Design of a Vector-Vorticity Dynamical Core on a Hexagonal Grid (Hex-VVDC)

"A Progress report"

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What is Hex-VVDC ?

- **It is an application of the VVDC of Jung and Arakawa (2008) to a regular *hexagonal grid on a planar domain*.**

  - ***VVDC predicts the horizontal vorticity (η) and diagnoses the vertical vorticity (ζ) from η, instead of predicting horizontal and vertical velocities. By predicting vorticity, we can maintain major properties involving vorticity in the discrete model.***

  - ***VVDC is based on the nonhydrostatic anelastic equations in the the height (z) vertical coordinate.***

Integration Procedure of Hex-VVDC

3D Prediction of horizontal vorticity (η) through buoyancy, horizontal and vertical advections, stretching and twisting

Prediction of vertical vorticity (ζ) at a particular height level through horizontal and vertical advections, stretching and twisting

3D determination of vertical vorticity (ζ) through vertical integral of

$$\nabla_H \cdot \eta + \frac{\partial \zeta}{\partial z} = 0$$

Vertical velocity (w) is obtained from a 3D elliptic equation, which is obtained through vertical derivative of anelastic continuity equation and definition of η

Horizontal velocity (v) at a particular height level is obtained from velocity potential and streamfunction

Horizontal velocity (v) is obtained through vertical integral of definition of η using w

Computational Requirement with VVDC

One 3D prediction + One 2D prediction

+ Two vertical summations

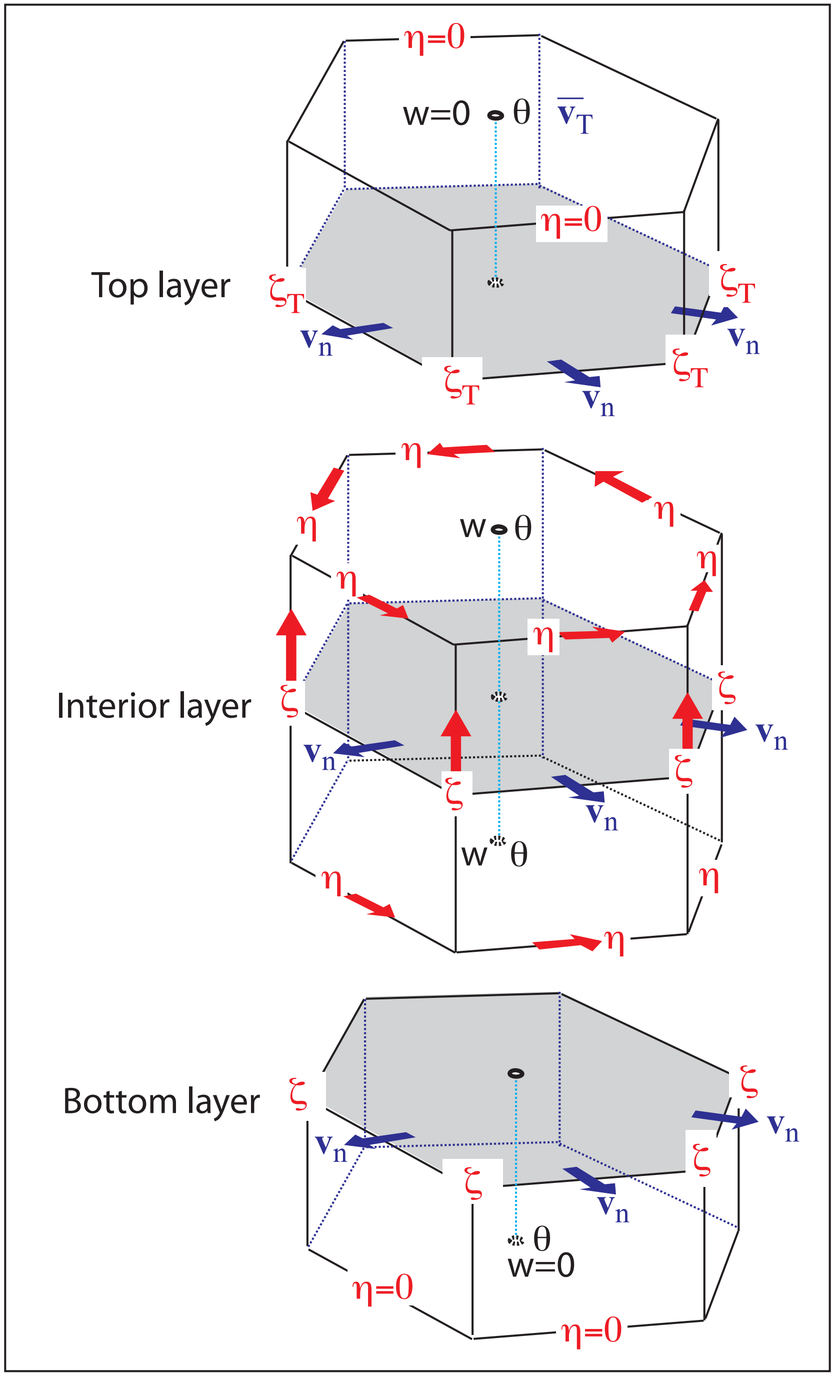
+ One 3D elliptic solver + Two 2D elliptic solvers

Is Hex-VVDC limited to anelastic system?

- **The current version is based on the nonhydrostatic anelastic system, which can be extended to the unified system (Arakawa and Konor, 2009, *MWR*) through add-on modules.**

  - ***Unified system unifies the quasi-hydrostatic and anelastic systems of equations. It does not require a basic (or mean) state, which is replaced by local hydrostatic state. Vertically propagating sound waves are filtered while large-scale compressibility is maintained. Mass (quasi-hydrostatic density) and energy are conserved. No assumption is made in the momentum and thermodynamic equations.***

3D Grid of the Hex-VVDC



- η=0 at the upper boundary
- ζ_T is predicted at top layer
- Upper boundary condition is w=0
- $\mathbf{v}_n$ is determined from streamfunction and velocity potential. Mean velocity is predicted

- η is predicted at interior interfaces
- ζ is diagnosed from ζ_T and η at layers
- w is solved from the 3D elliptic equation
- $\mathbf{v}_n$ is determined from η and w
- θ is predicted at every interface

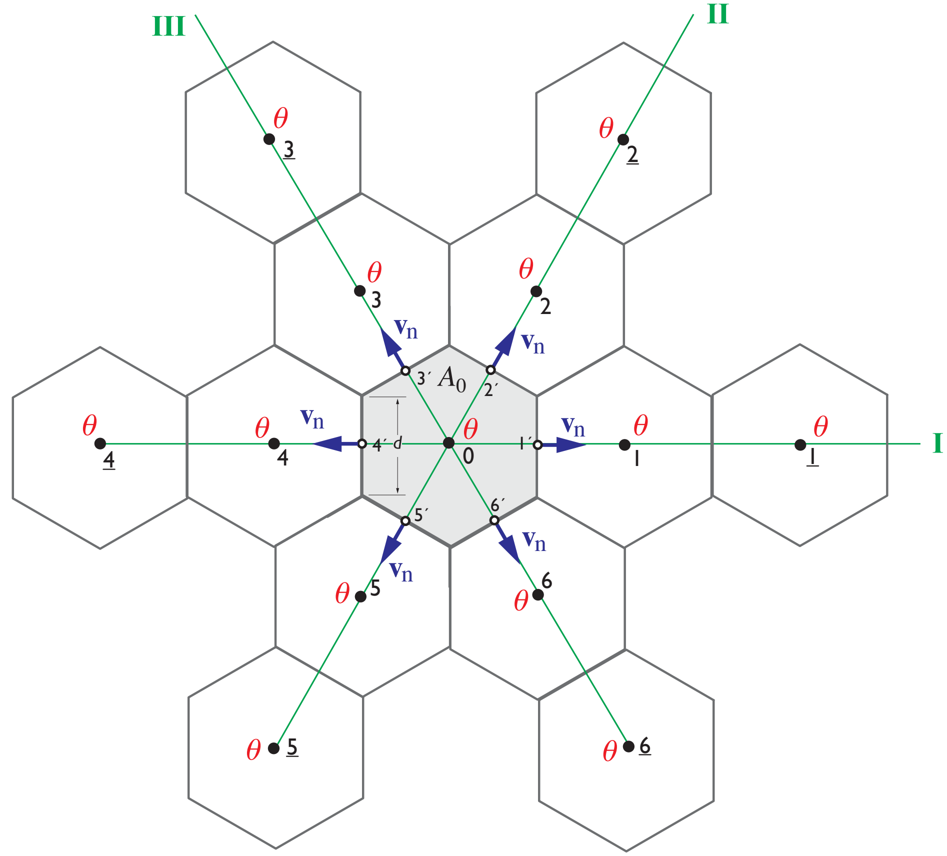
CP-grid instead of Lorenz-grid

- η=0 at the lower boundary
- Lower boundary condition is w=0

Discretization on Regular Hexagonal Grid

- **Heikes and Randall (1995) and Ringler and Randall (2002) present many of the discretization techniques we use in this model.**

Flux Convergence for the Cell Centers



Discretization on Regular Hexagonal Grid (Cont.)

- **Determination of the flux convergence of η vector for the cell walls is a real discretization challenge.**
- **The challenge appears due to difficulties in,**

i) properly determining a horizontal control volume,

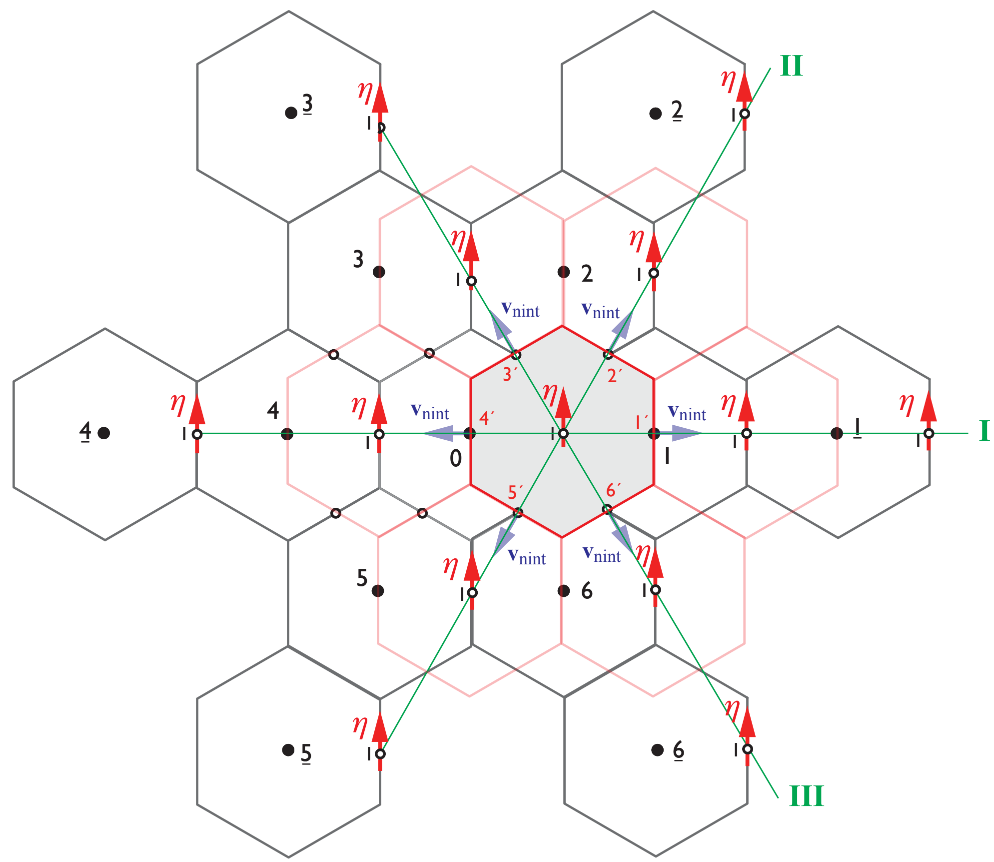
ii) properly interpolating the velocity to the edges of this control volume, and

iii) properly determining advecting a vector.

Flux convergence of horizontal vorticity

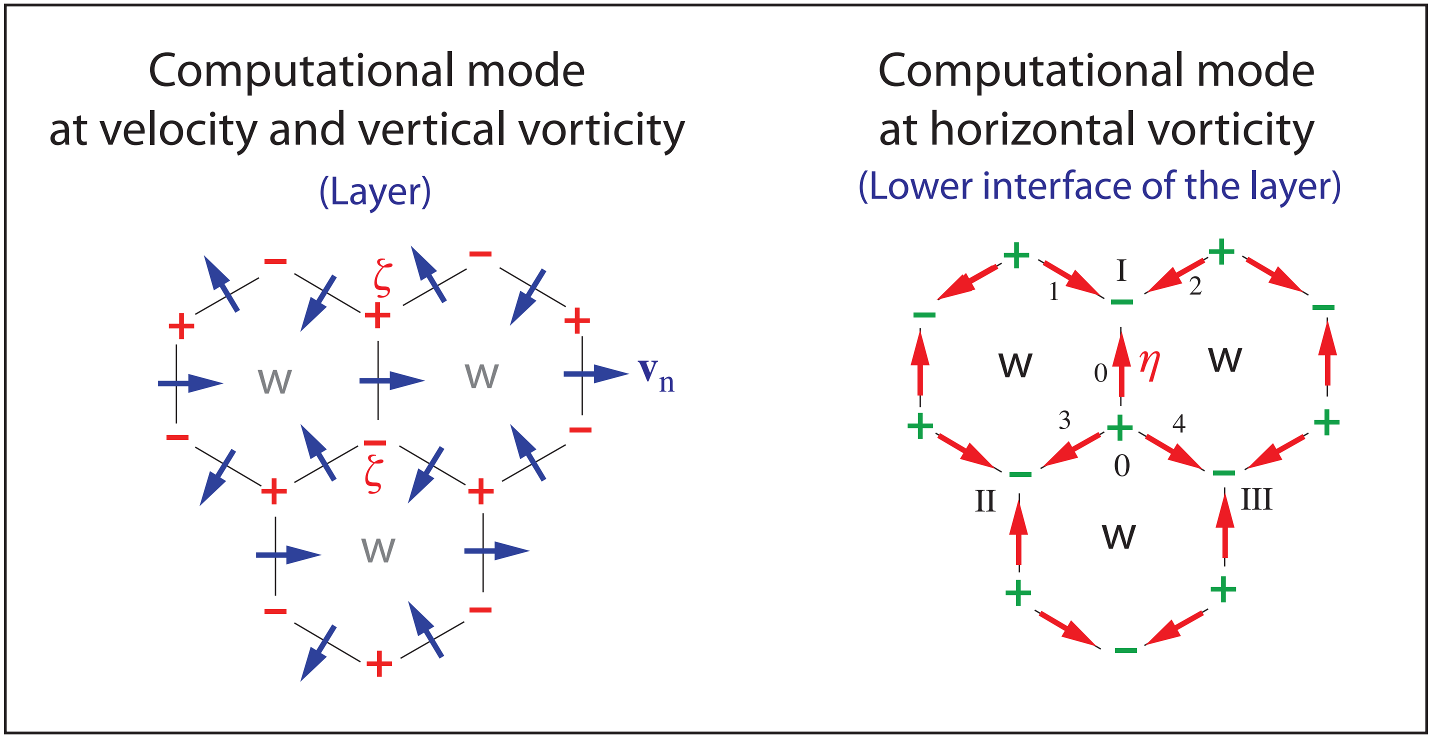
$$\frac{\partial \boldsymbol{\eta}}{\partial t} = -\nabla_H \cdot (\boldsymbol{\eta}\mathbf{v}) - \frac{\partial}{\partial z}(\boldsymbol{\eta} w)$$

Flux Convergence of a vector for the Cell Walls



Demonstration of the Existence of a Computational Mode

- **A computational mode in η, v_n and ζ is identified in early simulations.**



- **The computational mode is removed by an especially designed smoother.**

$$D_0^* \equiv \frac{1}{2} D_0 + \frac{1}{6}\left(D_I + D_{II} + D_{III}\right) \qquad \eta_0^* \equiv \frac{2}{3}\eta_0 - \frac{1}{6}\left(\eta_1 + \eta_2 + \eta_3 + \eta_4\right)$$

- **Predicted η is not smoothed. Smoothed η is used to determine horizontal velocity.**

Reviewer Comments from the Mid-Term Project Review

Q. Order of accuracy will be degraded (to the first-order) when a vertically stretched grid is used.

A. The way the grid stretching is made in our model does not degrade the accuracy.

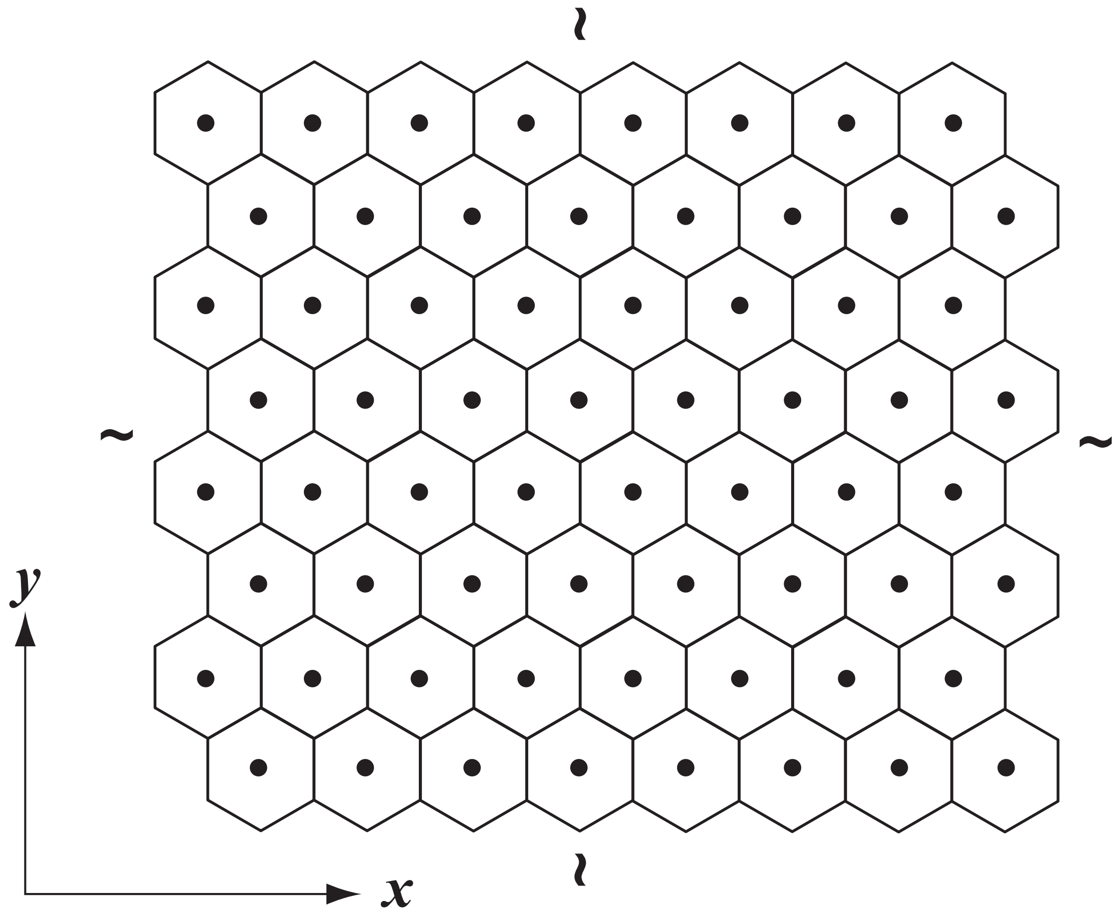
Q. The method used to minimize the computational mode will interfere with the physical mode (basic dynamics).

A. Similar methods are used to minimize the spurious modes caused by the discretization of Coriolis force on a hexagonal grid.
Effects can be assessed using horizontally discrete linearized systems.

Preliminary Results from the Test Simulations

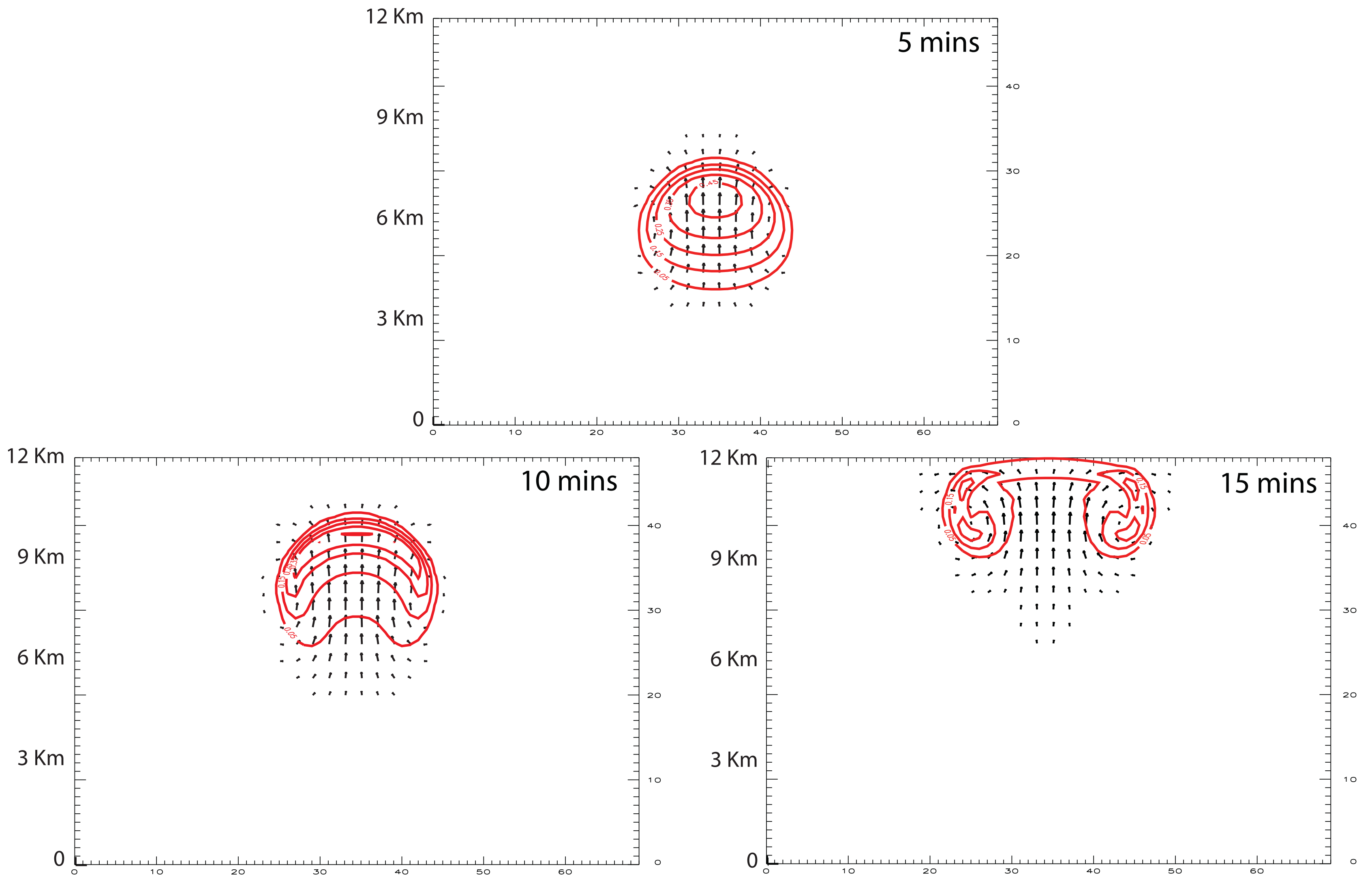
- **Based on various idealized basic states.**
- **Horizontal grid distance is 250m between the adjacent cell centers.**
- **There are 48 equally-sized layers between the surface and top at 12Km yielding 250m thickness per layer.**
- **Time step is 10 sec in most simulations.**

Horizontal Domain of the Hex-VVDC



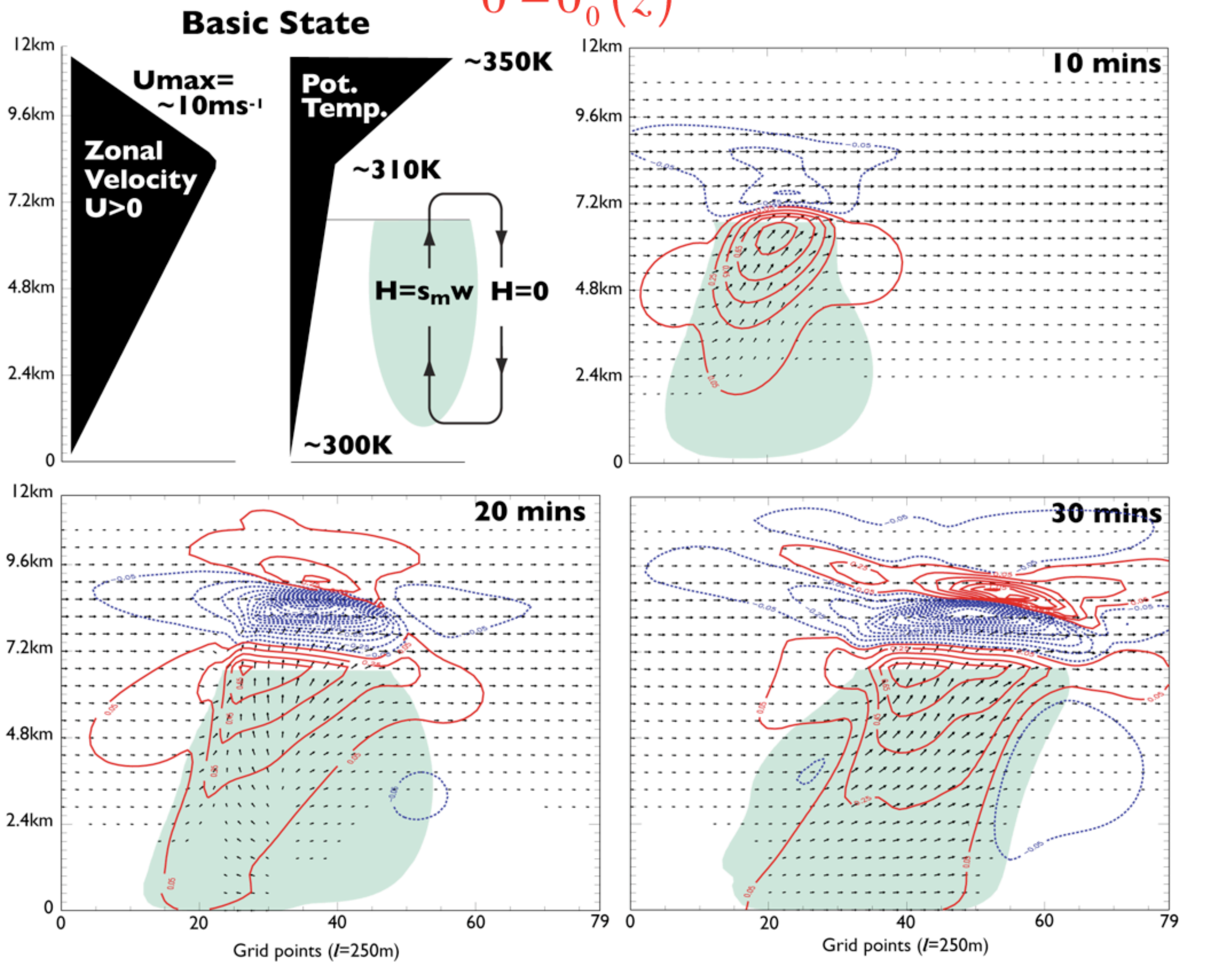
Hex-VVDC Simulation of the Ascent of a Buoyant Bubble on a Resting Isentropic Basic State

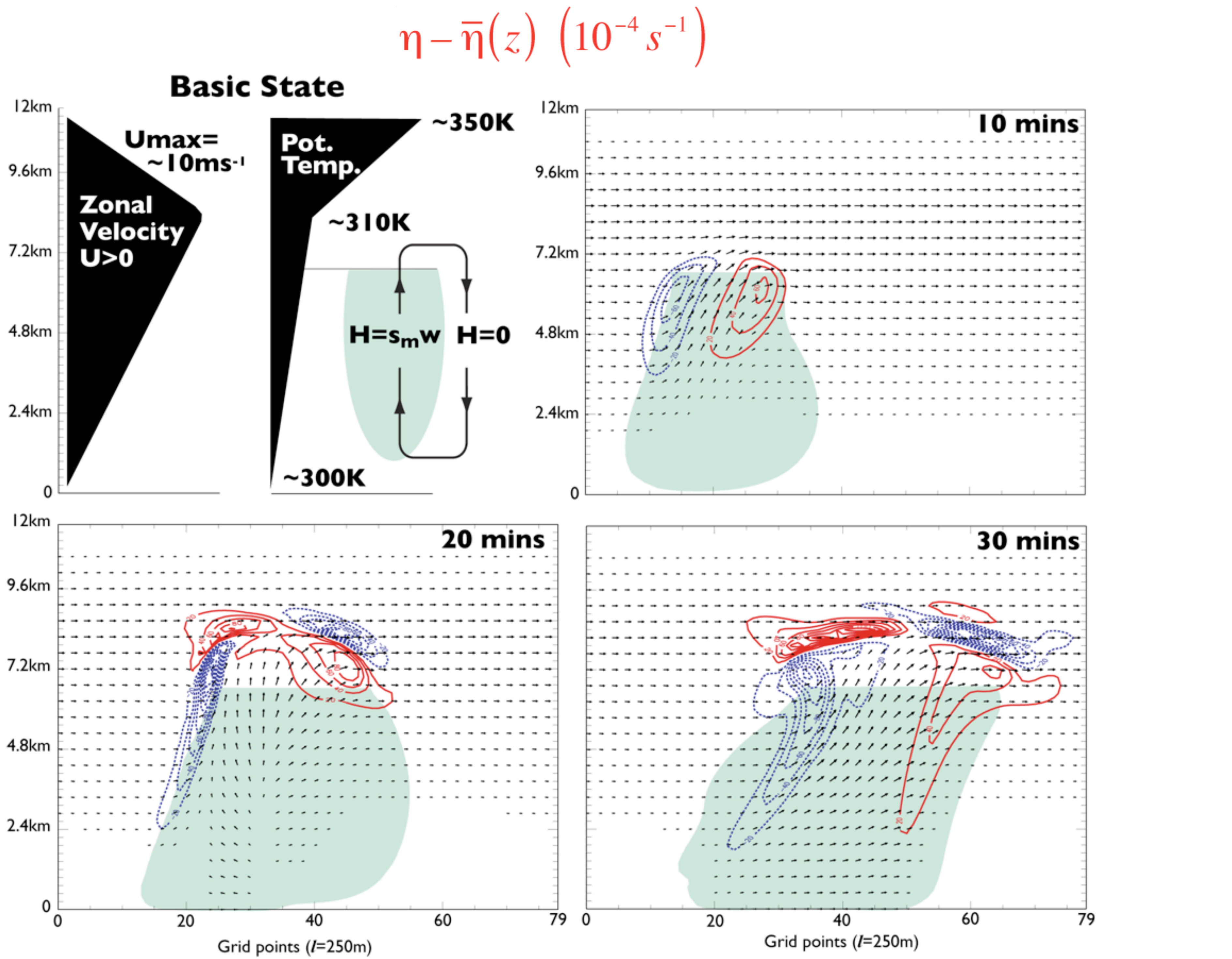
Cross-sections of simulated $\theta - \theta_0$ (K)



Hex-VVDC Simulation of the Ascent of a Buoyant Bubble (I)

$$\theta - \theta_0(z)$$

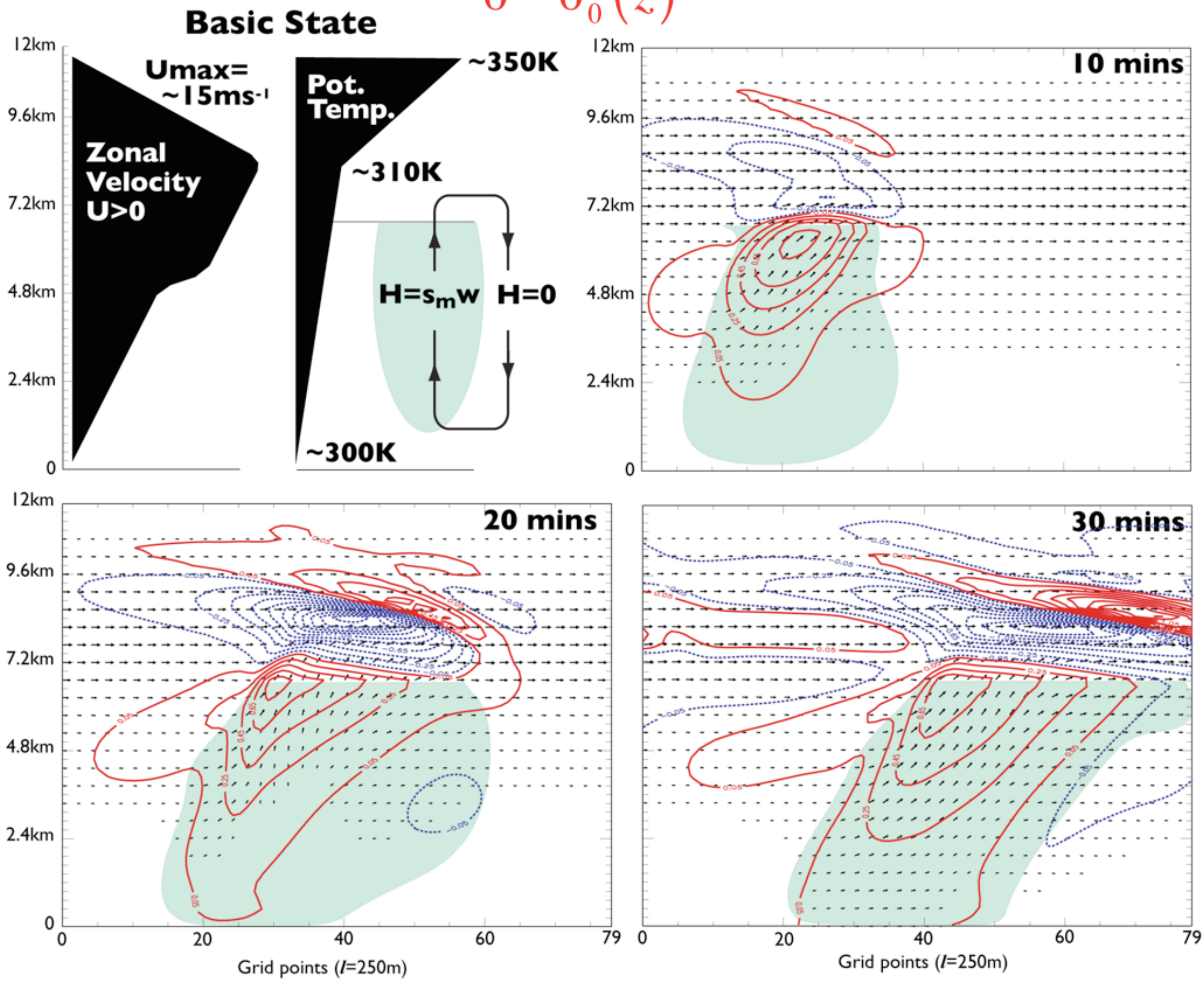




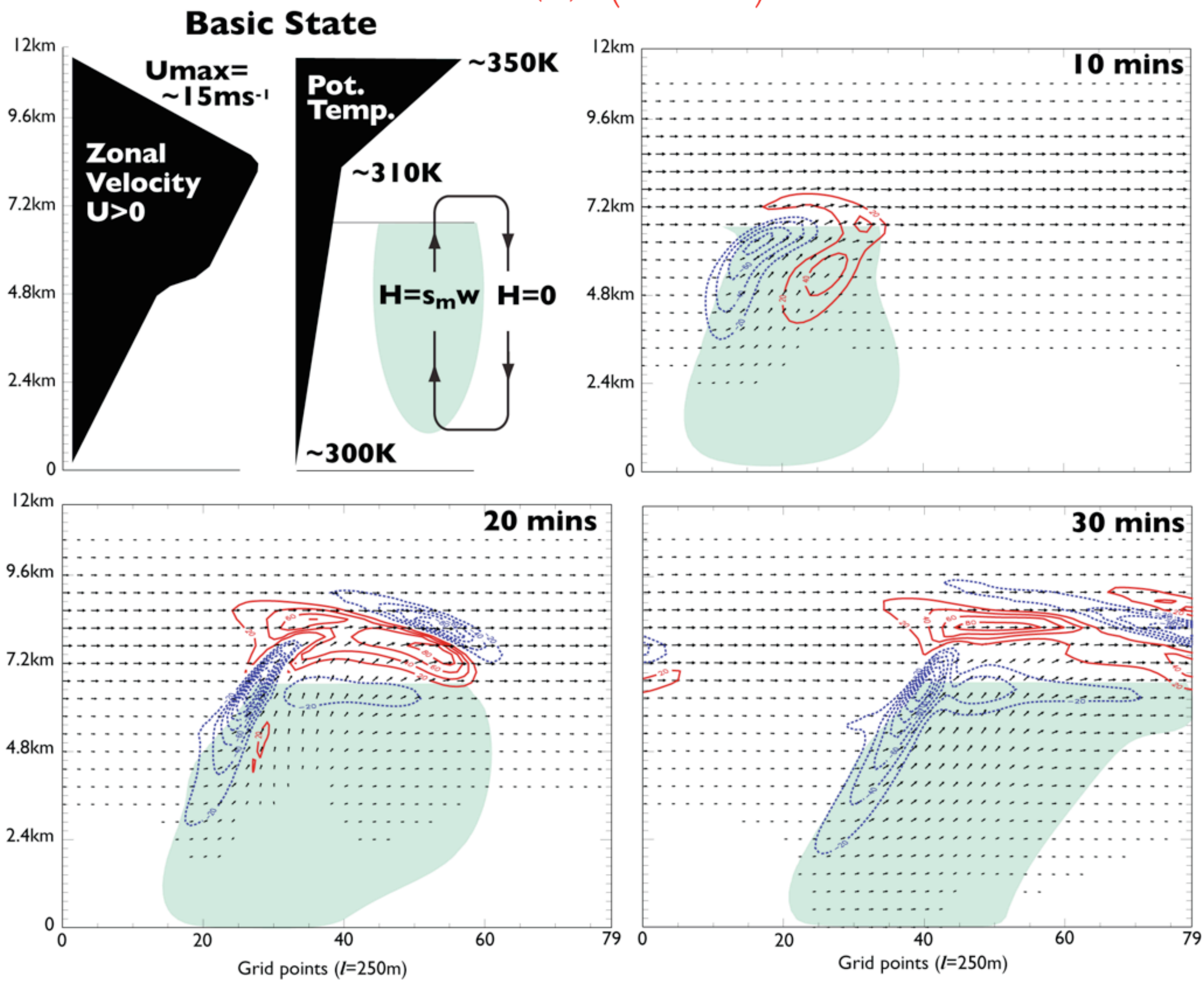
$\eta - \bar{\eta}(z) \ \left(10^{-4} s^{-1}\right)$
Basic State
Umax= ~10ms-1
Zonal Velocity U>0
Pot. Temp.
~350K
~310K
~300K
H=s_m w
H=0
12km
9.6km
7.2km
4.8km
2.4km
0
10 mins
20 mins
30 mins
0
20
40
60
79
Grid points (l=250m)

Hex-VVDC Simulation of the Ascent of a Buoyant Bubble (II)

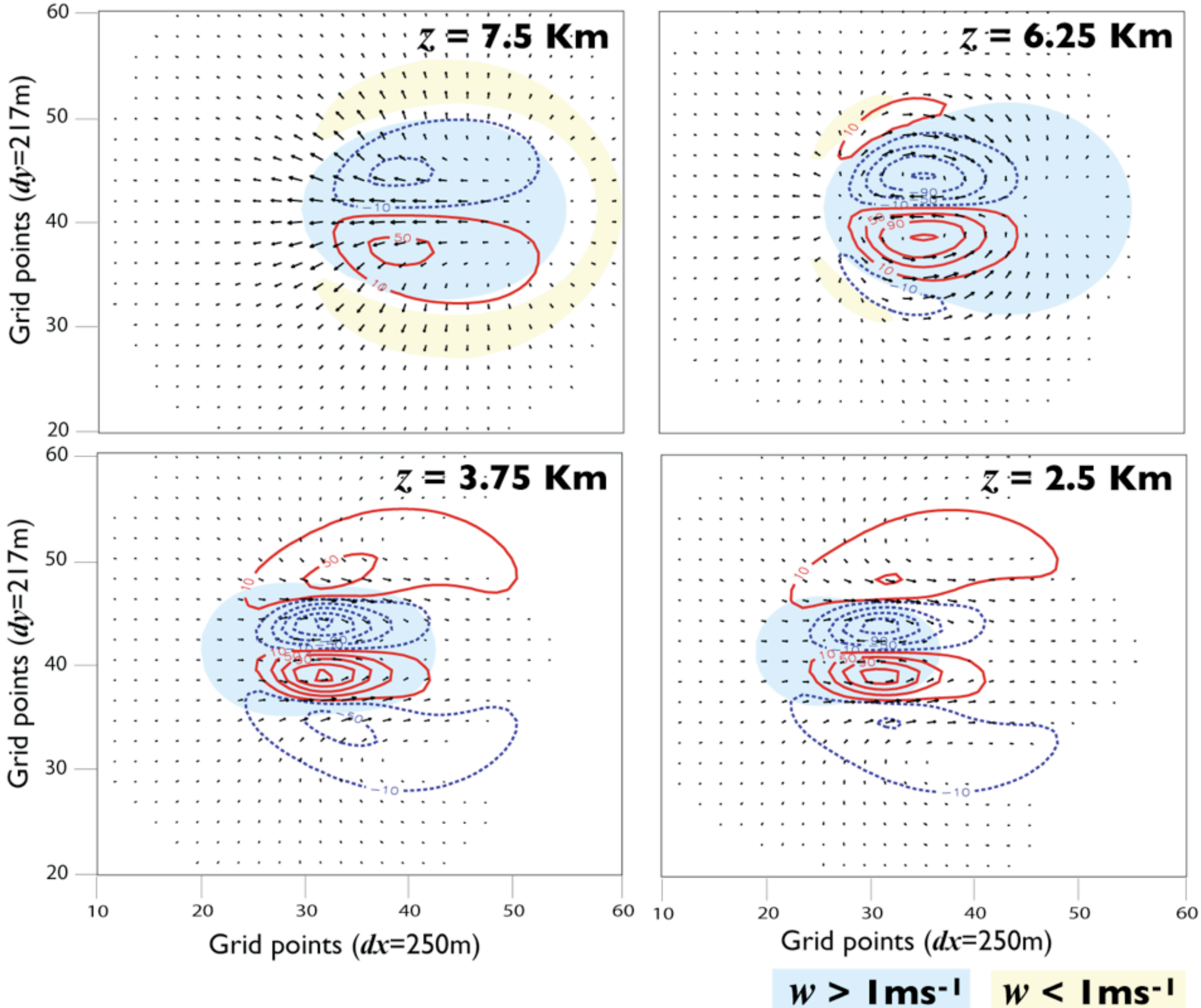
$$\theta - \theta_0(z)$$



$$\eta - \bar{\eta}(z) \ \left(10^{-4} s^{-1}\right)$$



Vertical Vorticity (10^{-4} s^{-4}) at Different Heights for 20 mins (II)



Conclusions and Outlook

- **The performance of Hex-VVDC so far is encouraging.**
- **A turbulence parameterization is included in the model.**
- **A surface flux parameterization is also included in the model.**
- **Adaptation of a microphysics and radiation parameterization is started.**