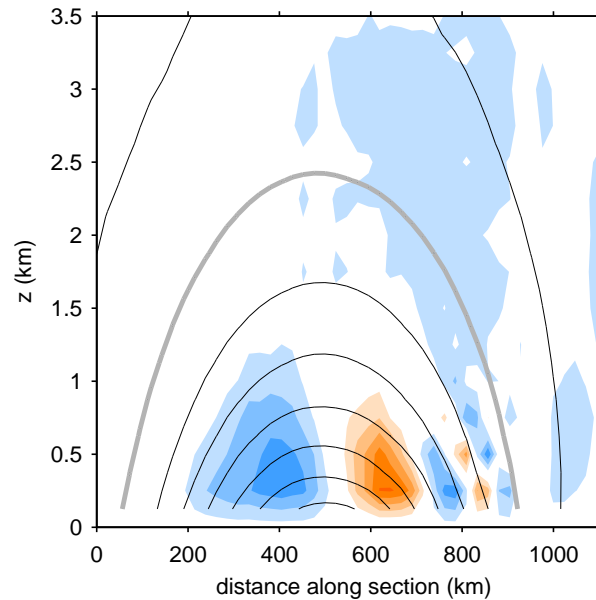
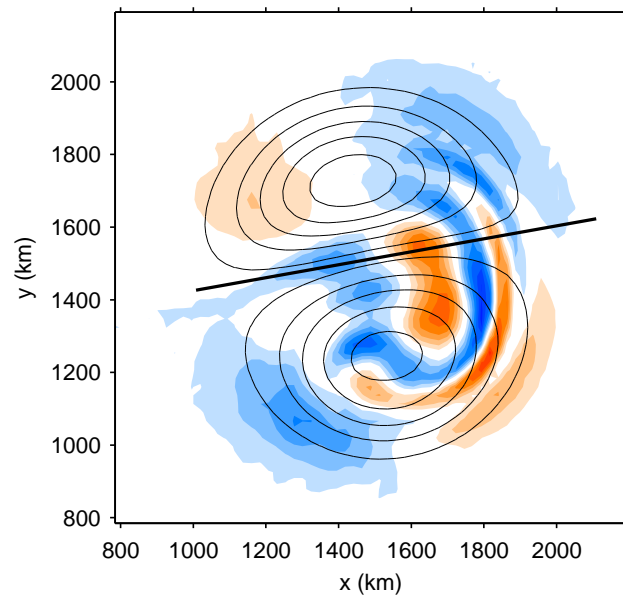


Inertia-Gravity Waves Generated within a Vortex Dipole



- ▷ Chris Snyder (NCAR)
- ▷ Dave Muraki (Simon Fraser)
- ▷ Riwal Plougonven (LMD)
- ▷ Fuqing Zhang (Texas A&M)

Introduction ---

Interest is interaction of i-g waves and balanced flow

- ▷ midlatitude troposphere and lower stratosphere
- ▷ $Ro \sim F \lesssim 1$

Observations

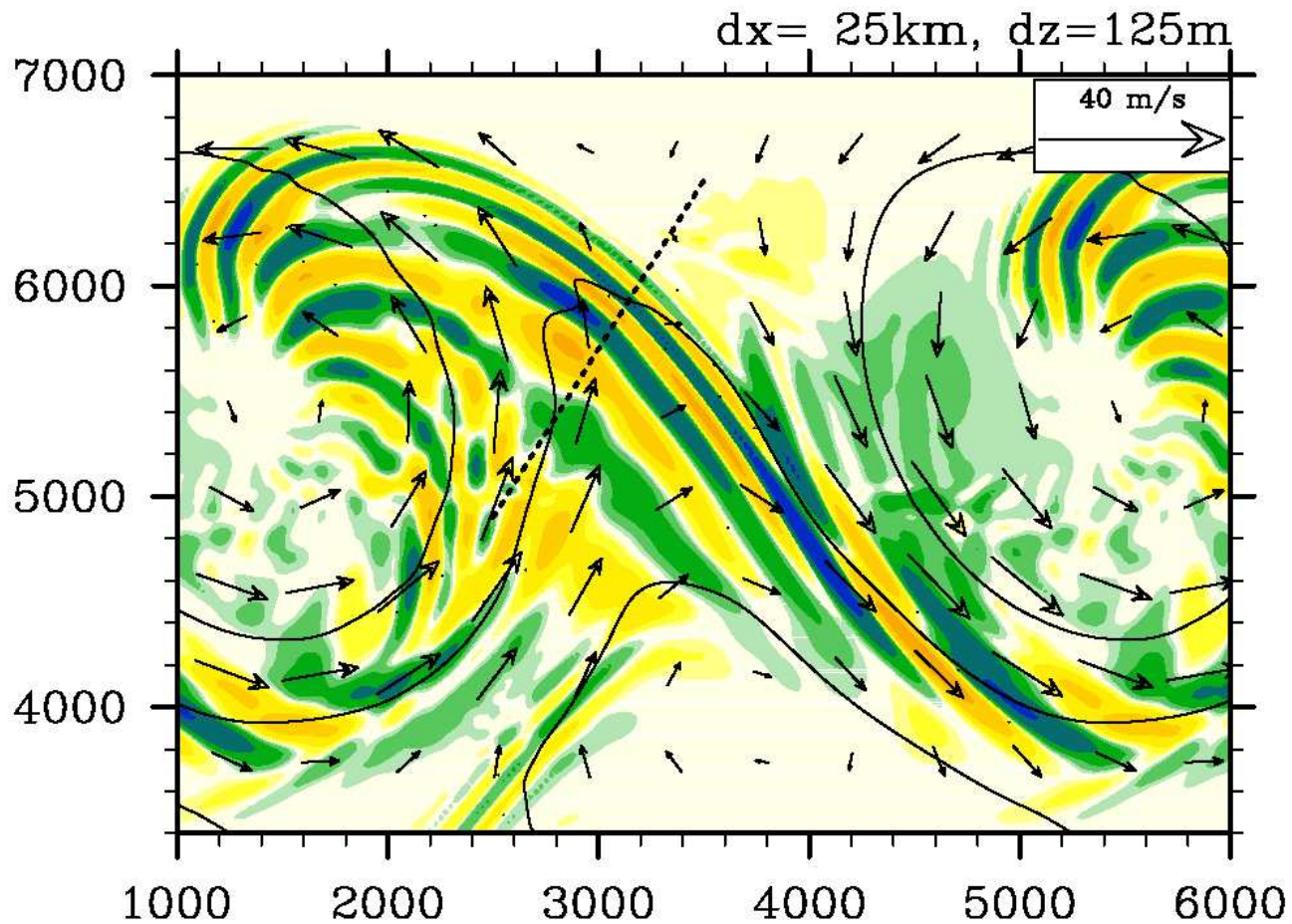
- ▷ tropospheric i-g waves associated with “jet streaks” near tropopause, embedded with synoptic-scale baroclinic waves (Uccellini and Koch 1987, etc.)

Idealization: jet streak \equiv vortex dipole at tropopause

- ▷ Houghton et al. 1981, Van Tuyl and Young 1982, Cunningham and Keyser 2000

Example

Flow relative to baroclinic wave



Plougonven and Snyder 2005

- ▷ horizontal divergence and system-relative wind vectors at 13 km

Experiments with a Dipole Vortex ---

Consider rotating, stratified flow

- ▷ rigid, flat lower boundary
- ▷ doubly periodic domain on an f -plane

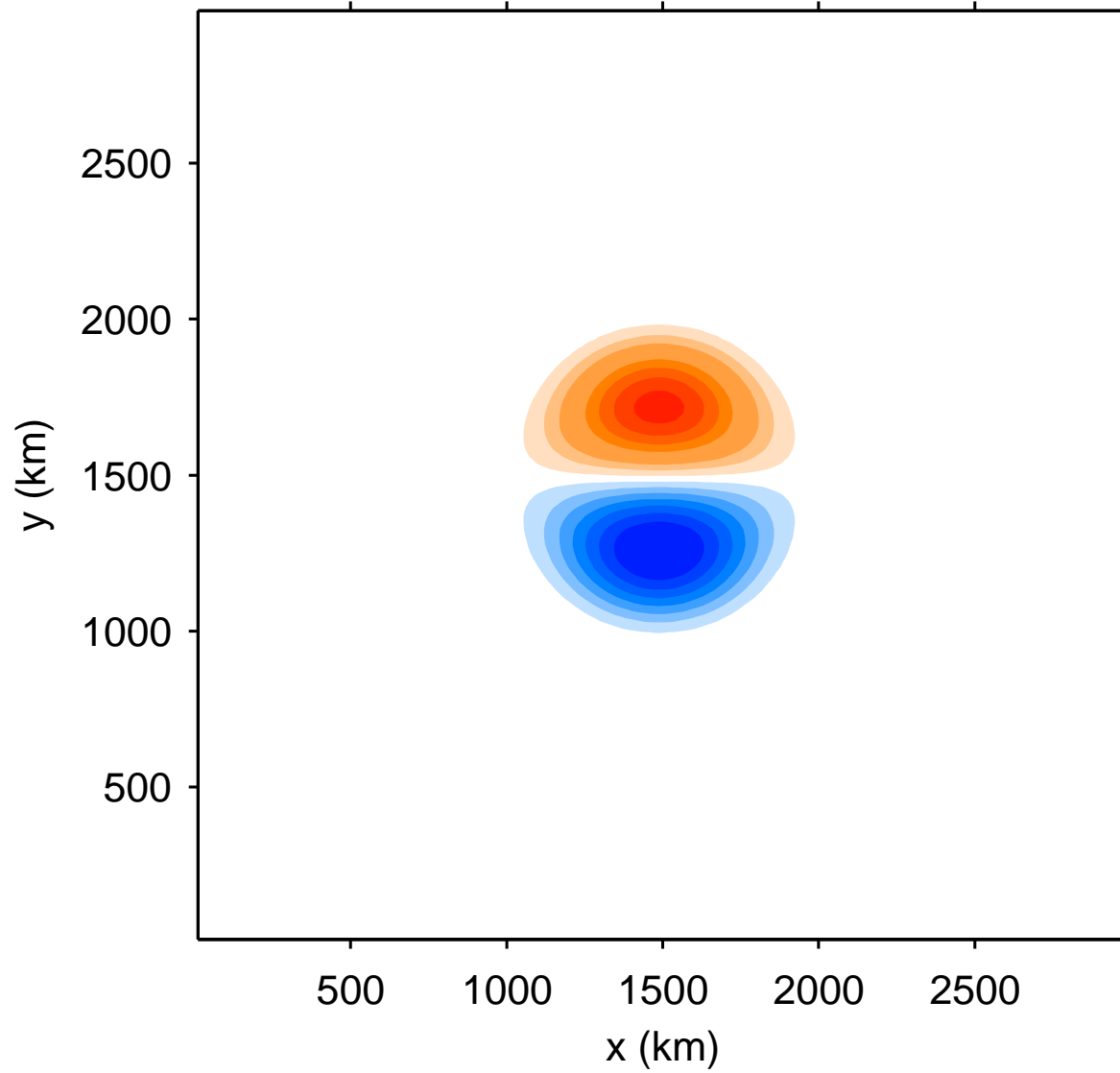
Surface-trapped quasigeostrophic dipole vortex

- ▷ exact, steadily propagating solution with uniform potential vorticity
- ▷ surface θ : warm in cyclone, cold in anticyclone, uniform outside dipole
- ▷ See

Muraki, D. M., and C. Snyder, 2006: Vortex dipoles for surface quasigeostrophic models. *J. Atmos. Sci.*, accepted.

QG Dipole

▷ surface θ



Primitive-Equation Simulations ---

Numerical details

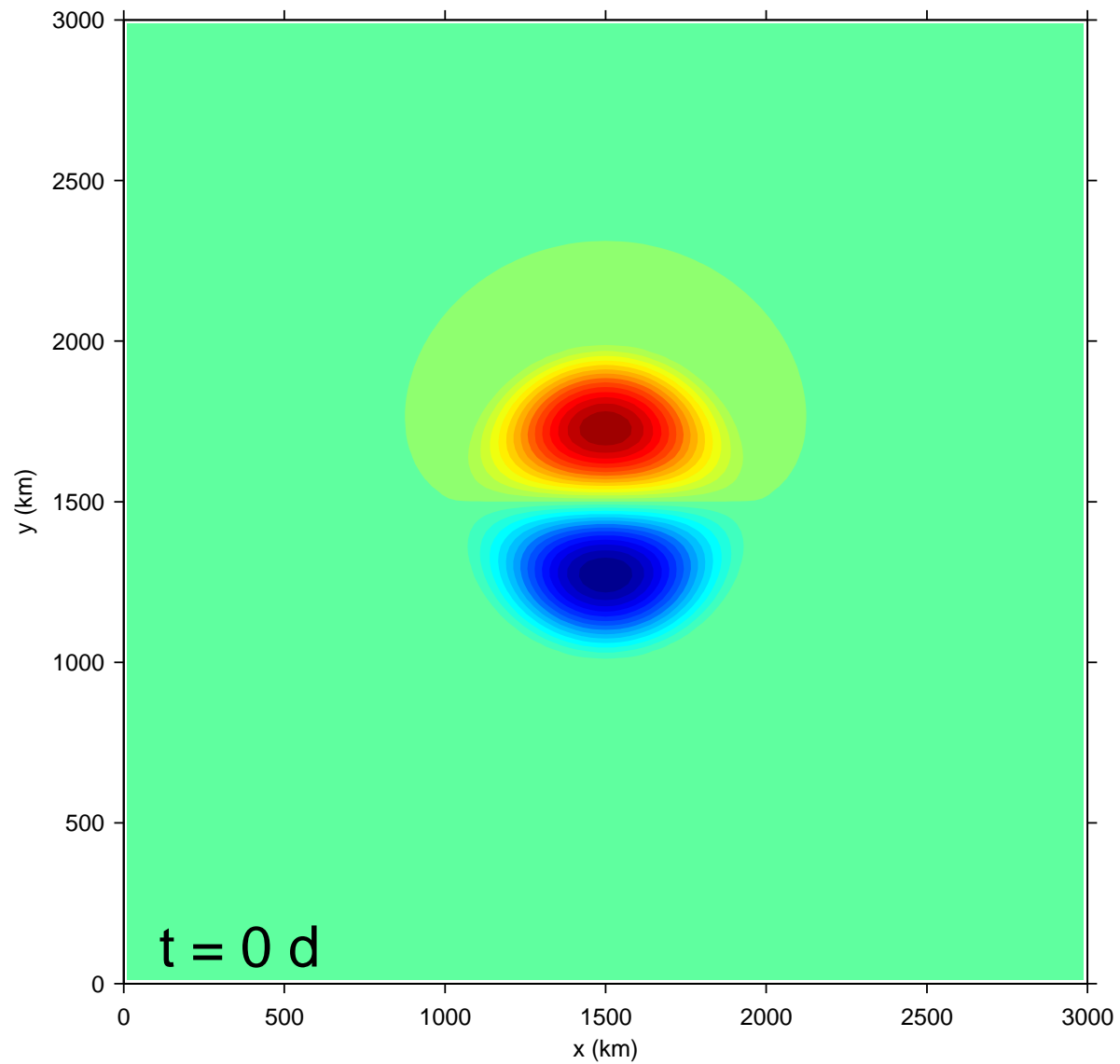
- ▷ non-hydrostatic, compressible (neither important)
- ▷ horizontally periodic domain of 3000 km; 15 km vertically
- ▷ $128 \times 128 \times 30$ points, or $256 \times 256 \times 60$ points,
- ▷ sponge layer above 10 km

ICs from QG dipole

- ▷ dipole has 500-km radius, $\max(u) = 5$ m/s
- ▷ velocities are geostrophic

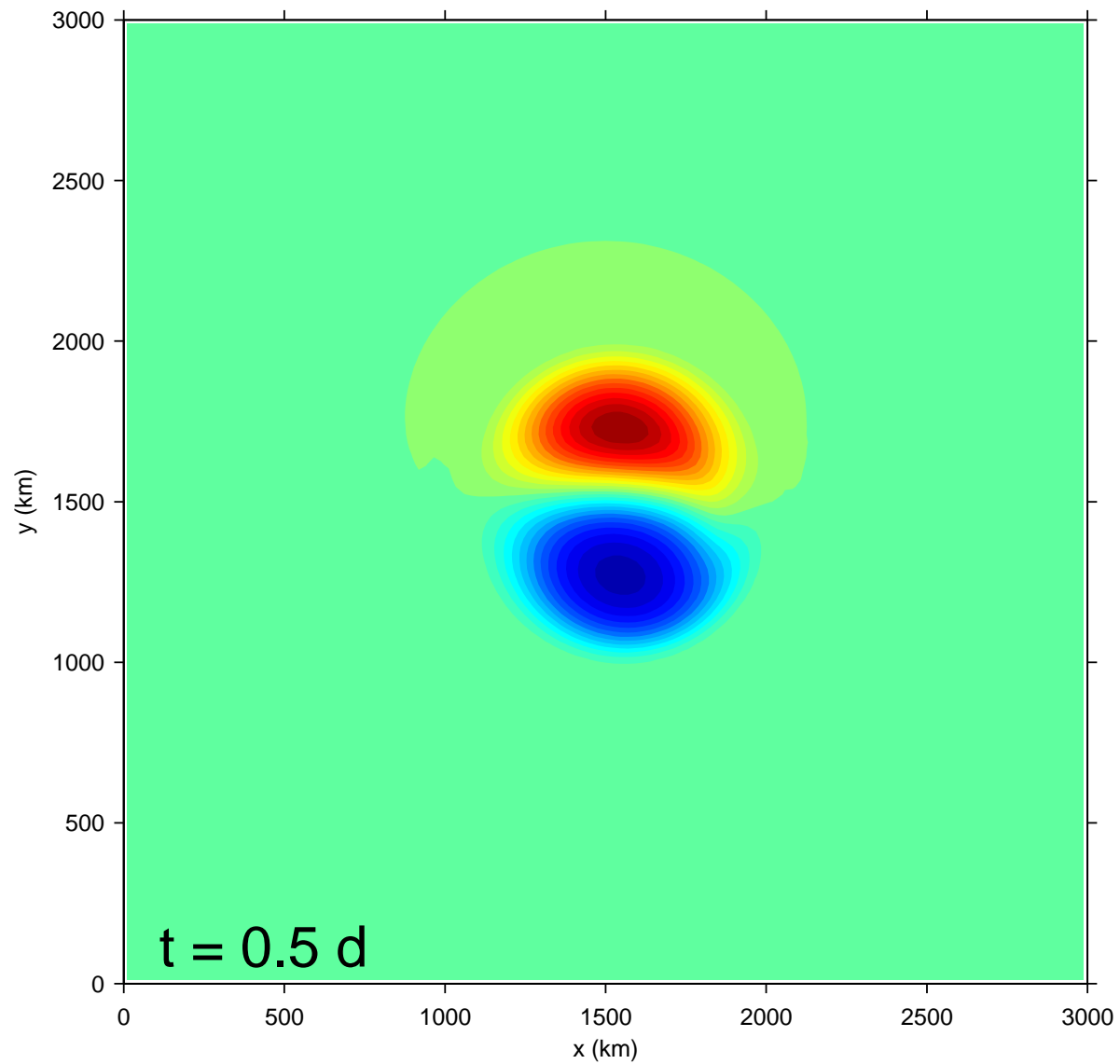
Time Evolution

▷ θ at lowest model level



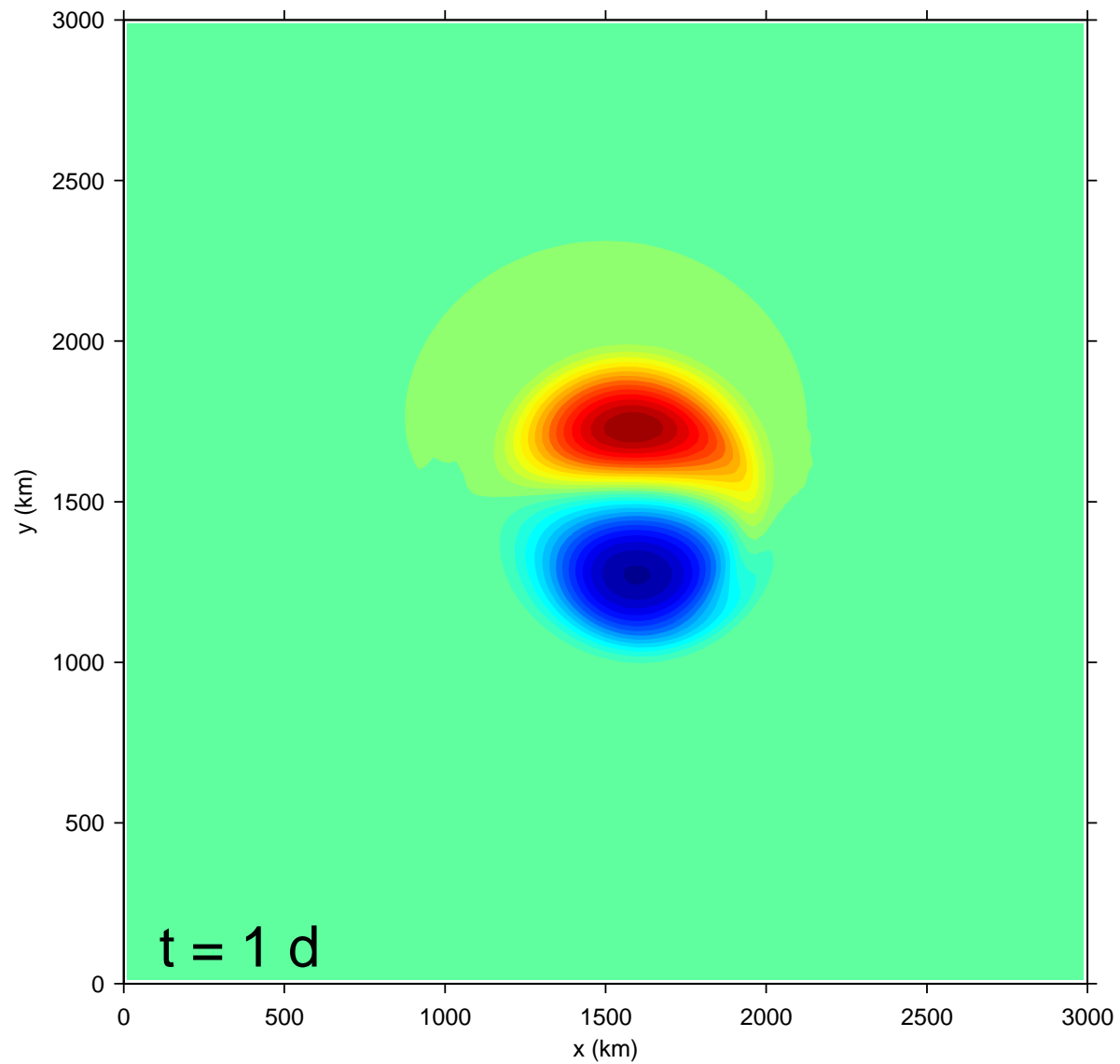
Time Evolution

▷ θ at lowest model level



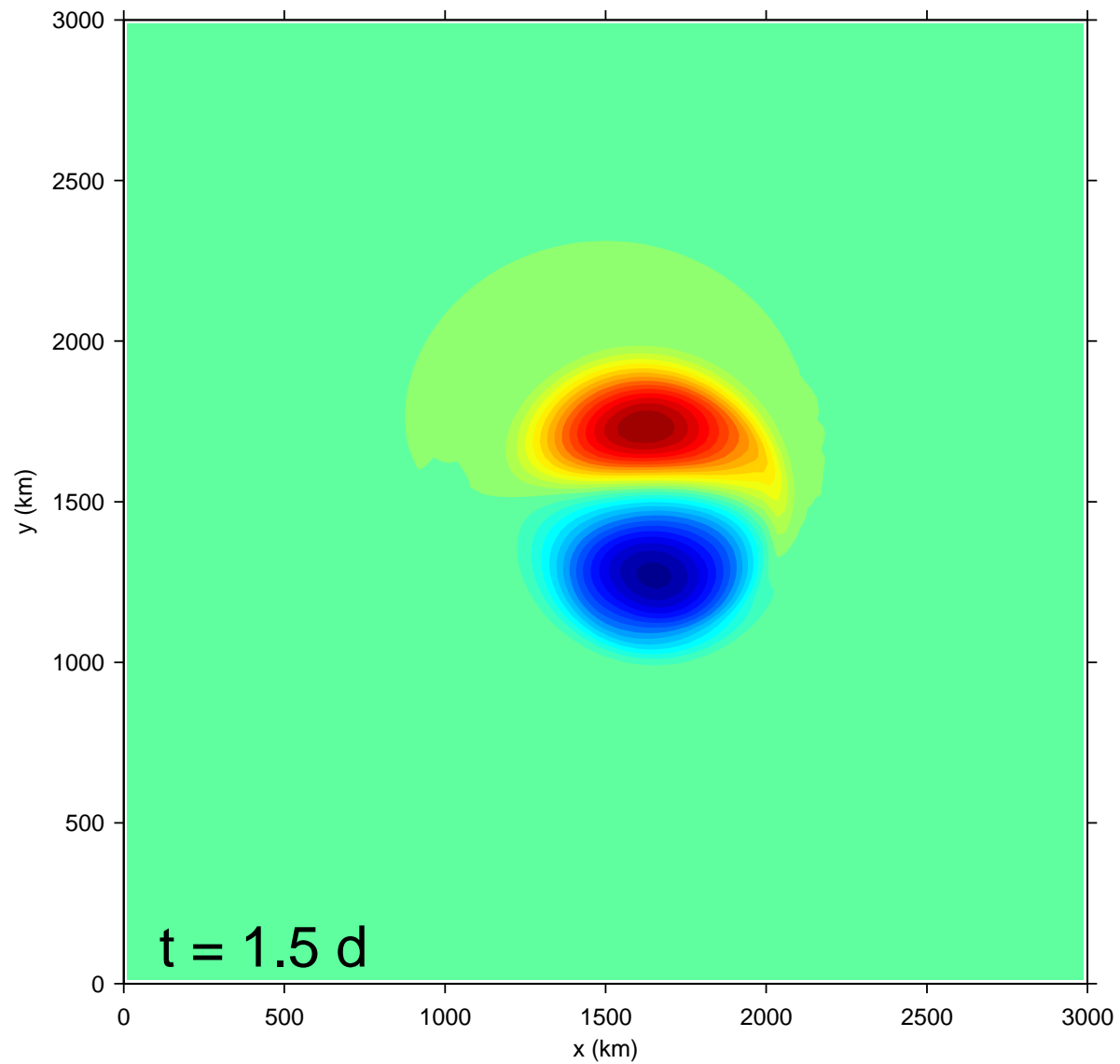
Time Evolution

▷ θ at lowest model level



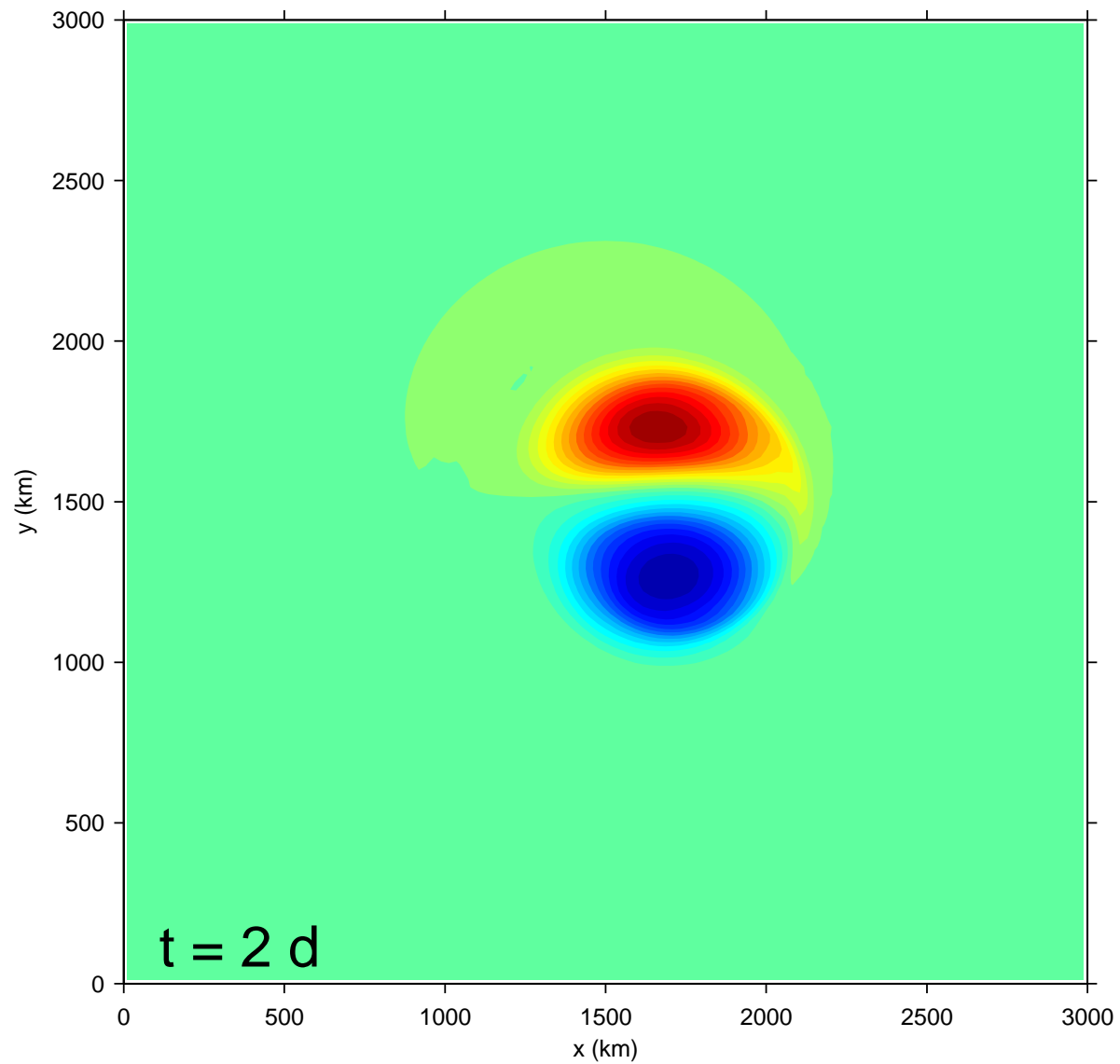
Time Evolution

▷ θ at lowest model level



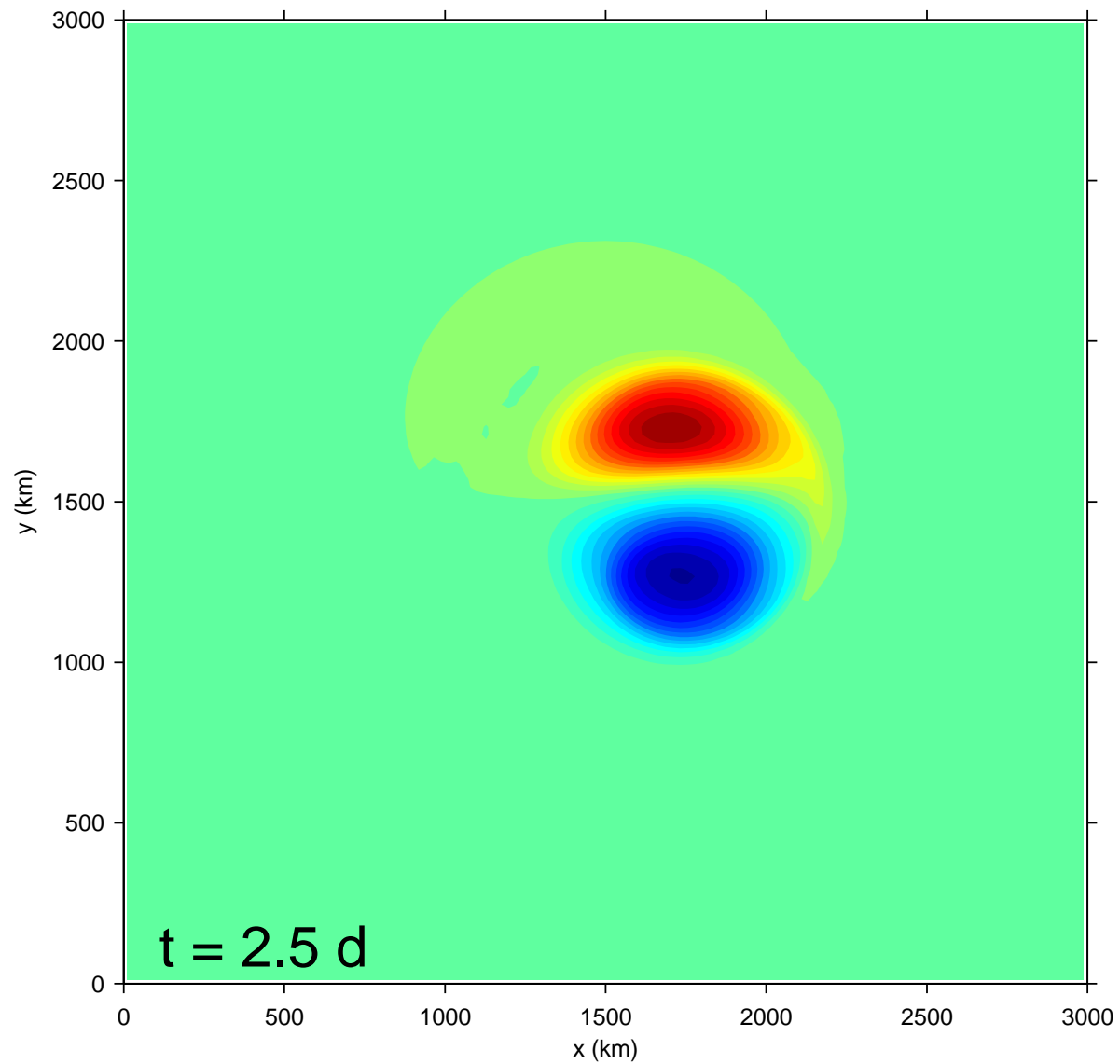
Time Evolution

▷ θ at lowest model level



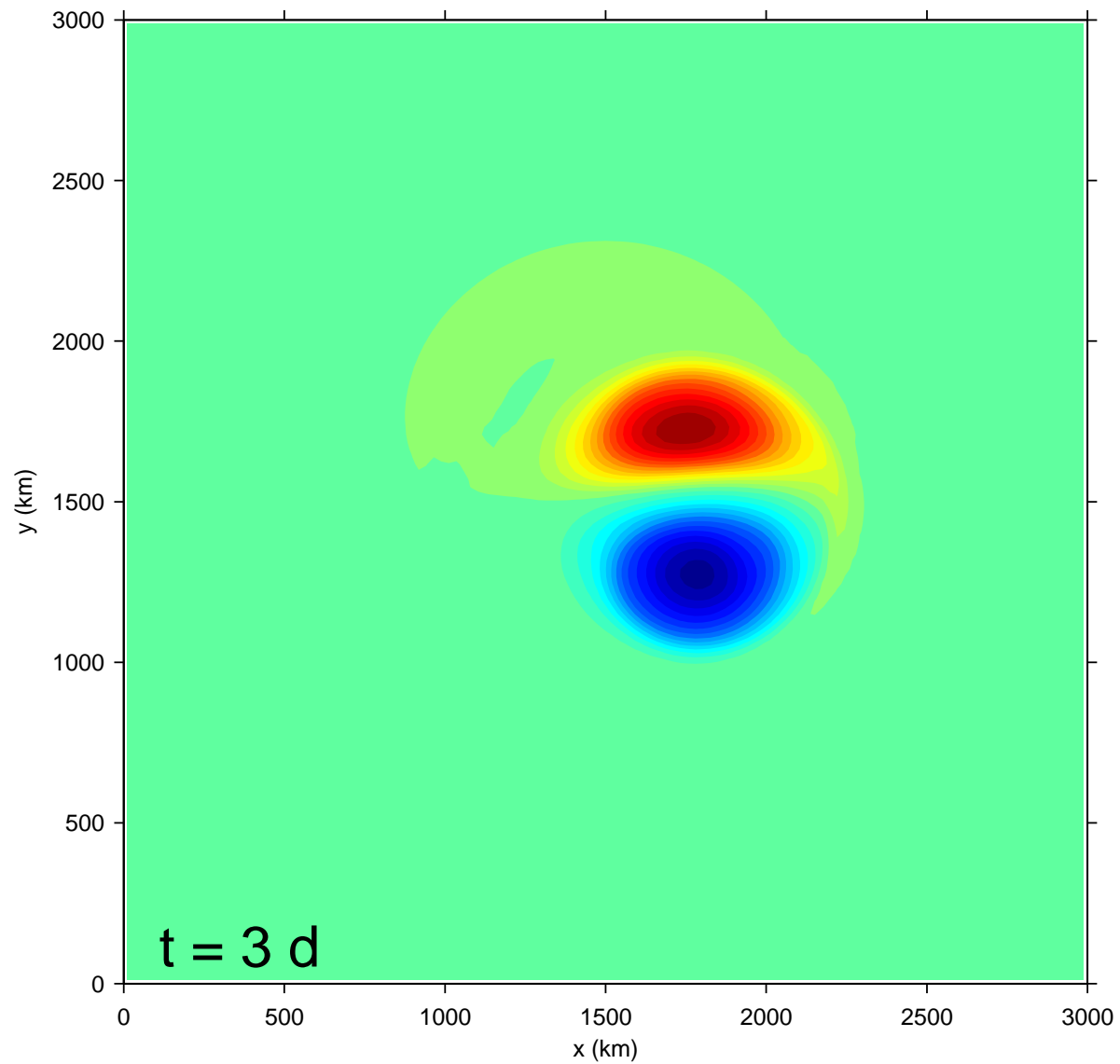
Time Evolution

▷ θ at lowest model level



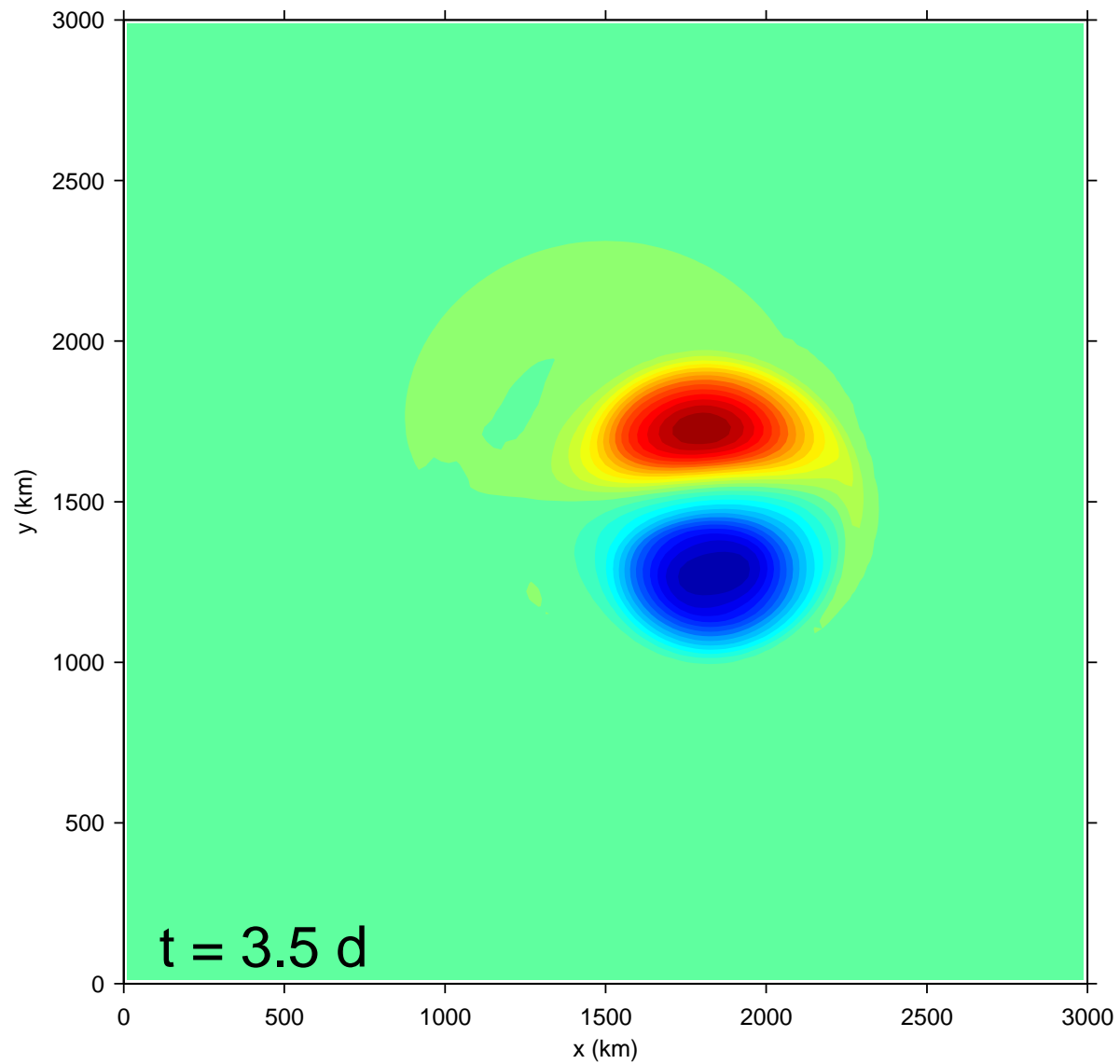
Time Evolution

▷ θ at lowest model level



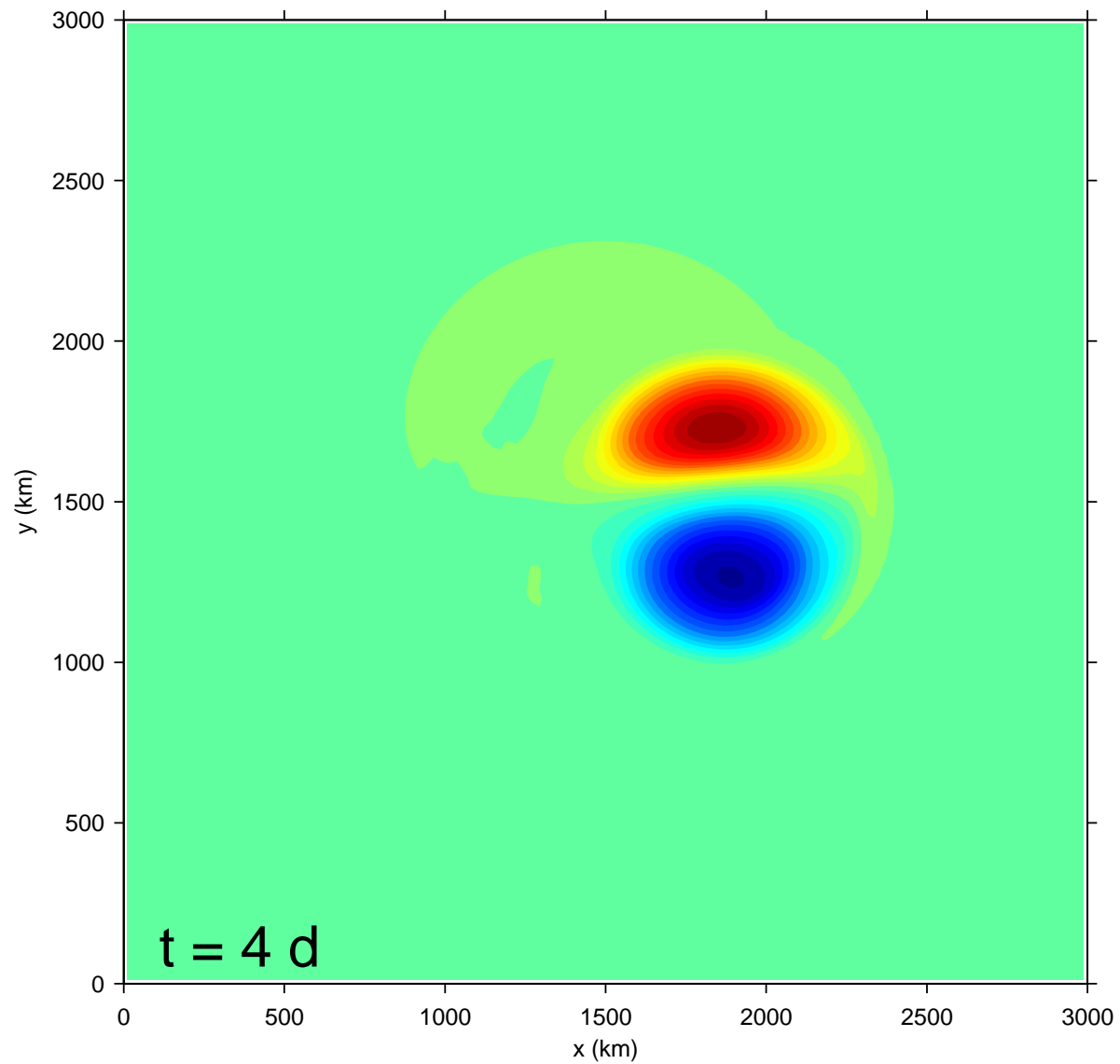
Time Evolution

▷ θ at lowest model level



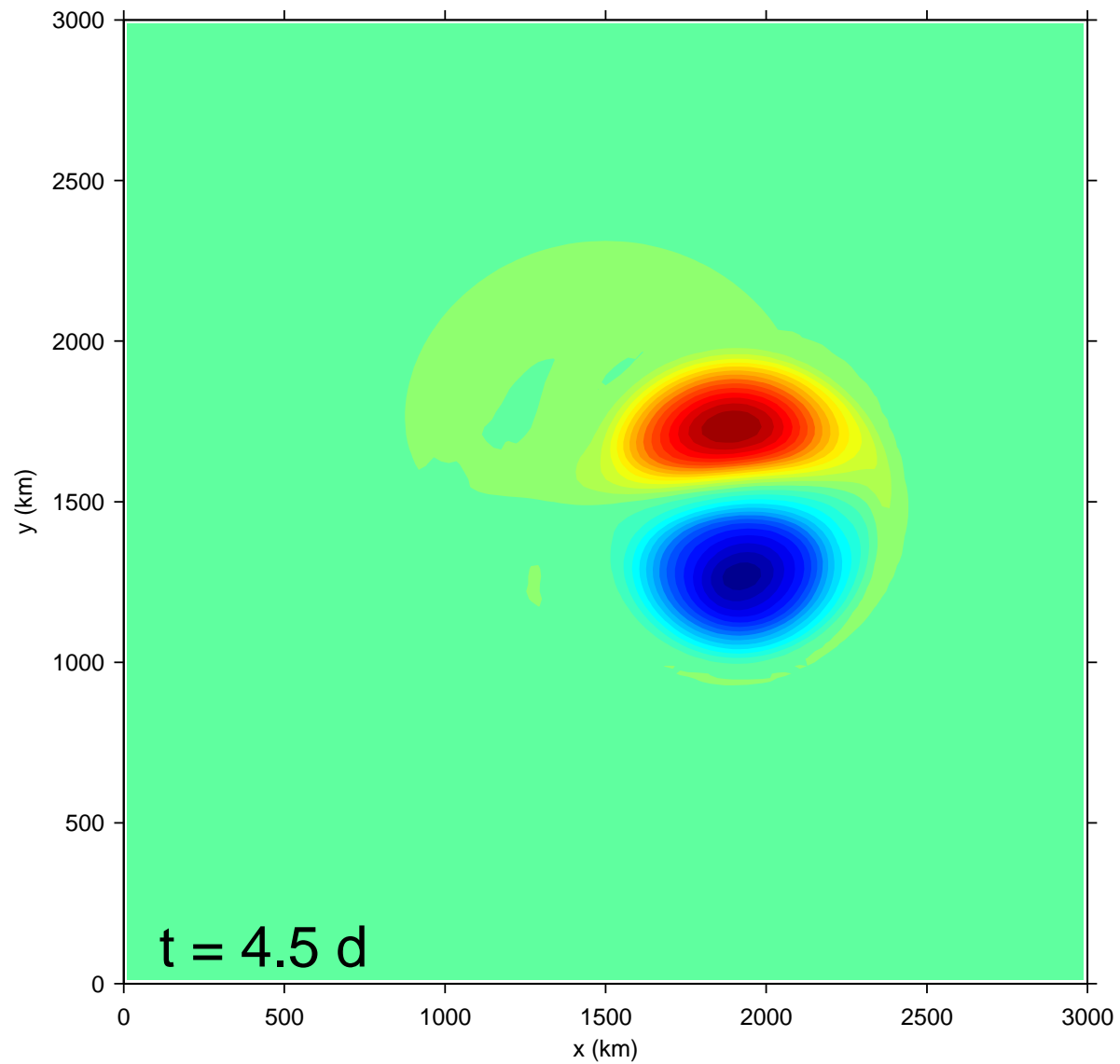
Time Evolution

▷ θ at lowest model level



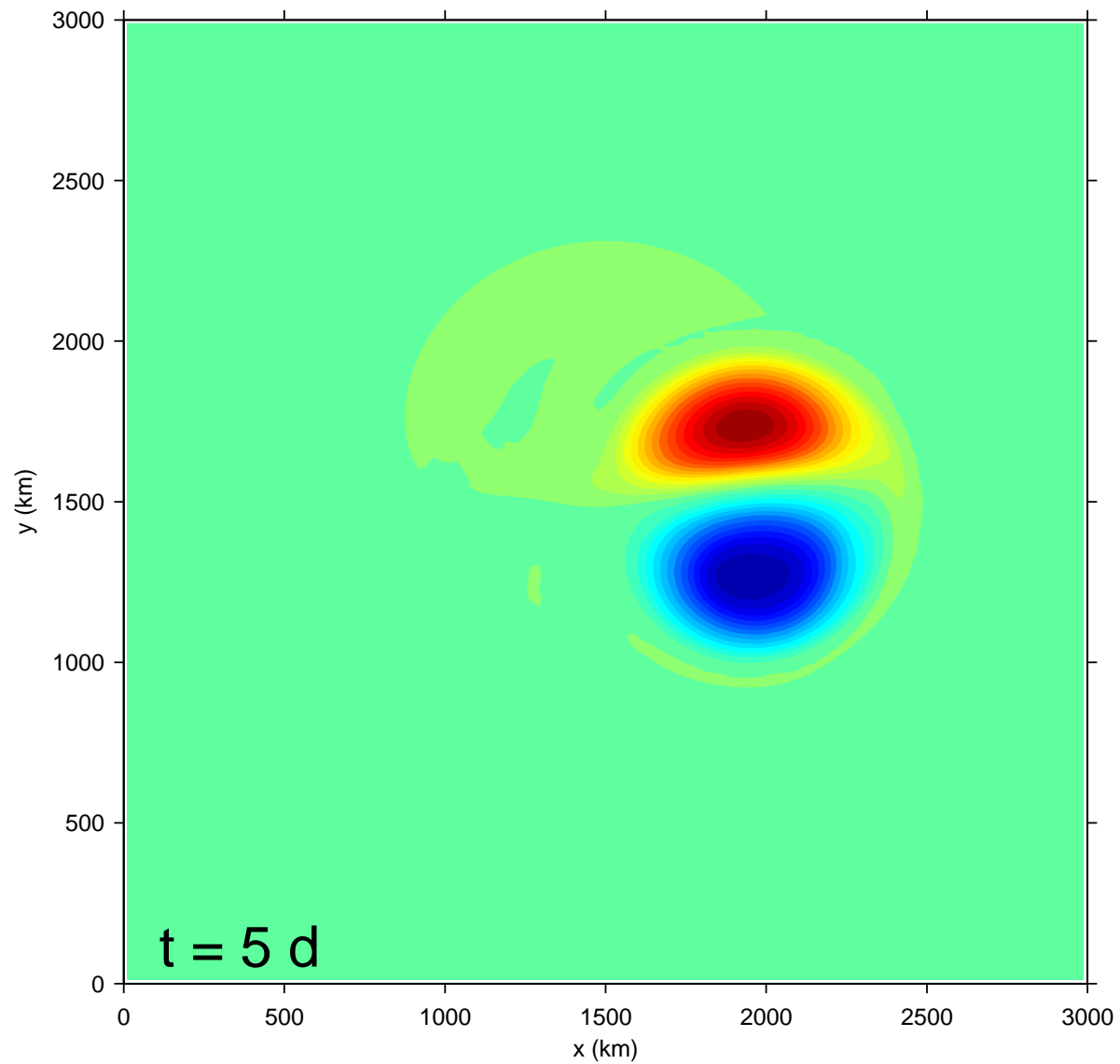
Time Evolution

▷ θ at lowest model level



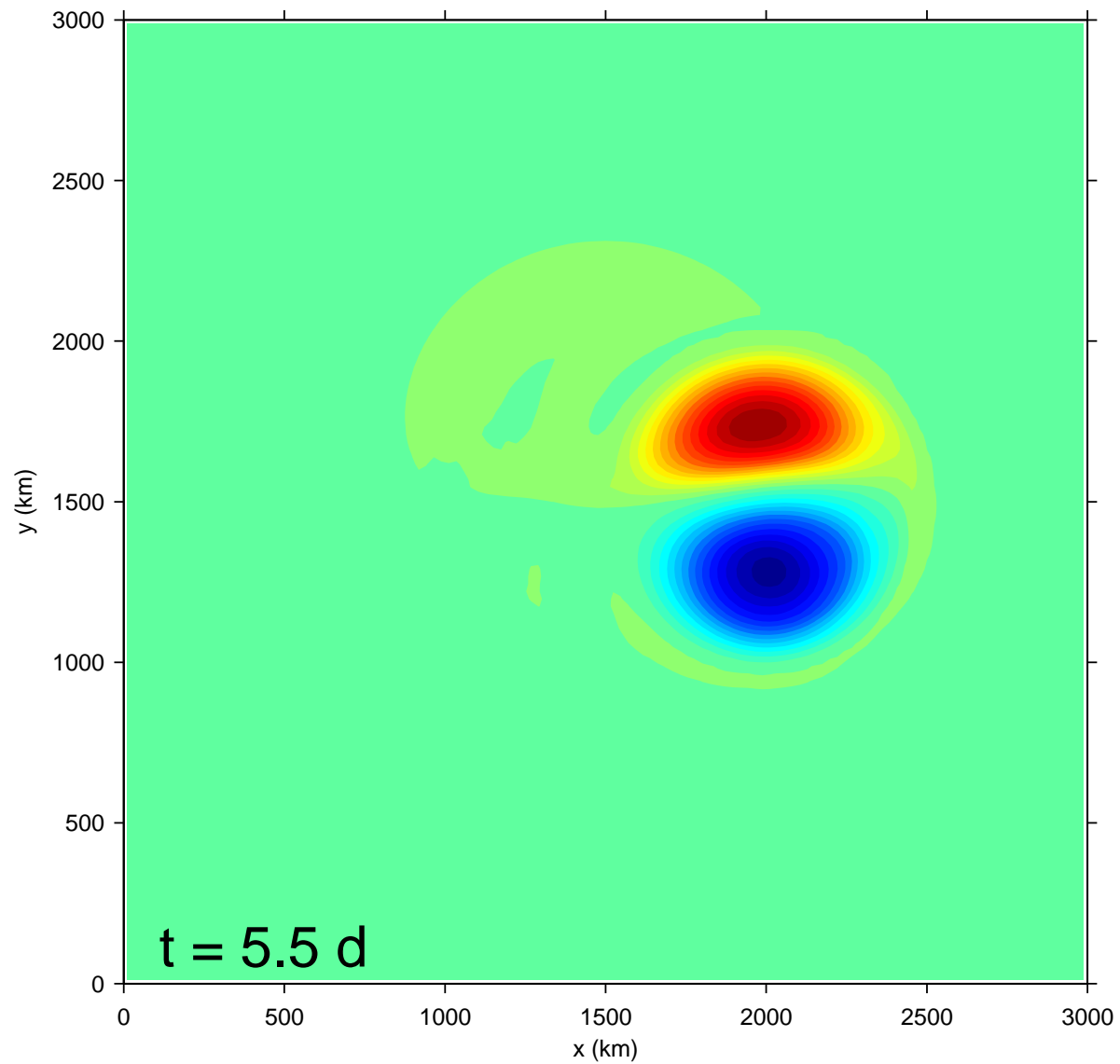
Time Evolution

▷ θ at lowest model level



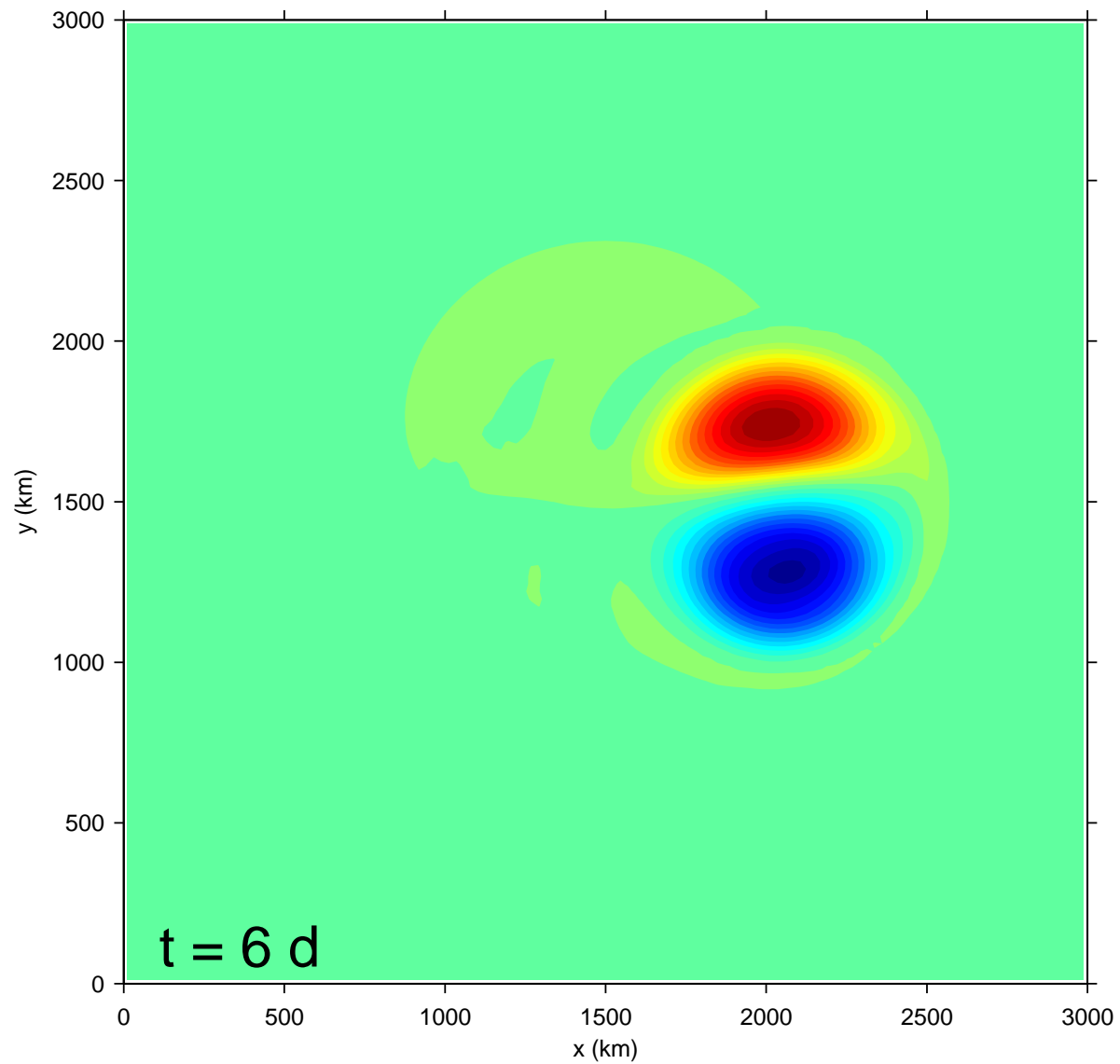
Time Evolution

▷ θ at lowest model level



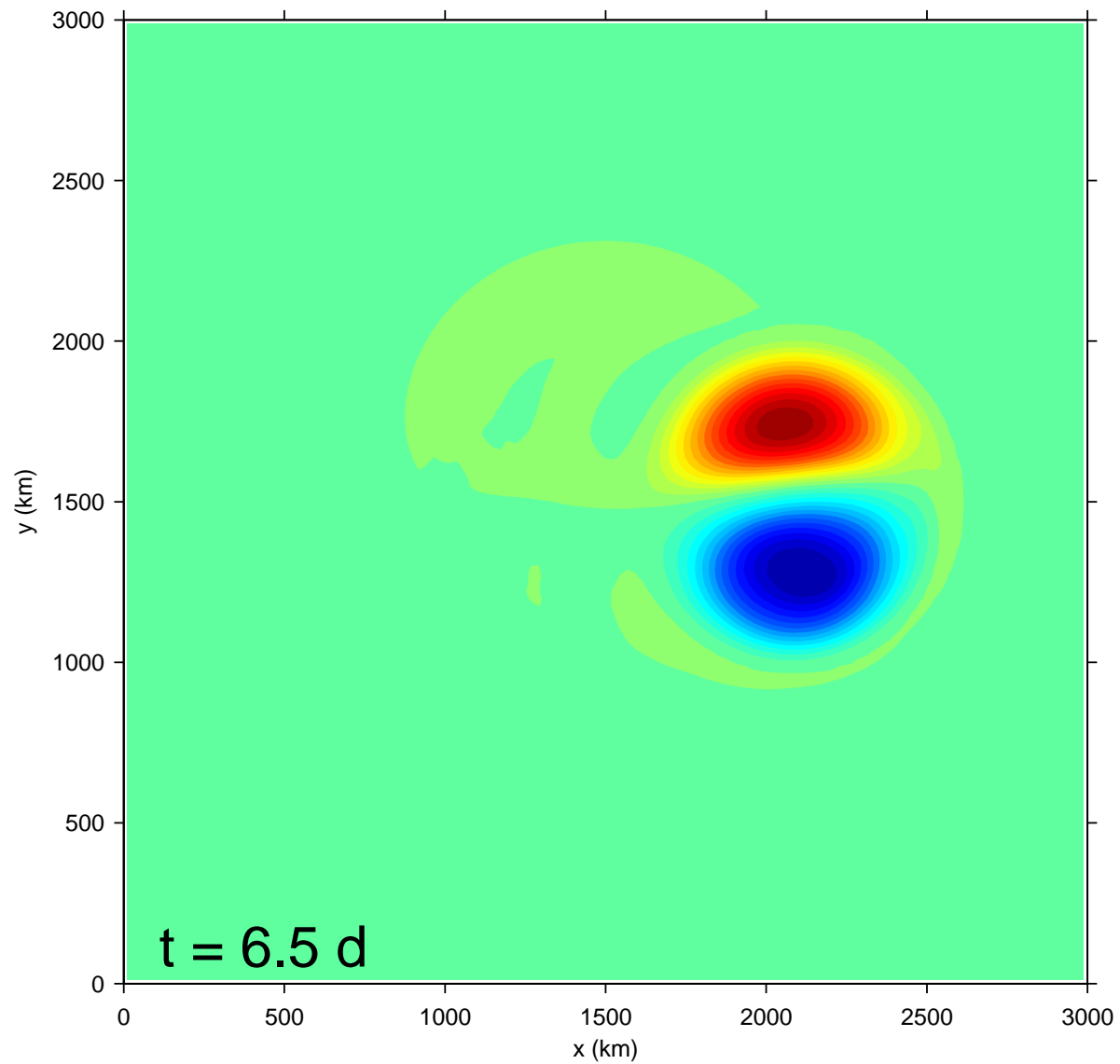
Time Evolution

▷ θ at lowest model level



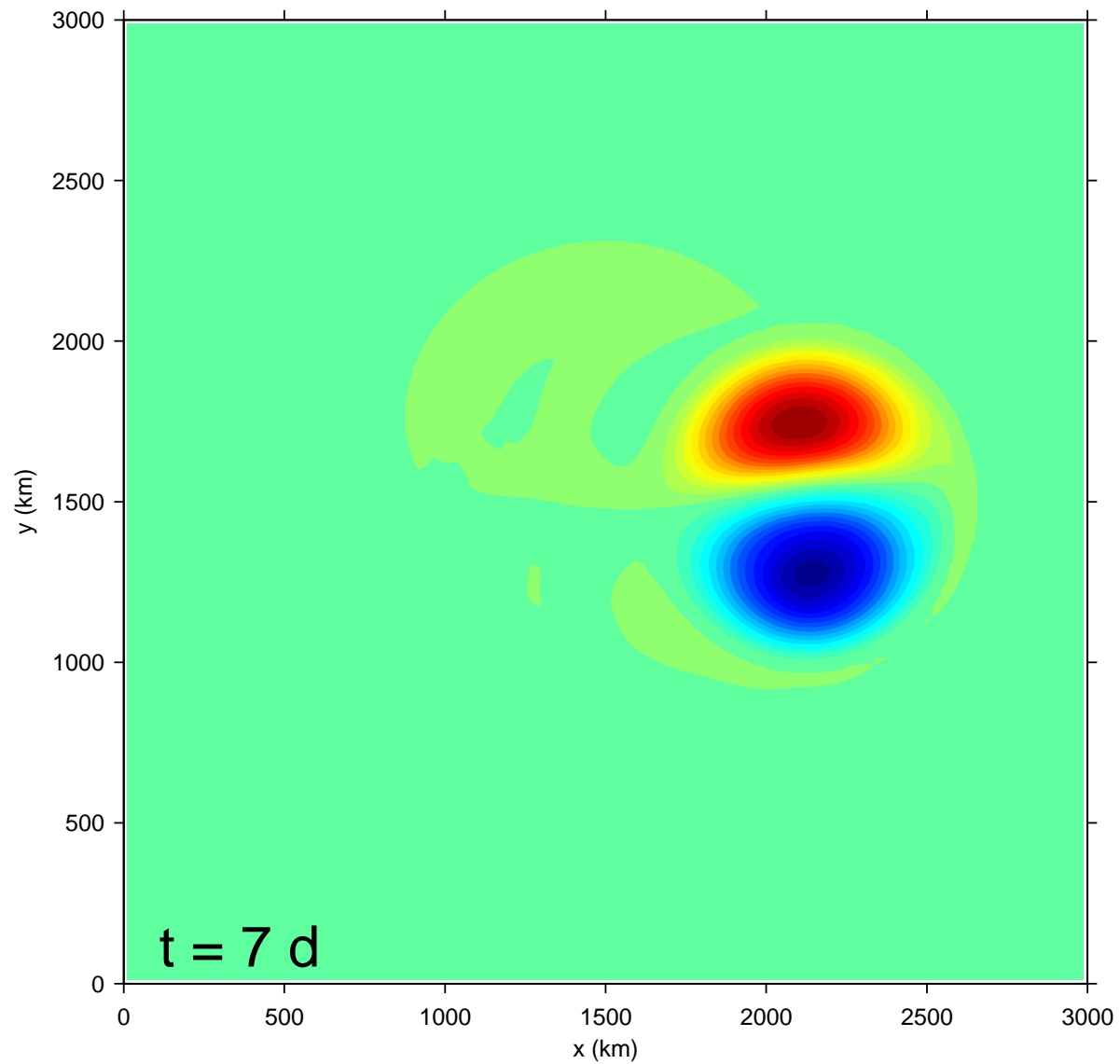
Time Evolution

▷ θ at lowest model level



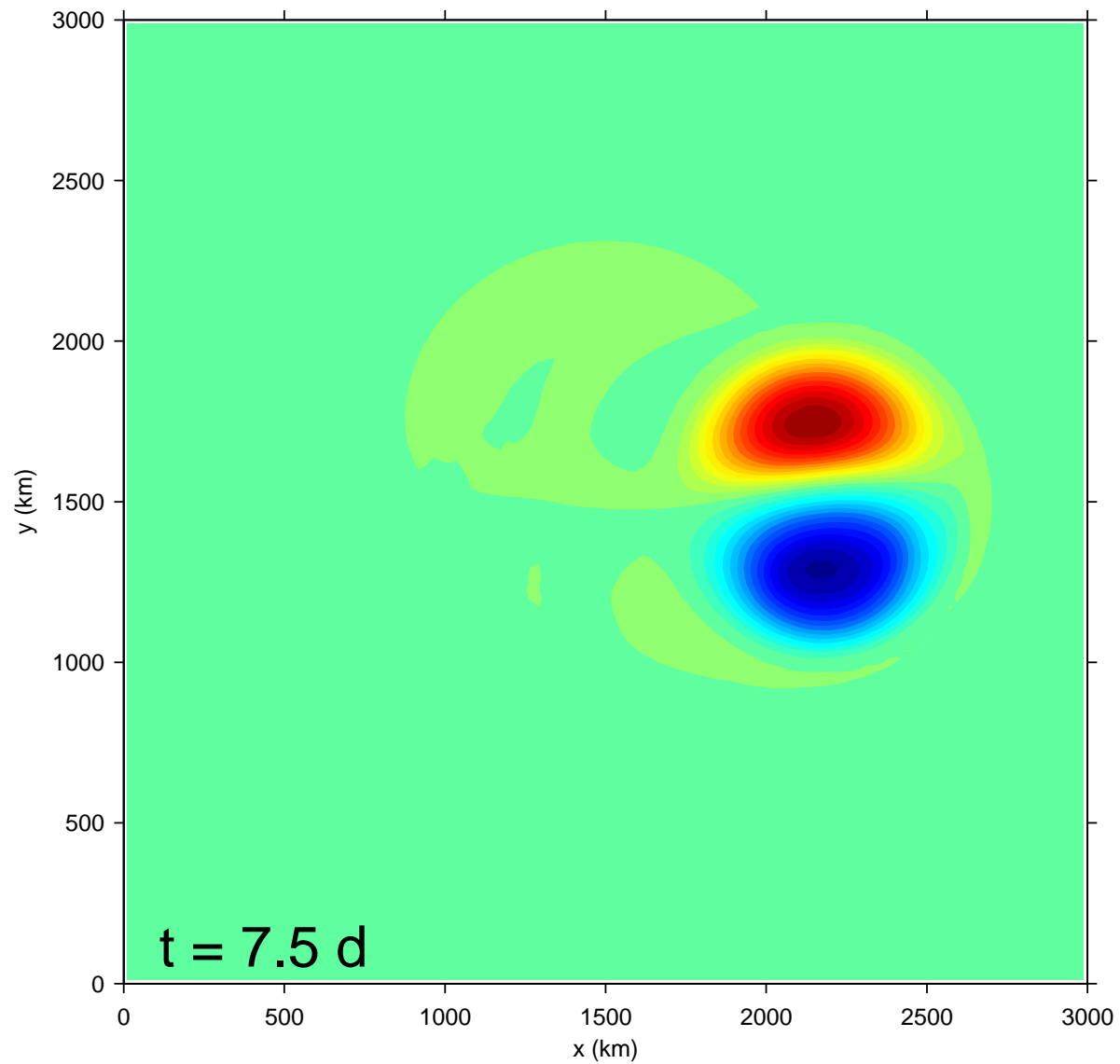
Time Evolution

▷ θ at lowest model level



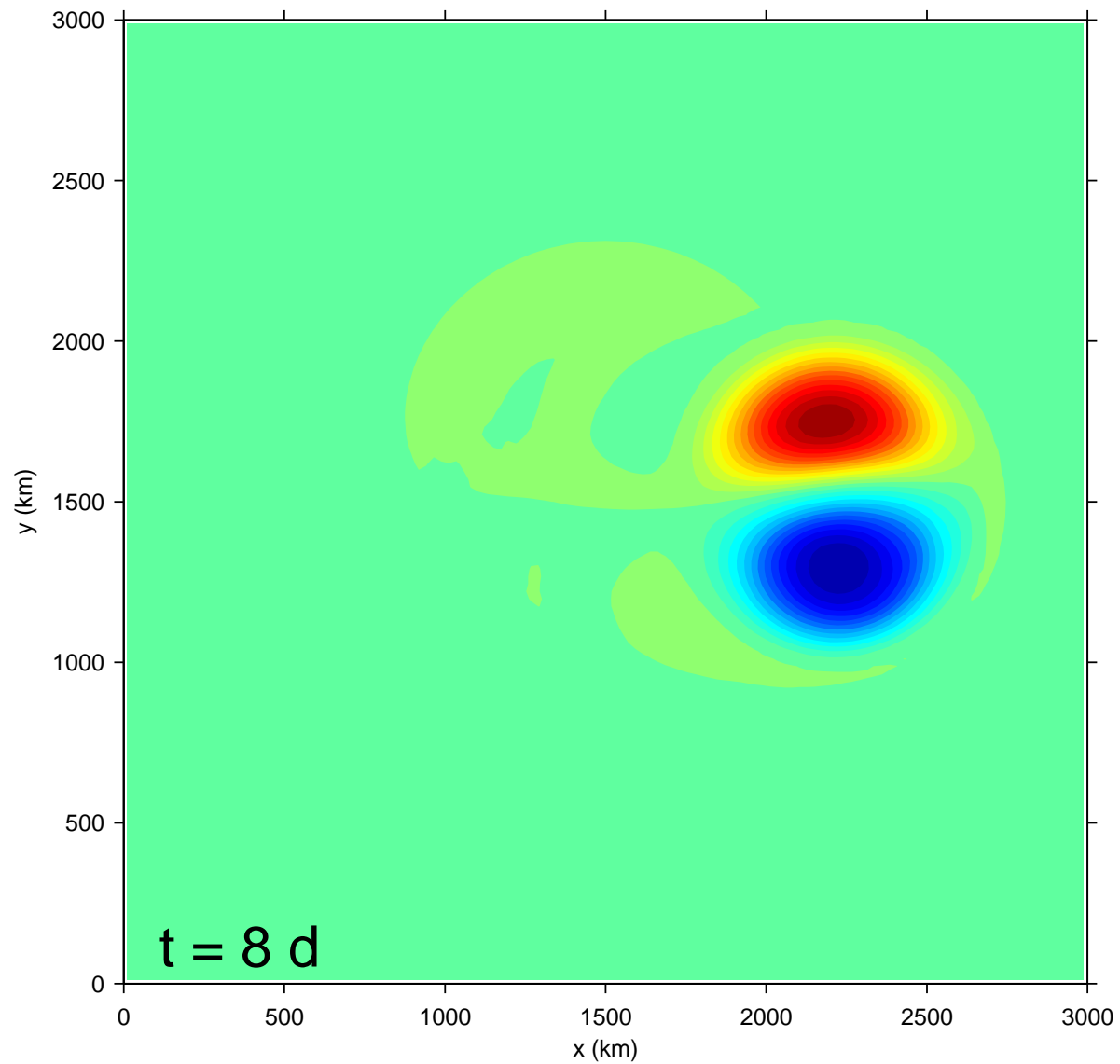
Time Evolution

▷ θ at lowest model level



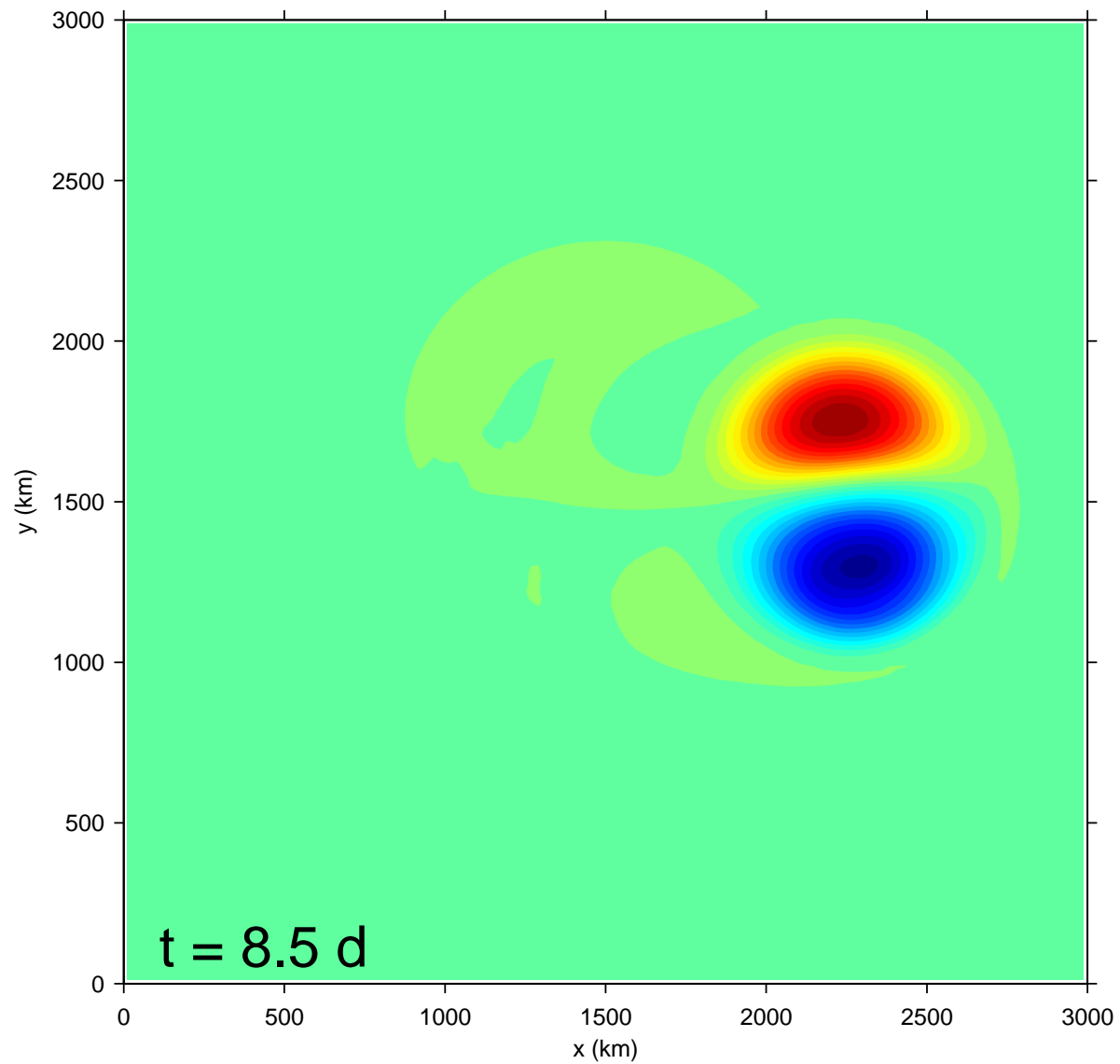
Time Evolution

▷ θ at lowest model level



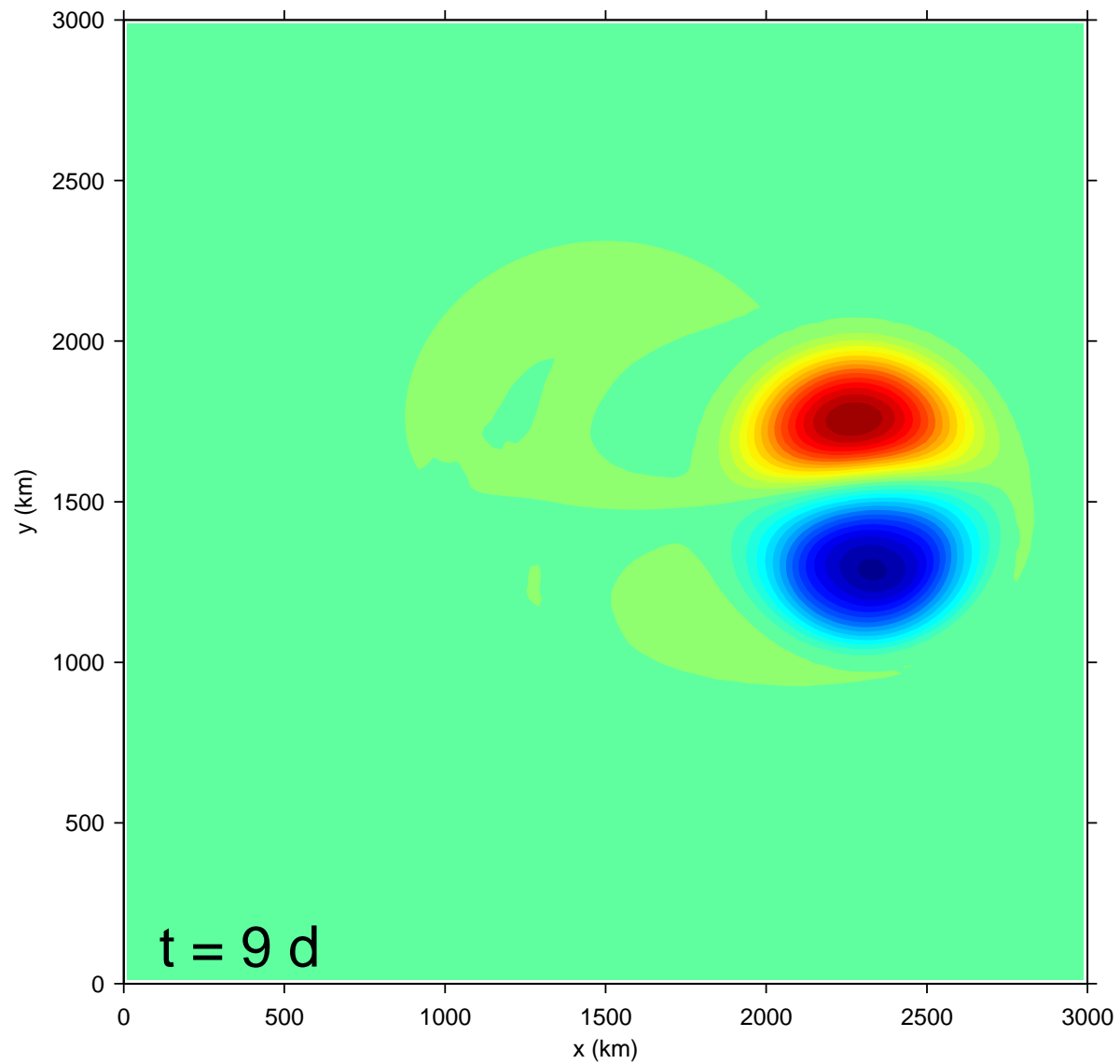
Time Evolution

▷ θ at lowest model level



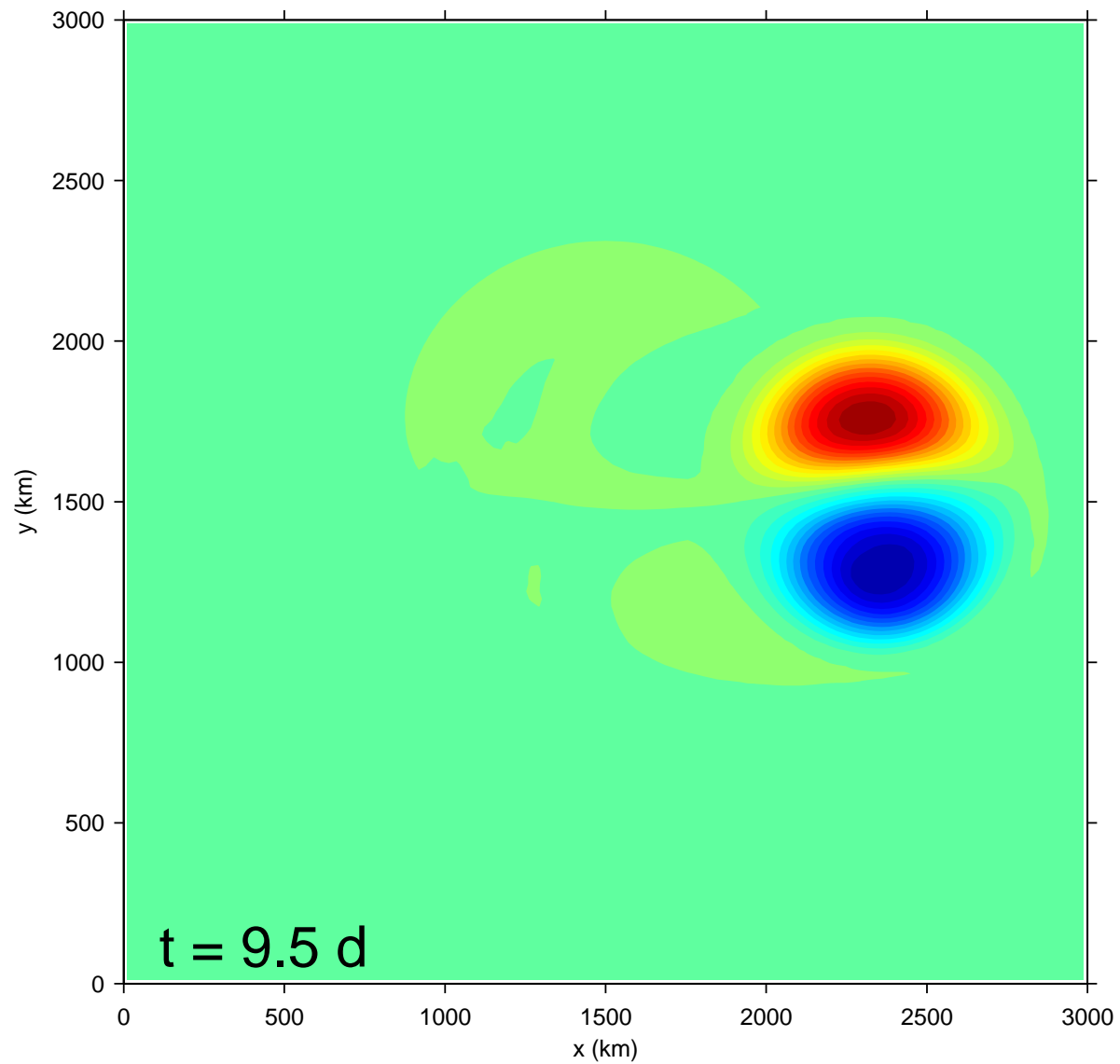
Time Evolution

▷ θ at lowest model level



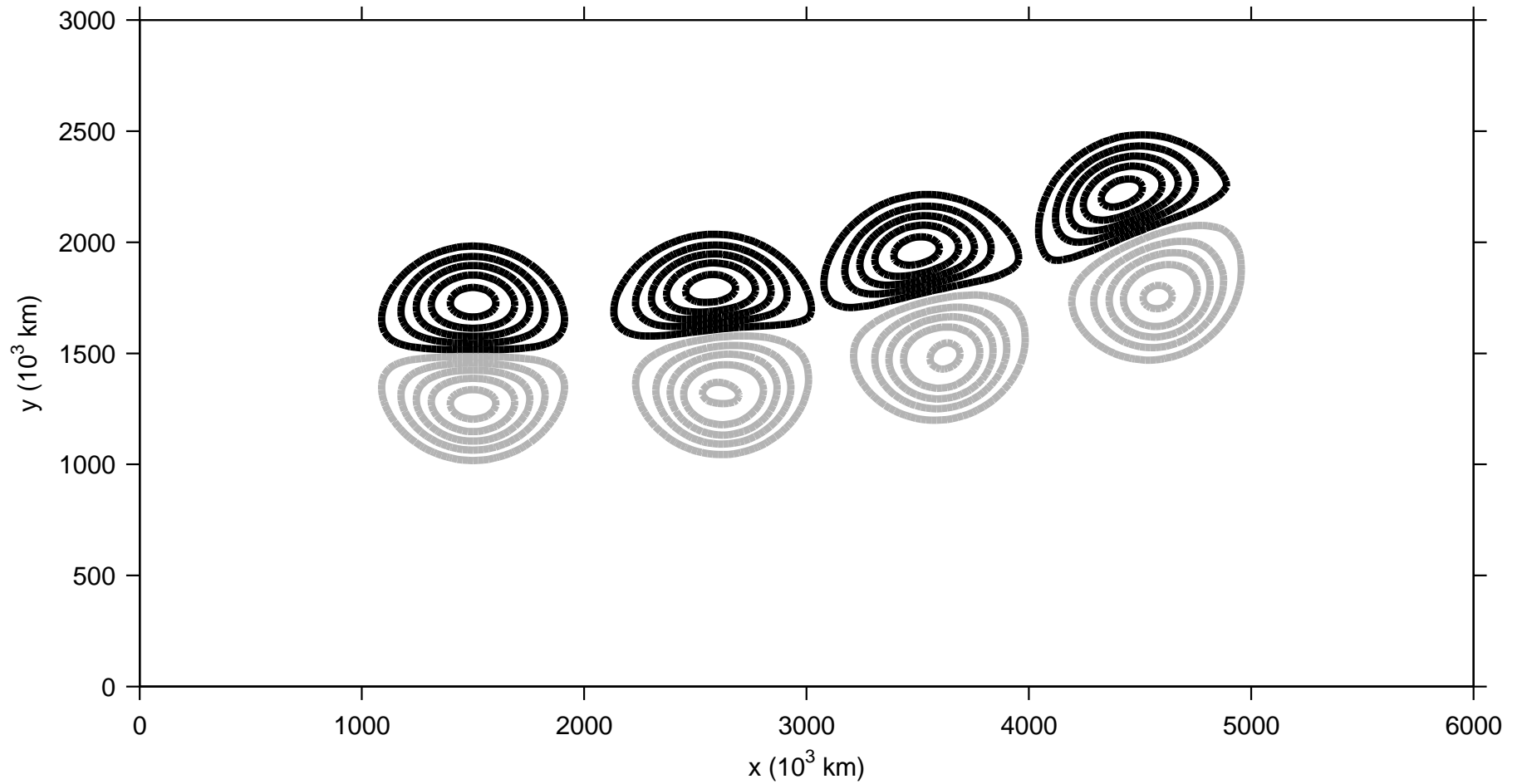
Time Evolution

▷ θ at lowest model level



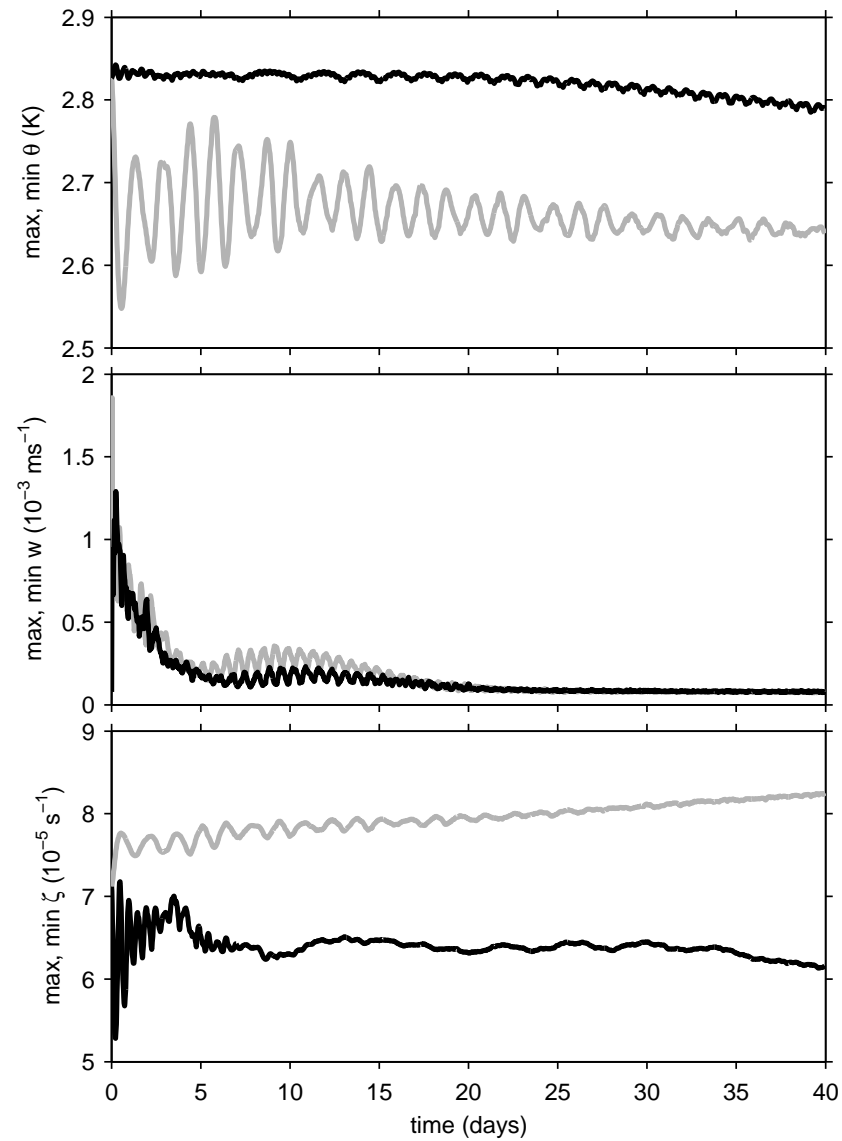
Time Evolution

- ▷ surface θ at $t = 0, 12.5, 25, 37.5$ d.



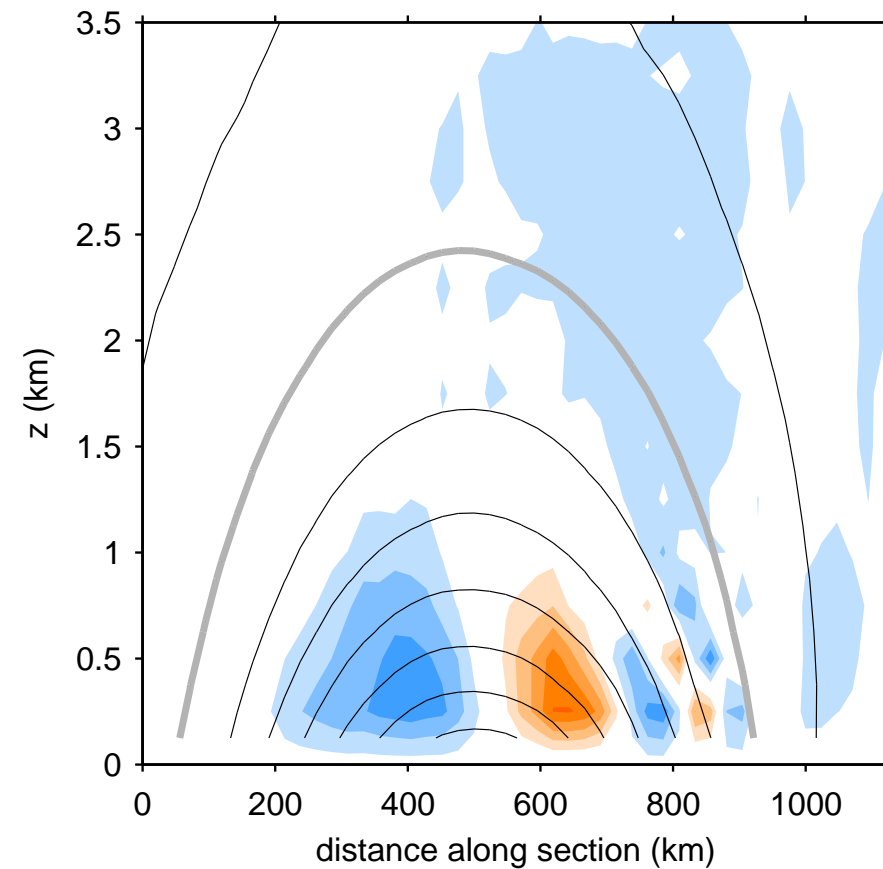
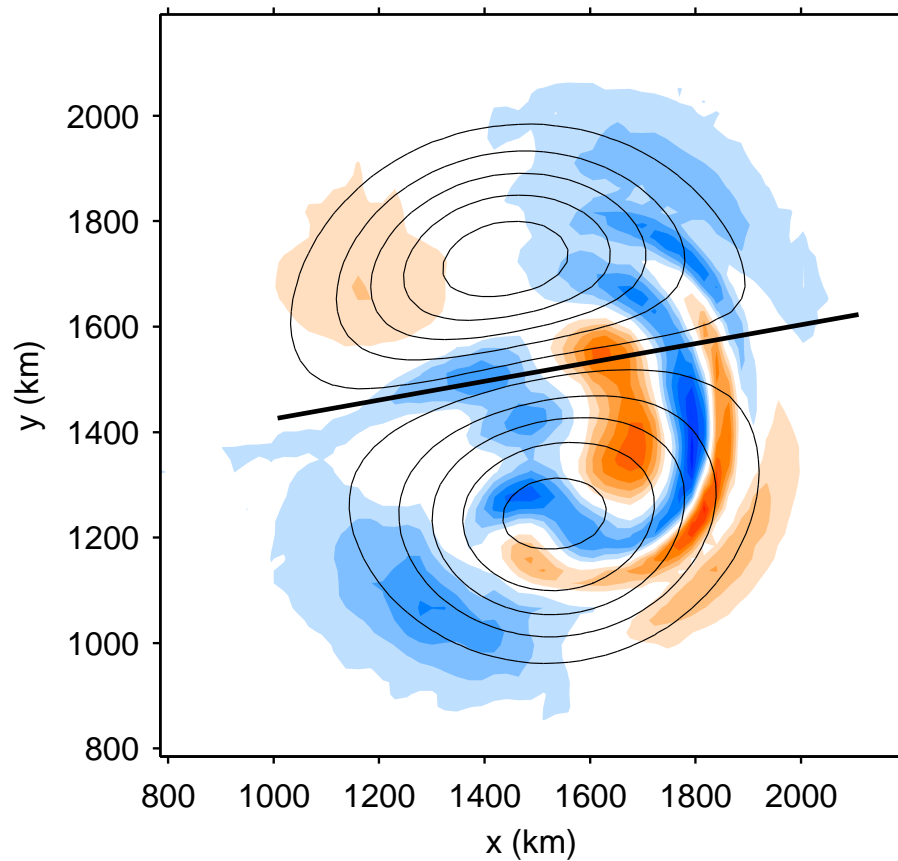
Time Evolution

- ▷ max, min of surface θ , w at 5 km, surface ζ



Long-Time Structure in w

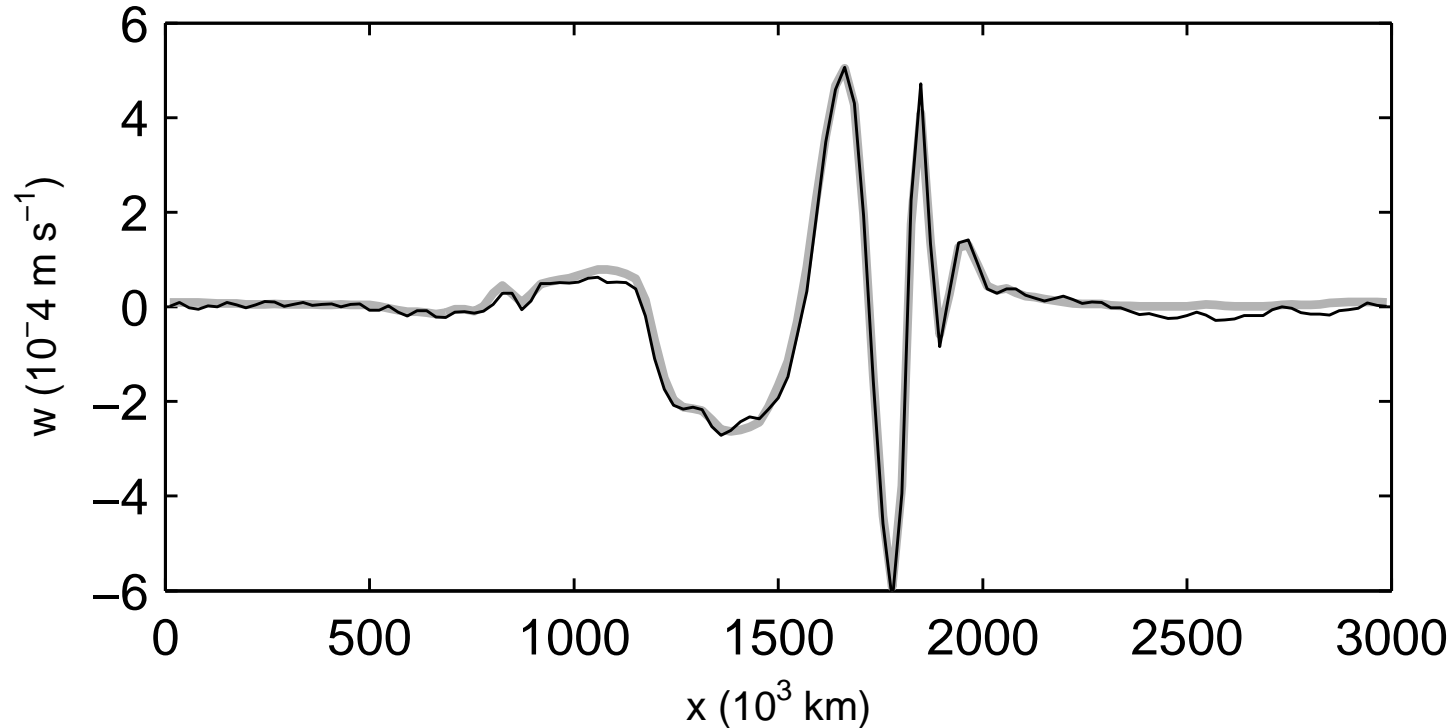
- ▷ (left) w and θ at 1st model level, day 22
- ▷ (right) cross-section of w and section-parallel wind



Long-Time Structure in w

Bands are stationary w.r.t. dipole

- ▷ time average (2 days) in frame of ref. moving with dipole
- ▷ $w(x, 1500 \text{ km})$ at lowest level and \bar{w} (average)



Long-Time Structure in w

Bands are stationary w.r.t. dipole

Bands are inertia-gravity waves

- ▷ vert. wavelegth consistent with local k , U , N and dispersion reln.
- ▷ upward propagating

Are waves remnants of initial conditions?

If not, what is their origin?

Messy Details ---

Solution nearly steadily propagating

- ▷ still time dependence, even moving with dipole

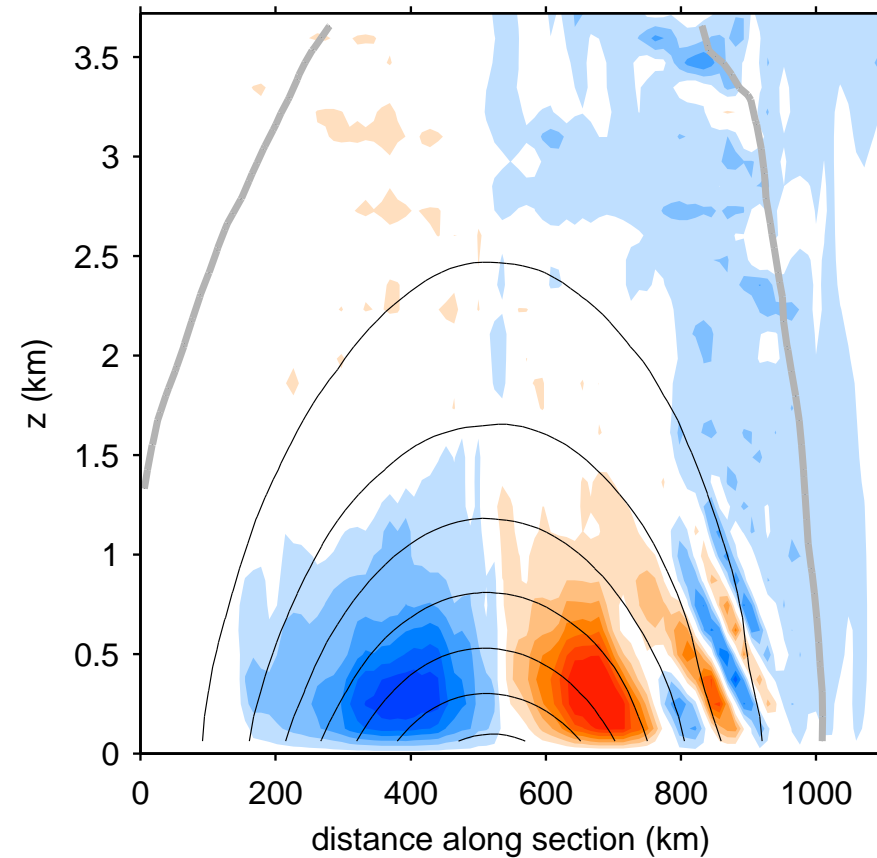
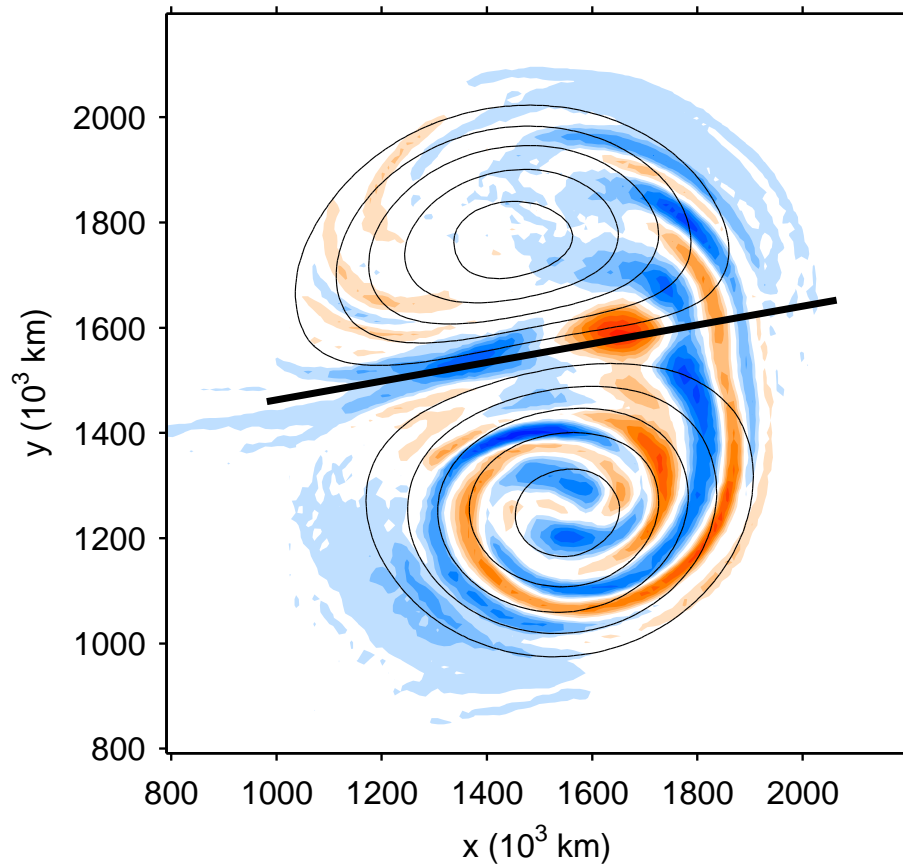
Time average in frame of ref. moving with dipole

- ▷ use time-mean (2 day) fields as ICs

Time-Averaged Fields as ICs

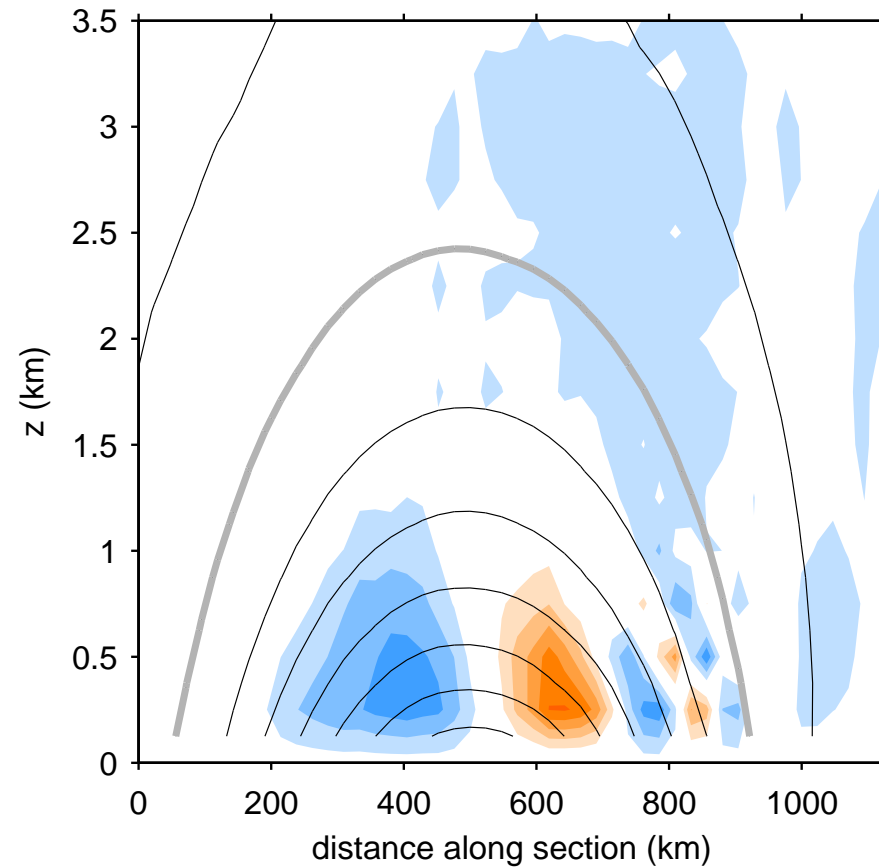
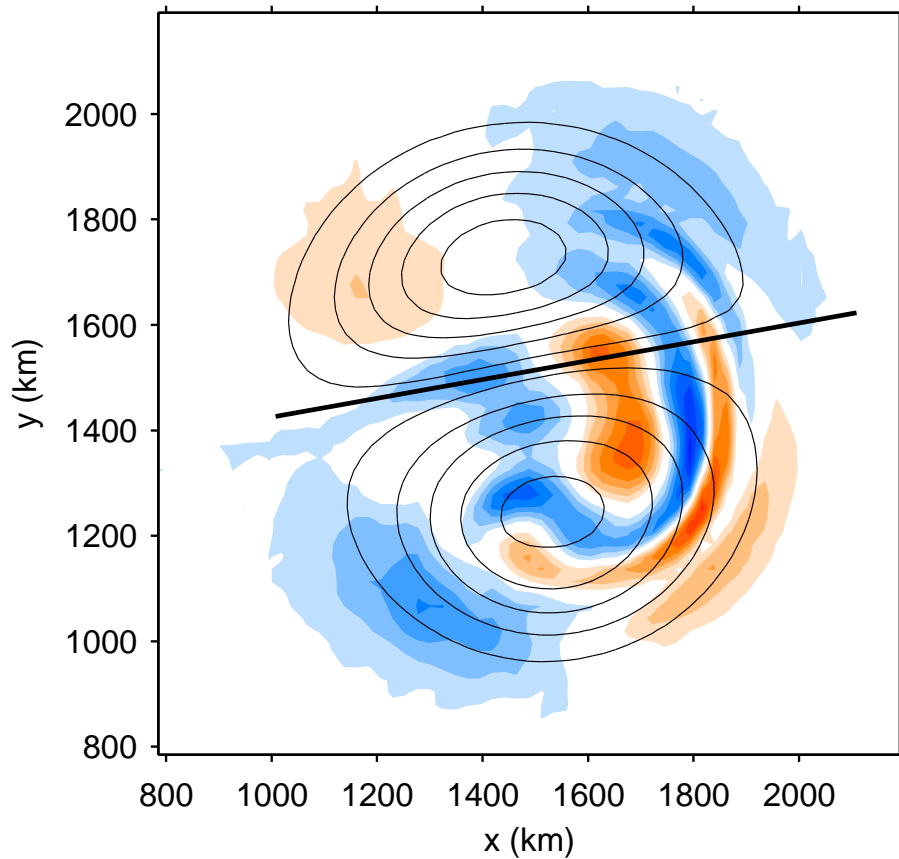
But stationary waves persist

- ▷ simulation with doubled resolution



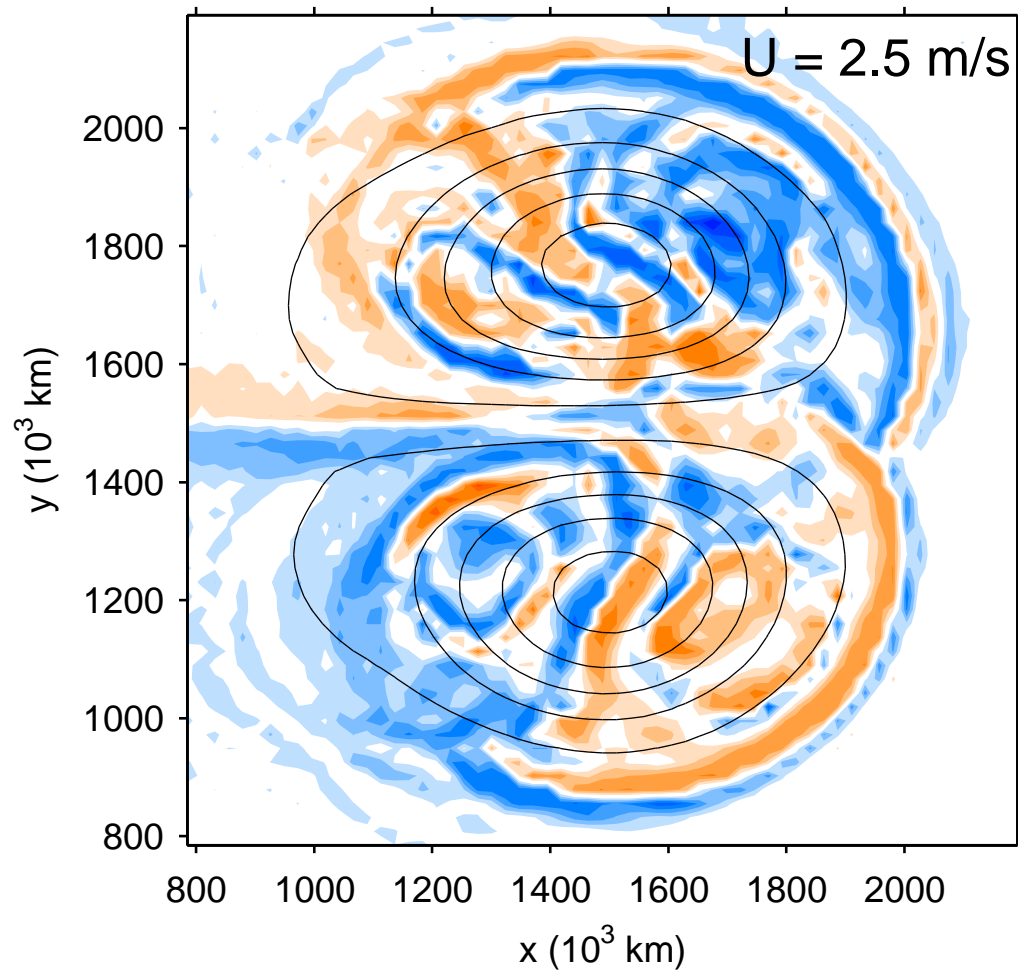
Time-Averaged Fields as ICs

- ▷ compare with lower-resolution solution, geostrophic ICs



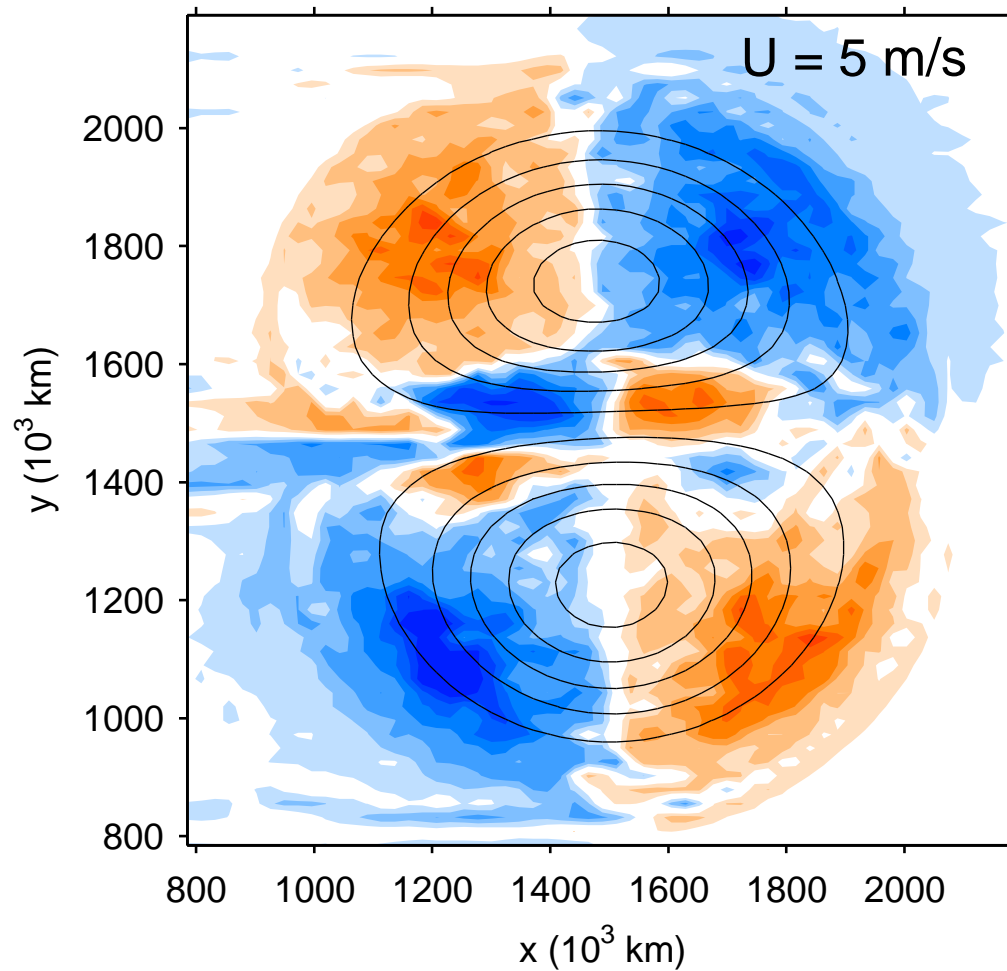
Dependence on Ro

- ▷ simulations with initial jet $U = 2.5, 5, 7.5, 10, 12.5, 15$ m/s



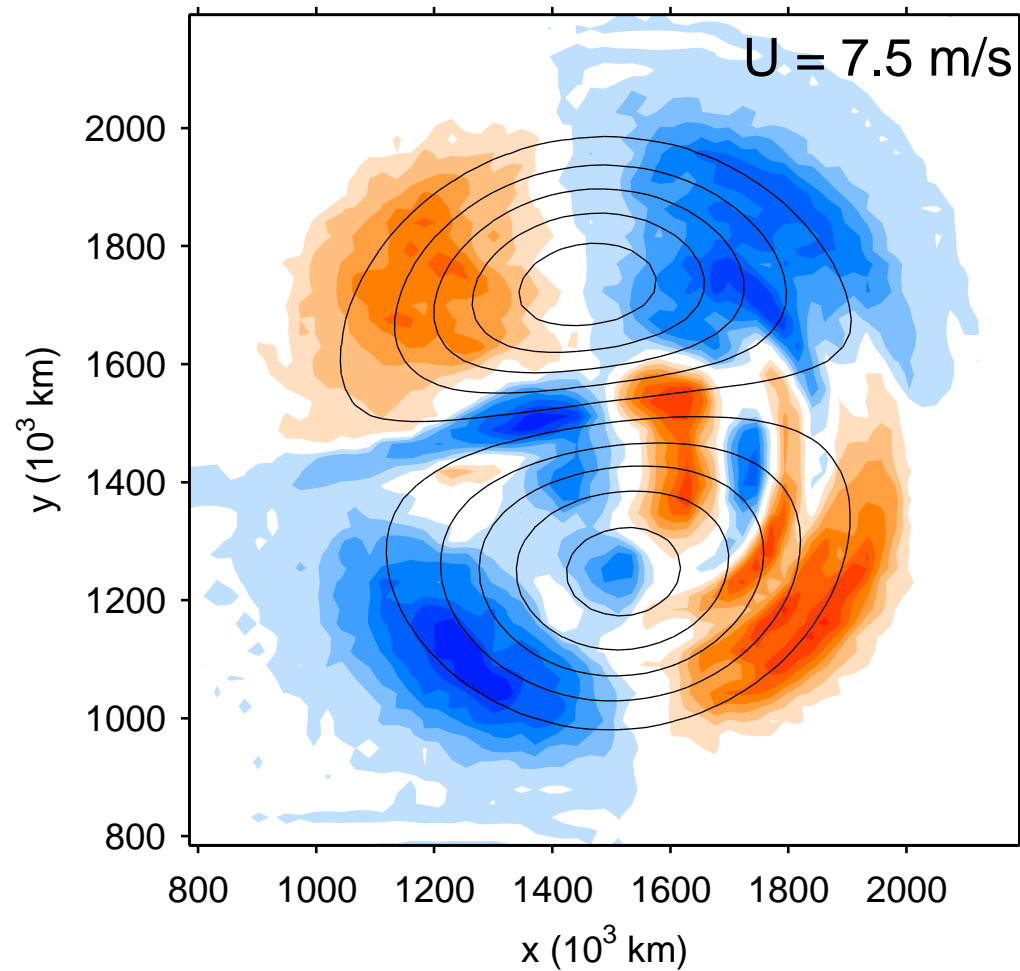
Dependence on Ro

- ▷ simulations with initial jet $U = 2.5, 5, 7.5, 10, 12.5, 15$ m/s



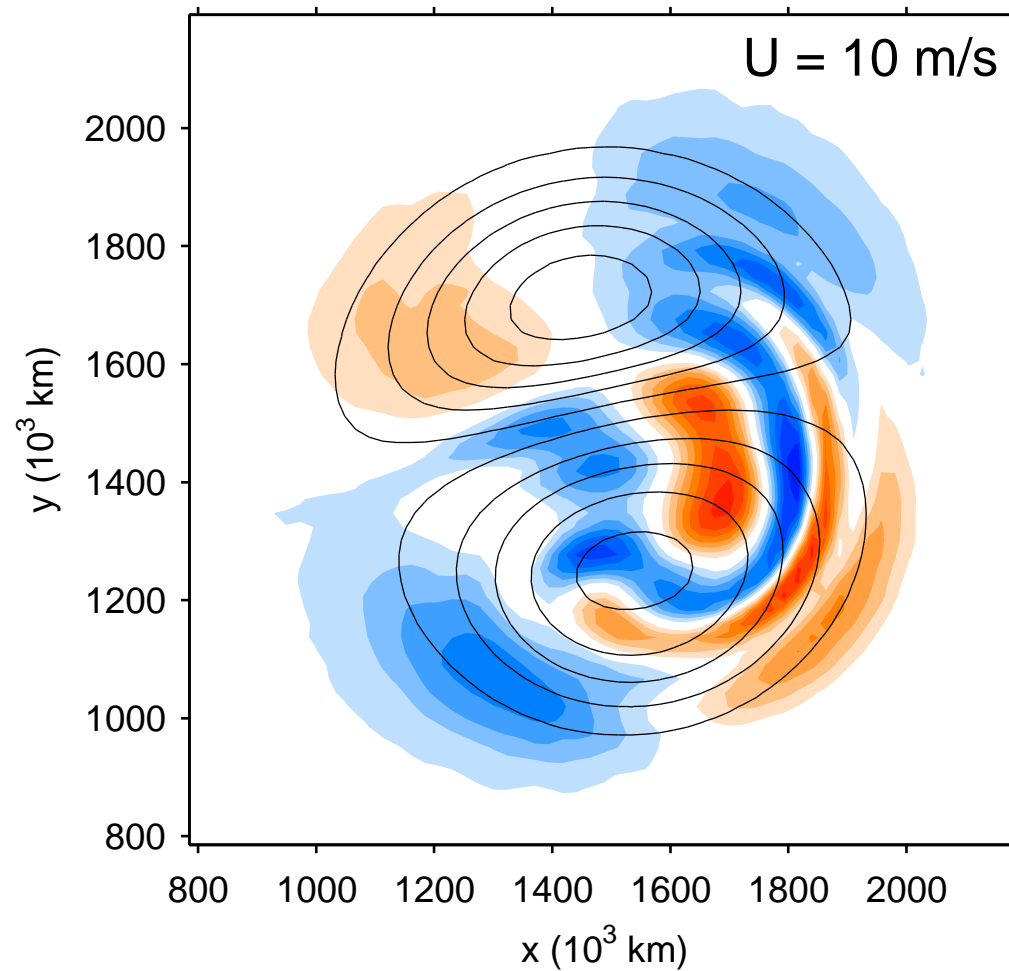
Dependence on Ro

- ▷ simulations with initial jet $U = 2.5, 5, 7.5, 10, 12.5, 15$ m/s



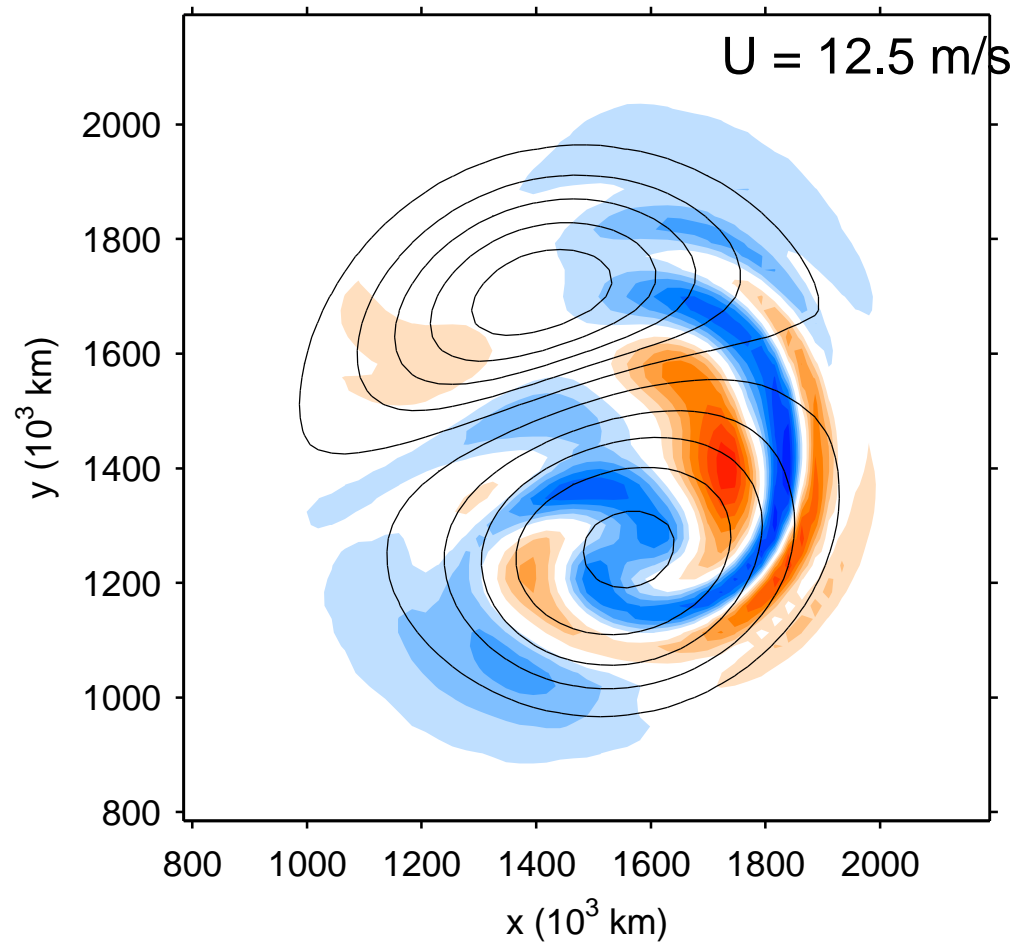
Dependence on Ro

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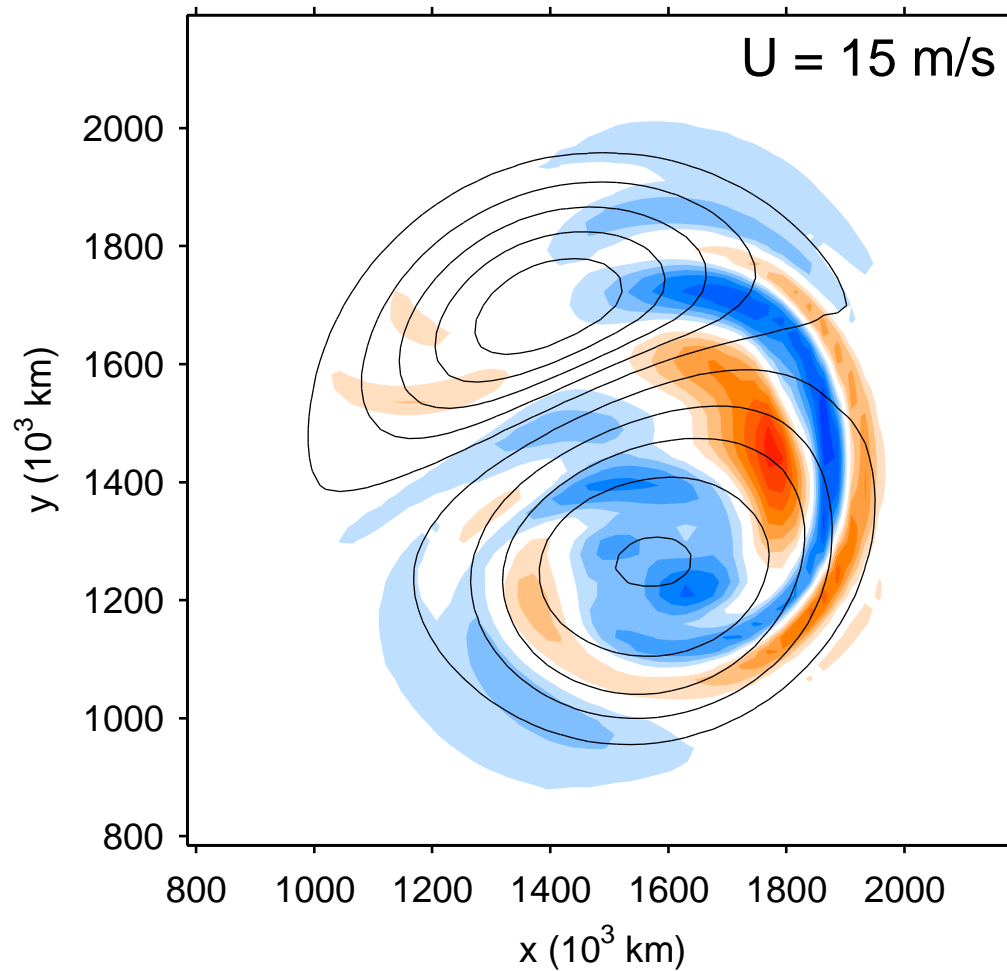
Dependence on Ro

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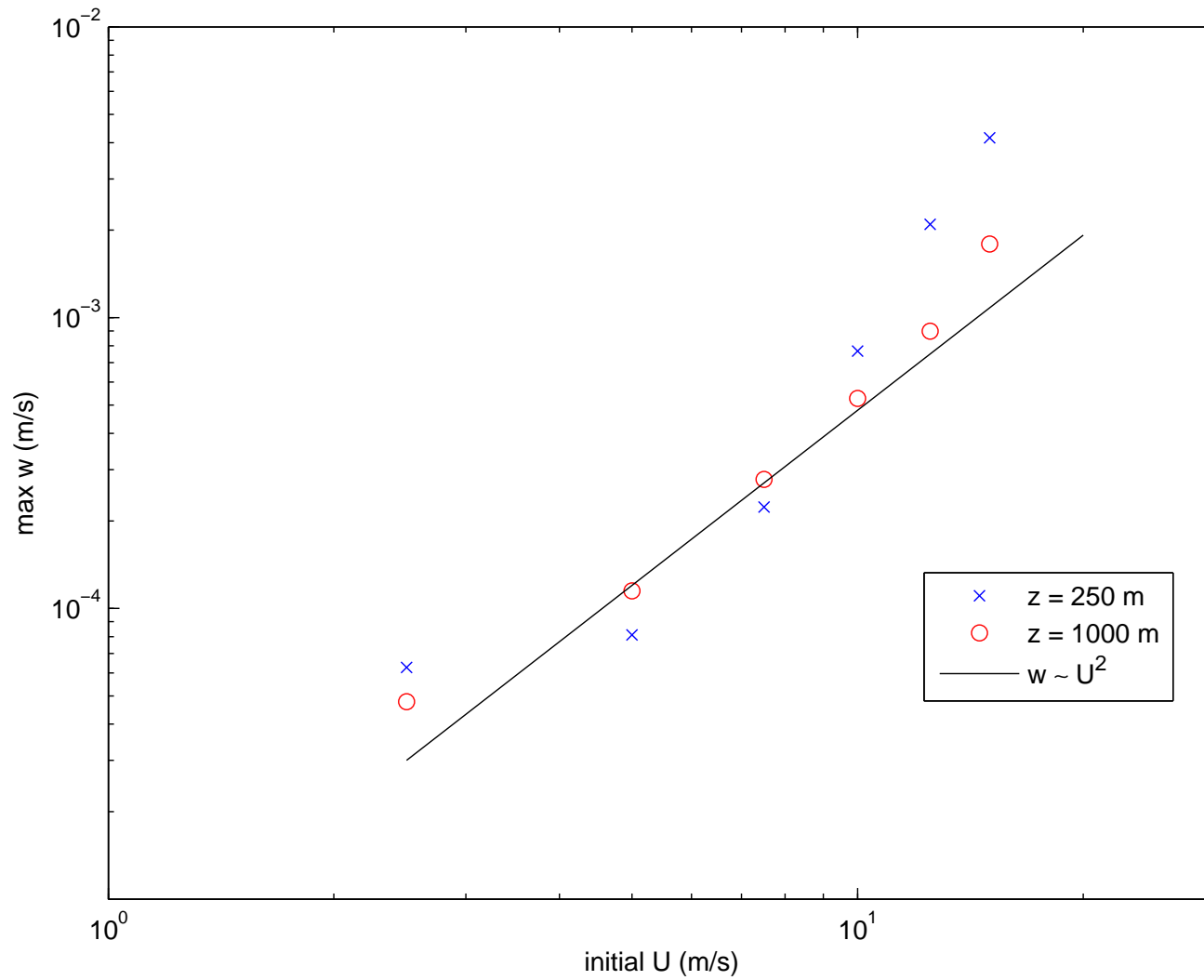
Dependence on Ro

- ▷ simulations with initial jet $U = 2.5, 5, 7.5, 10, 12.5, 15$ m/s



Dependence on Ro

- ▷ $\max(w)$ at $z = 250$ m, 1000 m



Wave Sources

“Adjustment?”

- ▷ No
- ▷ proposed in observational lit. on mesoscale gravity waves (e.g. Uccellini and Koch 1987)
- ▷ reserve use of term “adjustment” for transients

Instability?

- ▷ baroclinic, stratified flows subject to “wavy” instabilities (Plougonven et al. 2005 and refs.)

Wave emission?

Wave Sources

Schematic

- ▷ evolution eqn. for state $\mathbf{x}(t)$:

$$\partial\mathbf{x}/\partial t = \mathbf{f}(\mathbf{x})$$

- ▷ assume that we have an approximate solution $\hat{\mathbf{x}}(t)$, and that $\mathbf{x}' = \mathbf{x} - \hat{\mathbf{x}}$ is small over some time interval

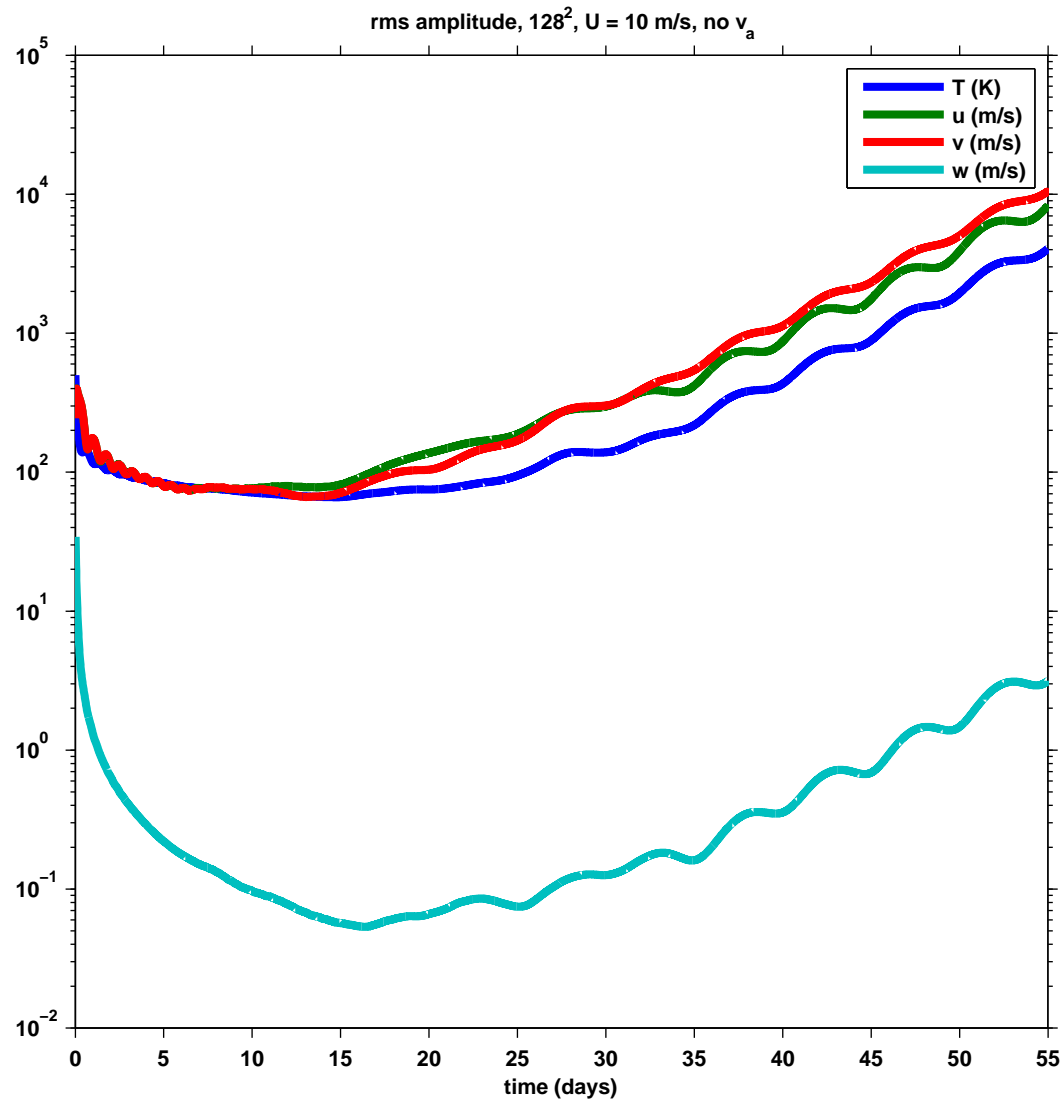
- ▷ then evolution of \mathbf{x}' given approximately by

$$(\partial/\partial t - \partial\mathbf{f}/\partial\mathbf{x}) \mathbf{x}' = \mathbf{f}(\hat{\mathbf{x}}) - \partial\hat{\mathbf{x}}/\partial t$$

- ▷ properties of both $\partial\mathbf{f}/\partial\mathbf{x}$ and $\mathbf{f}(\hat{\mathbf{x}}) - \partial\hat{\mathbf{x}}/\partial t$
- ▷ if stable, steady forcing gives steady response

Stability of QG dipole

- ▷ integrations starting from noise of PE linearized about QG dipole



Summary

(Nearly) steady dipole with embedded inertia-gravity waves.

- ▷ waves stationary with respect to dipole and of smaller spatial scale
- ▷ wave characteristics strongly influenced by propagation through balanced flow
- ▷ waves become clear at $Ro \sim 0.2$

Wave sources

- ▷ steady response to steady forcing?
- ▷ [Vanneste/Yavneh in x ; flow over 2D ridge]
- ▷ possible role of weak instabilities

Other open issues

- ▷ secular increase in anticyclone's strength
- ▷ dependence on resolution and numerical dissipation