Test Cases for Atmospheric Model Dynamical Cores

Christiane Jablonowski
(email: cjablono@umich.edu)
University of Michigan

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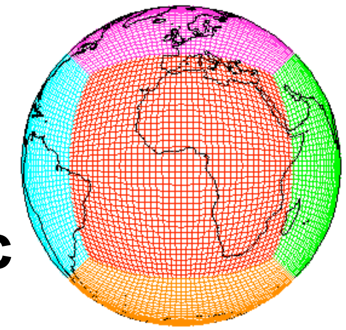
Motivation

- Test cases for 3D dynamical cores on the sphere
  - are hard to find in the literature
  - are often not fully documented
  - have (often) not been systematically applied by a large number of modeling groups
  - lack standardized & easy-to-use analysis techniques
- Idea: Establish a collection of test cases that finds broad acceptance in the community
- Test suite that clearly describes the initial setups and suggests evaluation methods like the
  - Test suite for the SW equations (Williamson et al. 1992)
  - Proposed test suite for 2D non-hydrostatic dynamical cores (Bill Skamarock, NCAR, see Bill's web page: http://www.mmm.ucar.edu/projects/srnwp_tests/#proposal)

NASA/GFDL



Goals of the Test Suite

Test cases should

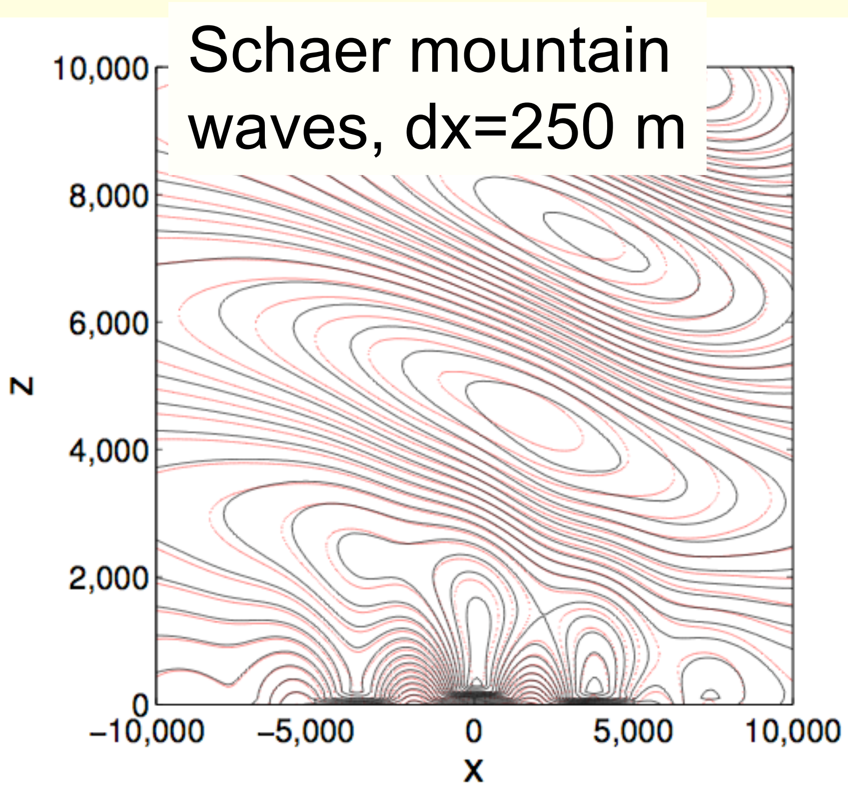
- be designed for **hydrostatic** and **non-hydrostatic** dynamical cores on the sphere, for both **shallow** and **deep atmosphere** models
- be easy to apply: analytic initial data (if possible) suitable for **all grids**, formulated for **different vertical coordinates**
- be easy to evaluate: standard diagnostics
- be relevant to atmospheric phenomena
- reveal important characteristics of the numerical scheme
- have an analytic solution or converged reference solutions

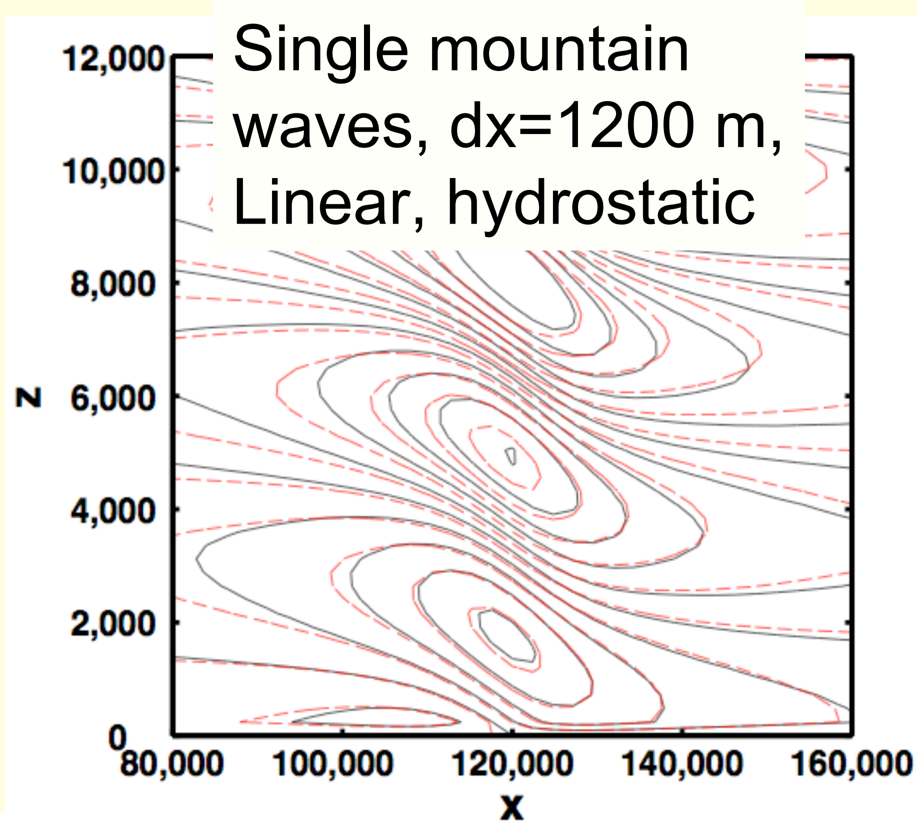
Review of non-hydrostatic test cases

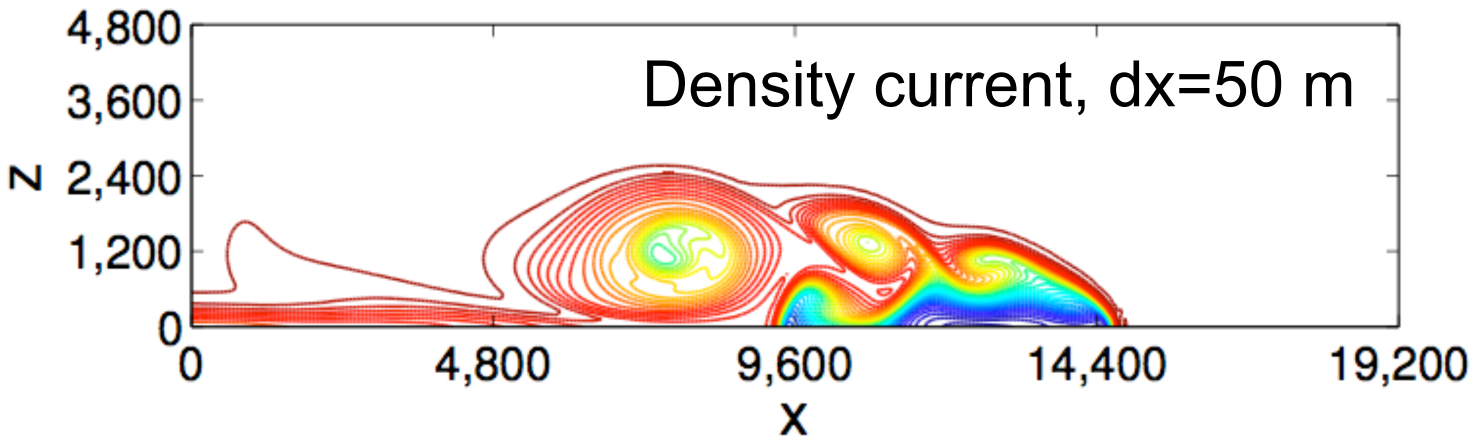
Most often: formulated for **2D (x-z) Cartesian** geometry without the Earth's rotation:

- **Thermally induced circulation:**
  - Density current (Straka et al. (1993))
  - Warm bubble (Robert, JAS (1993), Bryan and Fritsch (2002), …): triggered by convective instability
  - Cold bubble
- **Mountain-induced gravity waves**
  - Hydrostatic / nonhydrostatic determined by ratio $(N\ d)/u_0$
  - Linear / nonlinear determined by ratio $(N\ h)/u_0$
  - Either single mountain (Dudhia, MWR (1993))
    or more complex topography (Schaer et al, MWR (2002))
- **Inertia-gravity waves in periodic channel** (Skamarock and Klemp, MWR, (1994)), includes Coriolis forces

Review of non-hydrostatic test cases







from Giraldo and Restelli, JCP in press

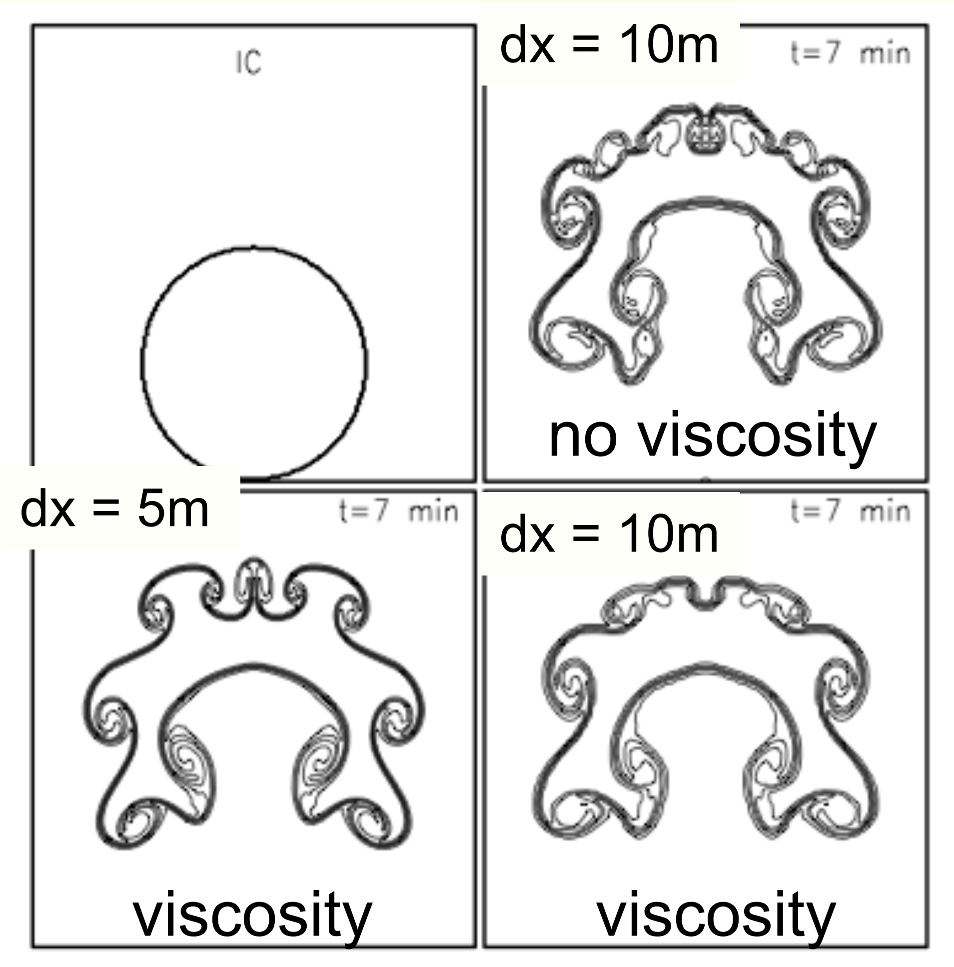
Review of non-hydrostatic test cases

Observations:

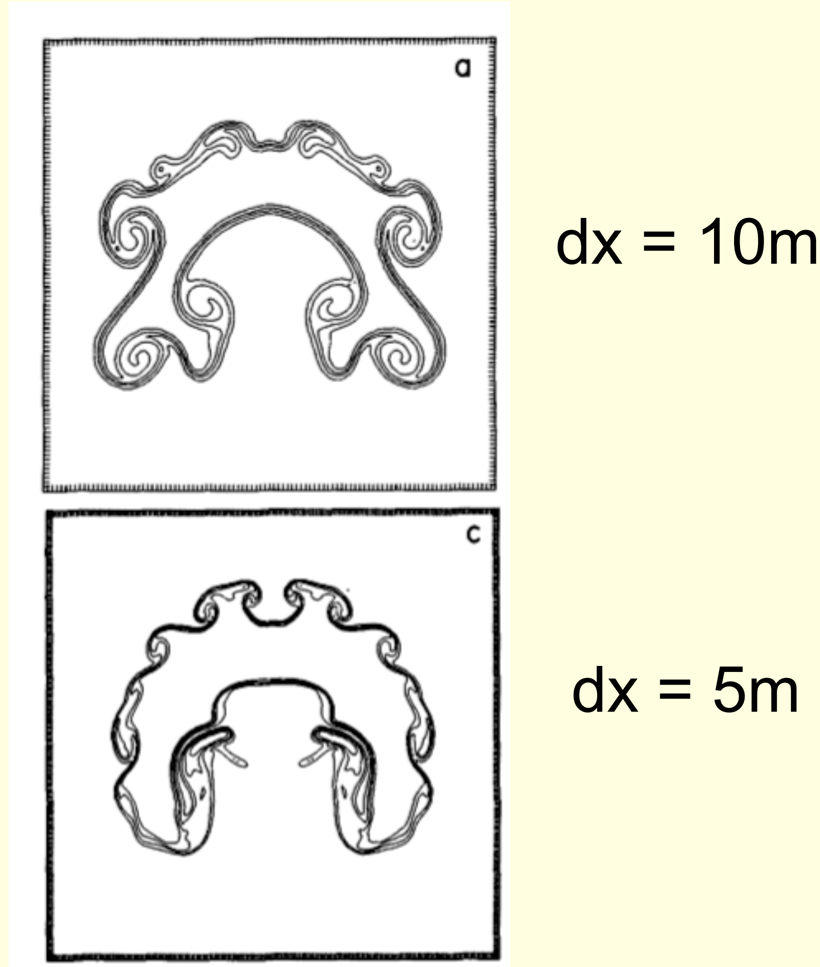
- Tests need very **high resolutions** in the horizontal and vertical directions (sometimes on the order of 10-100 m)
- Tests run for very **short** time periods, e.g. 10 minutes
- Tests run in **small** domains (a few km)
- Some tests have linear analytic solutions (e.g. some mountain wave test cases)
- Modelers often **vary** the initial conditions and sizes of the domains: very difficult to compare model results unless they are compared against analytic solutions
- High-resolution reference solutions depend strongly on the **diffusion characteristics** (either implicit or explicit)
- **Eyeball-norm** comparisons: Assessments lack additional diagnostics

Example: non-hydrostatic test cases

Warm bubble experiment: Fine scales differ, rely on viscosity



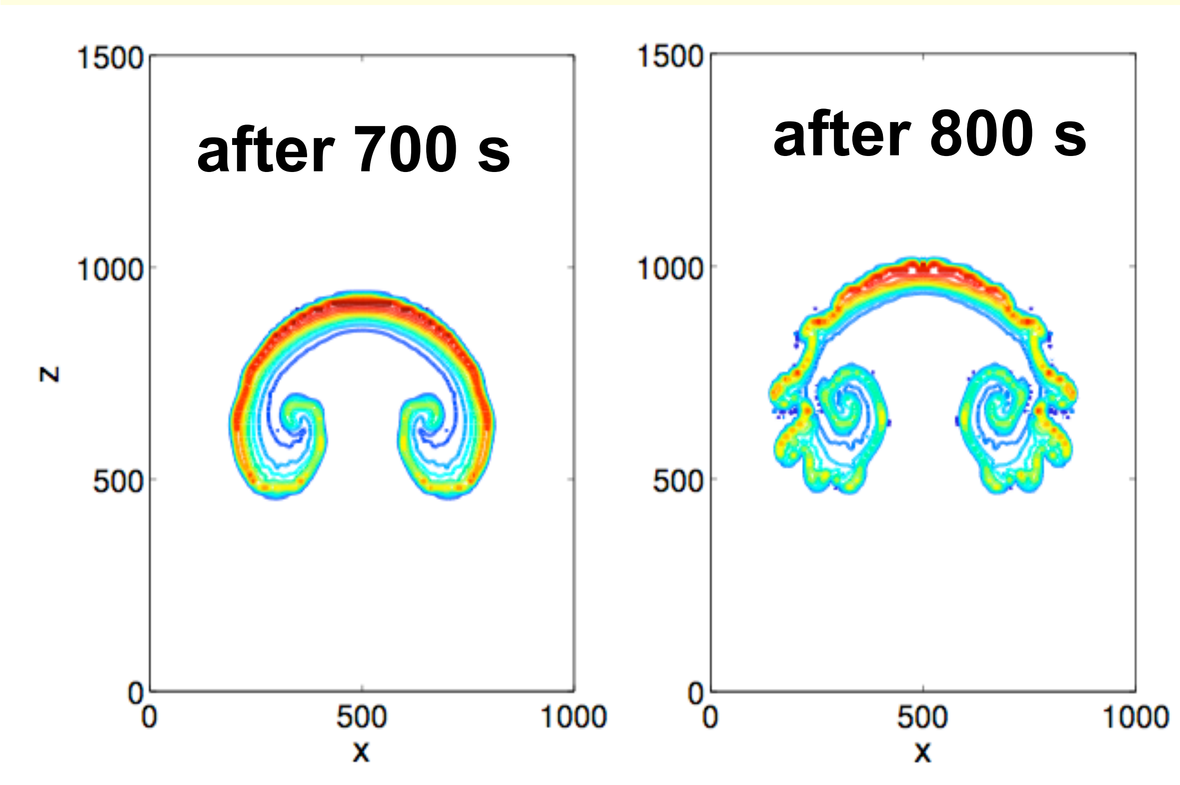
Lin, QJ (in review)



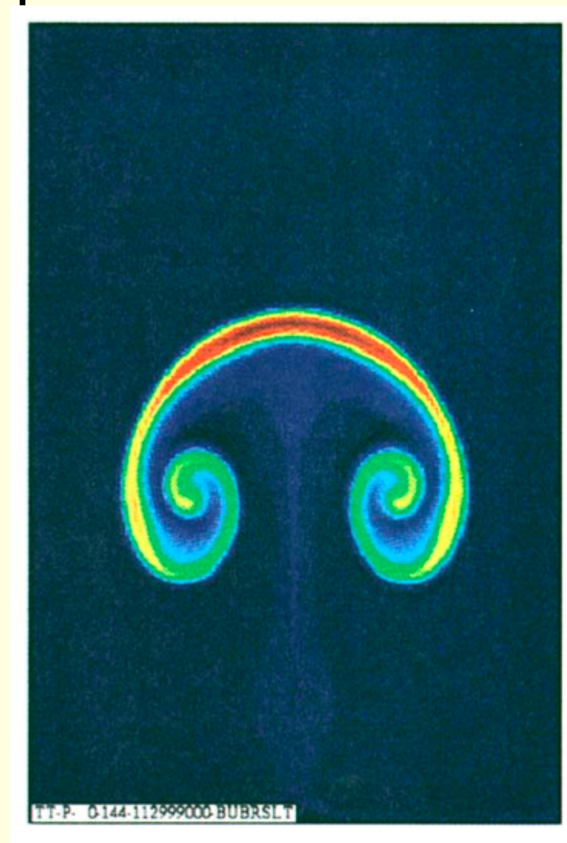
Robert (1993), after 7 min.

Example: non-hydrostatic test cases

Warm bubble experiment (Gaussian): Slightly different setups or/and time steps are difficult to compare



Giraldo and Restelli JCP, in press



Robert (1993), after 720 s

Review of idealized test cases on the sphere

So far in the literature:

- **Deterministic**
  - Polvani et al., MWR (2004)
  - Collection by Tomita and Satoh, Fluid Dyn. Res. (2004)
  - Jablonowski and Williamson, QJ (2006)
  - Test suite discussed today:
    http://www-personal.umich.edu/~cjablono/dycore_test_suite.html
    74-page 'Test Suite' document, to be submitted as journal paper and NCAR Tech Report
- **Climate-runs with idealized forcings**
  - Held-Suarez (1994)
  - Boer-Denis (1998)
  - Moist Held-Suarez (Galewsky et al. JAS (2005)
- **Aqua-planet simulations** (ocean-covered Earth with prescribed SST, full physics), Neale and Hoskins (2001)

Review of idealized test cases on the sphere

Some more comments on the test case collection in Tomita and Satoh, Fluid Dyn. Res. (2004)

- Used for **nonhydrostatic deep atmosphere** dycore
- But test cases are used **at hydrostatic scales**
- Test are formulated for **shallow** atmospheres

Two classes:

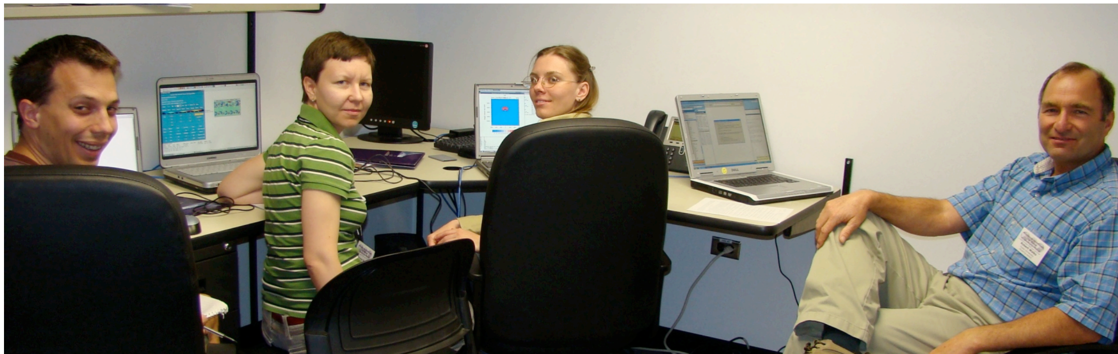
- Irrotational:
  - Sound waves
  - Gravity waves
  - Mountain waves
- Rotational:
  - Kelvin and Equatorial Rossby waves triggered by tropical heating
  - Rossby waves in midlatitudes (mountain induced)

Test cases on the sphere: NCAR 2008 ASP Colloquium

Peter Lauritzen, Christiane Jablonowski, Ram Nair, Mark Taylor

A community effort towards **standard evaluations** of dynamical cores with over 10 modeling groups, 36 students and 17 lecturers

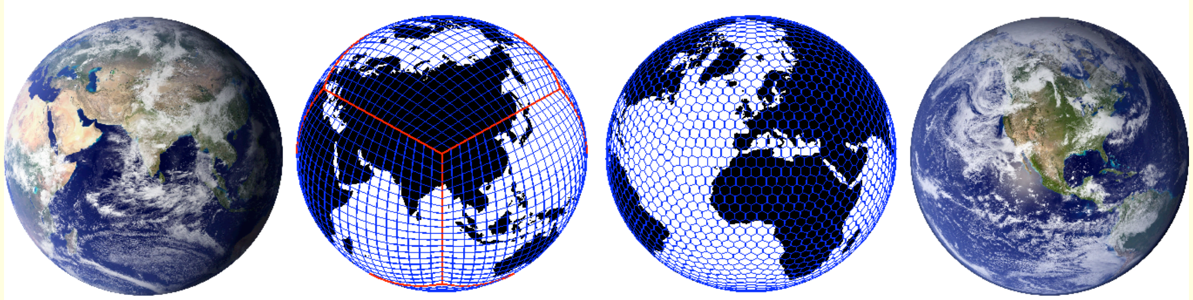
NCAR 2008 ASP Colloquium



Proposed Dynamical Core Test Suite used during the 2008 NCAR ASP Colloquium

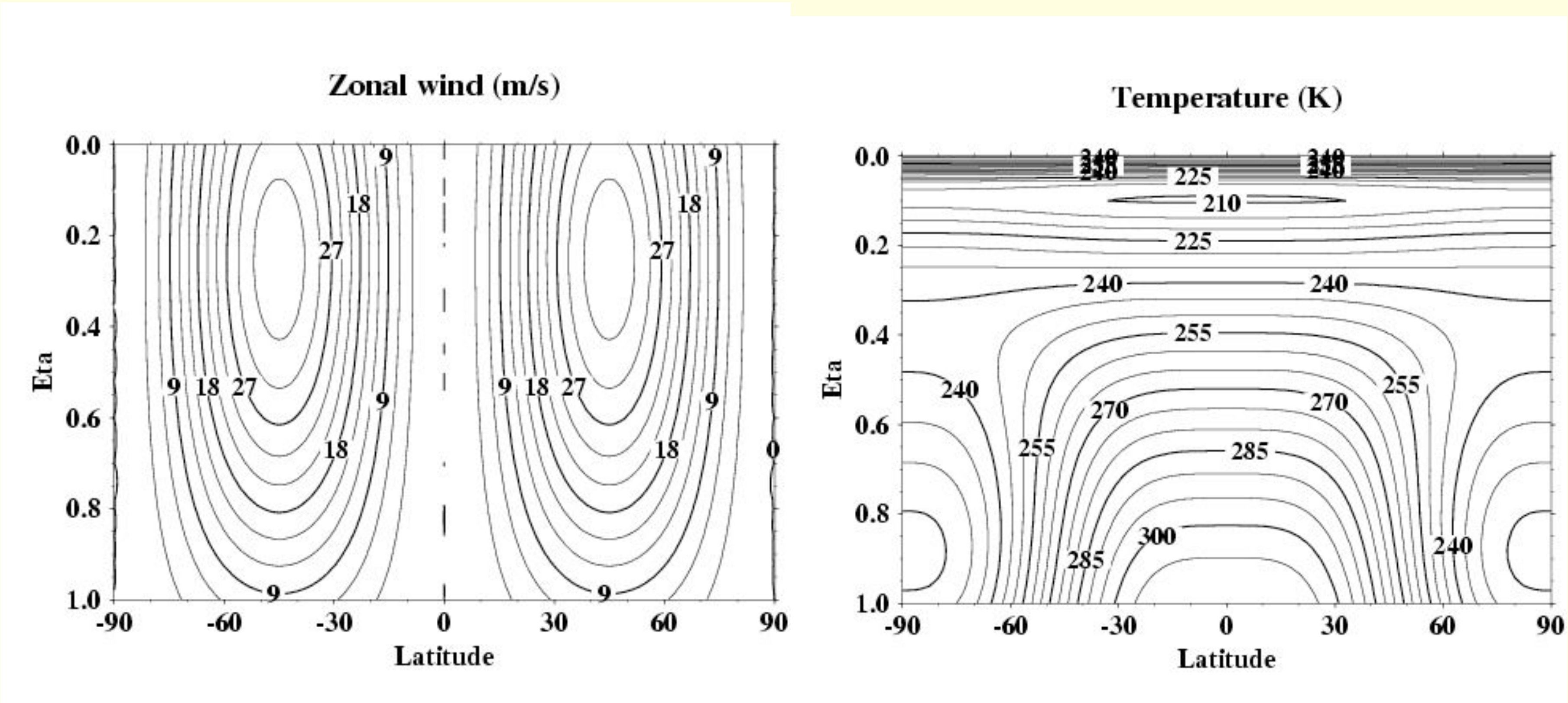
- All tests are formulated on the sphere
- Some have multiple test variants, e.g. rotation angle α

1. Steady-state test case
2. Evolution of a baroclinic wave
3. 3D advection experiments
4. 3D Rossby-Haurwitz wave with wavenumber 4
5. Mountain-induced Rossby wave train
6. Pure gravity waves and inertial gravity waves



Test 1: Steady-State Initial Conditions

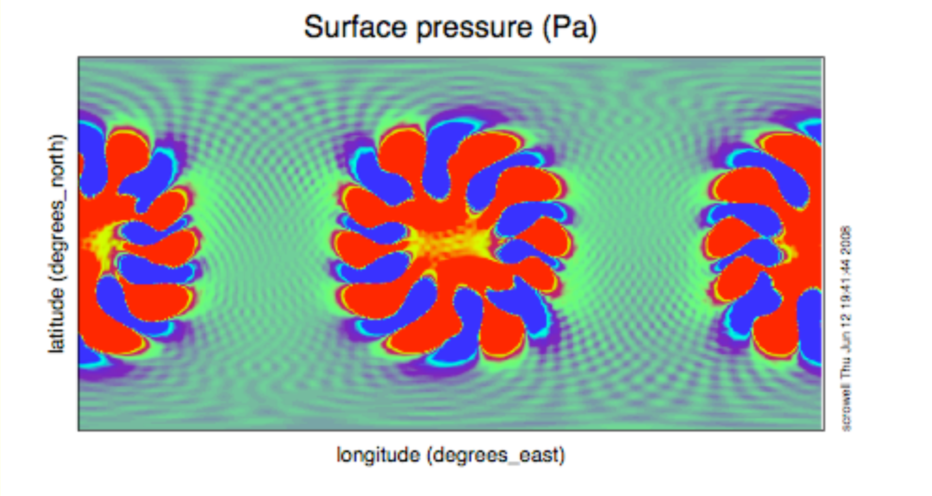
- Analytical solution to the Primitive Equations with pressure-based vertical coordinates (like σ or η)
- Prescribe v = 0 m/s, p_s = 1000 hPa
- Prescribe u ➡ derive Φ_s and T



Jablonowski and Williamson, QJ (2006) and NCAR Technical Report 2006

Test 1) Steady-State

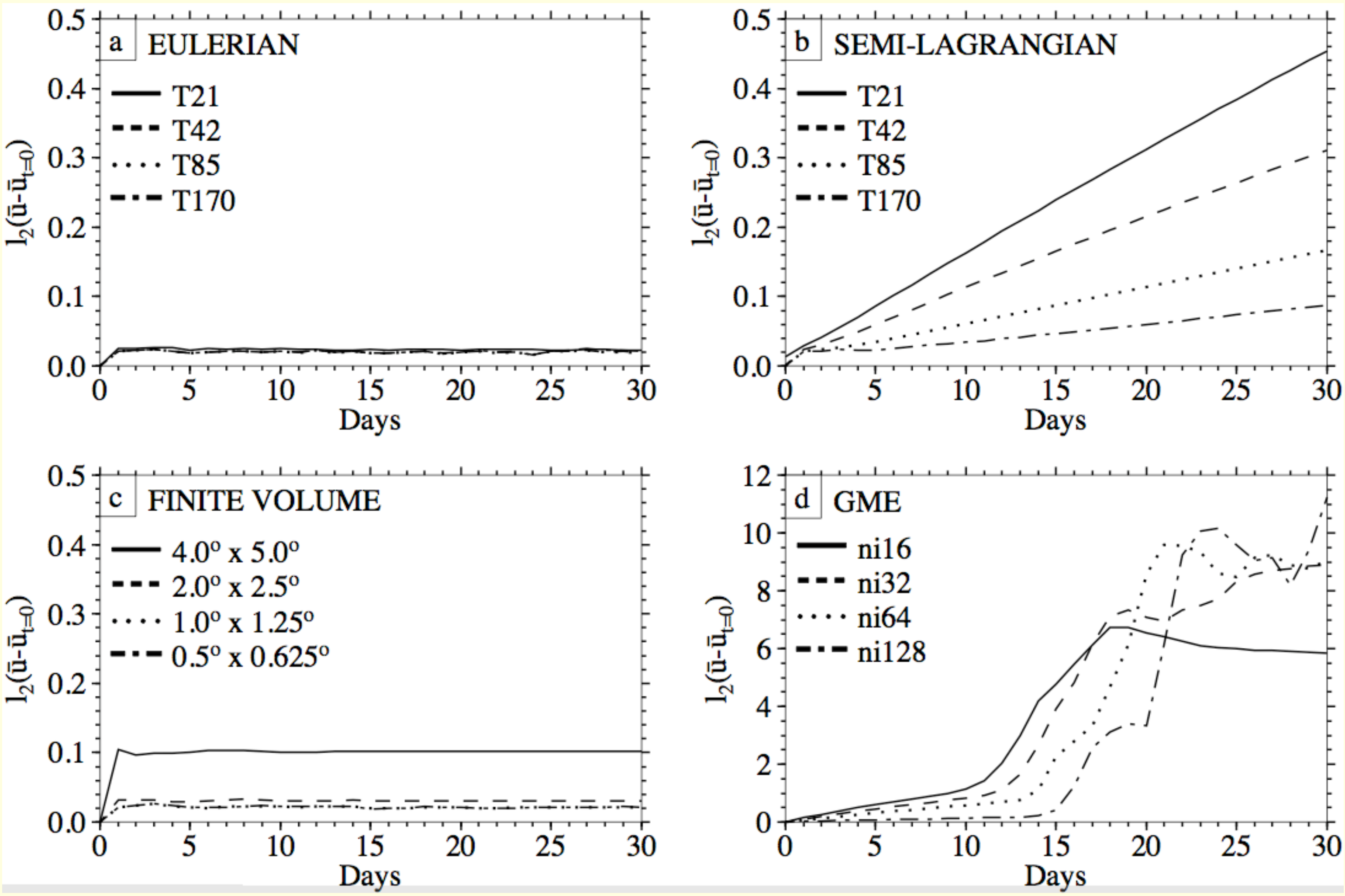
- Initialize the dynamical core with the analytic initial conditions (balanced & steady state)
- Let the model run over 30 days (if possible without explicit diffusion)
- Does the model maintain the steady state?
- The answer is **'sometimes'**:
- Yes if regular lat-lon grid is used and the flow is a pure W-E flow (no rotation)
- No for cubed-spheres, triangular grids (grid imprinting), or $\alpha > 0$
- Steady-state in irregular grids improves with increasing resolution



CAM-EUL, day 23 with α=90°

Test 1: Error analysis

- Initial state is analytic solution
- Maintenance of the zonal-mean initial u wind (l2 error)

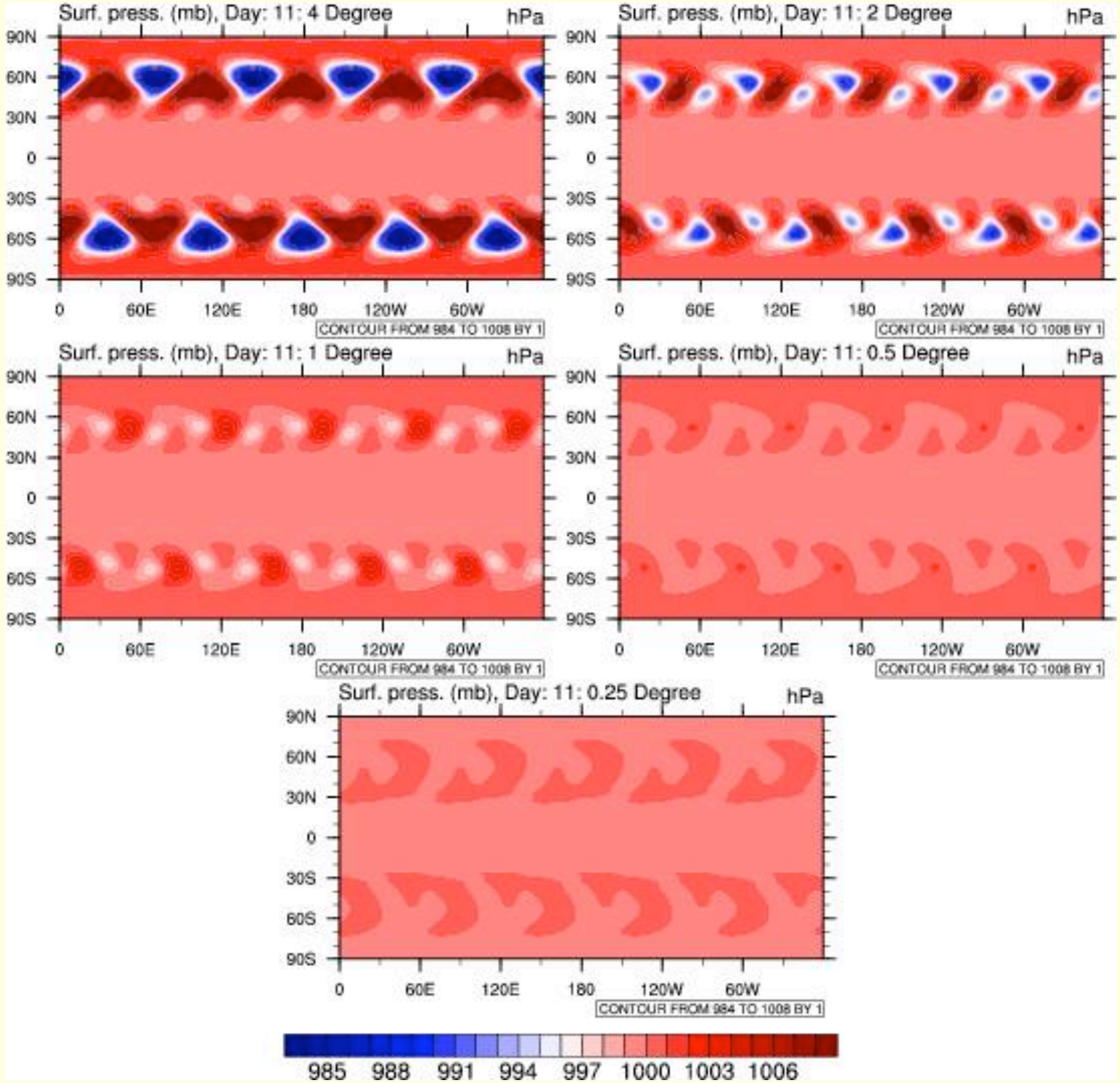


Decentering parameter effect

Wave number 5 effect

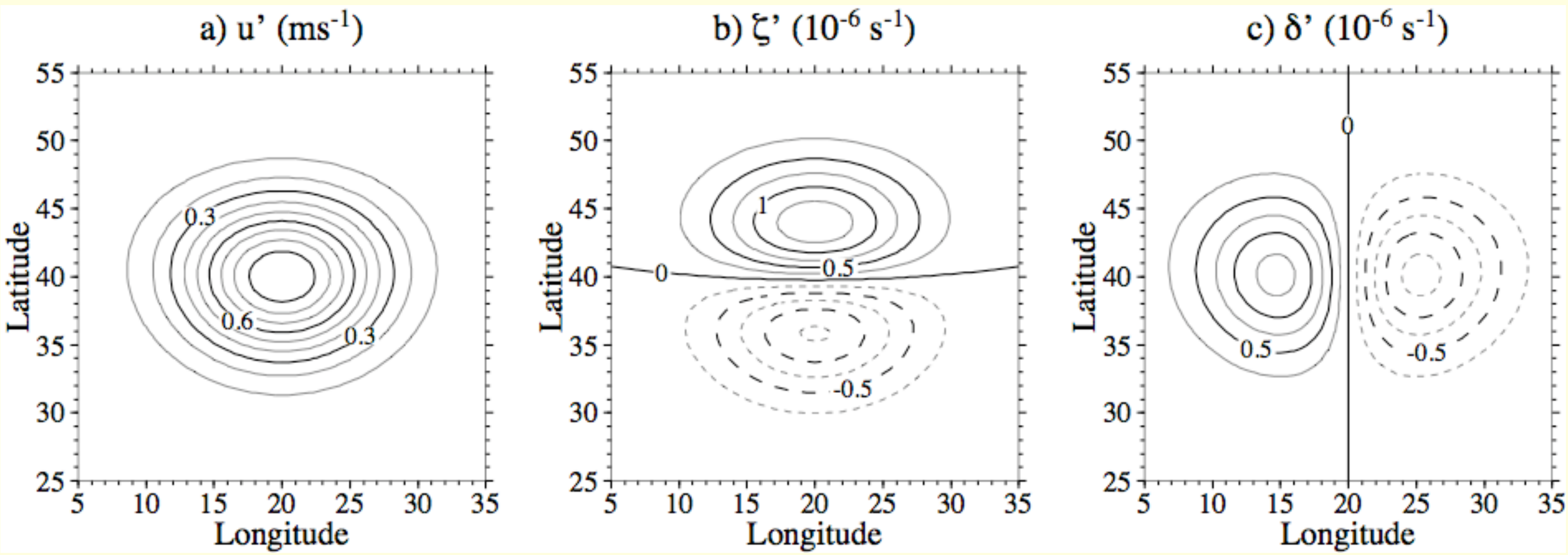
Test 1: Grid imprinting

- GME: p_s field, day 11
- Decreases with increasing resolution
- Emphasized by idealized test setup
- Important for real runs?

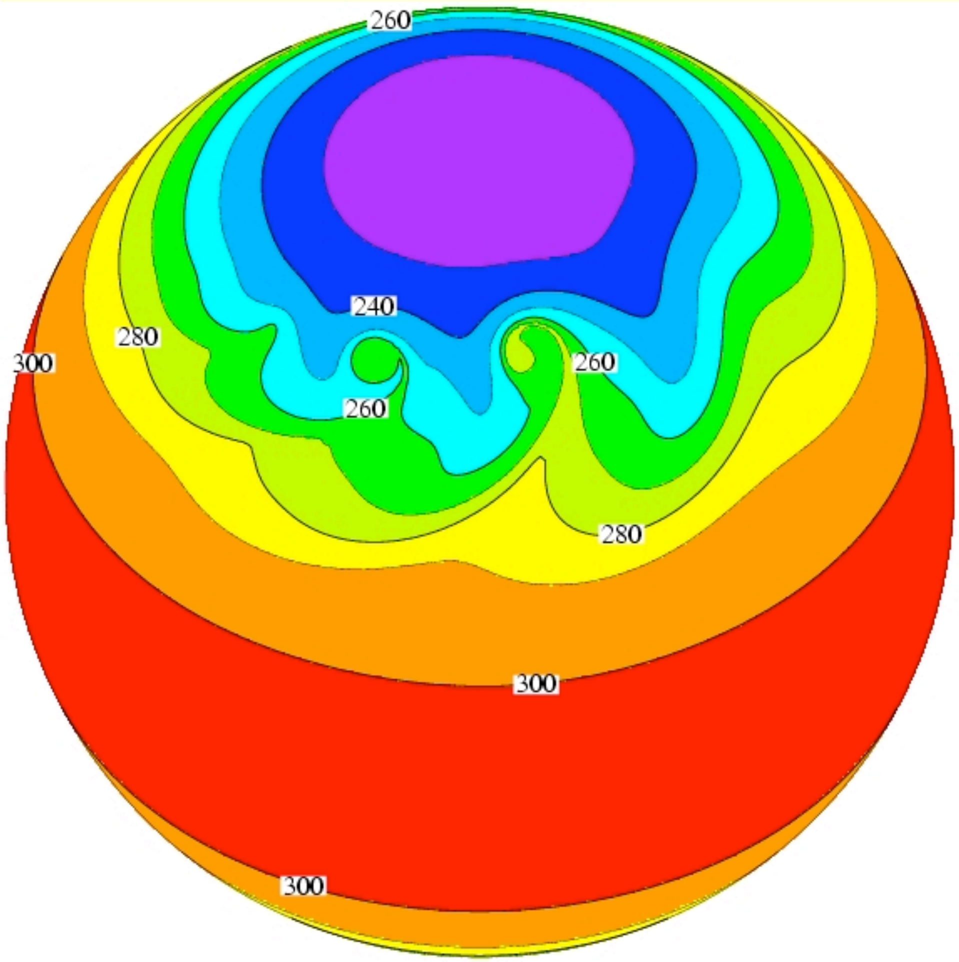


Test 2) Select Gaussian Hill Perturbation

- Start with initial conditions from test 1
- Overlay a Gaussian perturbation (at each level): triggers the evolution of a baroclinic wave over 10 days
- Suggested: pertubation of the zonal wind field ‘u’ or the vorticity and divergence (for models in ζ-δ form)



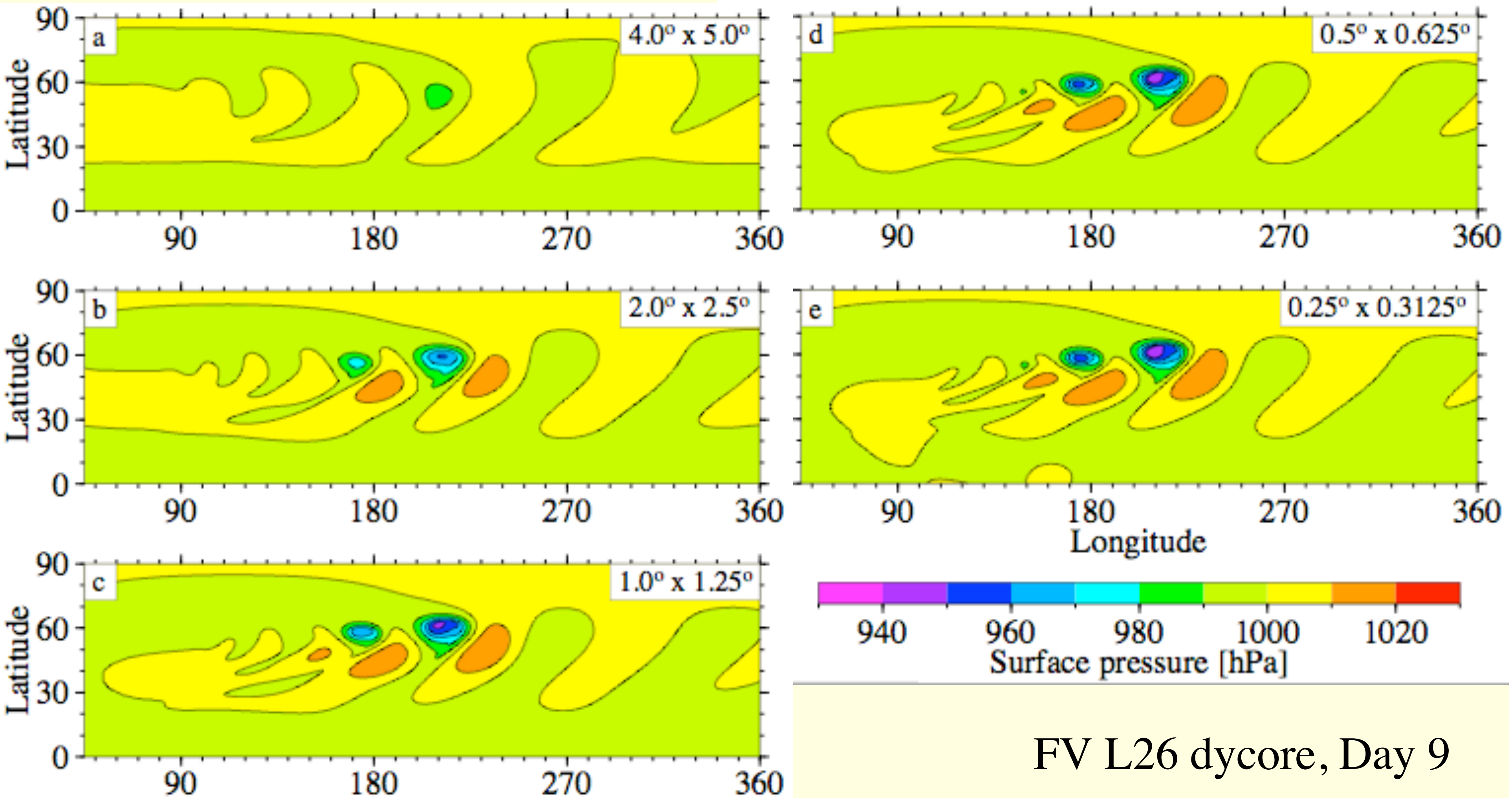
Test 2) Baroclinic Waves



- 850 hPa temperature field (in K) of an idealized baroclinic wave at model day 9
- Initially smooth temperature field develops strong gradients associated with warm and cold fronts
- Explosive cyclogenesis after day 7
- Baroclinic wave breaks after day 9

Analysis: Convergence with Resolution

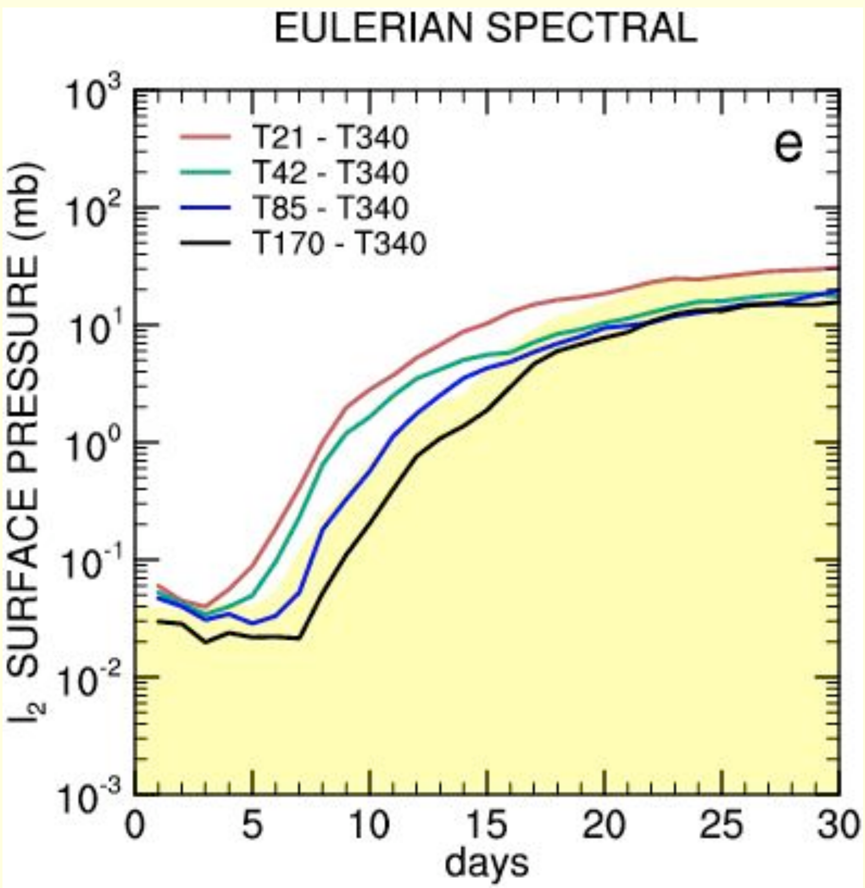
- Surface pressure starts converging at 1º x 1.25º

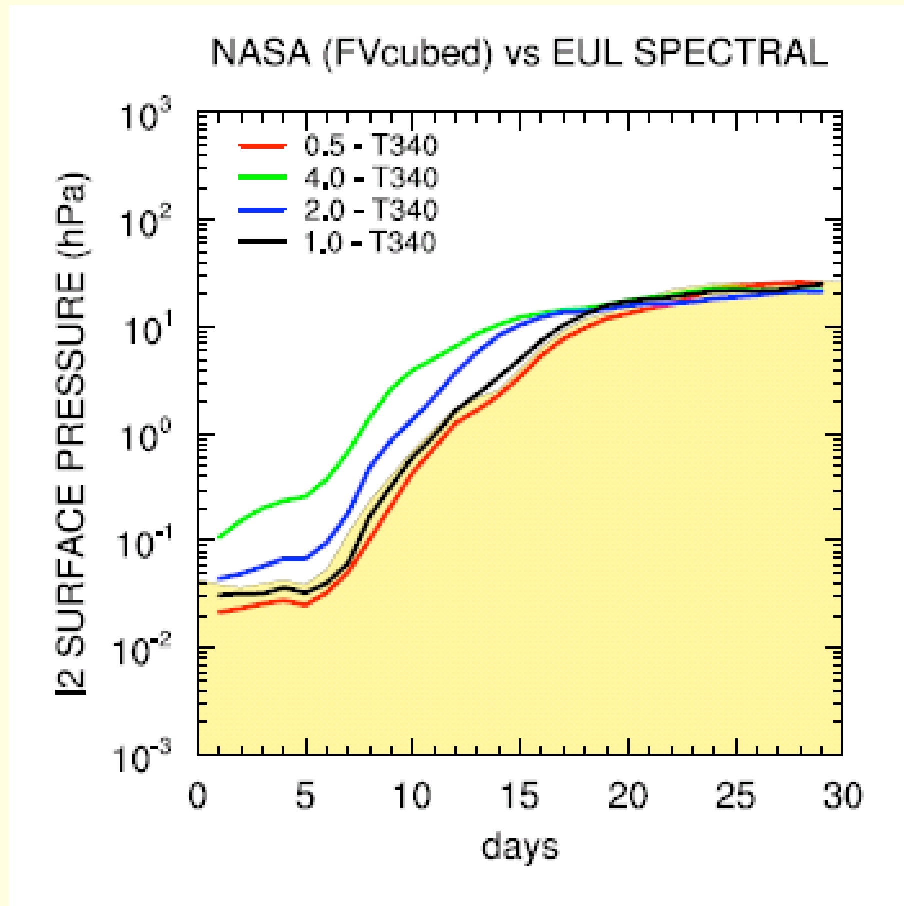


FV L26 dycore, Day 9

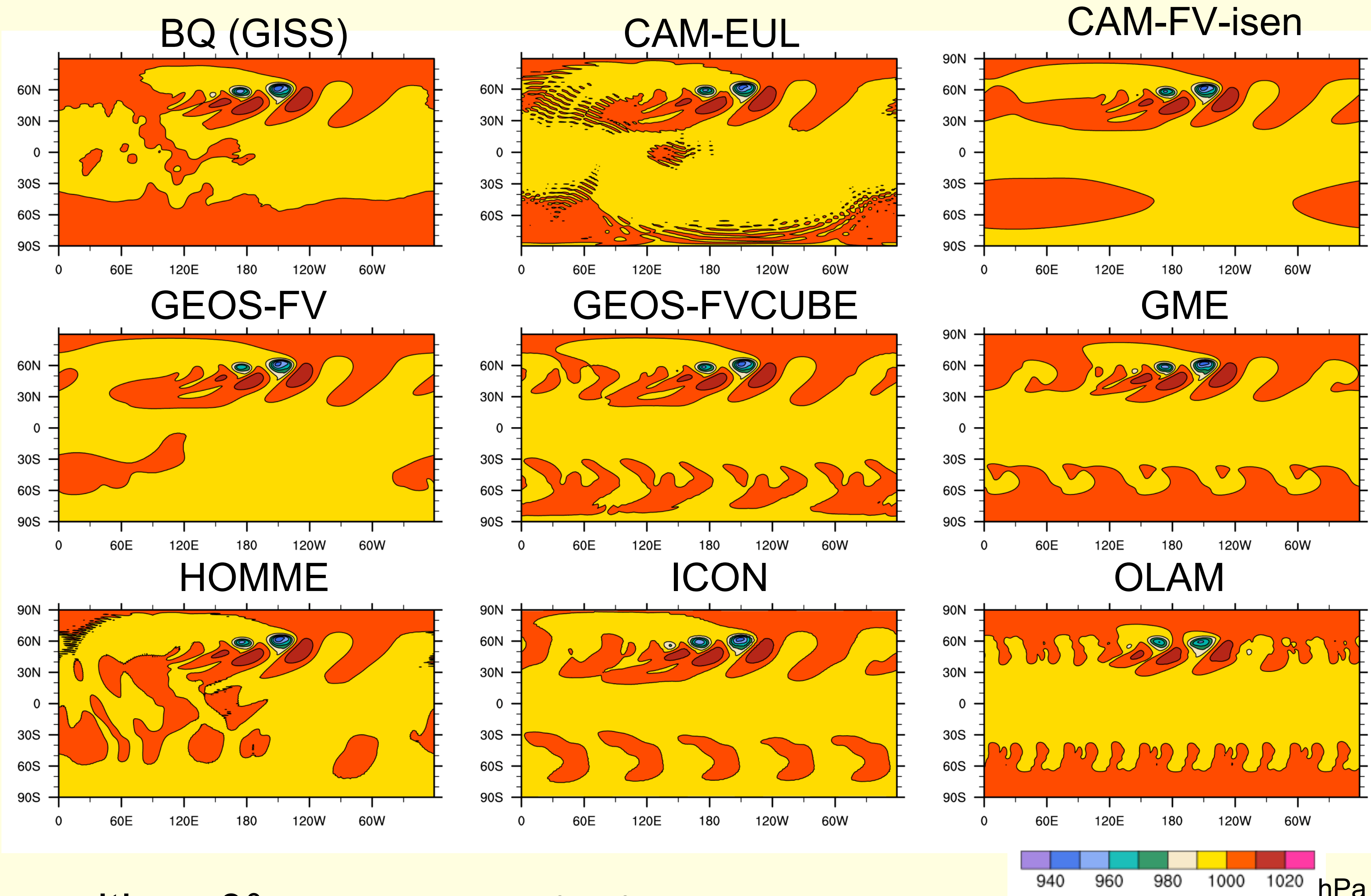
Model Convergence

- Single-model uncertainty stays well below the uncertainty across models
- Models converge within the uncertainty for the resolutions T85 (EUL & SLD), around 1º (FV), GME (55km / ni=128)





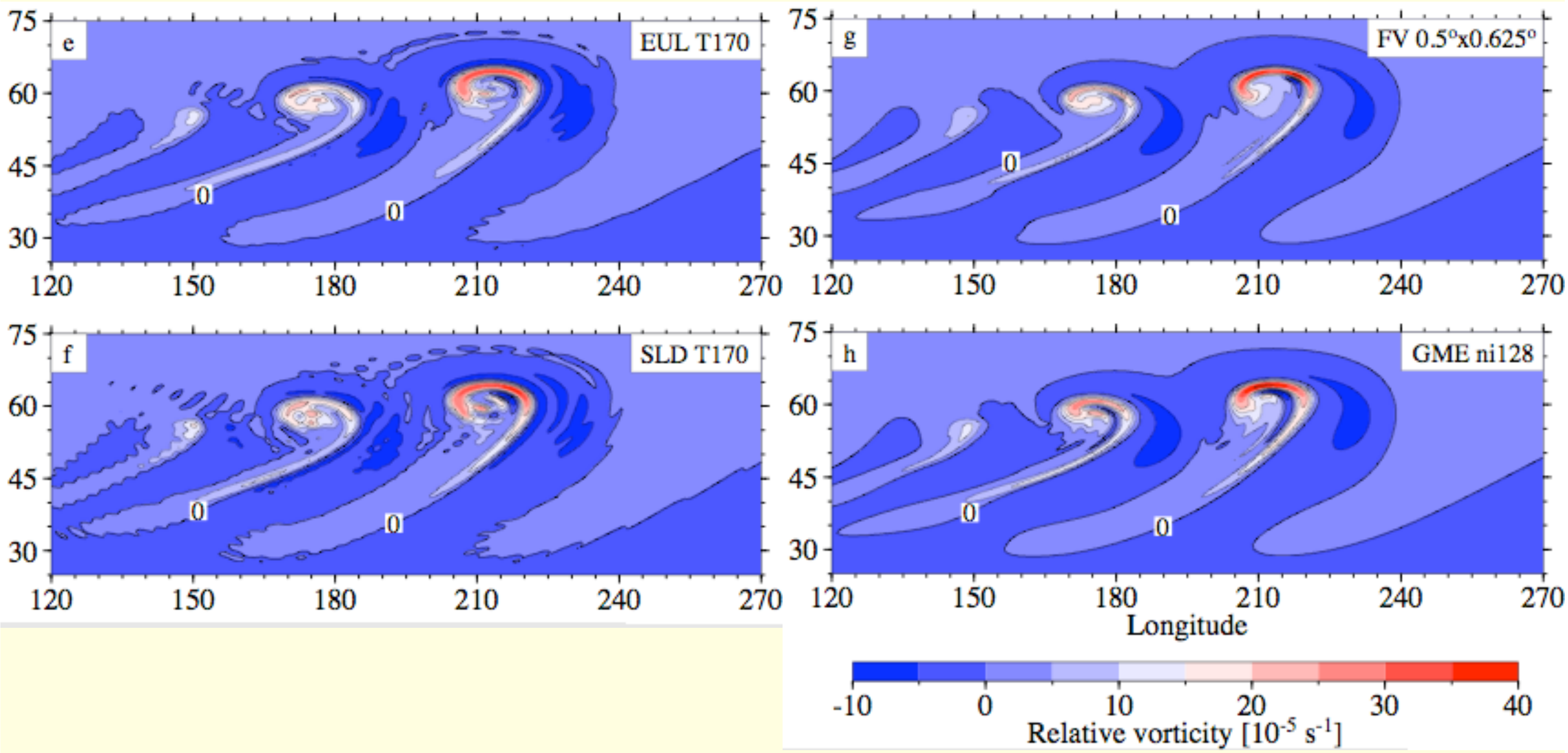
Model Intercomparison: p_s at Day 9



with α=0°, resolution ≈ 1°×1°L26

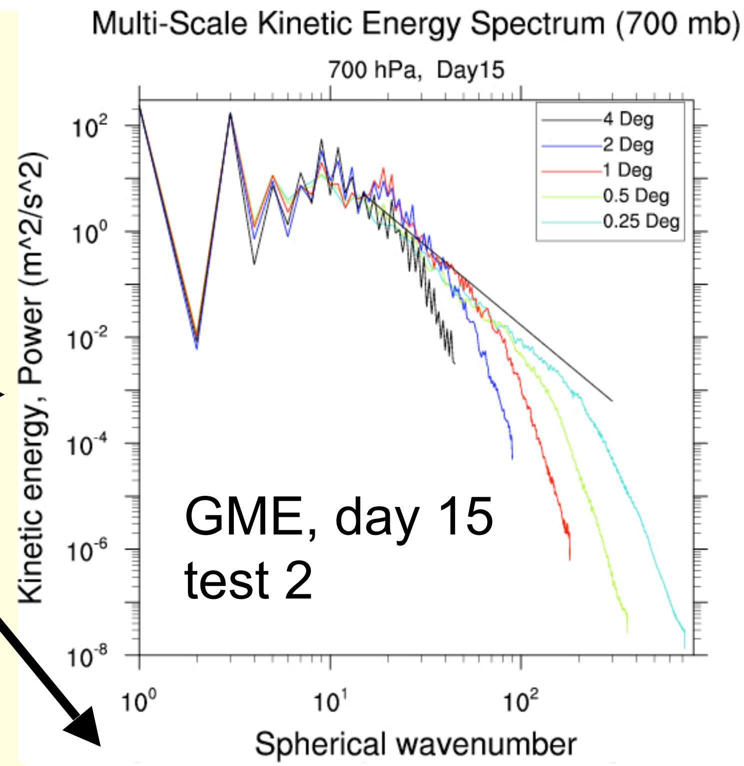
850 hPa Vorticity at Day 9

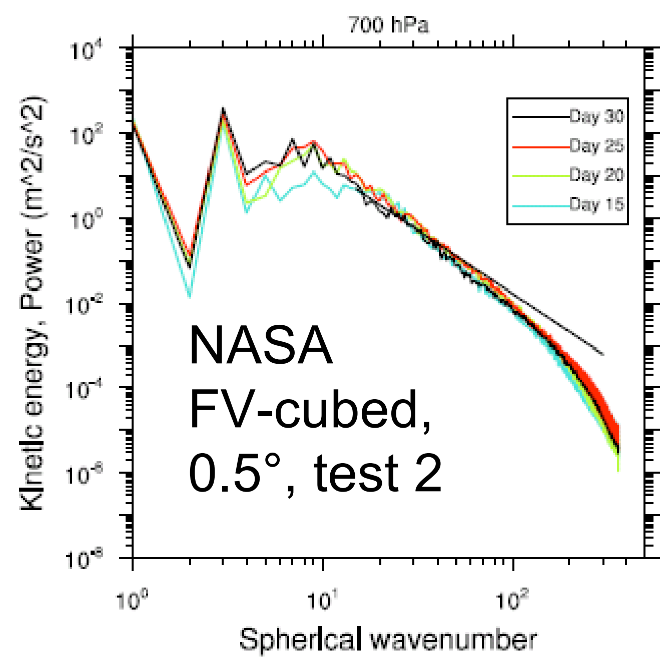
- Differences in the vorticity fields grow faster than p_s diff.
- Small-scale differences easily influenced by diffusion
- Spectral noise in EUL and SLD (L26)

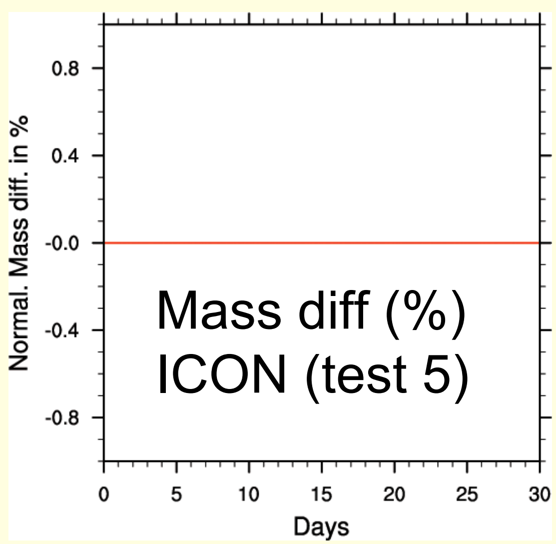


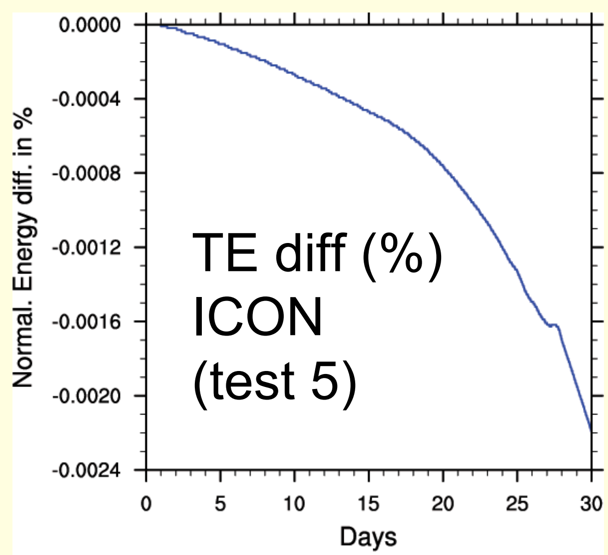
Standard diagnostics

- **Kinetic energy spectra**
  - Variation with resolution
  - Variation with time
- Assessments of conserved quantities (compute on native grid)
  - **mass**
  - **total energy (TE)**



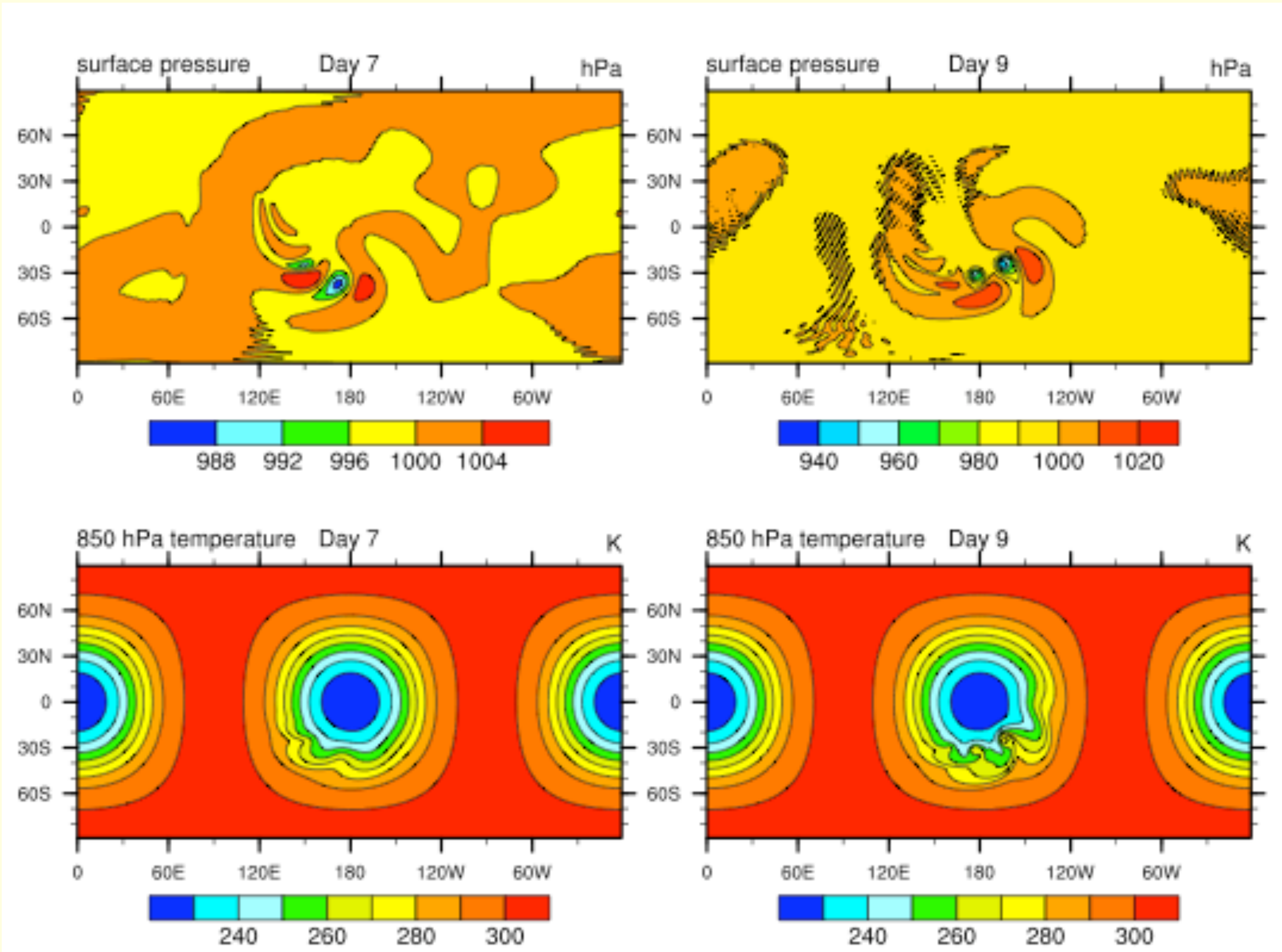






Test 2 with a rotation angle α=90°

- Increase the challenge for models with regular grids



Test 2 with tracer q1(α=0°)

- Explore the diffusive properties
- Mass conservation
- Over- and undershoots
- Consistency (does a constant stay a constant?)

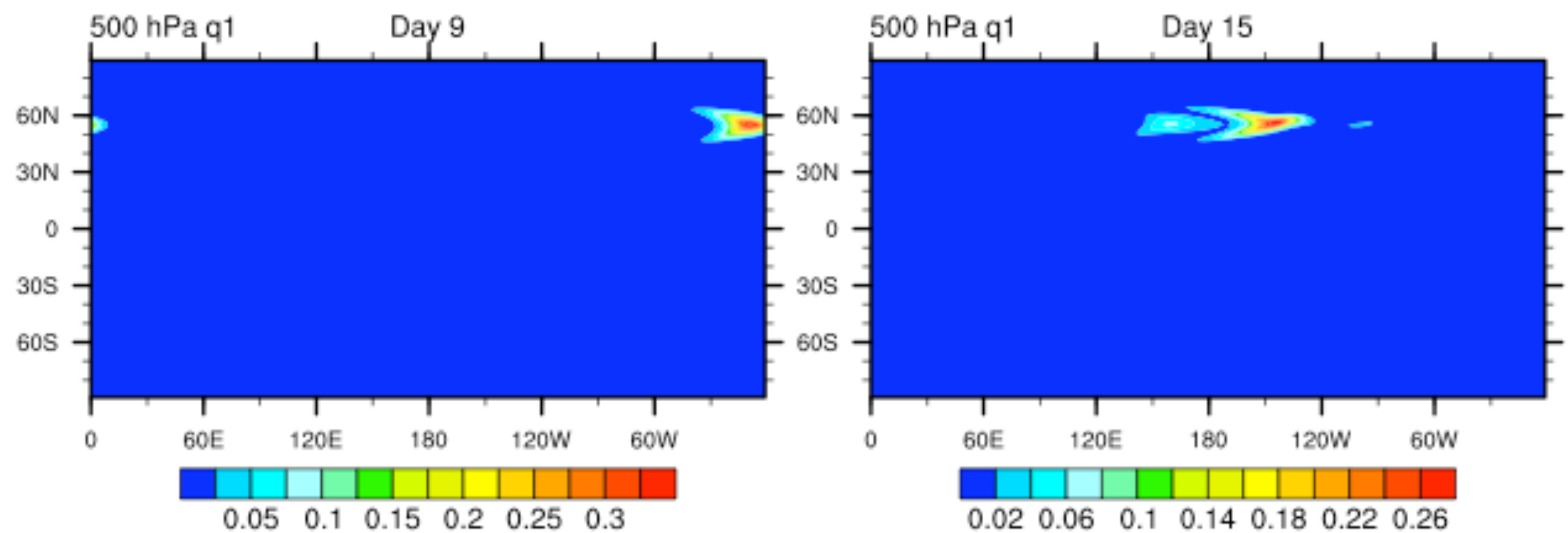
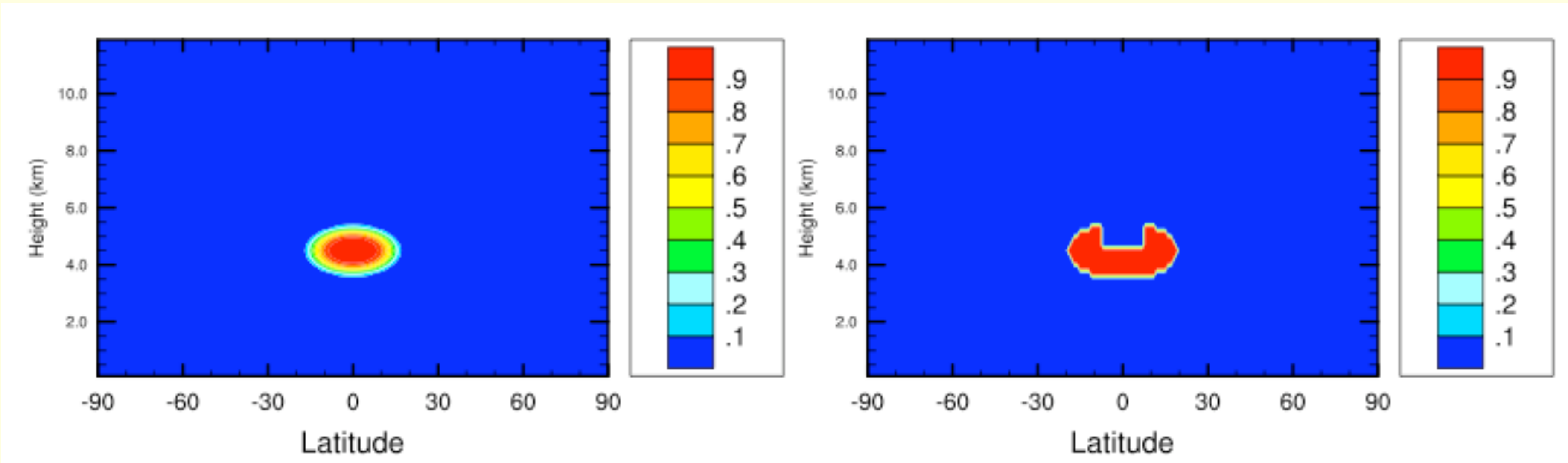


Figure 6: [2-0-1] simulated with EULT106L26: Tracer distribution $q1$ at day 9 and day 15 at the pressure levels 700, 600 and 500 hPa. The flow orientation angle is $\alpha = 0$.

Test 3) 3D Advection Tests

Prescribe two 3D tracer distributions:
Latitude-height cross sections



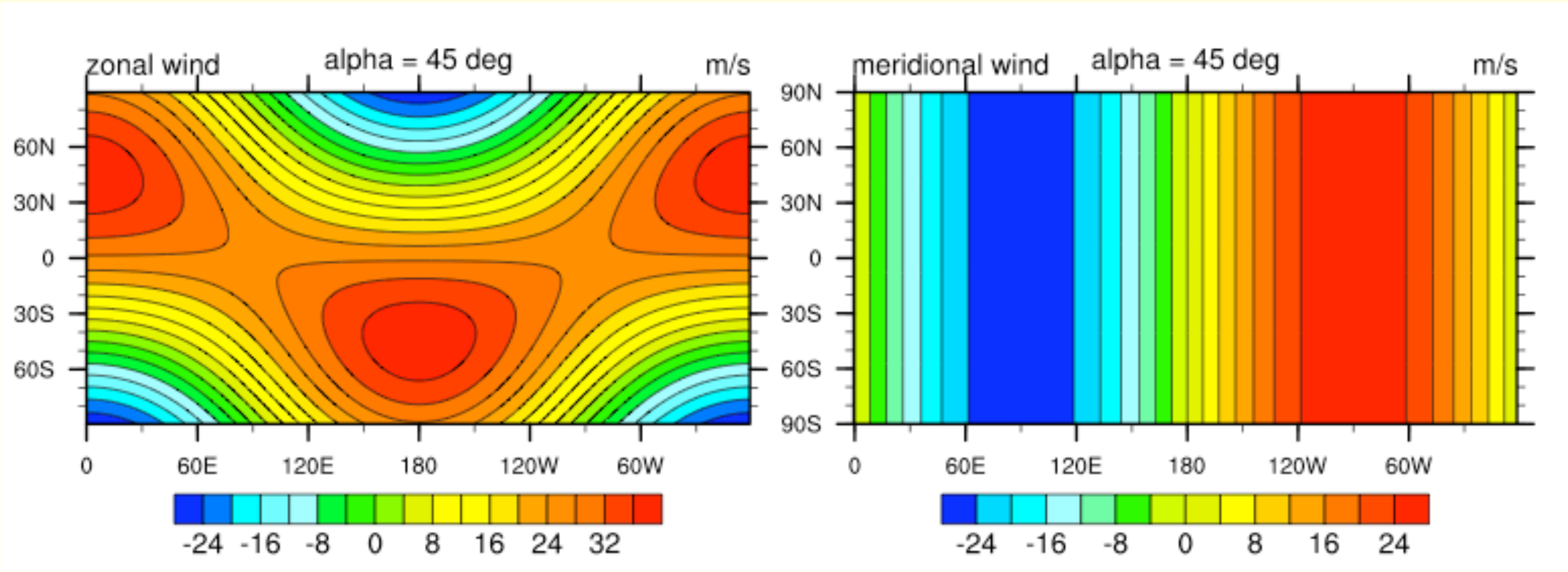
Smooth

Non-smooth: Slotted ellipse

Test 3) Advecting wind speeds

Example: Prescribed horizontal winds with $\alpha = 45°$

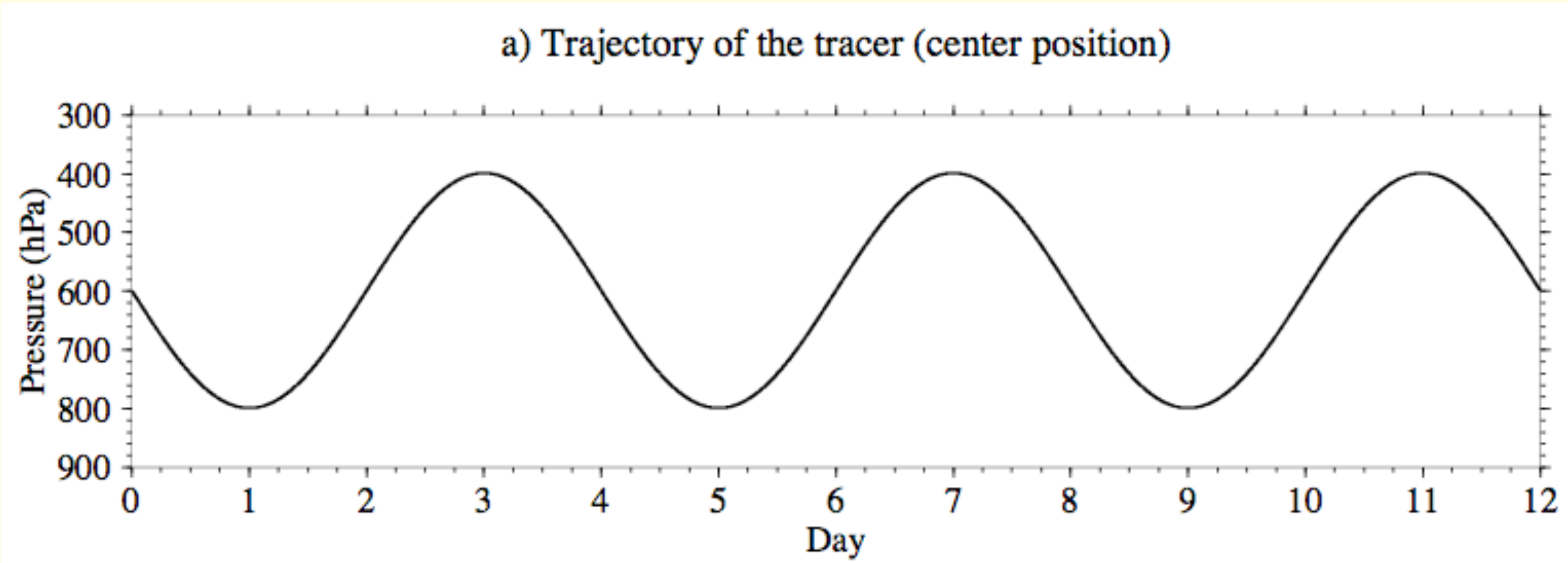
U **V**



Velocities transport the tracers once around the sphere within 12 days

Test 3) Vertical advection

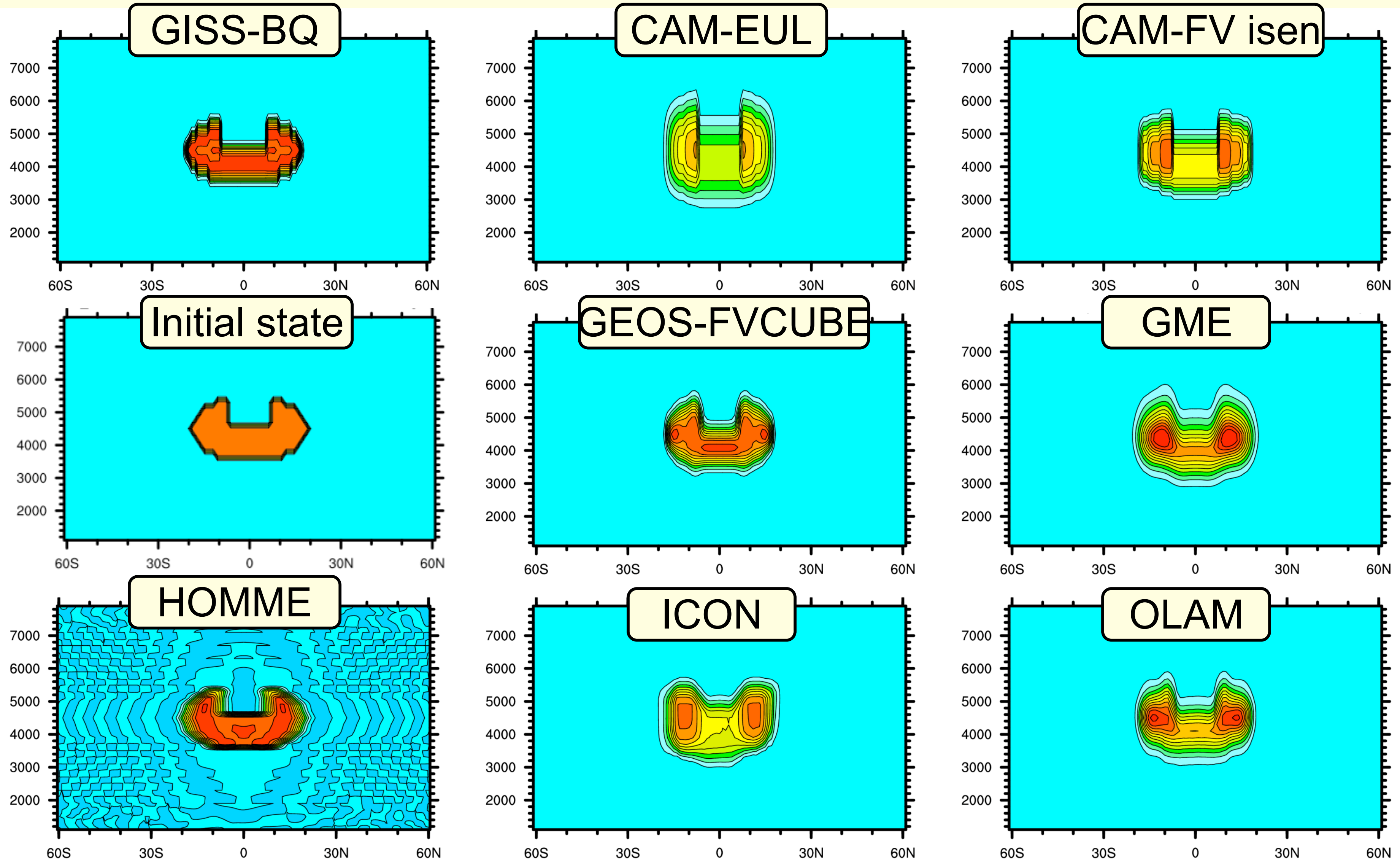
Tracers undergo 3 wave cycles in the vertical

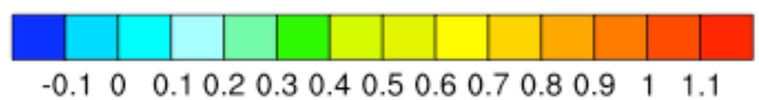


Tracers return to initial position after 12 days
(initial state is analytic solution):

Allows assessment of the diffusion

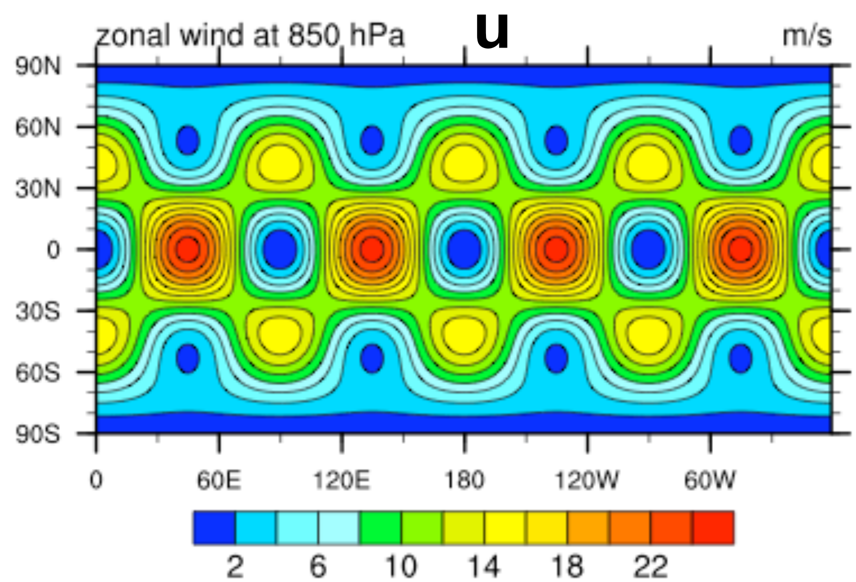
Test 3) Slotted Ellipse after 12 Days

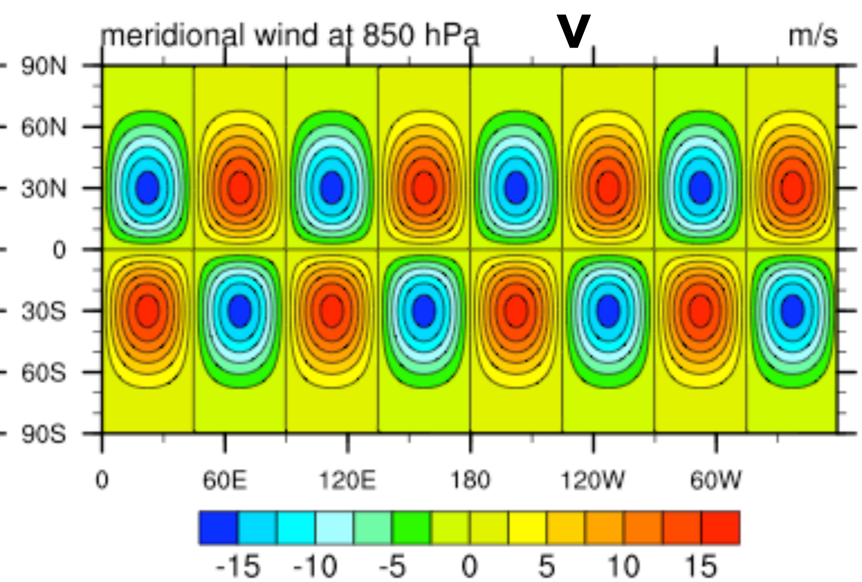


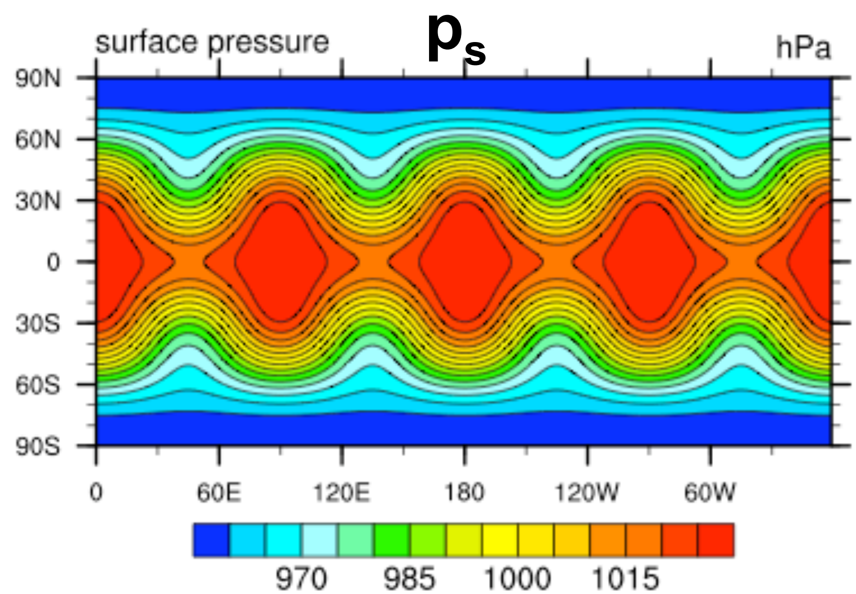


with α=0°, (≈1°×1°L60, dz=250 m)

Test 4) 3D Rossby-Haurwitz Wave



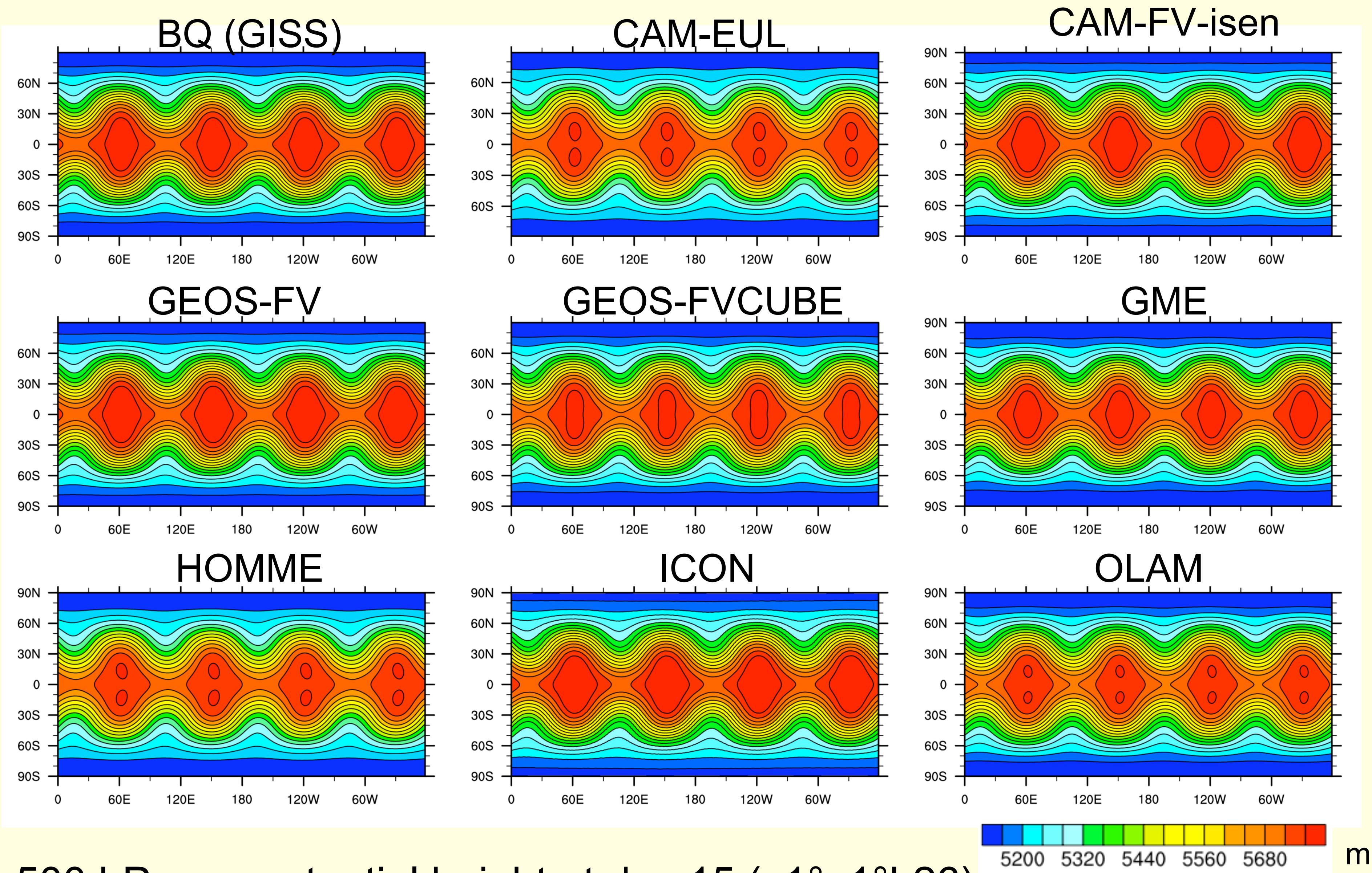




Wavenumber 4:
Initial u, v, p_s fields

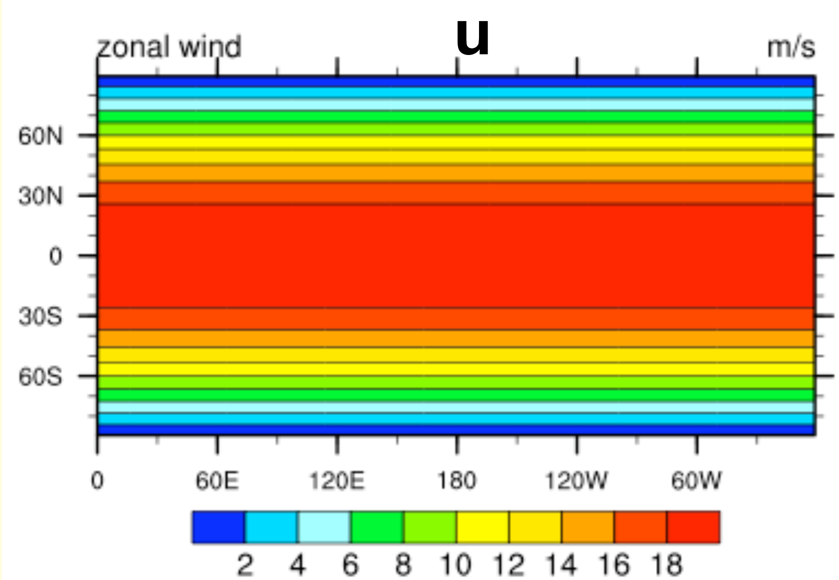
Pattern moves westward without change of shape (≈ -15.2° / day)

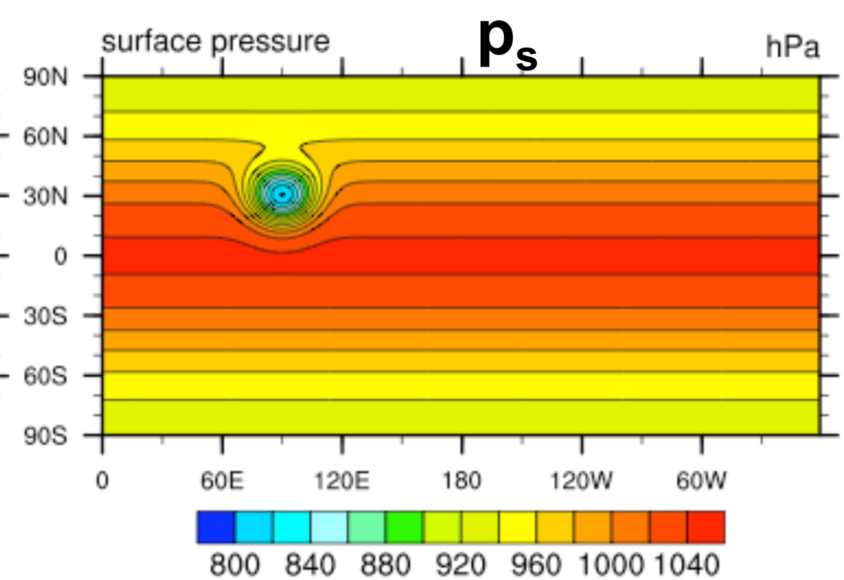
Test 4: Assess diffusion and symmetry

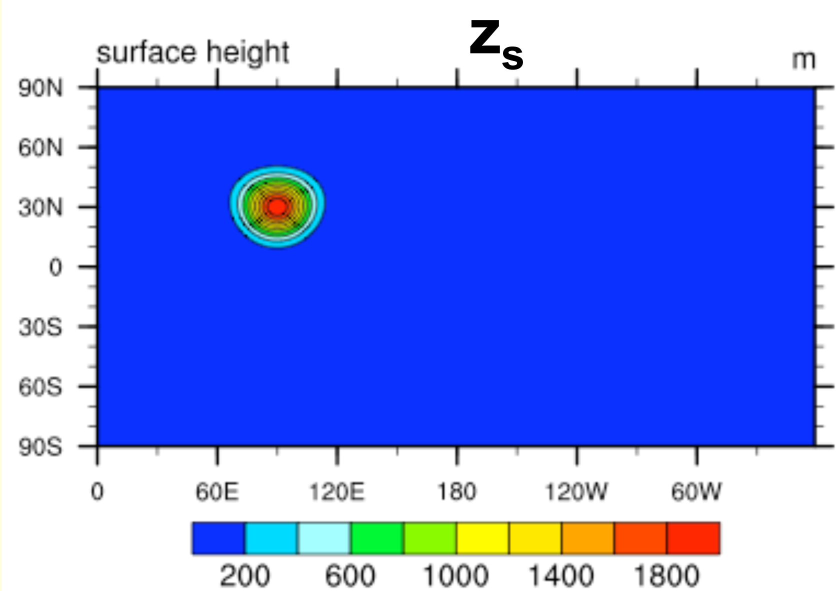


500 hPa geopotential height at day 15 (≈1°×1°L26)

Test 5) Mountain-induced Rossby waves



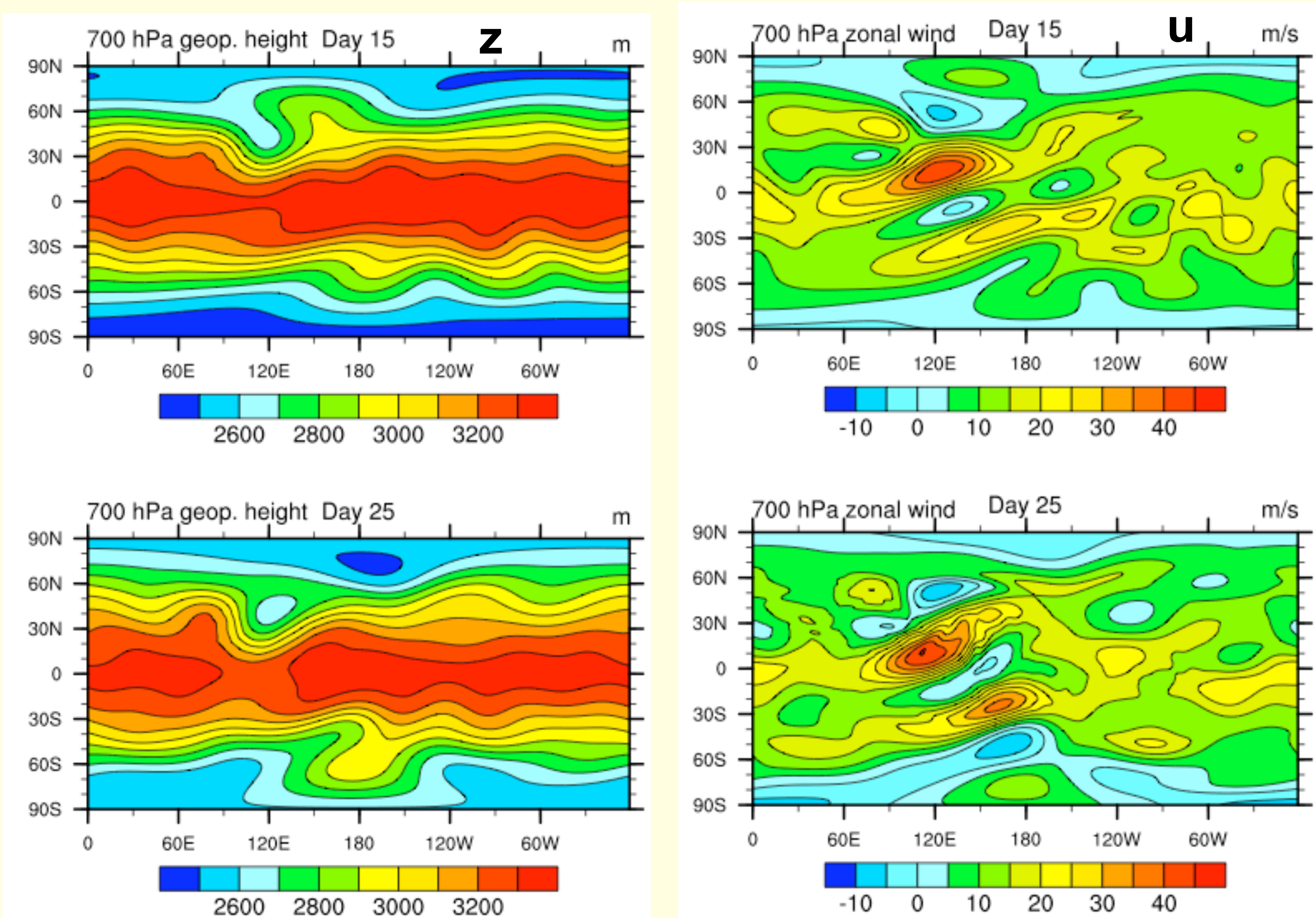




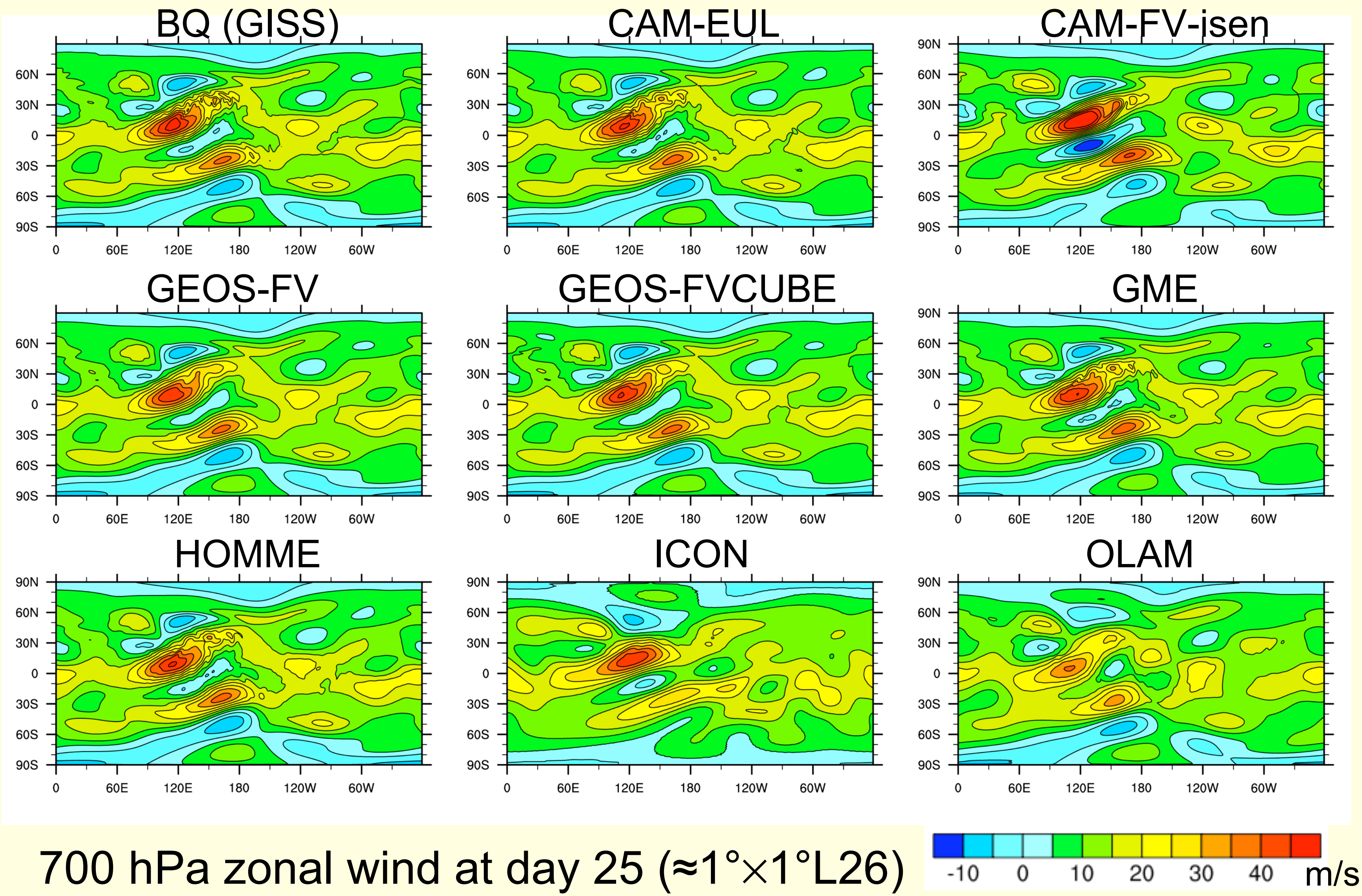
- Initial u, p_s, z_s fields, isothermal, v=0 m/s, balanced
- Mountain triggers the evolution of Rossby waves
- Hydrostatic, nonlinear regime

Days 15 & 25: Mountain-induced waves

CAM-FV 180x360L26



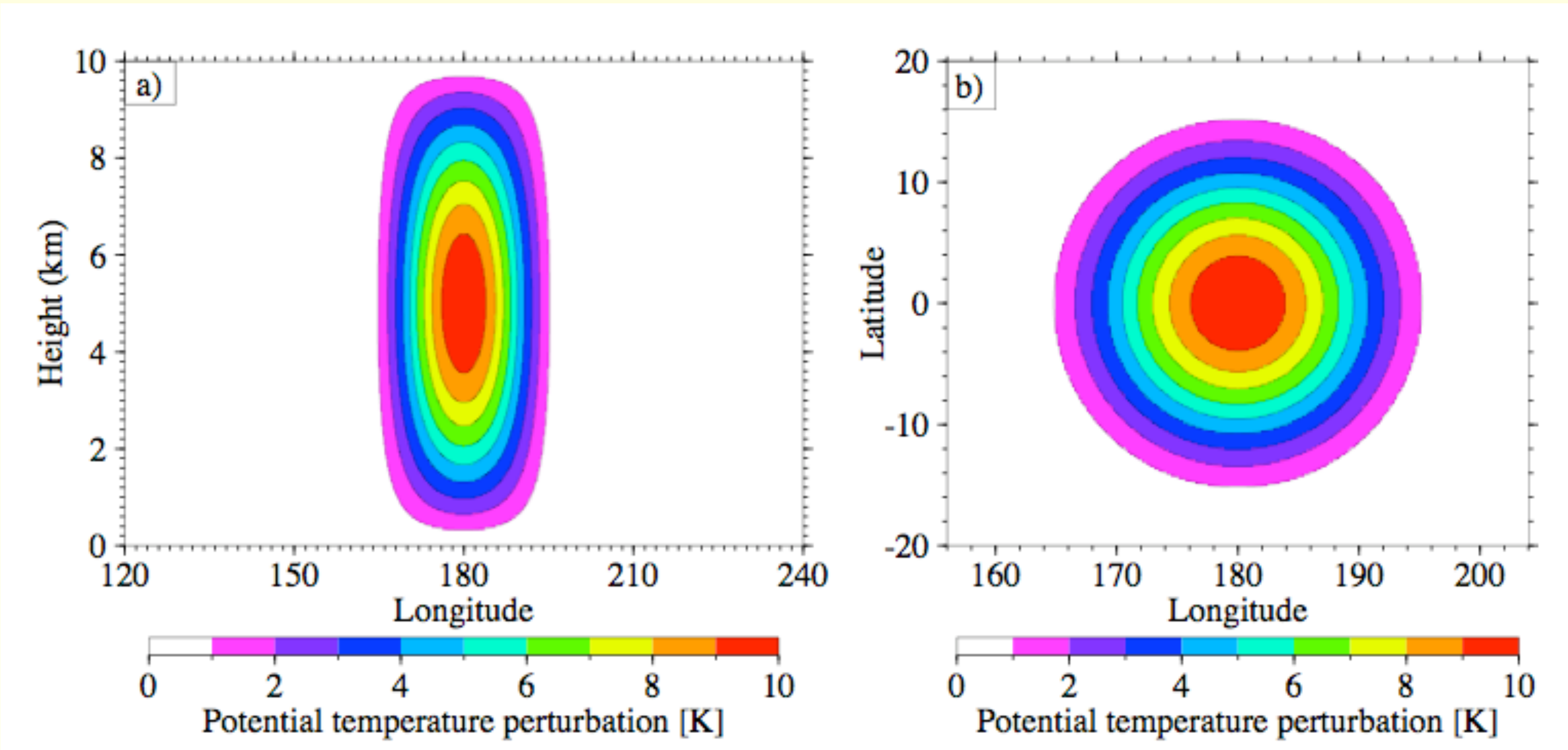
Day 25: Mountain-induced waves - noise?



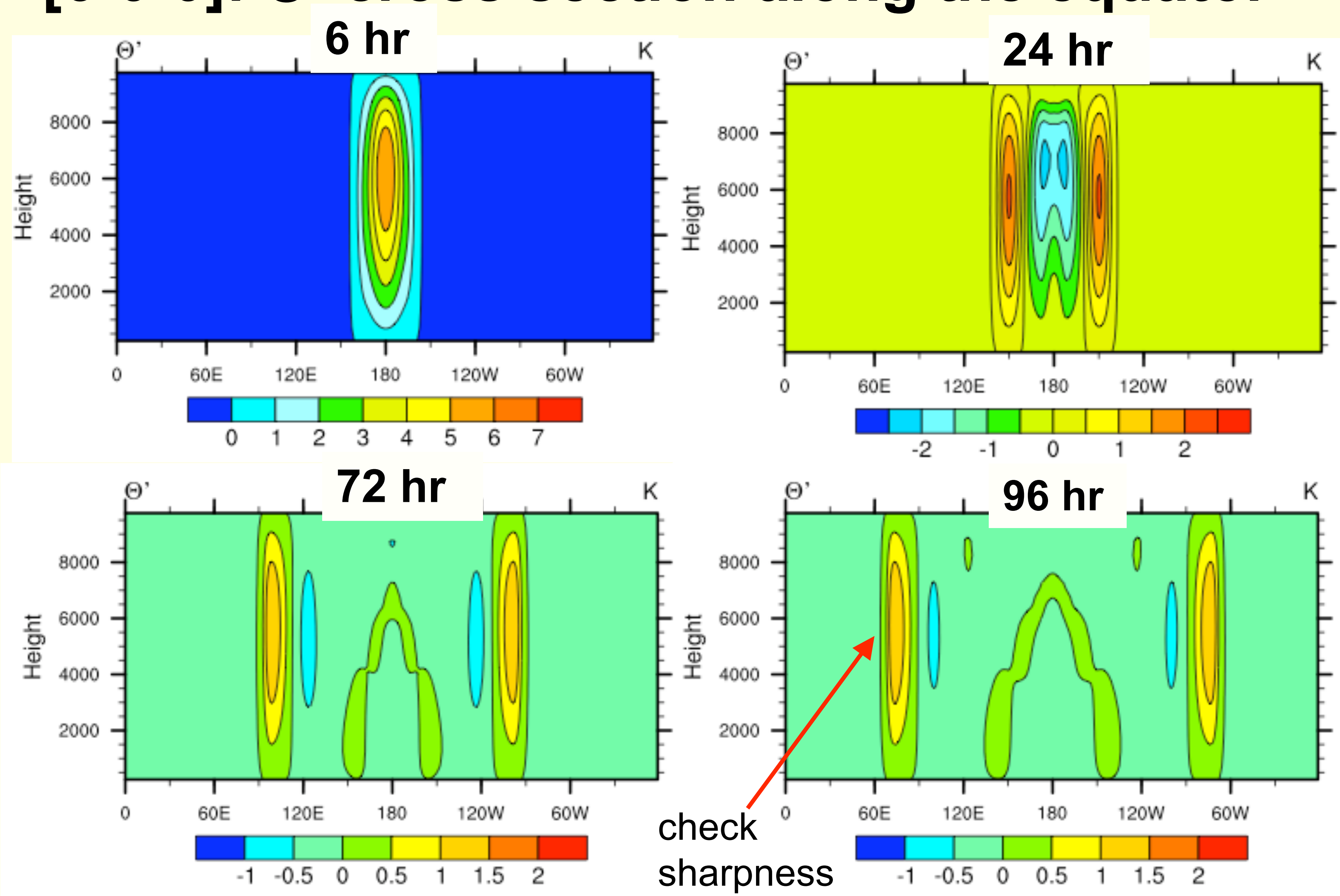
700 hPa zonal wind at day 25 (≈1°×1°L26)

Test 6) Gravity Waves, Inertial Gravity Waves

- No rotation in test [6-0-0], rotation in [6-3-0]
- Balanced initial state with potential temperature perturbation
- Perturbation triggers hydrostatic gravity waves

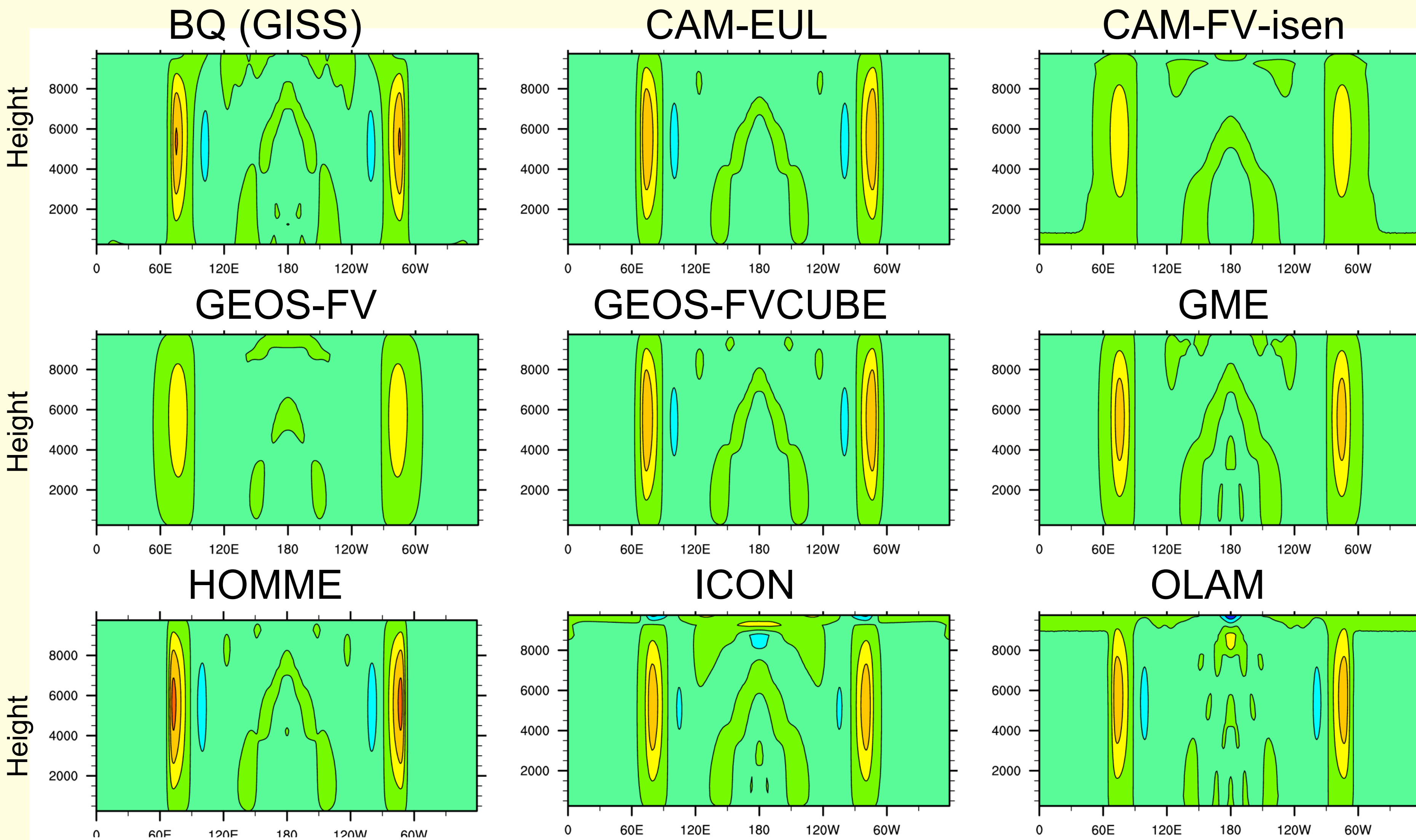


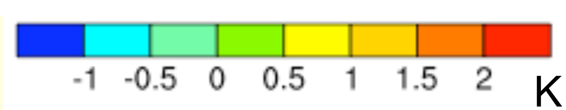
[6-0-0]: Θ' cross section along the equator



CAM-EUL T106 L20 with standard diffusion

[6-0-0]: Θ' cross section along the equator





Day 4, (≈1°×1°L20)

Check sharpness
amplitude, speed

Dynamical Core Intercomparison

- Modeling mentors and students produced a 1.2 TB data base that is open to the community
- Data files are stored as netcdf files and are available on the Earth System Grid, our gateway is http://dycore.ucar.edu
- We work closely with the Earth Curator Project (NCAR group in CISL): http://www.earthsystemcurator.org to provide Metadata that describe the model configurations
- We provide NCL scripts for standard evaluations

Observations

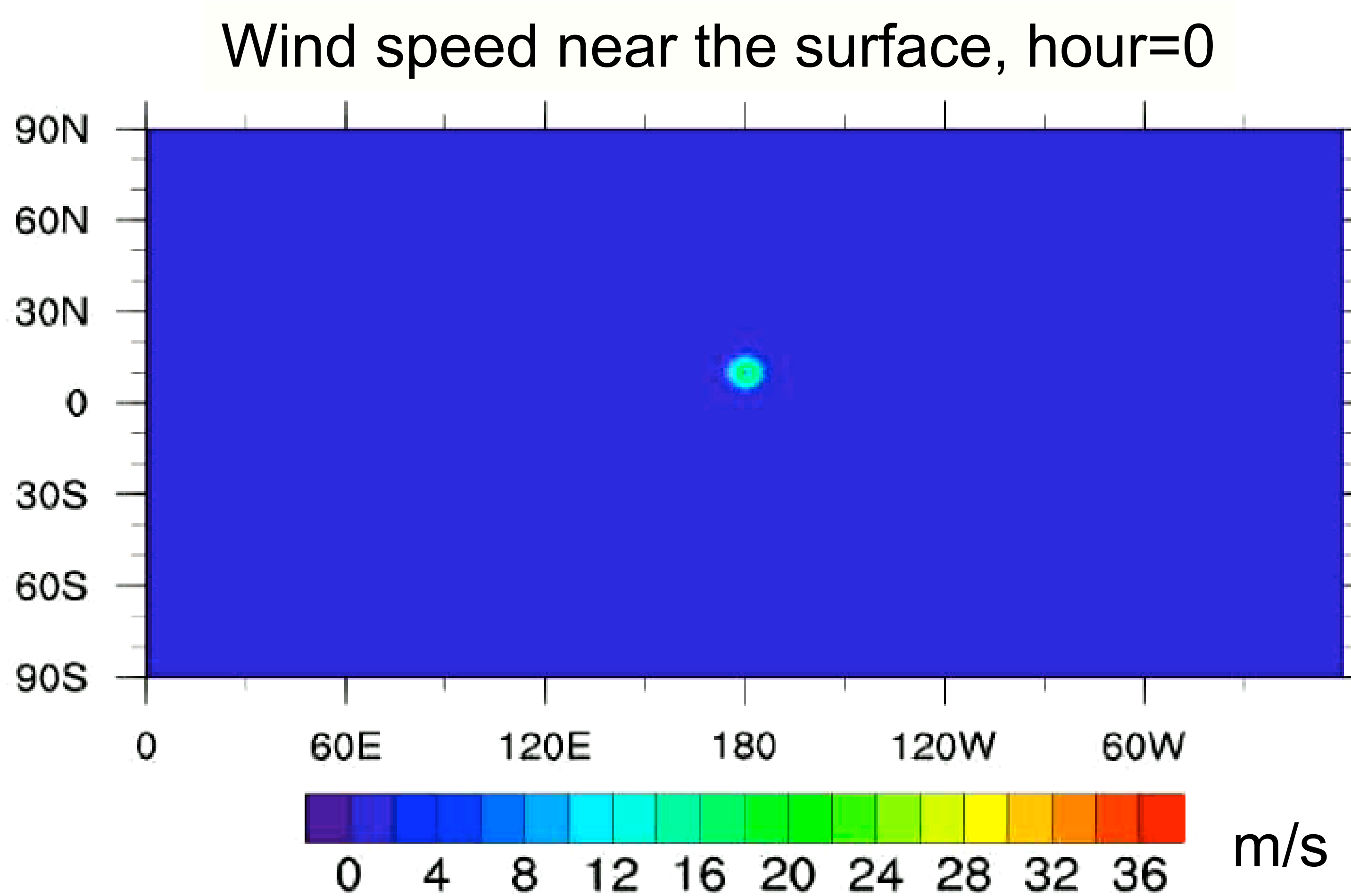
- Test suite used during the ASP colloquium got very positive feedback from the modeling community
- We suggested specific diagnostics and the evaluation of specific time snapshots
- Tests have different complexities:
  - Pure advection
  - Irrotational
  - Steady state
  - Idealized topography
  - From large to small scales, nonlinear barclinic waves
- Next version of the test suite needs
  - More nonlinear, small-scale tests
  - Non-hydrostatic tests on the sphere
  - More diagnostics
  - Extensions/provisions for deep-atmosphere dynamical cores
  - Simplified physics?

Future test case candidates

- 3D Mountain Waves (irrotational) on the sphere: hydrostatic & non-hydrostatic, linear & non-linear
- Acoustic Waves (non-hydrostatic)
- Dycore tests with more complex (or real) orography
- Unsteady tests with analytic solutions (Staniforth and White, QJ (in review), time-dependent Coriolis force
- Steady-state, deep atmospheres (Staniforth and White, QJ (2007))
- 3D Advection with divergent and convergent flows
- Idealized cyclones:
  - Prescribed tropical vortex with balanced initial conditions, ocean-covered surface with specified (e.g. constant) SST, (see 1st movie)
  - Qualitative similar test possible with the shallow water equations (Lin, Putman) (see 2nd movie)
  - On a smaller scale: idealized tornados

Idealized (Tropical) Cyclones

CAM3.1 - FV dycore, 15-day aqua-planet run with 0.5°× 0.5° L26



Kevin Reed and Christiane Jablonowski