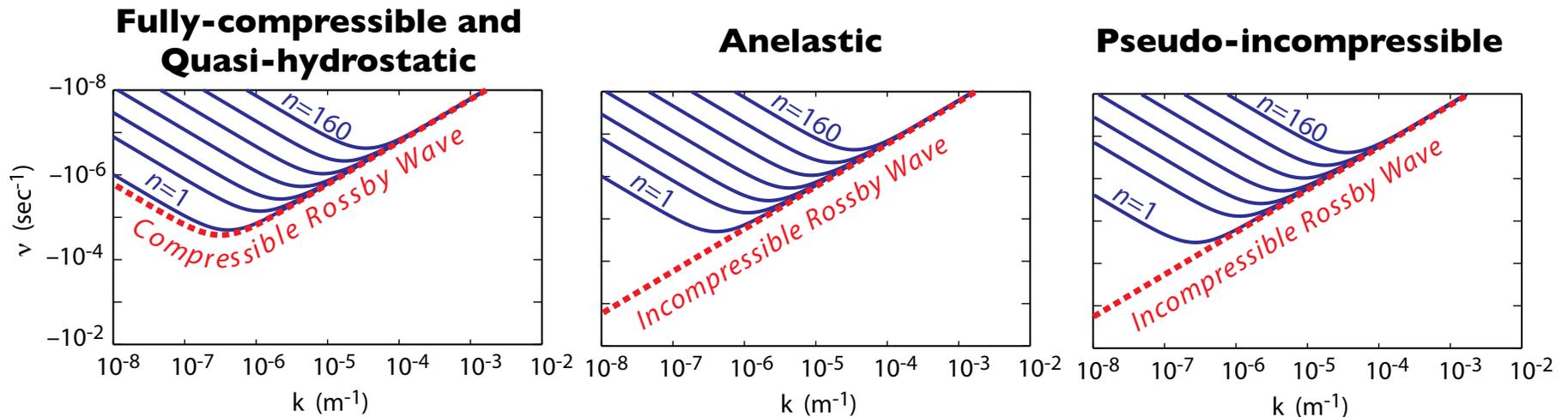


## Frequency error with the pseudo-incompressible system



# A normal mode analysis applied on a middle-latitude $\beta$ -plane with the quasi-geostrophic approximation

## Frequencies of normal modes vs. horizontal wavenumber



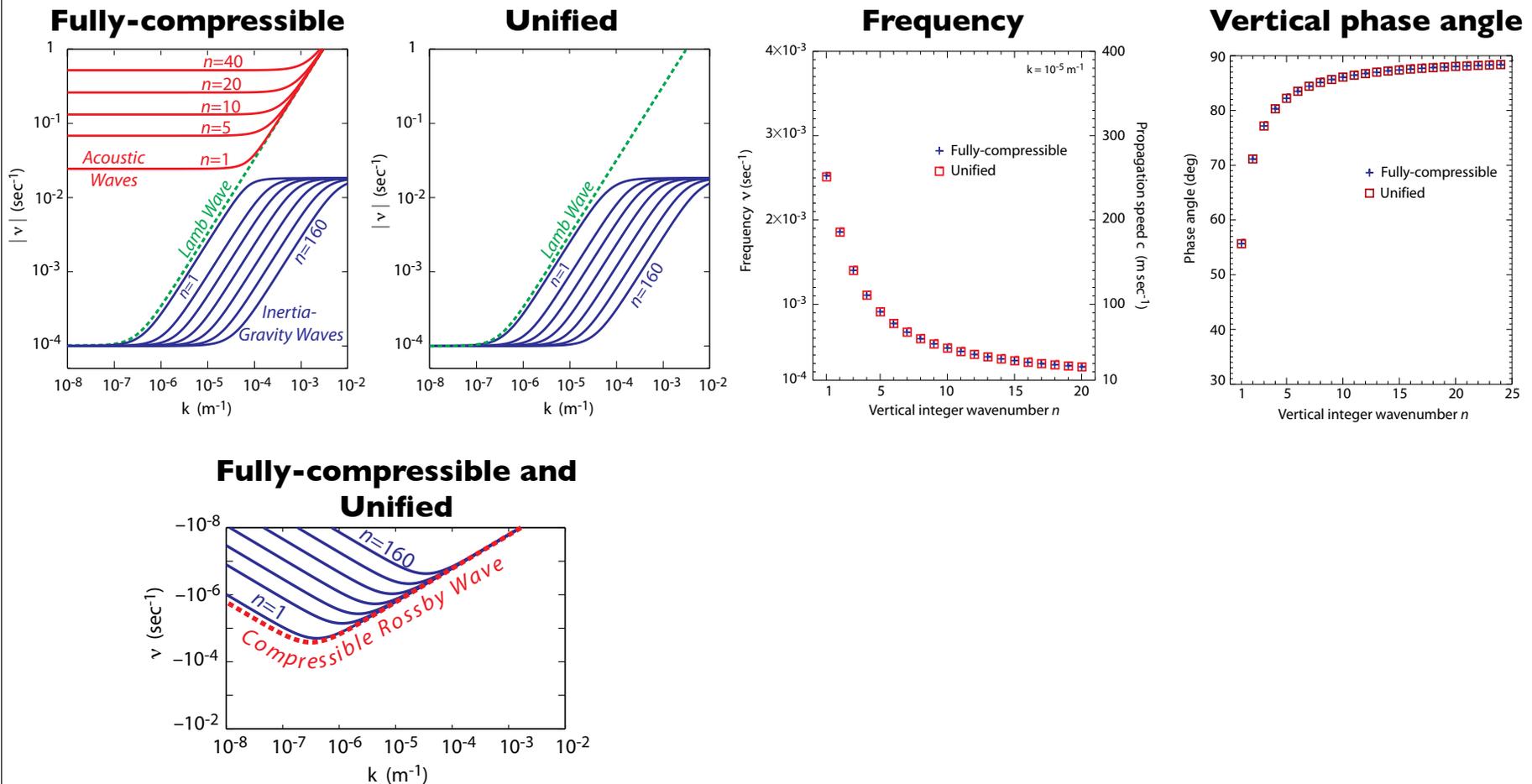
\* Proponents of the anelastic and pseudo-incompressible systems claim, on the other hand, that the errors inferred by the normal mode analyses with these systems are less than those due to discretization.

## Our opinion

- \* *Although the normal mode analyses reveal no error with the fully-compressible system, dealing with the sound waves in the discrete model may introduce additional discretization errors.*
- \* *Errors with the anelastic and pseudo-incompressible systems revealed by the normal mode analyses can be eliminated.*

# Unified System of equations

- Unifies the anelastic and quasi-hydrostatic systems of equations
- Filters vertically propagating sound waves of all scales
- Eliminates the problems with the anelastic system



Arakawa and Konor (2008)

## Unified System of equations (Cont.)

- No need for a mean (or a basic) state
- No assumptions made in the momentum and thermodynamic equations
- The continuity equation is diagnostic with a time change of the “quasi-hydrostatic density”.
- Conserves energy
- No ambiguity in determining the domain-mean part of nonhydrostatic pressure
- Can be applied to any vertical coordinate that is usable by the quasi-hydrostatic system
- Can be implemented in an anelastic model through add-on modules.

*The ambiguity in prescribing upper and lower boundary conditions for nonhydrostatic pressure is not necessarily solved by the use of unified system.*

Arakawa and Konor (2008)

# Vector vorticity equations for dynamical cores based on anelastic system

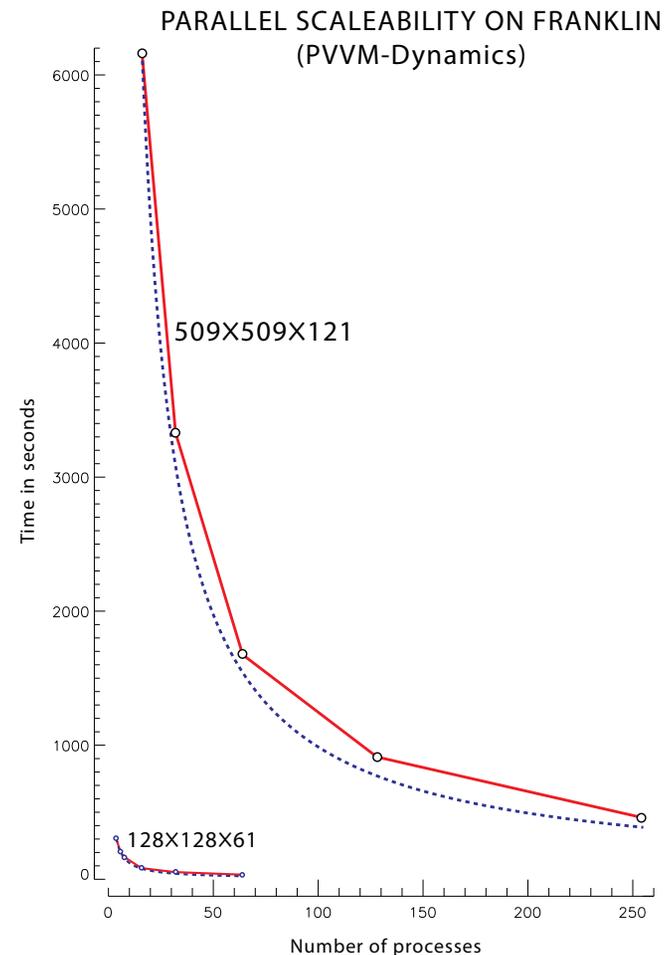
- Predicts 3D vorticity instead of momentum
- No pressure gradient term appears in the vorticity prediction equations
- Therefore, no need for the nonhydrostatic pressure for dynamics.
- The 3D elliptic equation determines vertical velocity instead of nonhydrostatic pressure
- Non divergence of 3D vorticity is enforced

*Jung and Arakawa has developed a model based on these equations, which we call the Vector Vorticity Model (VVM).*

Jung and Arakawa (2008)

# Further Development of VVM (MingXuan Chen)

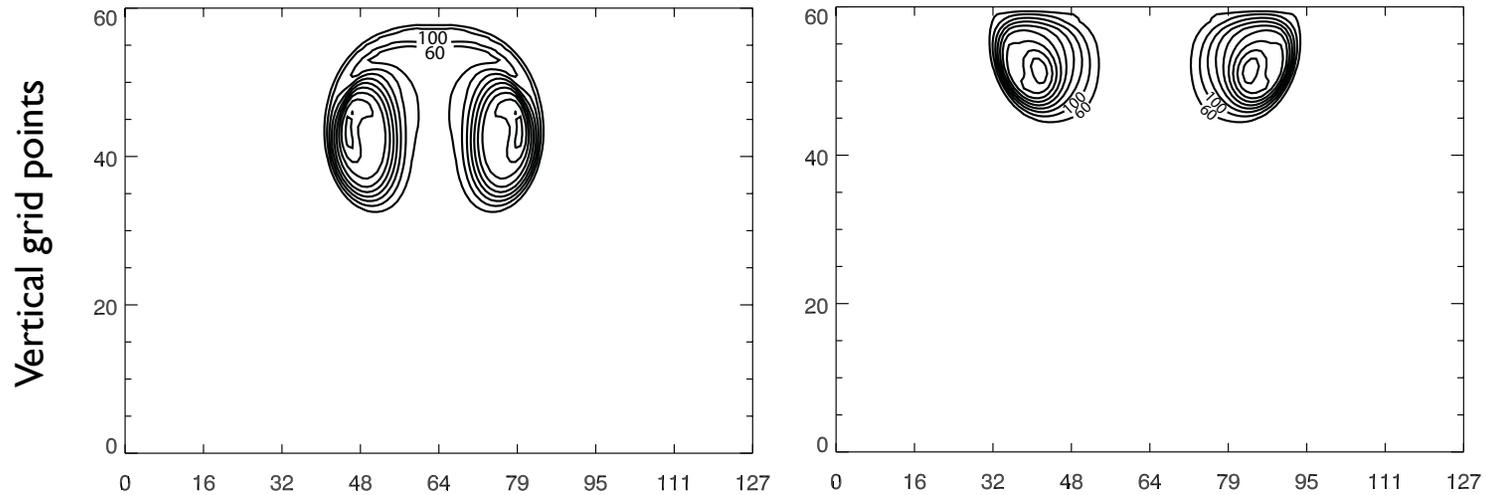
- Based on Cartesian grid in a doubly-periodic rectangular domain
- Code for the dynamical core is parallelized
- Partially fifth-order advection scheme is added as an option for advection
- A positive definite treatment (for third- and fifth-order schemes) is applied to the tracer and moisture advections
- Necessary structure is added to the dynamical core for turbulence. Turbulent mixing is applied to the conserved quantities



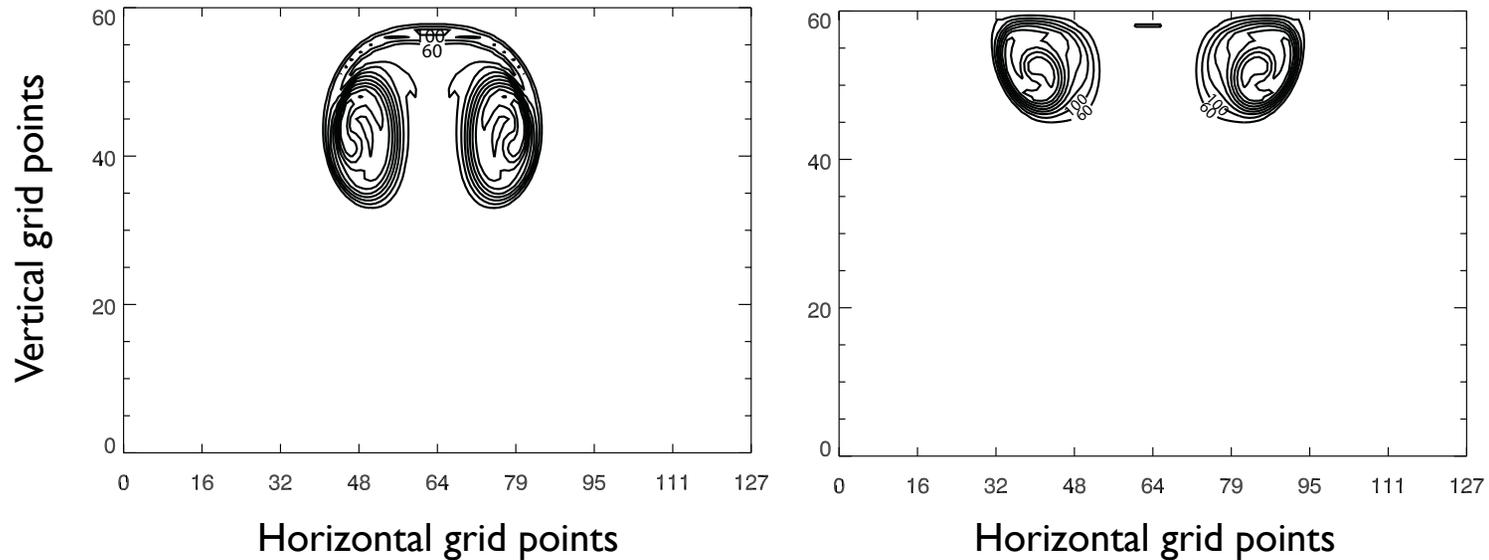
# Comparison of simulations with third- and fifth-order advection schemes

Vertical cross section of *potential vorticity*

Partially third-order scheme



Partially fifth-order scheme



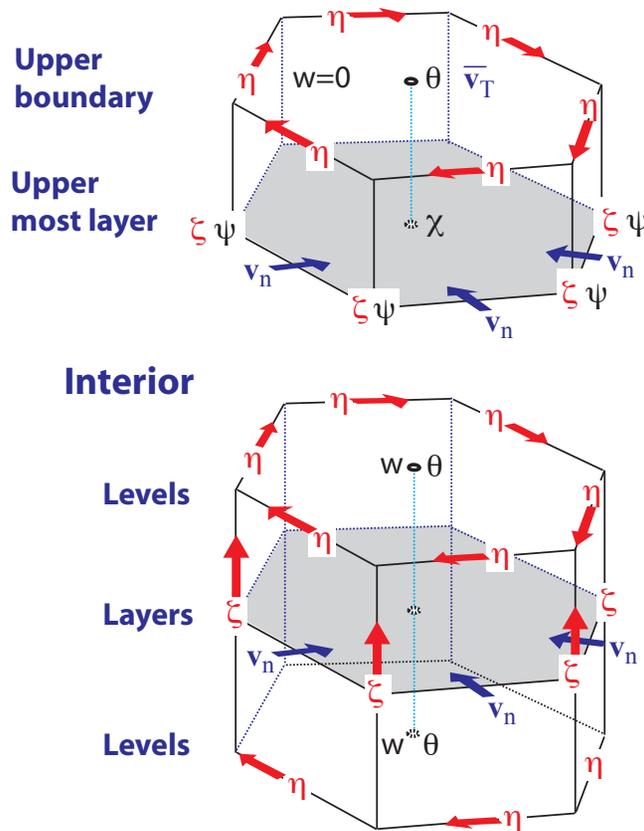
# Physics of Vector Vorticity Model

- Original model's turbulence, surface layer, microphysics and radiation parameterizations are included into the parallel code.
- Thomas Cram has included the CAM radiation parameterization as an option to the model. Now, he is making RRTMG radiation parameterization available for the model.
- VVM will be coupled to a land model.
- We are planning to participate various case studies with this model.

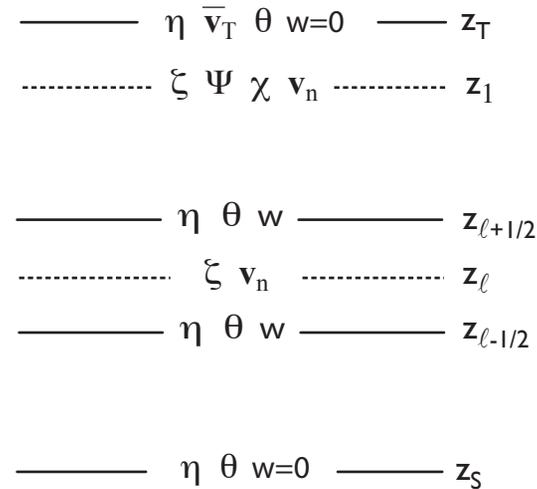
# Hexagonal Vector Vorticity Dynamical Core

## Grid Structure of the Hex-VVM

### 3-D view of the grid



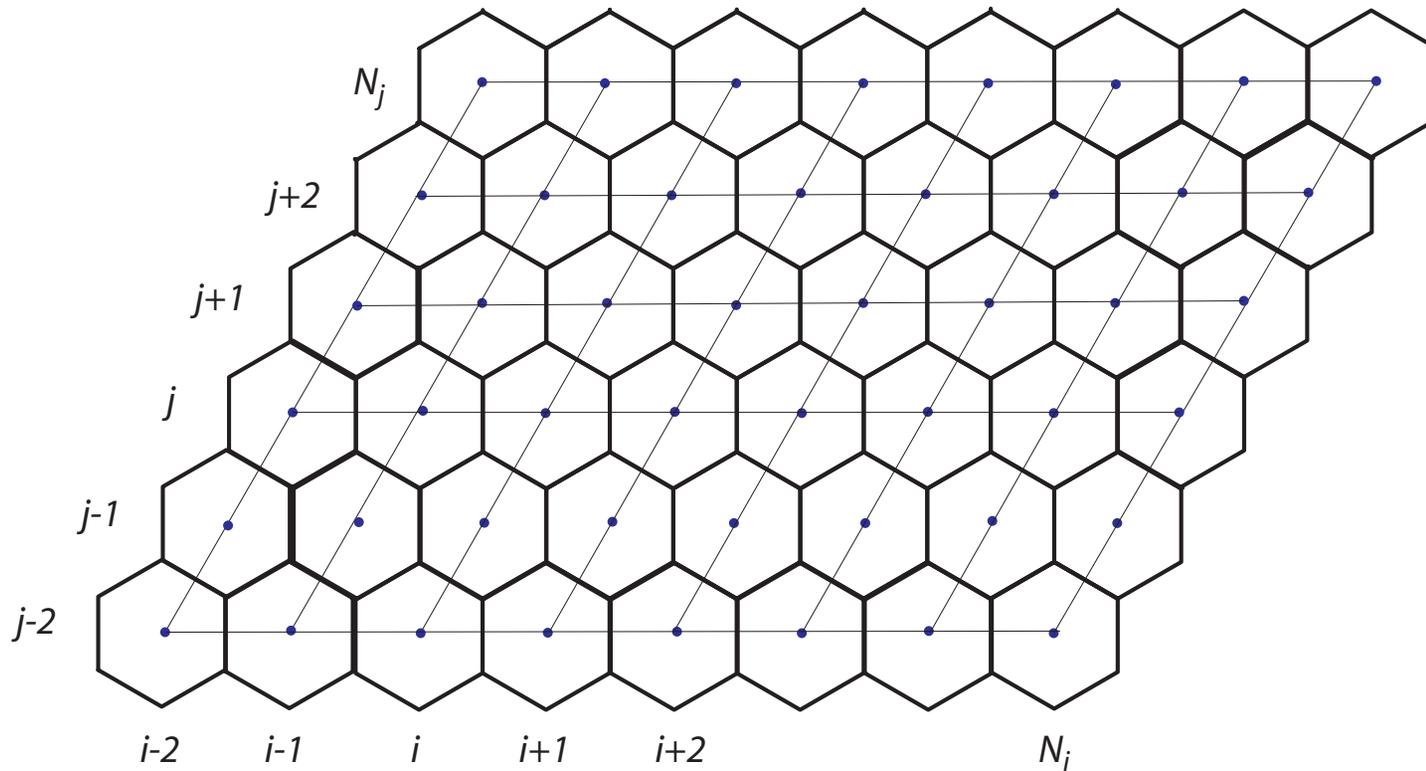
### Charney-Phillips vertical grid



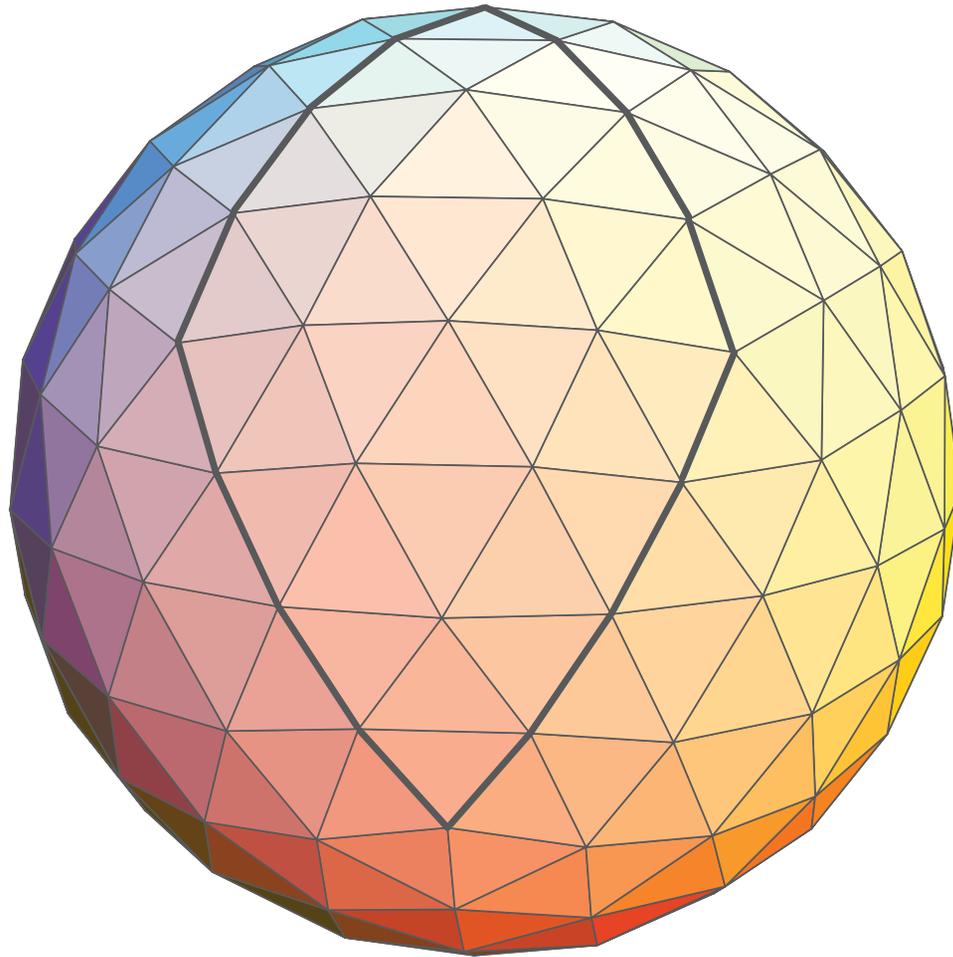
● Advections of quantities defined at walls, corners and centers are needed.

# Hexagonal Vector Vorticity Dynamical Core (Cont.)

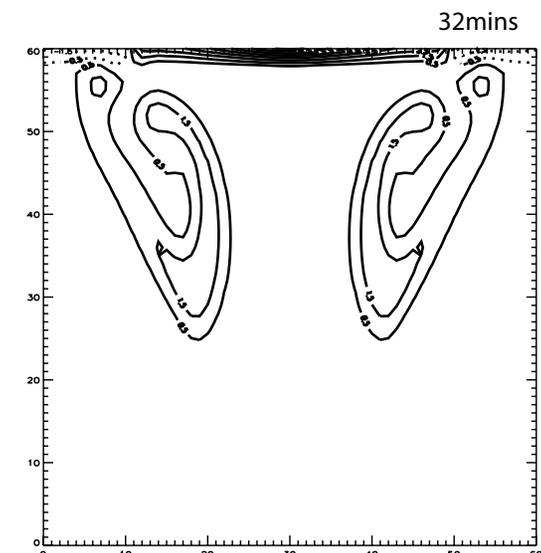
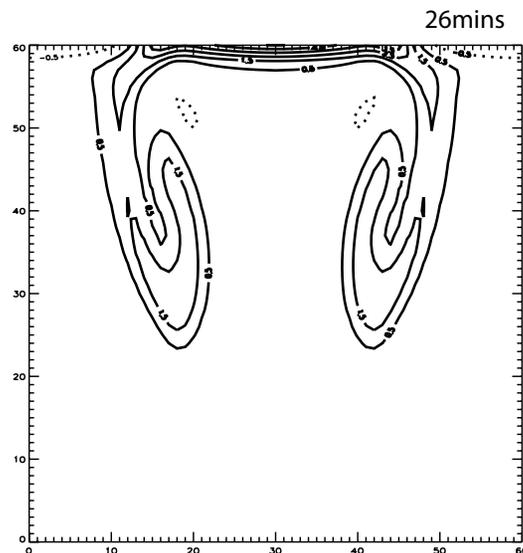
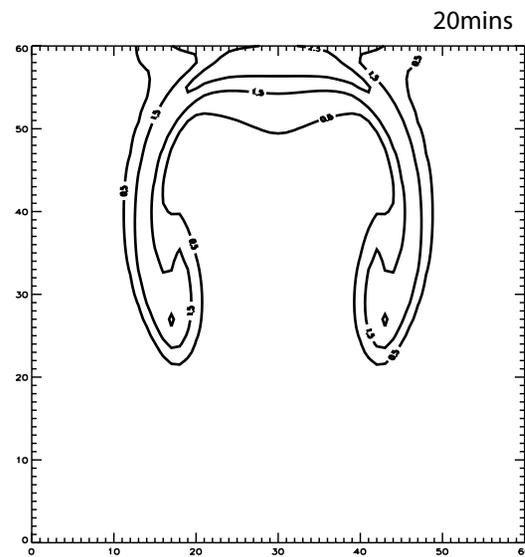
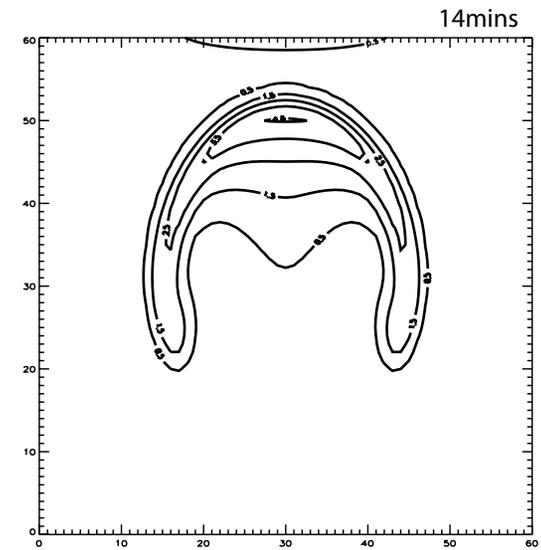
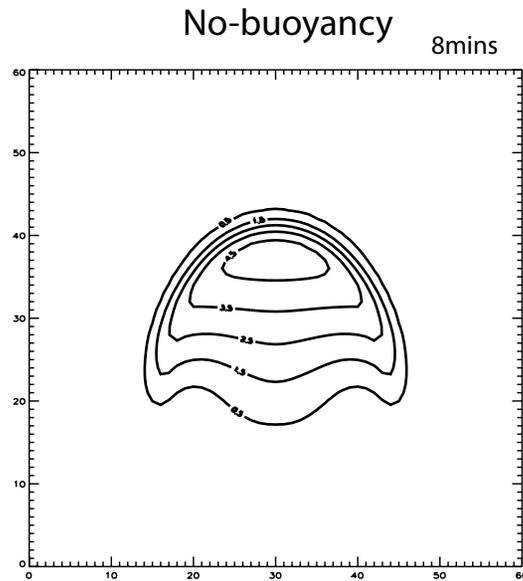
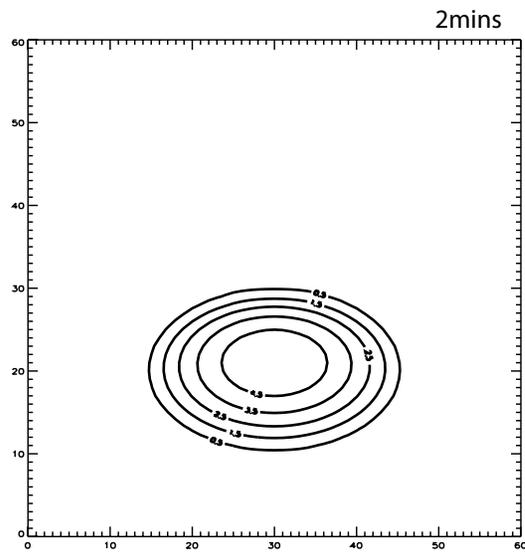
## Horizontal domain of Hex-VVM



## **Implementation to geodesic hexagon/pentagon grid**



# Simulation of a nonbuoyant bubble with the hex-VVM



# Summary

- The unified system of equations, which combines the anelastic and quasi-hydrostatic systems of equations, is derived for use in the GCRM.
- The improved (Cartesian) VVM is ready for case studies.
- Development of the Hex-VVM is continuing.
- Development of GCRM is moving forward.