A Progress Report and More on the Unified System

Celal Konor

Department of Atmospheric Science
Colorado State University

Eleventh CMMAP Team Meeting, 9-11 August 2011, Fort Collins, CO
Dynamical Framework Working Group

Progress

- A dynamical core based on the unified system has been developed
- A paper describing the dynamical core and presenting the results has beed submitted for publication to JAMES.
- Development of a global dynamical core based on the unified system is nearly completed

Unified System

Arakawa and Konor (2009, *MWR*)

A nonhydrostatic system applicable to wide range of atmospheric scales of motion

- Filters vertically propagating acoustic waves while allowing elasticity due to thermal expansion
- Does not require a basic or mean state
- Does not introduce any approximation to the momentum and thermodynamic equations
- Introduces a minor approximation to the continuity equation
- Conserves energy

Unified System (Cont.)

A normal mode analysis confirms the followings:

- The unified system does not show the errors that appear with the anelastic and pseudo-incompressible systems while filtering vertically propagating acoustic waves
- Ultra-long Rossby waves are compressible and their retrogression speed is realistic

Comparison of the Equations of the Unified System to Those of Some Other Systems

State Equation

Fully Compressible

$$\rho = \frac{p_{00}\pi^{(1-\kappa)/\kappa}}{R\theta}$$

Quasi-Hydrostatic	Anelastic	Unified
$\rho_{qs} = \frac{p_{00}\pi_{qs}^{(1-\kappa)/\kappa}}{R\theta}$	$\rho = \frac{p_{00}\pi^{(1-\kappa)/\kappa}}{R\theta}$ and $\bar{\rho} = \frac{p_{00}\bar{\pi}^{(1-\kappa)/\kappa}}{R\bar{\theta}}$ $\pi = \bar{\pi}(z) + \pi'$ $\theta = \bar{\theta}(z) + \theta'$ $\rho = \bar{\rho}(z) + \rho'$	$\rho = \frac{p_{00}\pi^{(1-\kappa)/\kappa}}{R\theta}$ and $\rho_{qs} = \frac{p_{00}\pi_{qs}^{(1-\kappa)/\kappa}}{R\theta}$ $\pi = \pi_{qs} + \delta\pi$ $\rho = \rho_{qs} + \delta\rho$ $T_{qs} = \pi_{qs}\theta$ $T = \pi\theta$
qs: Quasi-hydrostatic	*Bar: Basic/Mean state* *prime: Deviation*	*qs: Quasi-hydrostatic* *d: Non-hydrostatic*

Comparison of Equations

Horizontal Momentum

Fully Compressible

$$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} + c_p\theta\nabla_H\pi_{qs} + c_p\theta\nabla_H\delta\pi = \mathbf{F}_H$$

$$\pi = \pi_{qs} + \delta\pi$$

Quasi-Hydrostatic	Anelastic	Unified
$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} + c_p\theta\nabla_H\pi_{qs} = \mathbf{F}_H$	$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} + c_p\bar{\theta}\nabla_H\pi' = \mathbf{F}_H$	$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} + c_p\theta\nabla_H\pi_{qs} + c_p\theta\nabla_H\delta\pi = \mathbf{F}_H$
$\pi = \pi_{qs}$	$\pi = \bar{\pi}(z) + \pi'$, $\theta = \bar{\theta}(z) + \theta'$; $\pi' \ll \bar{\pi}$, $\theta' \ll \bar{\theta}$	$\pi = \pi_{qs} + \delta\pi$
qs: Quasi-hydrostatic	Bar: Basic/Mean state prime: Deviation	qs: Quasi-hydrostatic d: Non-hydrostatic

Comparison of Equations

Vertical Momentum

Fully Compressible

$$\frac{Dw}{Dt} + c_p \theta \frac{\partial}{\partial z} \delta\pi = F_w$$

$$\pi = \pi_{qs} + \delta\pi$$

Quasi-Hydrostatic	Anelastic	Unified
	$\frac{Dw}{Dt} + c_p \bar{\theta} \frac{\partial}{\partial z} \pi' - g \frac{\theta - \bar{\theta}}{\bar{\theta}} = F_w$ $\pi' \ll \bar{\pi}$ $\theta' \ll \bar{\theta}$ $\pi = \bar{\pi}(z) + \pi'$ $\theta = \bar{\theta}(z) + \theta'$ Bar: Basic/Mean state prime: Deviation	$\frac{Dw}{Dt} + c_p \theta \frac{\partial}{\partial z} \delta\pi = F_w$ $\pi = \pi_{qs} + \delta\pi$ qs: Quasi-hydrostatic d: Non-hydrostatic
		Not used to predict w

Comparison of Equations

Hydrostatic Equation

Fully Compressible

$$c_p \theta \frac{\partial}{\partial z} \pi_{qs} = -g$$

Quasi-Hydrostatic	Anelastic	Unified
$c_p \theta \frac{\partial}{\partial z} \pi_{qs} = -g$		$c_p \theta \frac{\partial}{\partial z} \pi_{qs} = -g$

Comparison of Equations

Thermodynamic Equation

Fully Compressible

$$\frac{D\theta}{Dt} = \frac{Q}{c_p \pi}$$

Quasi-Hydrostatic	Anelastic	Unified
$\frac{D\theta}{Dt} = \frac{Q}{c_p \pi_{qs}}$	$\frac{D\theta}{Dt} = \frac{Q}{c_p \pi}$	$\frac{D\theta}{Dt} = \frac{Q}{c_p \pi}$

Comparison of Equations

Continuity Equation

Fully Compressible

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

Quasi-Hydrostatic	Anelastic	Unified
$\frac{\partial(\rho_{qs} w)}{\partial z} = -\nabla_H \cdot (\rho_{qs} \mathbf{v}) - \frac{\partial \rho_{qs}}{\partial t}$	$\frac{\partial(\bar{\rho} w)}{\partial z} = -\nabla_H \cdot (\bar{\rho} \mathbf{v})$ $\rho' \ll \bar{\rho}$ $\quad$ $\partial \rho' / \partial t \approx 0$ $\rho = \bar{\rho}(z) + \rho'$ Bar: Basic/Mean state $\quad$ prime: Deviation	$\frac{\partial(\rho_{qs} w)}{\partial z} = -\nabla_H \cdot (\rho_{qs} \mathbf{v}) - \frac{\partial \rho_{qs}}{\partial t}$ $\delta\rho \ll \rho_{qs}$ $\quad$ $\partial \delta\rho / \partial t \approx 0$ $\rho = \rho_{qs} + \delta\rho$ qs: Quasi-hydrostatic $\quad$ d: Non-hydrostatic
		Not used to predict quasi-hydrostatic density, but used to determine w

Comparison of Equations

Elliptic Equation

	Fully Compressible	
Quasi-Hydrostatic	*Anelastic*	*Unified*
	$\bar{\rho}\nabla_H \cdot \left(c_p \bar{\theta} \nabla_H \pi'\right) + \frac{\partial}{\partial z}\left(\bar{\rho} c_p \bar{\theta} \frac{\partial}{\partial z}\pi'\right) = G_{AN}$ *Generally requires more iterations than the unified counterpart since p' also includes a quasi-hydrostatic component.*	$\rho_{qs}\nabla_H \cdot \left(c_p \theta \nabla_H \delta\pi\right) + \frac{\partial}{\partial z}\left(\rho_{qs} c_p \theta \frac{\partial}{\partial z}\delta\pi\right) = -\rho_{qs}\nabla_H \cdot \left(c_p \theta \nabla_H \pi_{qs}\right) + G + \frac{\partial^2 \rho_{qs}}{\partial t^2}$

The Integration Procedure used in the Dynamical Core

1-Predict q

$$\frac{D\theta}{Dt} = \frac{Q}{c_p \pi}$$

2-Determine quasi-hydrostatic quantities

$$\frac{\partial \pi_{qs}}{\partial z} = -\frac{g}{c_p \theta}$$

$$\rho_{qs} = \frac{p_{00} \pi_{qs}^{(1-\kappa)/\kappa}}{R\theta}$$

$$\partial \rho_{qs} / \partial t \qquad \partial^2 \rho_{qs} / \partial t^2$$

3-Determine nonhydrostatic quantities

$$\rho_{qs} \nabla_H \cdot \left(c_p \theta \nabla_H \delta\pi \right) + \frac{\partial}{\partial z}\left(\rho_{qs} c_p \theta \frac{\partial}{\partial z} \delta\pi \right) = -\rho_{qs} \nabla_H \cdot \left(c_p \theta \nabla_H \pi_{qs} \right) + G + \frac{\partial^2 \rho_{qs}}{\partial t^2}$$

4-Predict horizontal momentum

$$\frac{D\mathbf{v}}{Dt} + f\mathbf{k} \times \mathbf{v} + c_p \theta \nabla_H \pi_{qs} + c_p \theta \nabla_H \delta\pi = \mathbf{F}_H$$

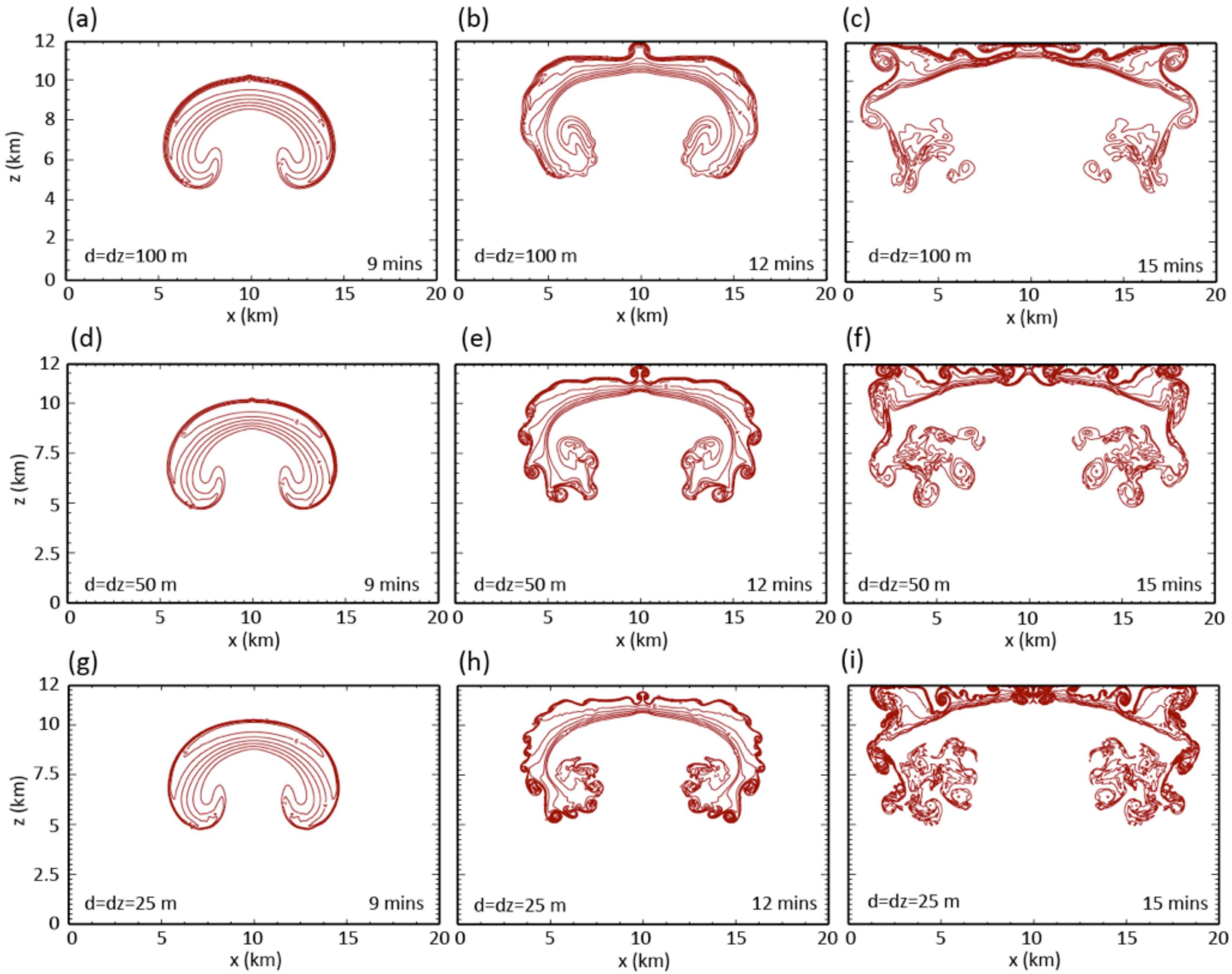
5-Determine vertical momentum

$$\frac{\partial \left(\rho_{qs} w \right)}{\partial z} = -\nabla_H \cdot \left(\rho_{qs} \mathbf{v} \right) - \frac{\partial \rho_{qs}}{\partial t}$$

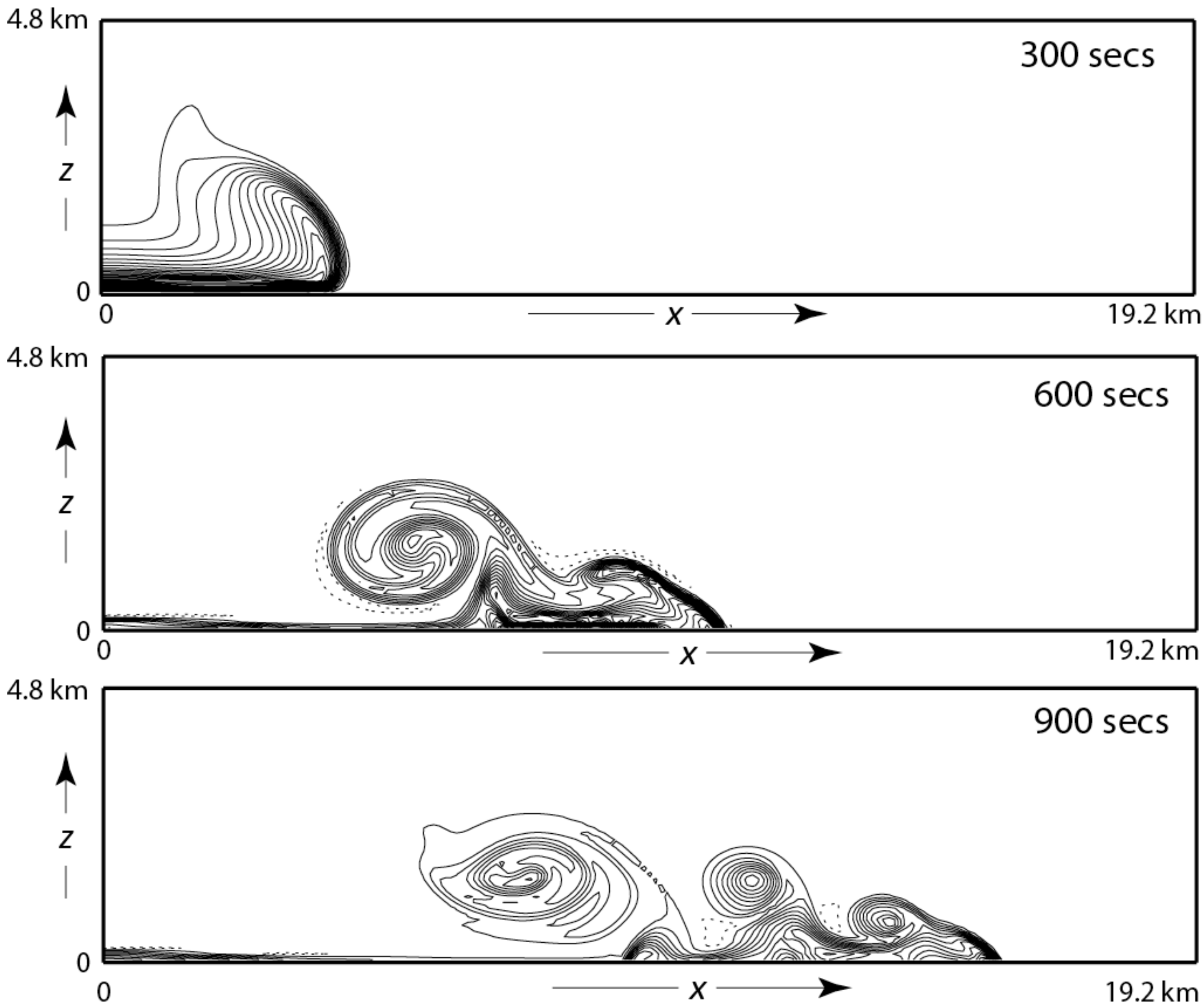
Some results from Konor (2011)

- Warm bubble tests
- Cold bubble tests
- Idealized extratropical cyclogenesis simulations

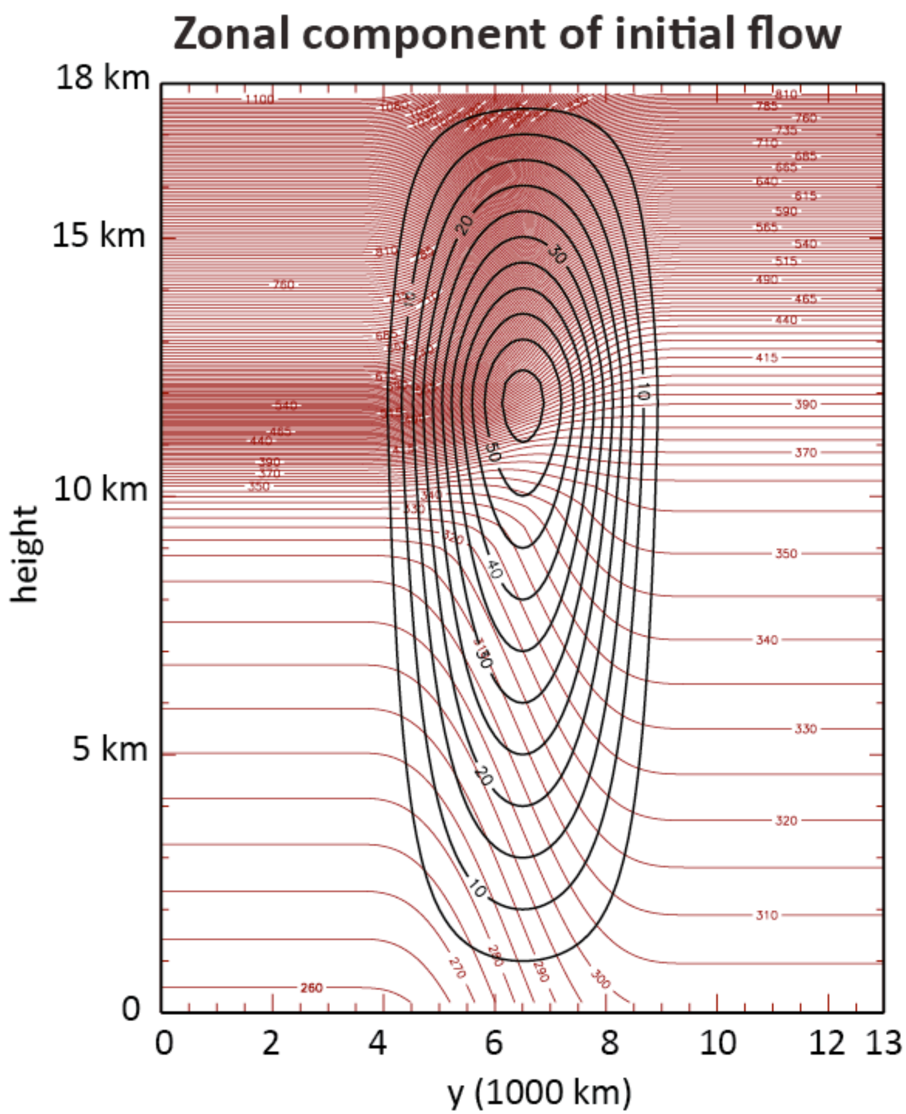
Warm bubble tests [Suggested by Mendez-Nunez and Carroll, 1993]



Cold bubble tests [Suggested by Straka et al., 1993]



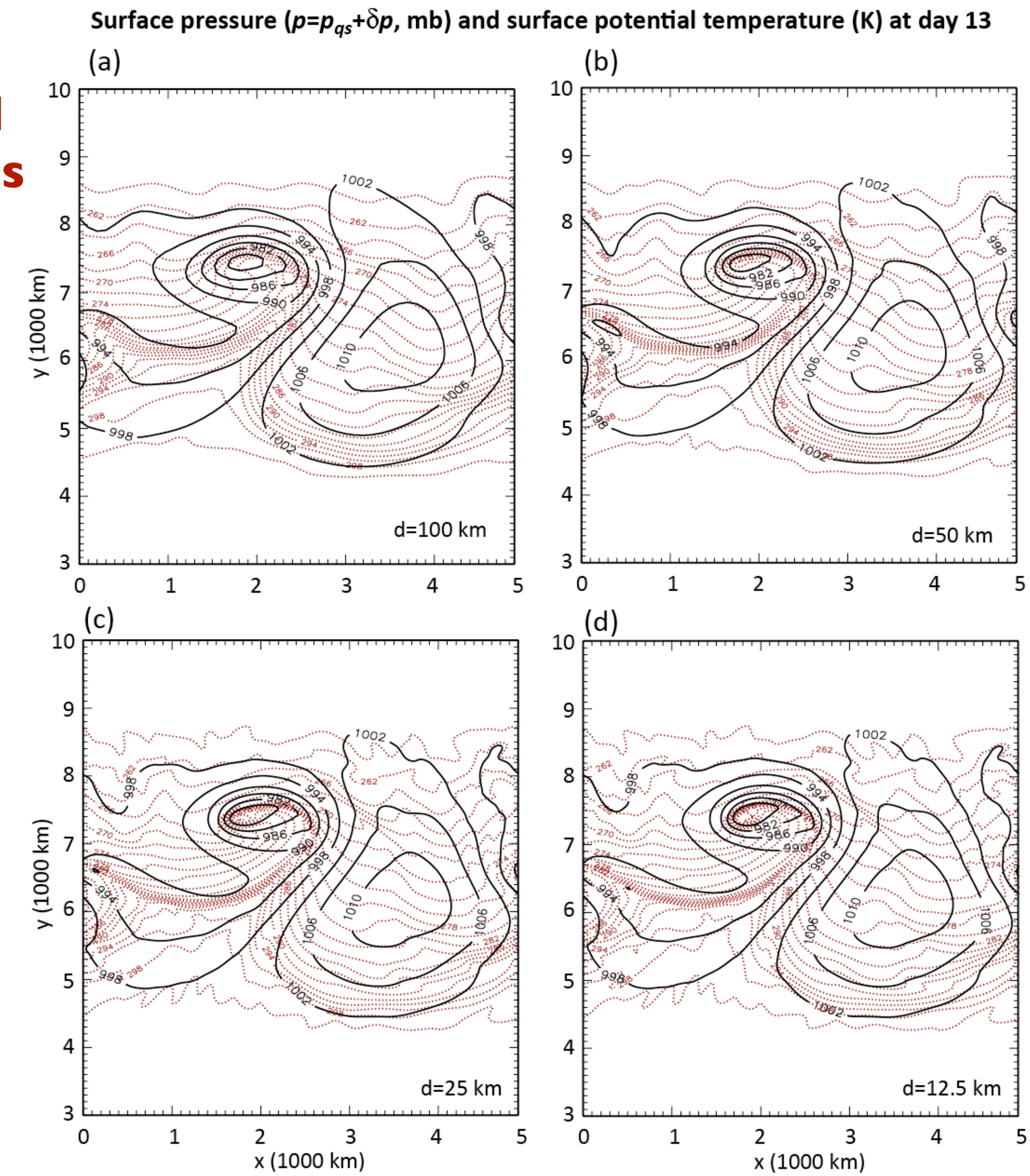
Idealized extratropical cyclogenesis simulations



- Domain is a 5000 km long channel on an extratropical b-plane
- Start from random perturbations of potential temperature
- 45 layers (400 m)
- Four different horizontal grid distances: 100 km, 50 km, 25 km and 12.5 km

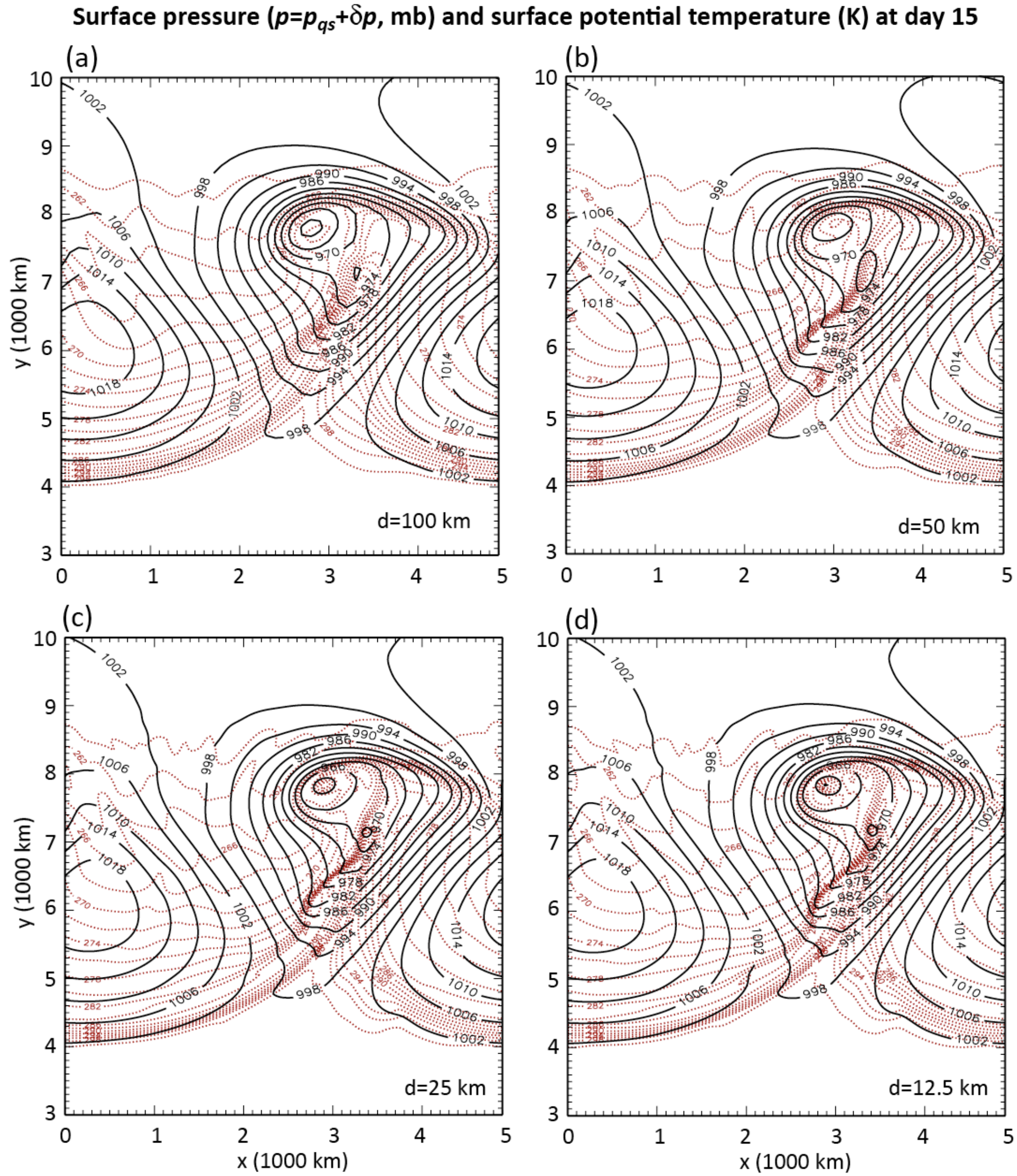
Idealized extratropical cyclogenesis simulations

Surface fields at Day 13



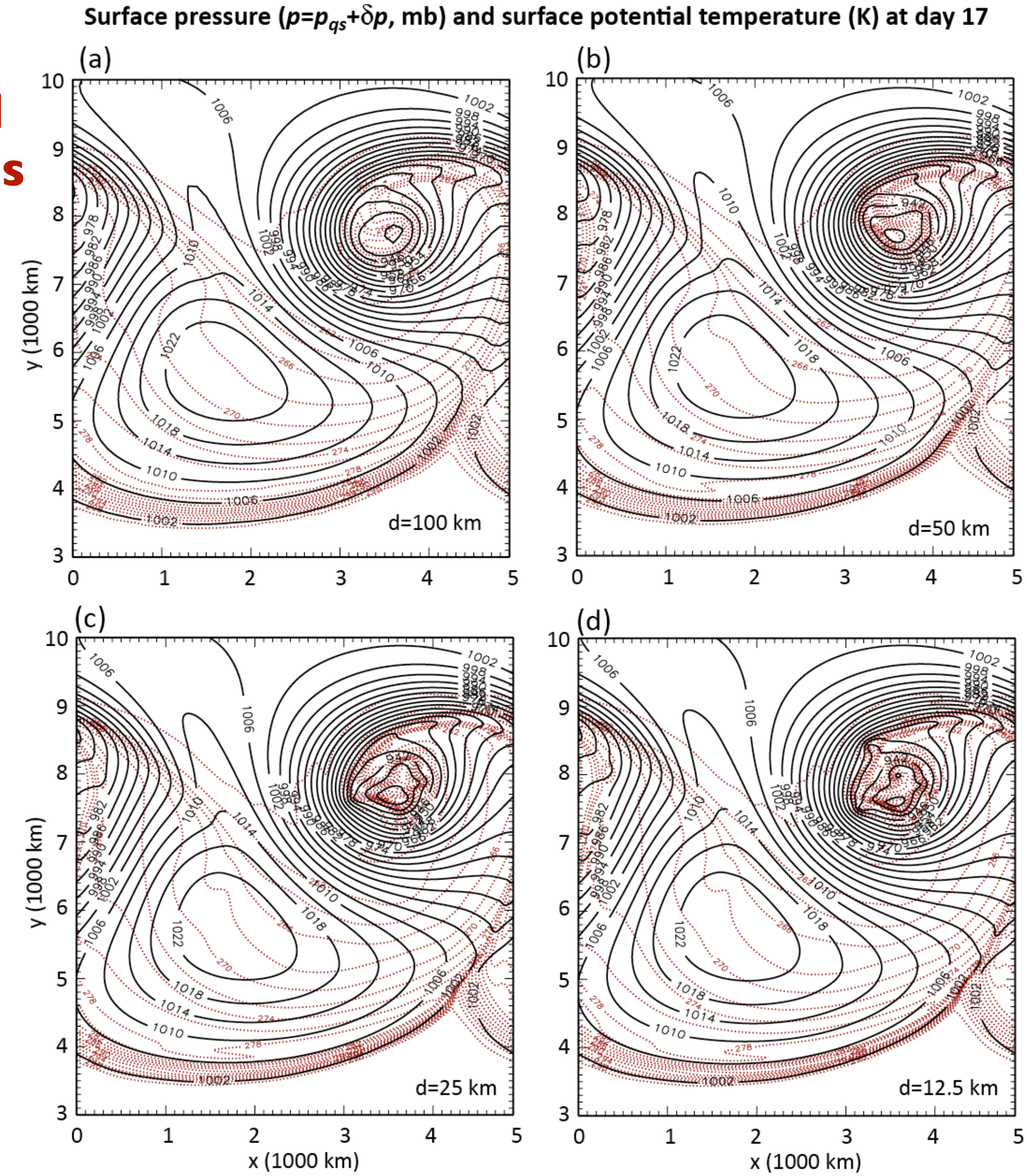
Idealized extratropical cyclogenesis simulations

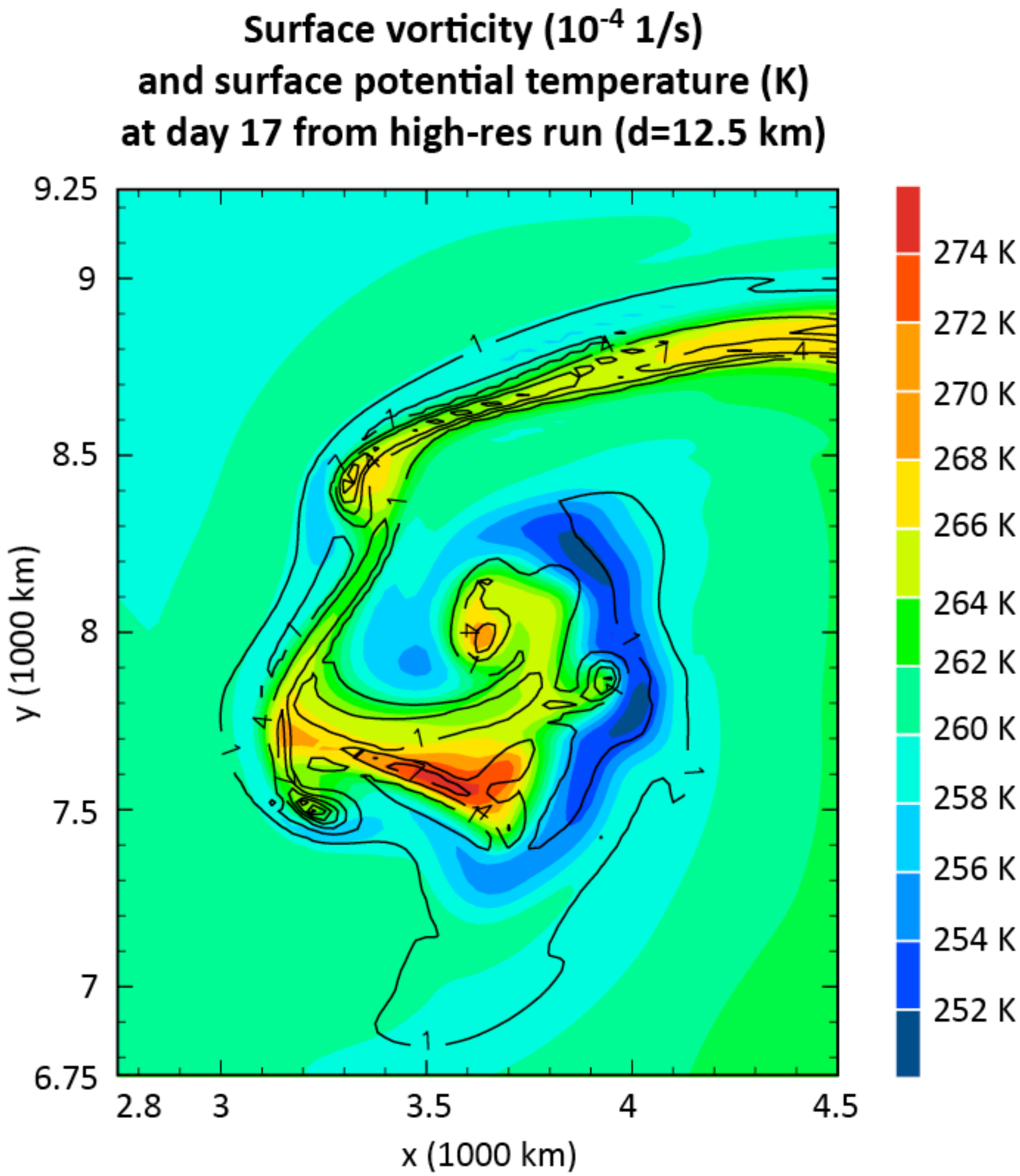
Surface fields at Day 15



Idealized extratropical cyclogenesis simulations

Surface fields at Day 17

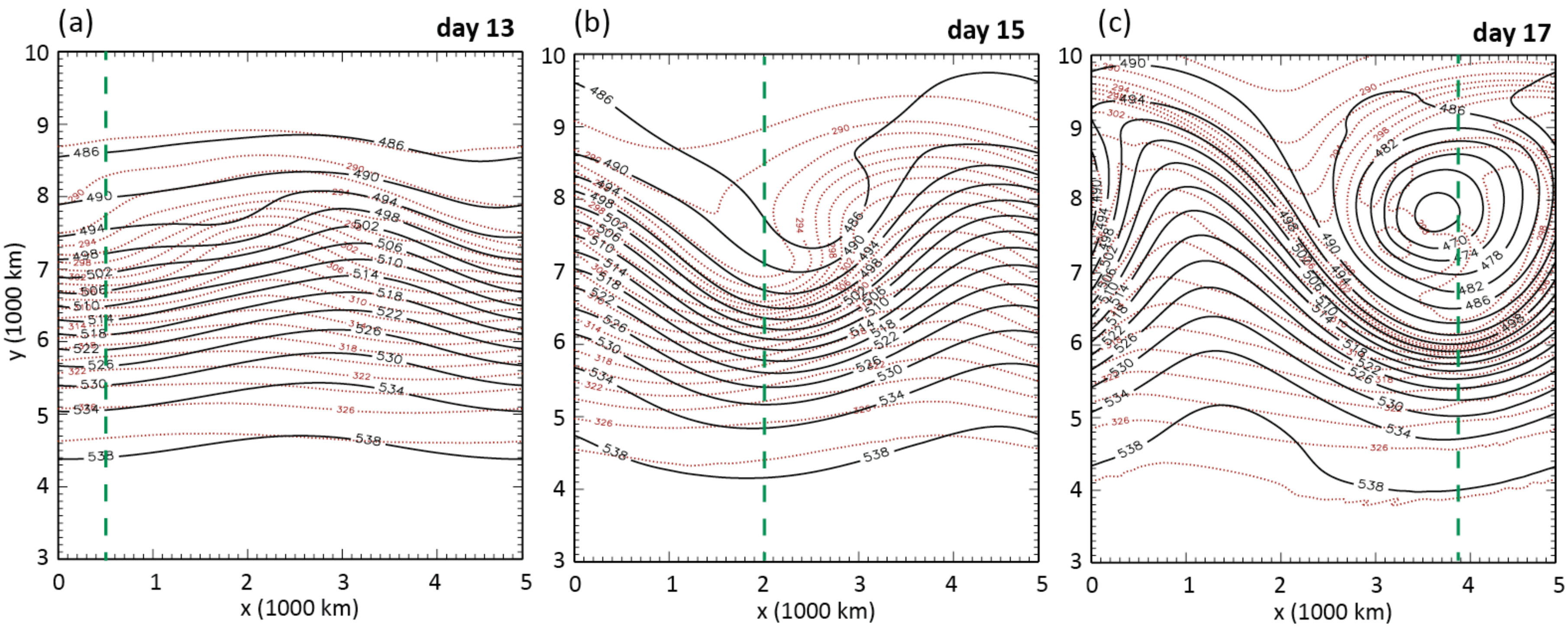



Surface vorticity (10^{-4} 1/s)
and surface potential temperature (K)
at day 17 from high-res run (d=12.5 km)
9.25
9
8.5
8
7.5
7
6.75
y (1000 km)
2.8
3
3.5
4
4.5
x (1000 km)
274 K
272 K
270 K
268 K
266 K
264 K
262 K
260 K
258 K
256 K
254 K
252 K

Idealized extratropical cyclogenesis simulations

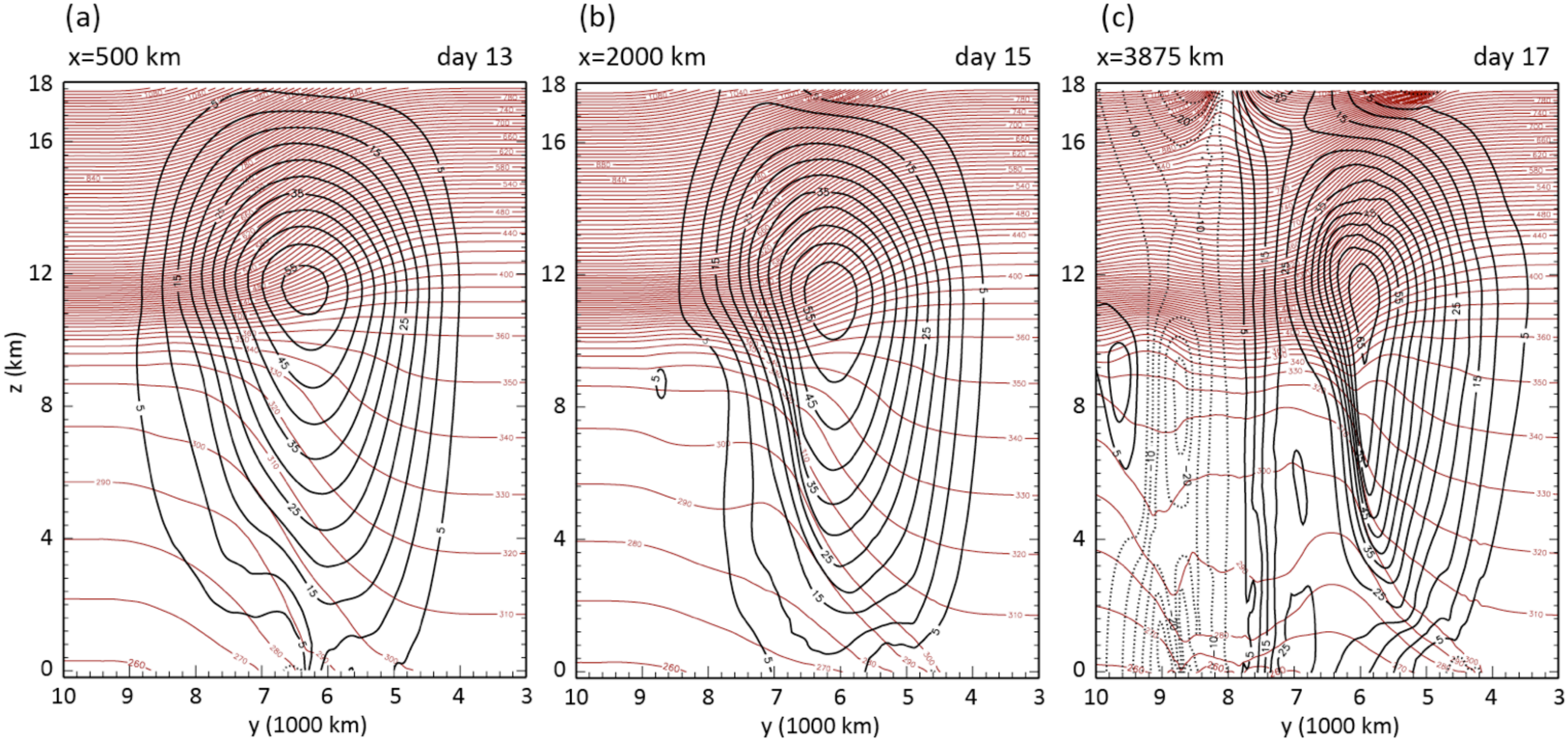
Middle troposphere fields from 12.5-km run at Days 13, 15 and 17

Pressure (p=p_{qs}+δp, mb) and potential temperature (K) for 5200 m height from high-resolution run (d=12.5 km)



Idealized extratropical cyclogenesis simulations

y-z cross-sections of zonal velocity (m/s) and potential temperature (K) from high-resolution run (d=12.5 km)



Summary

- The dynamical core based on the unified system performs well in the warm and cold bubble tests and in simulating idealized exratropical cyclogenesis
- A paper describing the dynamical core and presenting the results has beed submitted for publication to JAMES.

Remaining tasks

- Completion of a global dynamical core based on the unified system
- Inclusion of physics into the global dynamical core
- Construction of a new global MMF