A Test Suite for GCMs: An Intercomparison of 11 Dynamical Cores

Christiane Jablonowski[1], Peter Lauritzen[2],
Mark[3] Taylor, Ram Nair[2]

[1]University of Michigan,
[2]National Center for Atmospheric Research,
[3]Sandia National Laboratories

PDEs on the Sphere Workshop, Santa Fe
Apr/28/2009

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)

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

Deterministic Test Cases for Dry Dycores

- **Hydrostatic & shallow-atmosphere non-hydrostatic**
  - Baroclinic waves:
    - Jablonowski and Williamson, QJ (2006)
    - Polvani et al., MWR (2004)
  - Test case suite: http://www-personal.umich.edu/~cjablono/dycore_test_suite.html

- **Non-hydrostatic (deep and/or shallow atmosphere)**
  - Collection by Tomita and Satoh, Fluid Dyn. Res. (2004)
  - Exact solutions:
    - Steady-state: Staniforth and White, QJ (2007)
    - Unsteady: Staniforth and White, QJ (2008)
  - Reduced planet: Wedi and Smolarkiewicz, QJ (2009)

Test cases on the sphere: NCAR 2008 ASP Colloquium (June '08)

Peter Lauritzen, Christiane Jablonowski, Mark Taylor, Ram Nair

A community effort towards **standard evaluations** of dynamical cores with over 11 modeling groups, 36 students and 17 lecturers

NCAR 2008 ASP Colloquium

Participating Dynamical Cores

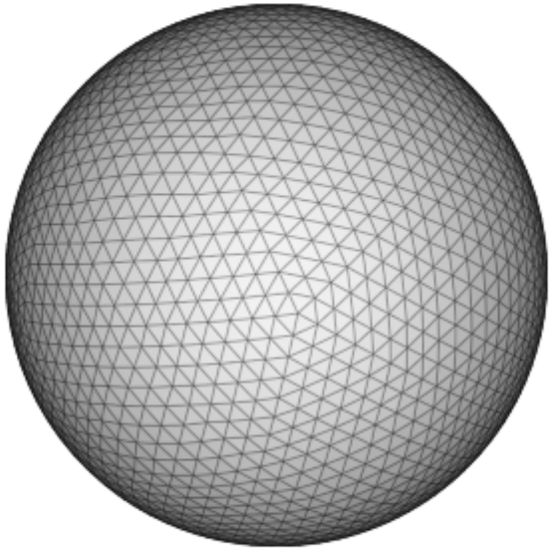
1) **GISS-BQ** (NASA GISS)
2) **CAM Eulerian** (NCAR)
3) **CAM FV-isen** with isentropic vertical coordinate (NCAR)
4) **CSU Model** (Colorado State University)
5) **GEOS FV** (NASA GSFC, GFDL, same as **CAM-FV** (NCAR))
6) **GEOS FV-CUBE** (NASA GSFC, GFDL)
7) **GME** (German Weather Service DWD)
8) **HOMME** (NCAR)
9) **ICON** (MPI, DWD)
10) **MIT GCM** (MIT)
11) **OLAM** (Duke University)

Models with Latitude-Longitude Grids

1) **GISS-BQ** (NASA GISS)
2) **CAM Eulerian** (NCAR)
3) **CAM FV-isen** with isentropic vertical coordinate (NCAR)
4) **CSU Model** (Colorado State University)
5) **GEOS FV** (NASA GSFC, GFDL, same as **CAM-FV** (NCAR))
6) **GEOS FV-CUBE** (NASA GSFC, GFDL)
7) **GME** (German Weather Service DWD)
8) **HOMME** (NCAR)
9) **ICON** (MPI, DWD)
10) **MIT GCM** (MIT)
11) **OLAM** (Duke University)

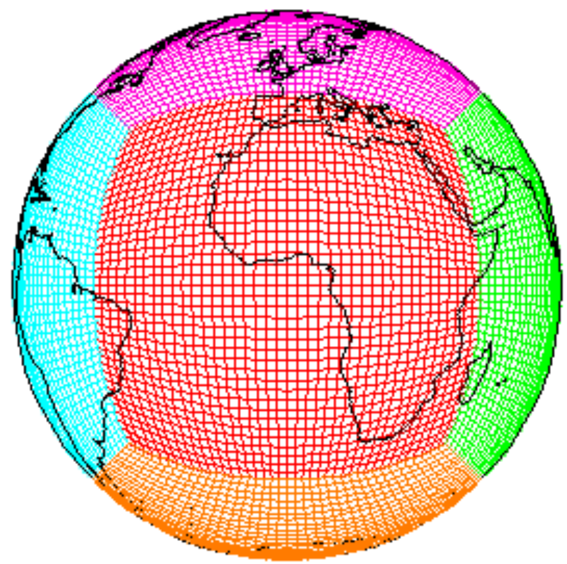
Models with Triangular/Icosahedral Grids

1) **GISS-BQ** (NASA GISS)
2) **CAM Eulerian** (NCAR)
3) **CAM FV-isen** with isentropic vertical coordinate (NCAR)
4) **CSU Model** (Colorado State University)
5) **GEOS FV** (NASA GSFC, GFDL, same as **CAM-FV** (NCAR))
6) **GEOS FV-CUBE** (NASA GSFC, GFDL)
7) **GME** (German Weather Service DWD)
8) **HOMME** (NCAR)
9) **ICON** (MPI, DWD)
10) **MIT GCM** (MIT)
11) **OLAM** (Duke University)



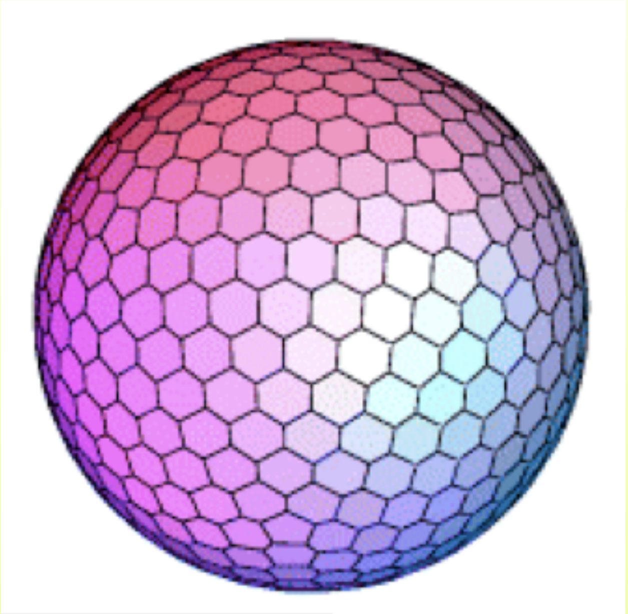
Models with Cubed-Sphere Grids

1) **GISS-BQ** (NASA GISS)
2) **CAM Eulerian** (NCAR)
3) **CAM FV-isen** with isentropic vertical coordinate (NCAR)
4) **CSU Model** (Colorado State University)
5) **GEOS FV** (NASA GSFC, GFDL, same as **CAM-FV** (NCAR))
6) **GEOS FV-CUBE** (NASA GSFC, GFDL)
7) **GME** (German Weather Service DWD)
8) **HOMME** (NCAR)
9) **ICON** (MPI, DWD)
10) **MIT GCM** (MIT)
11) **OLAM** (Duke University)



Models with Hexagonal Grids

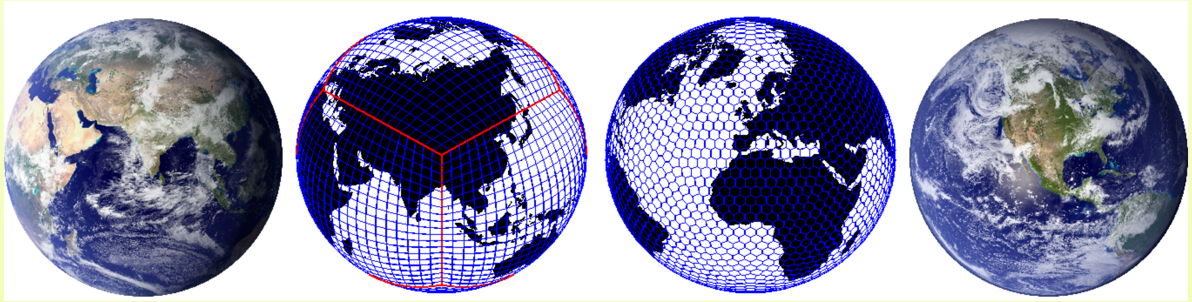
1) **GISS-BQ** (NASA GISS)
2) **CAM Eulerian** (NCAR)
3) **CAM FV-isen** with isentropic vertical coordinate (NCAR)
4) **CSU Model** (Colorado State University)
5) **GEOS FV** (NASA GSFC, GFDL, same as **CAM-FV** (NCAR))
6) **GEOS FV-CUBE** (NASA GSFC, GFDL)
7) **GME** (German Weather Service DWD)
8) **HOMME** (NCAR)
9) **ICON** (MPI, DWD)
10) **MIT GCM** (MIT)
11) **OLAM** (Duke University)



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

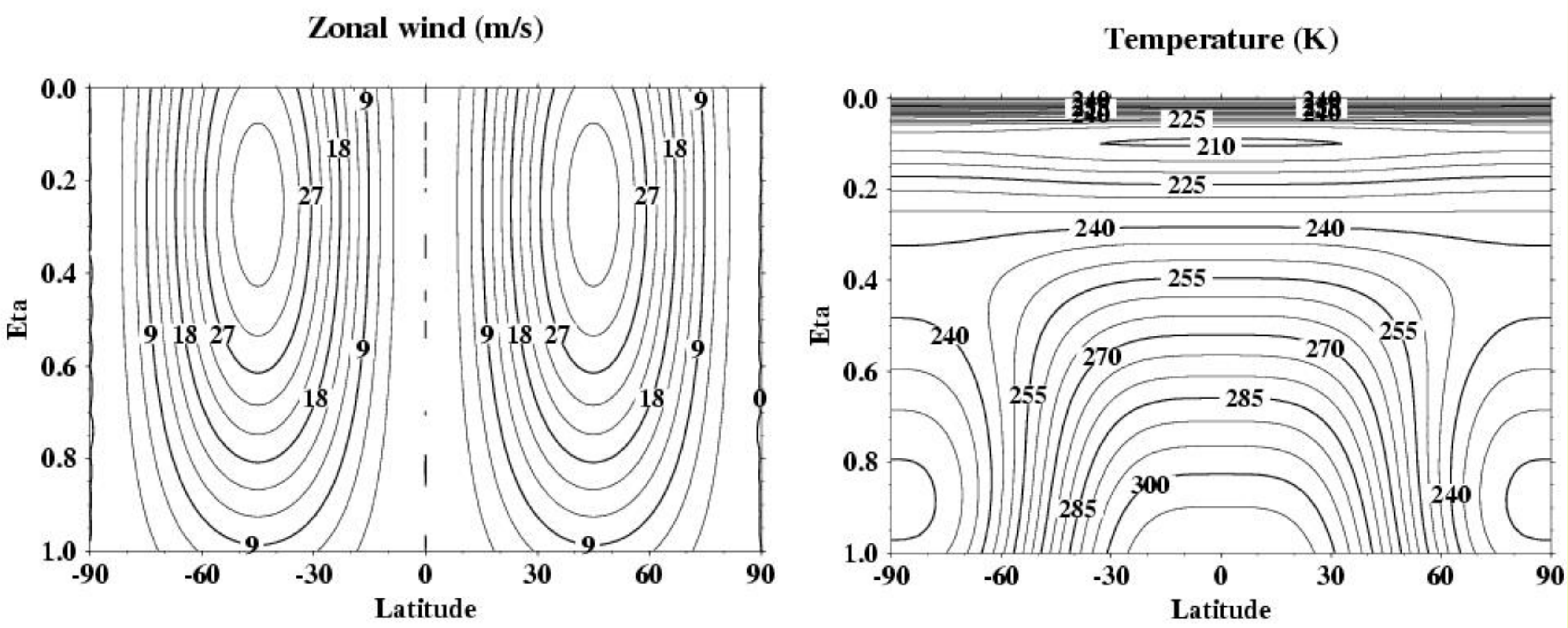
- All tests are formulated on the sphere
- Some have multiple test variants, e.g. rotation angle α

1. Steady-state test case (various rotations α)
2. Evolution of a baroclinic wave (various rotations α)
3. 3D advection experiments (various rotations α)
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)
- **Initial state is the analytic solution**
- Prescribe v = 0 m/s, p_s = 1000 hPa
- Prescribe u ➡ derive Φ_s and T

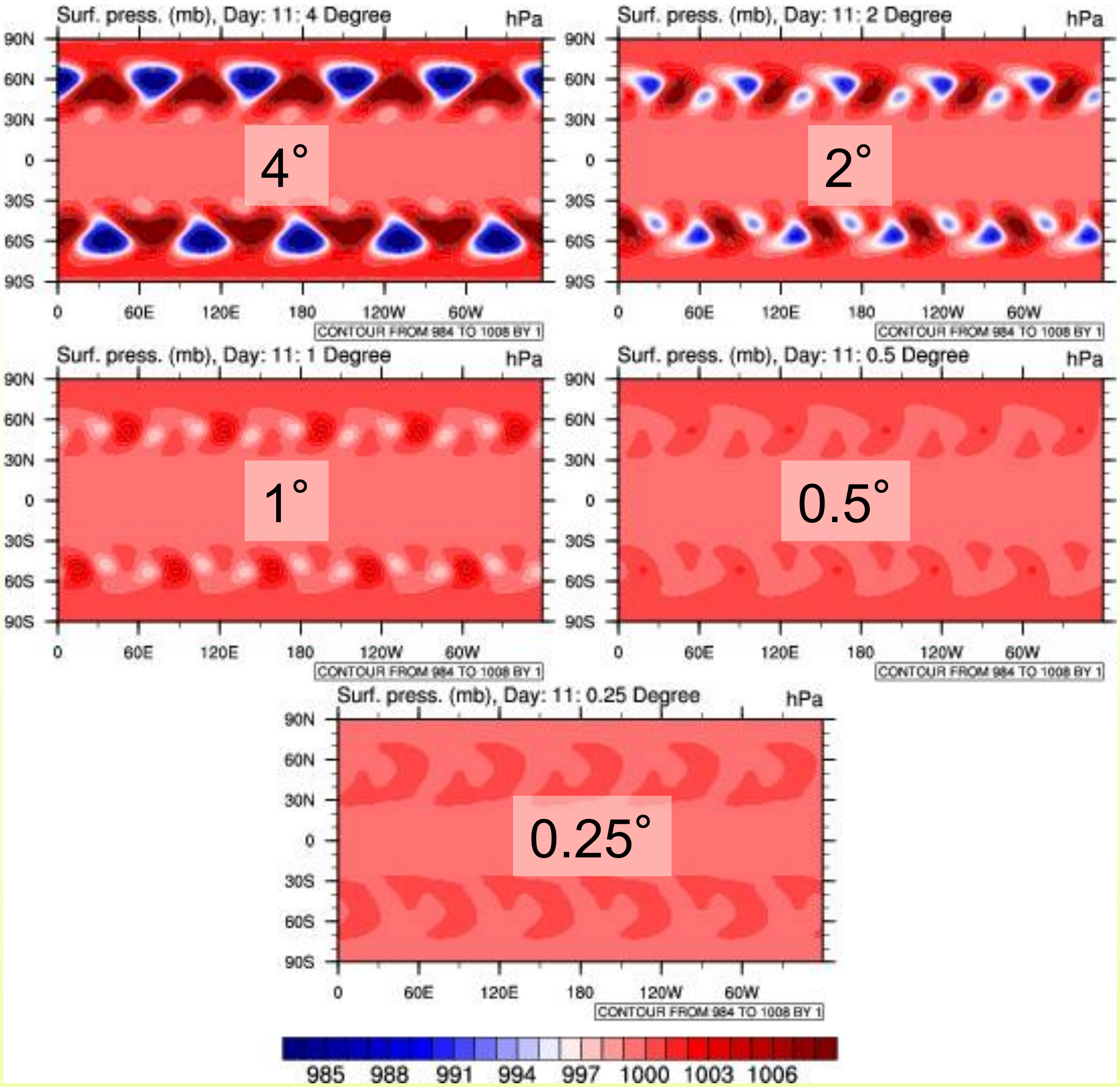


Jablonowski and Williamson, QJ (2006) and NCAR Technical Report 2006

Test 1: Grid imprinting

- Grid imprinting decreases with increasing resolution
- Emphasized by idealized test setup
- Important for real runs?

Model GME: Surface pressure at day 11



Test 1: p_s at day 1 with different α

(2° x2°)

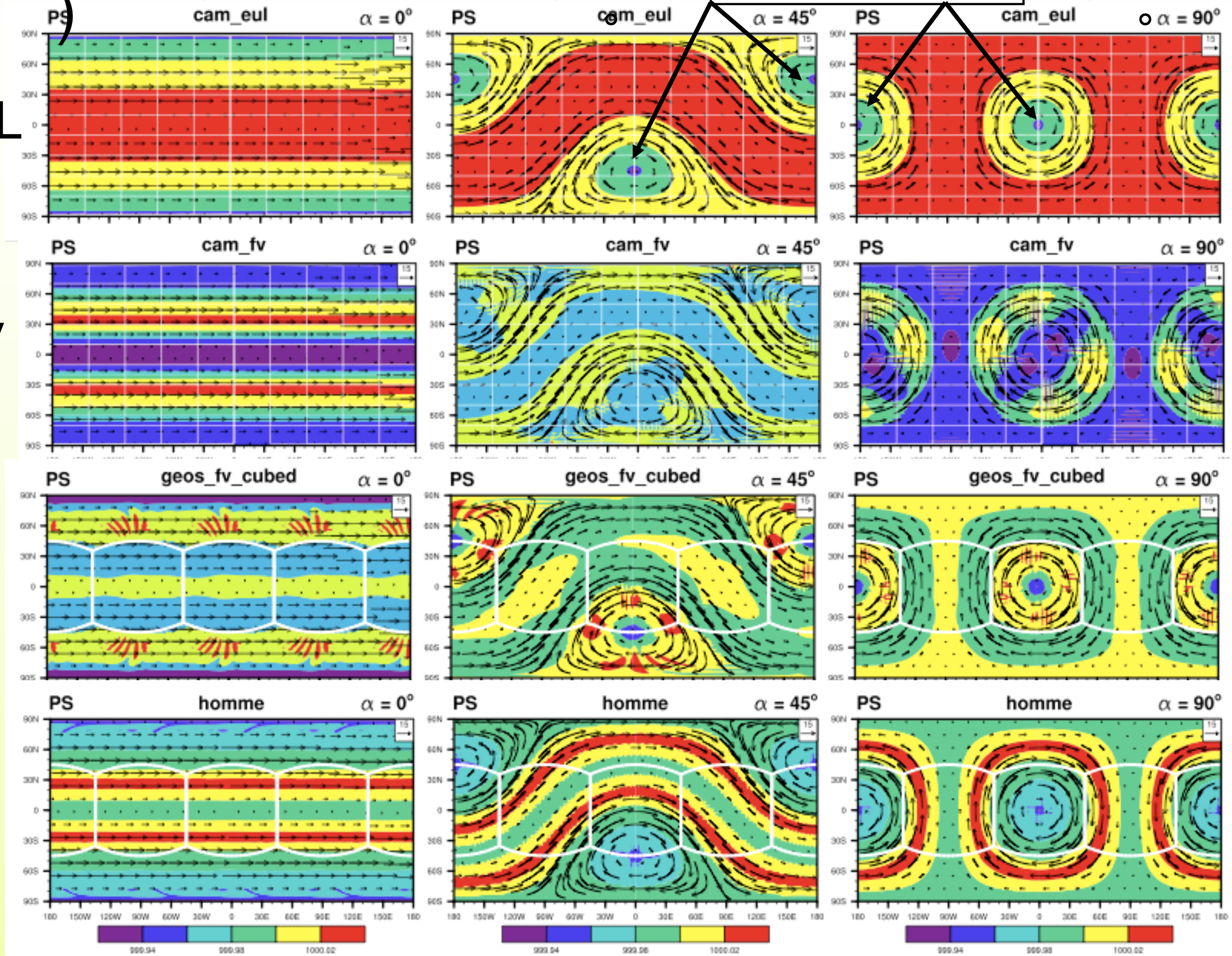
α=0 α=45 new 'poles' α=90

CAM-EUL

CAM-FV

FV-CUBE

HOMME



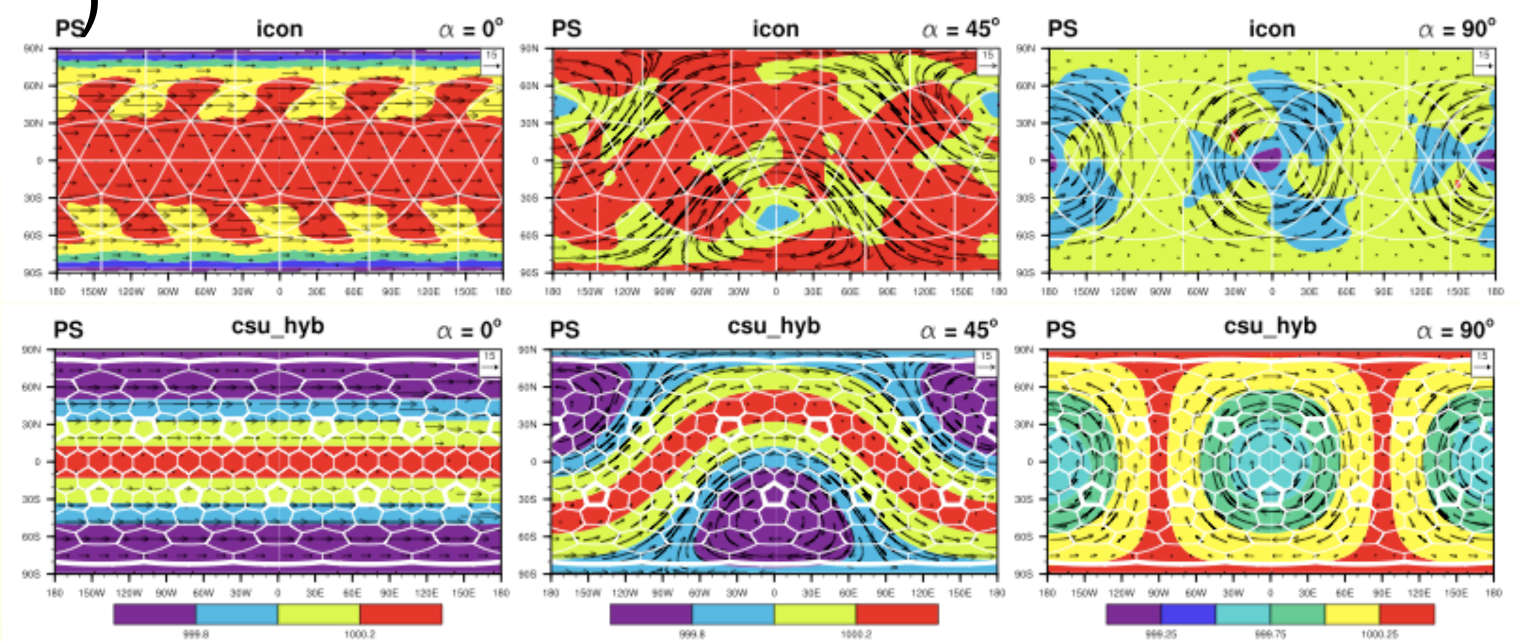
Test 1: p_s at day 1 with different α

(2° x2°)

α=0° α=45 α=90

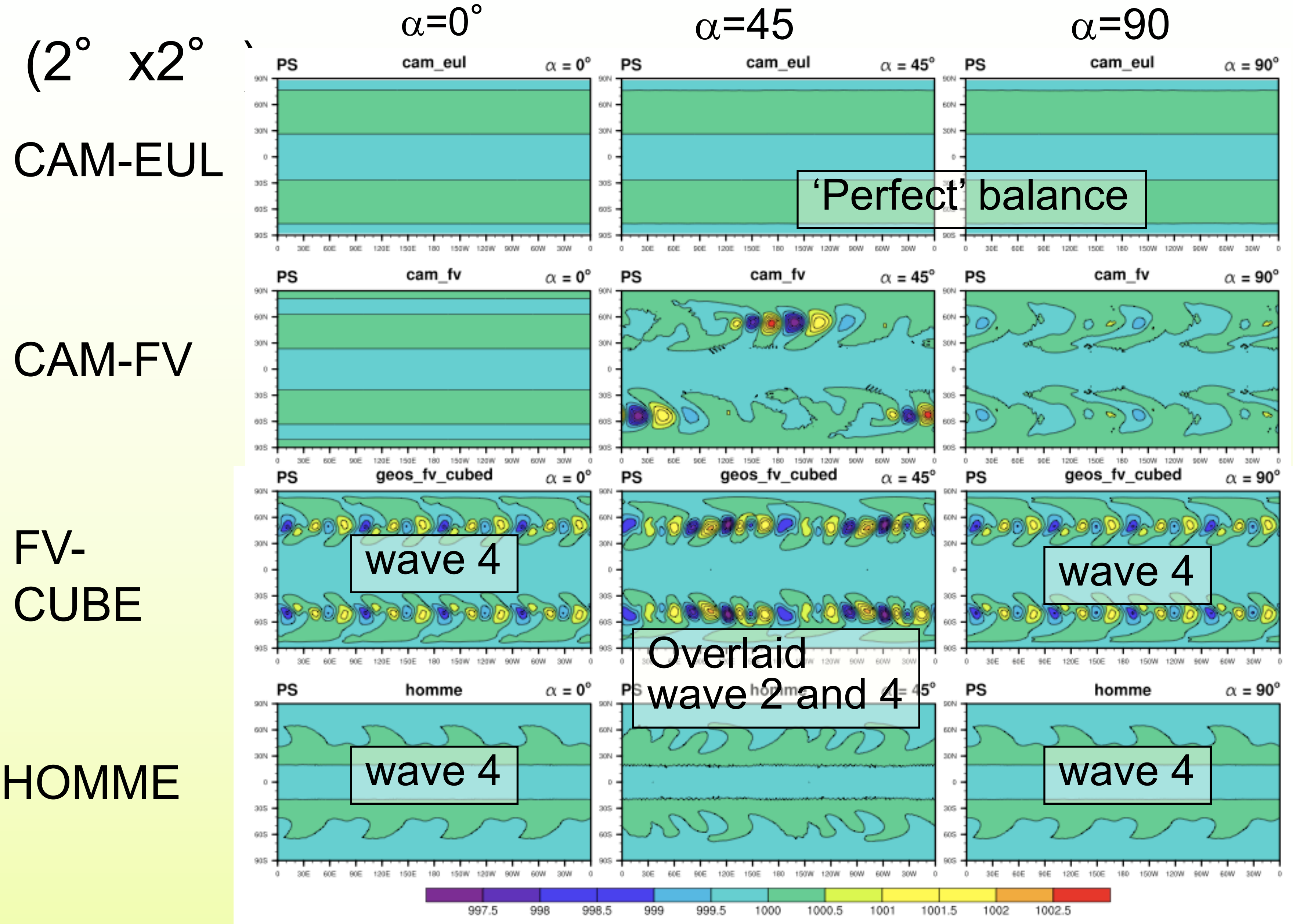
ICON

CSU (hybrid)



- Rotation angles increase the difficulty of the test and remove the grid alignment of the flow in lat-lon grids
- Test reveals problematic spots and grid imprinting
- Lauritzen et al., to be submitted to JAMES

Test 1: p_s at day 9, rotated back



Test 1: p_s at day 9, rotated back

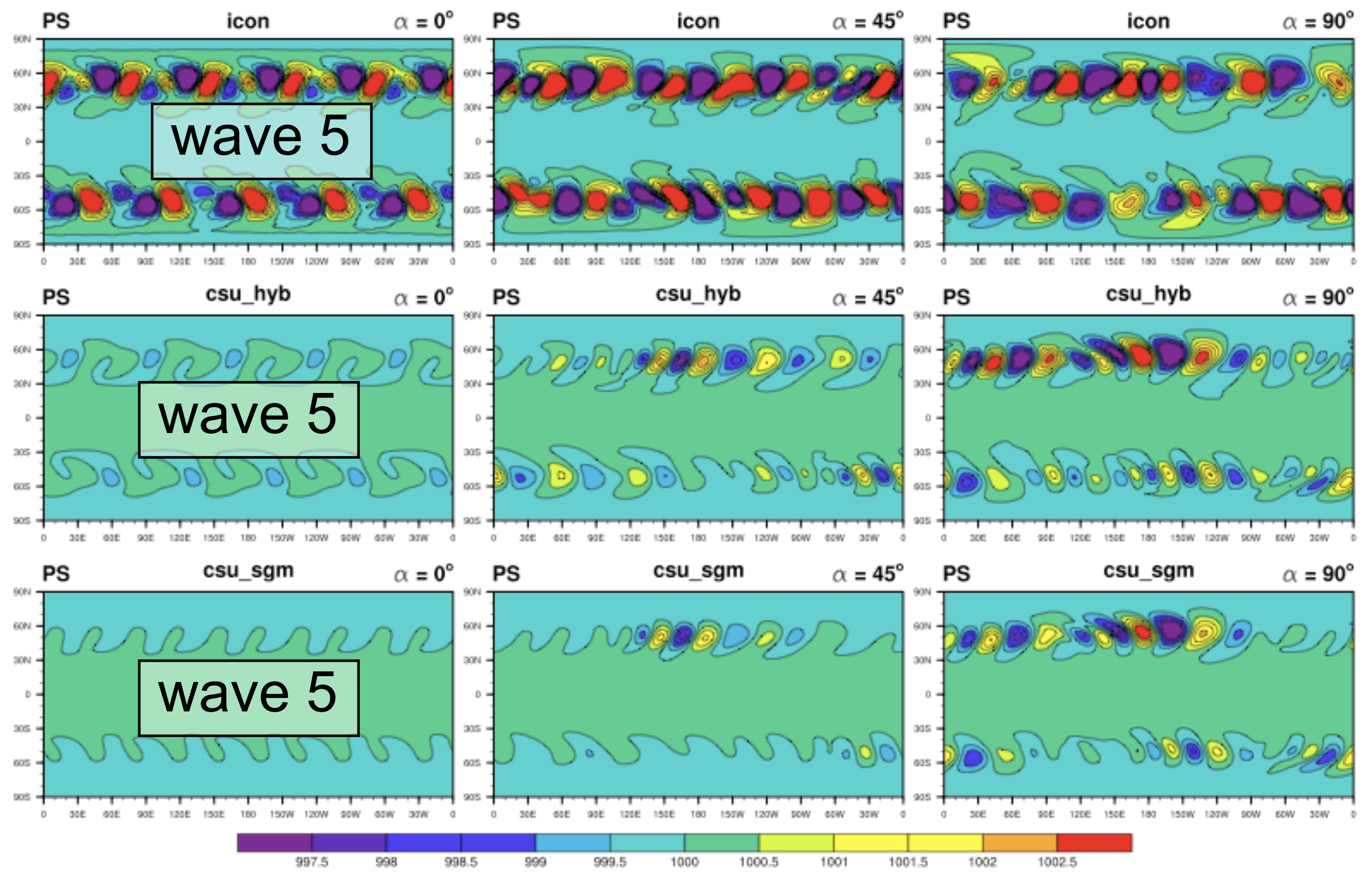
(2° x2°)

α=0°　　α=45　　α=90

ICON

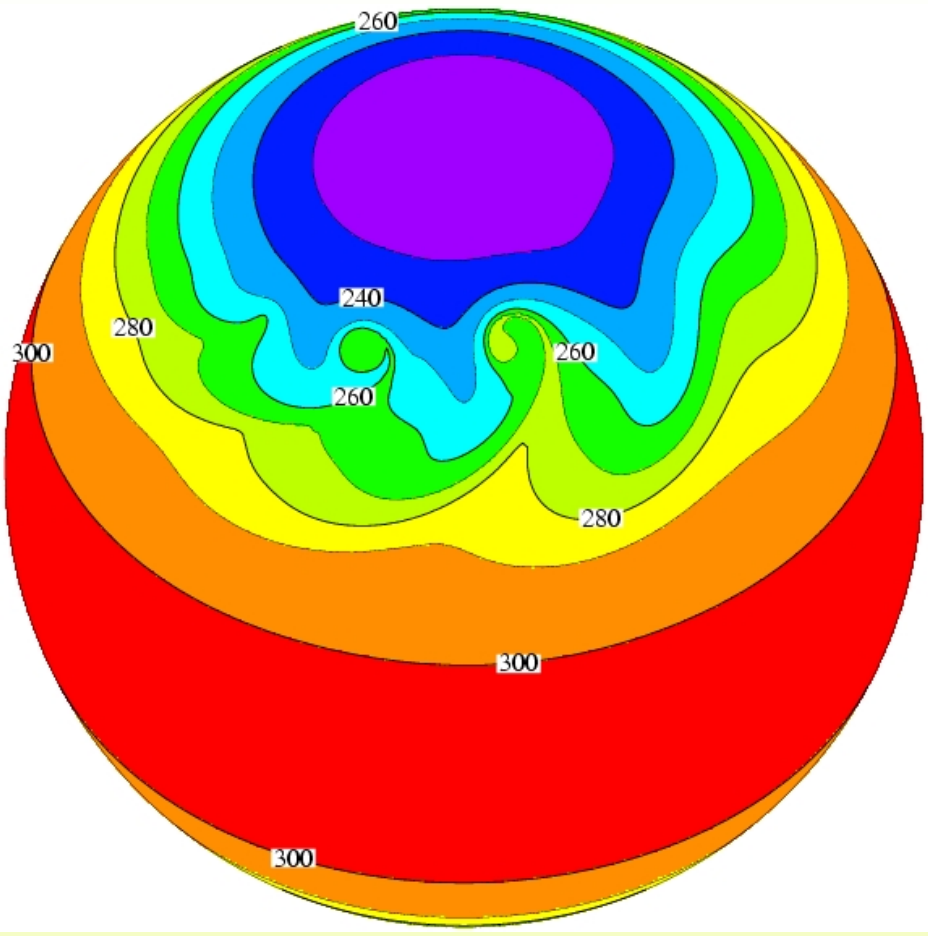
CSU (hybrid)

CSU (sigma)



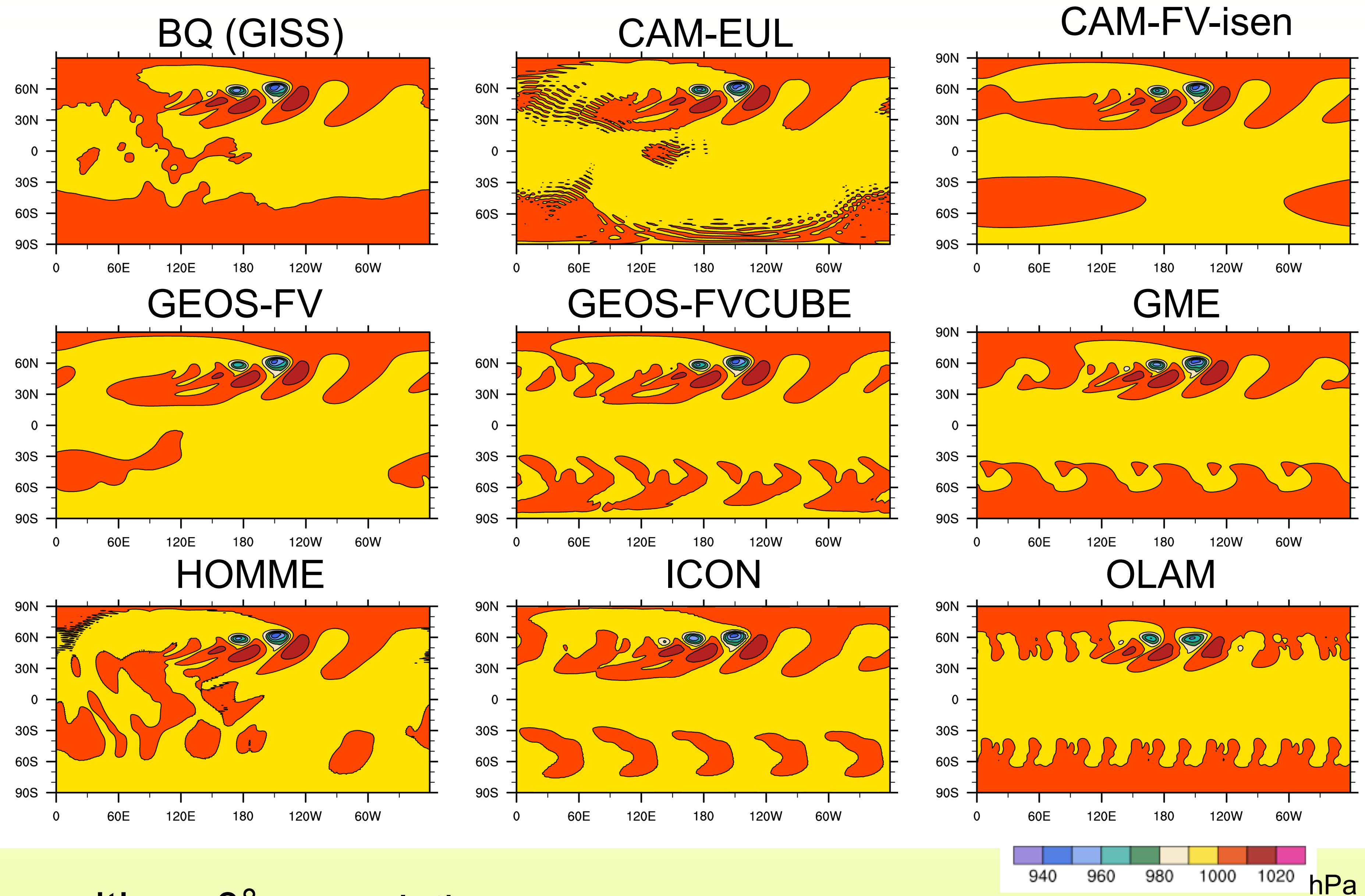
- Initial (grid-induced) perturbation has grown
- Vertical coordinate matters (CSU)

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
- Models start converging at 1°

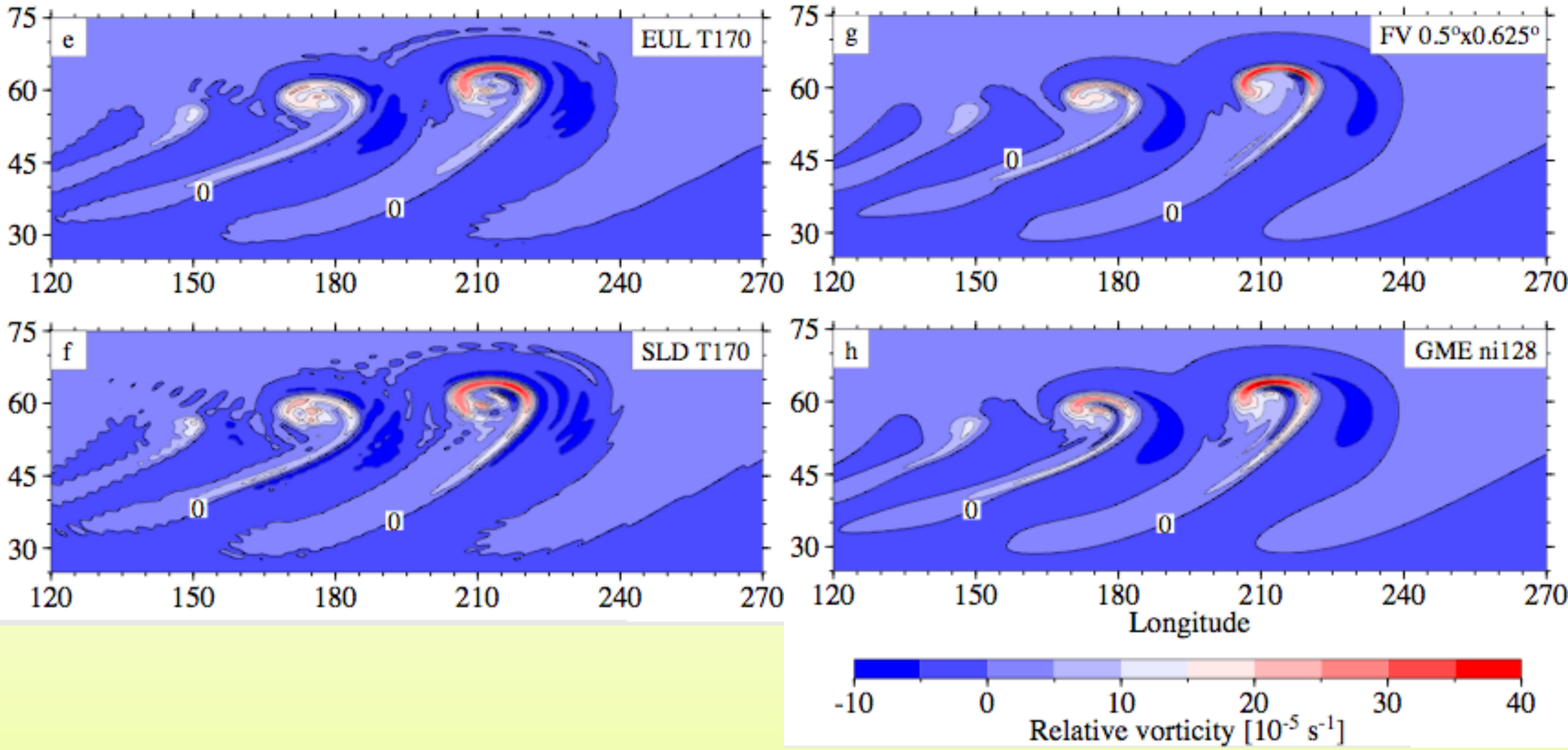
Test 2: Model Intercomparison, p_s at Day 9



with α=0° , resolution ≈

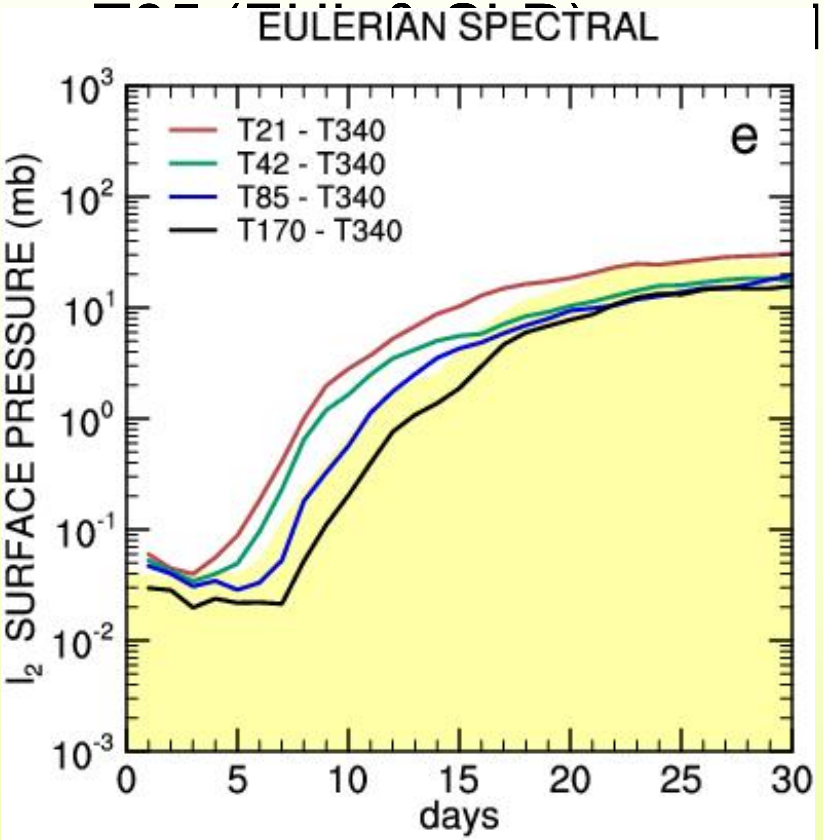
Test 2: 850 hPa Vorticity at Day 9

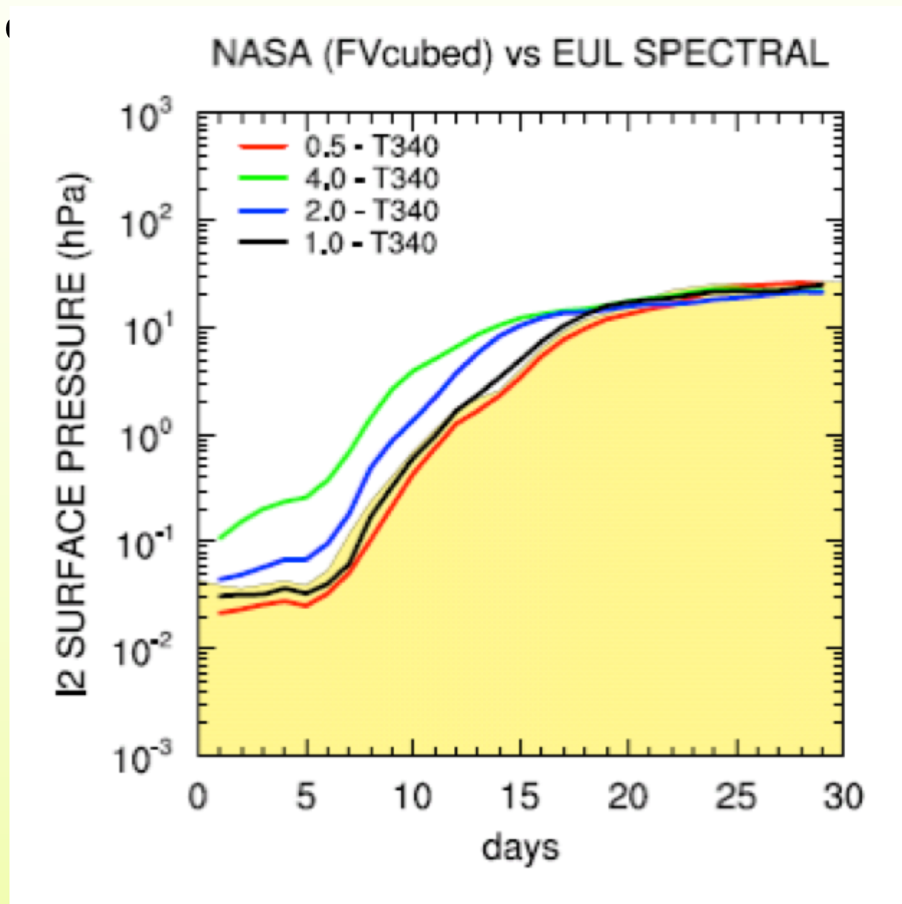
- Differences in the vorticity fields grow faster than p_s diff.
- Small-scale differences easily influenced by diffusion
- Spectral noise in EUL and SLD (L26)



Test 2: Model Convergence

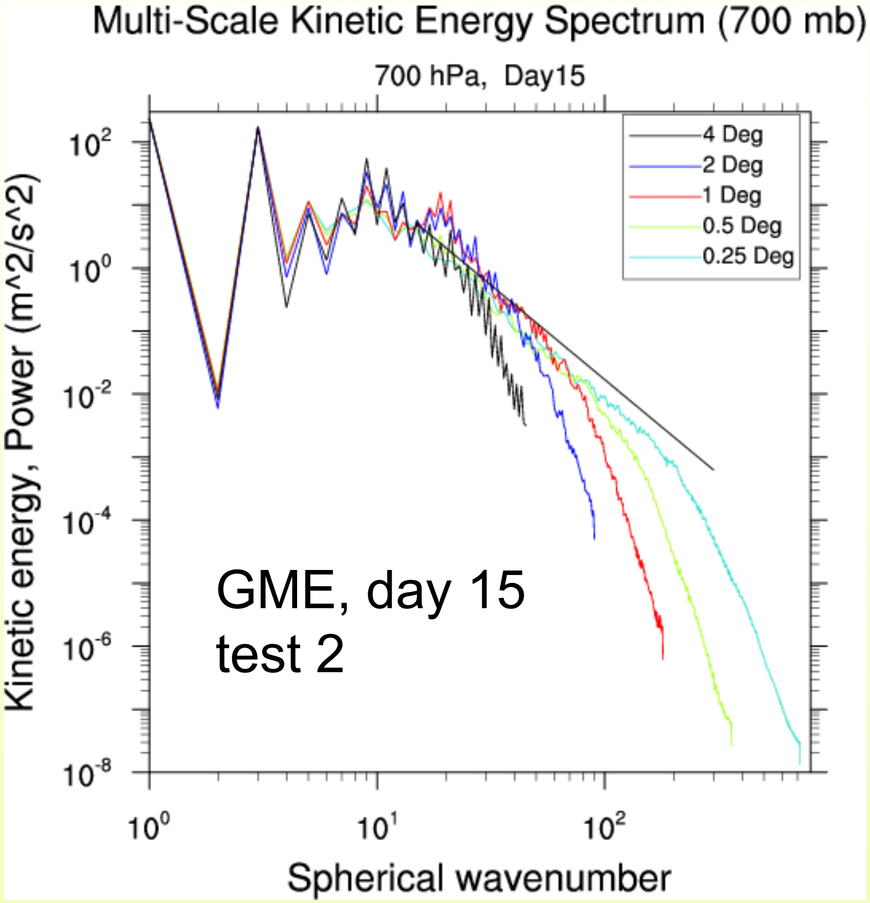
- Single-model uncertainty stays well below the uncertainty across models
- Models converge within the uncertainty for the resolutions



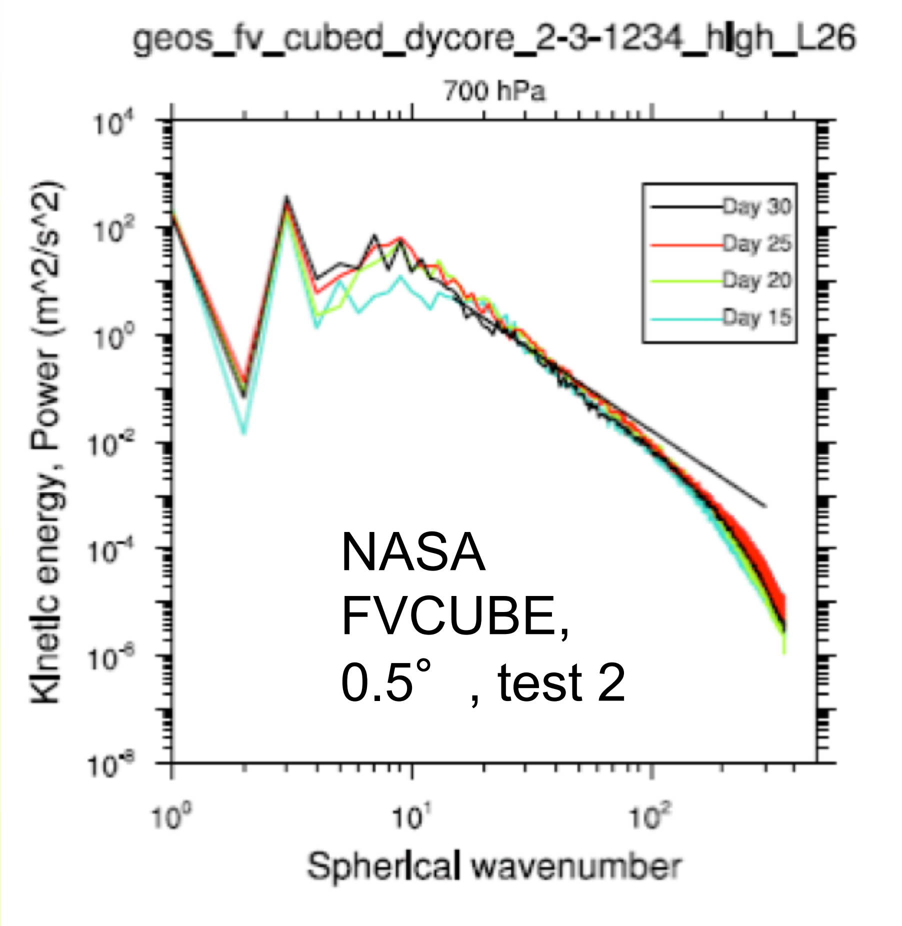


Test 2: Standard Diagnostics KE Spectra

Variation with resolution



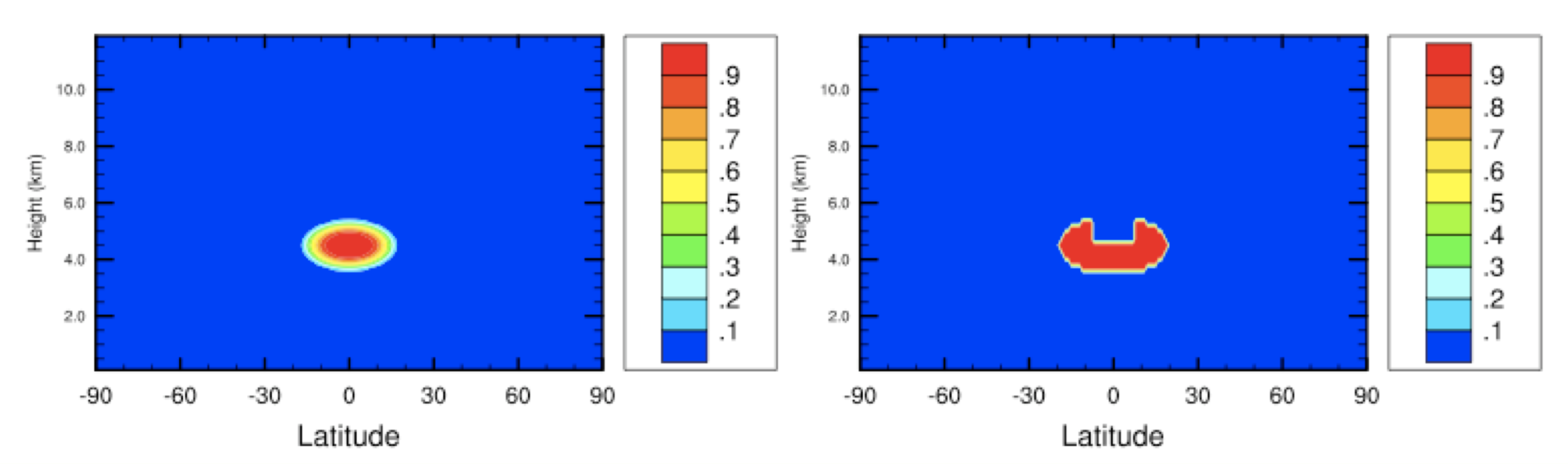
Variation with time



Test 3: 3D Advection Tests

- Prescribe the 3D wind field: Solid body rotation in 2D (Williamson et al. 1992) plus vertical velocity
- Use different rotation angles α

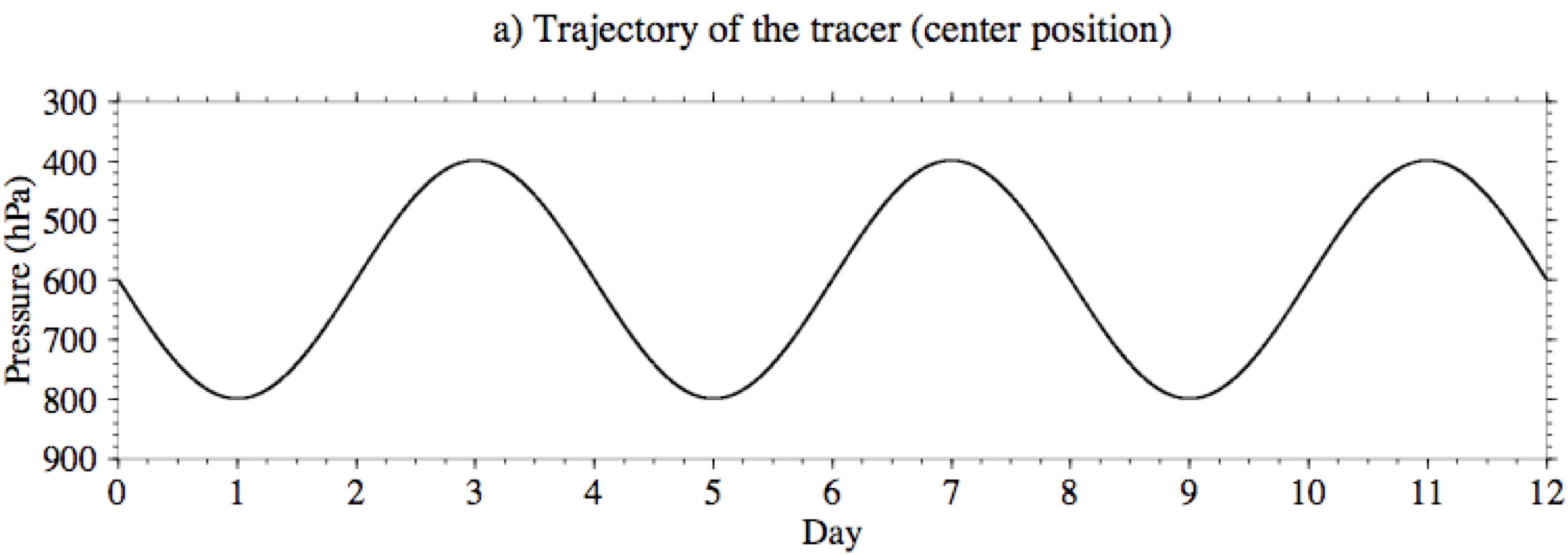
- Prescribe two 3D tracer distributions: z-φ cross section



Smooth: Cosine bell **Non-smooth: Slotted ellipse**

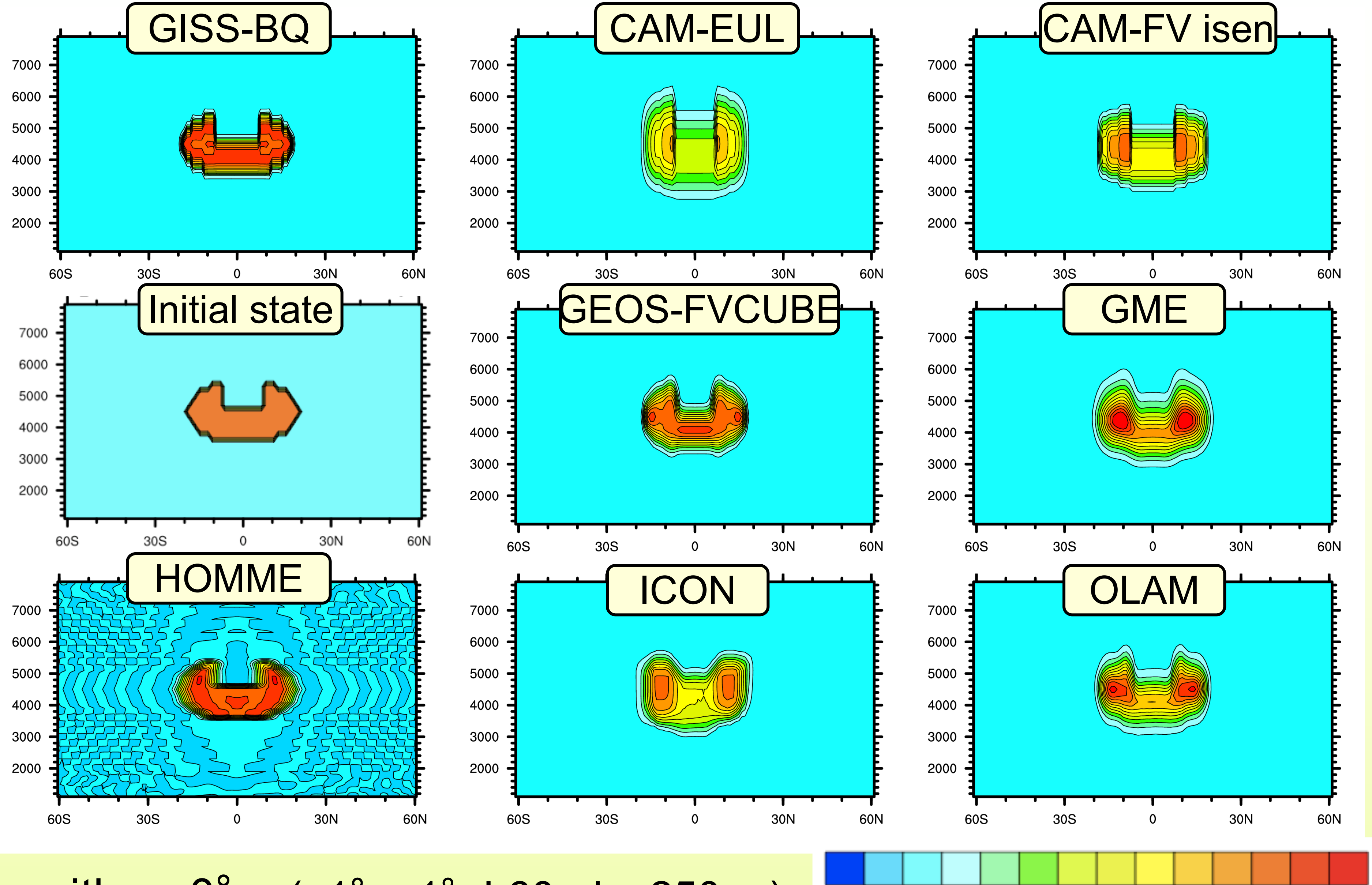
Test 3: Vertical advection

Tracers undergo 3 wave cycles in the vertical



Tracers return to initial position after 12 days:
Allows assessment of the diffusion

Test 3: Slotted Ellipse after 12 Days

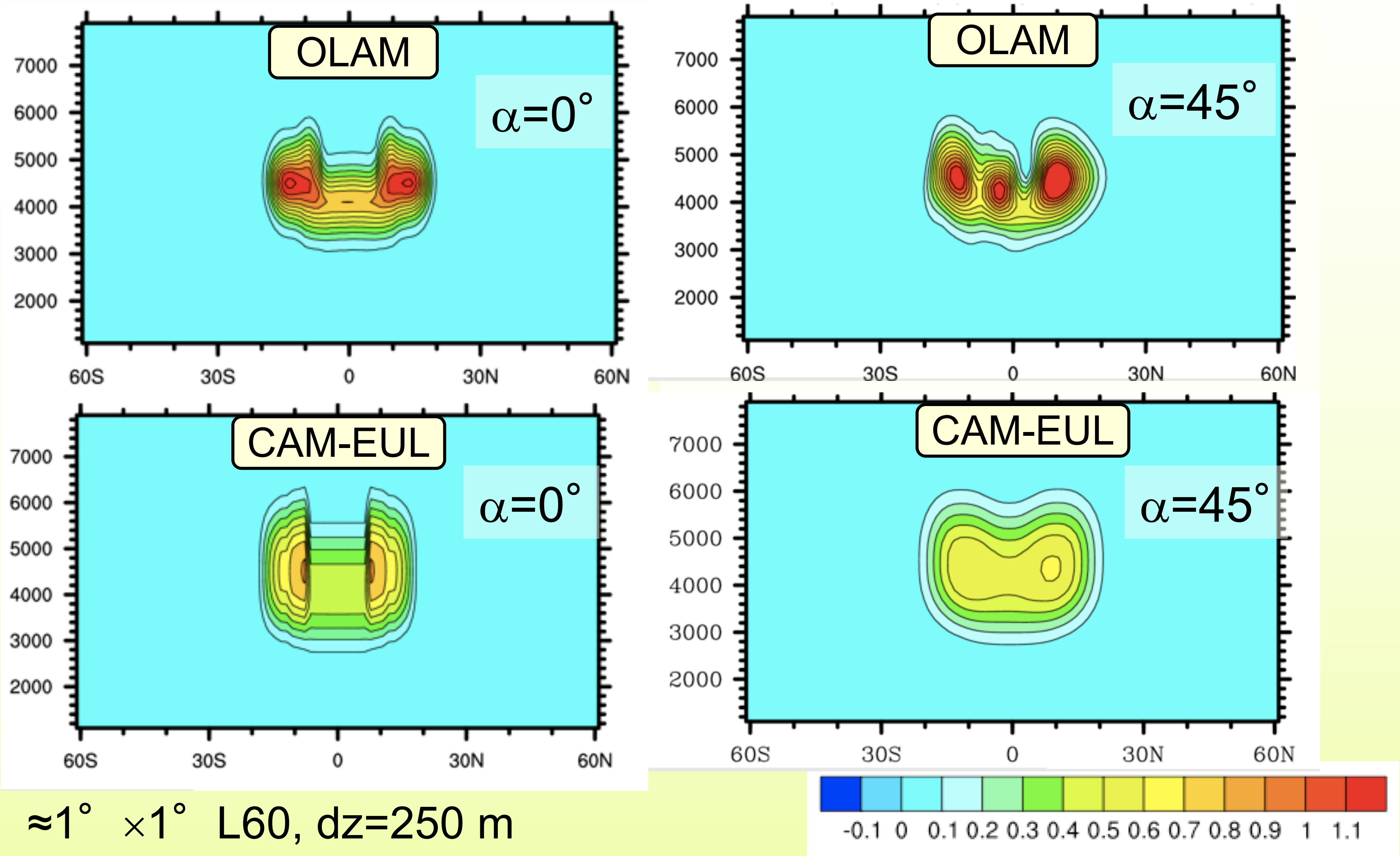


with $\alpha=0°$, ($\approx 1° \times 1°$ L60, dz=250 m)

Test 3: Slotted Ellipse after 12 Days

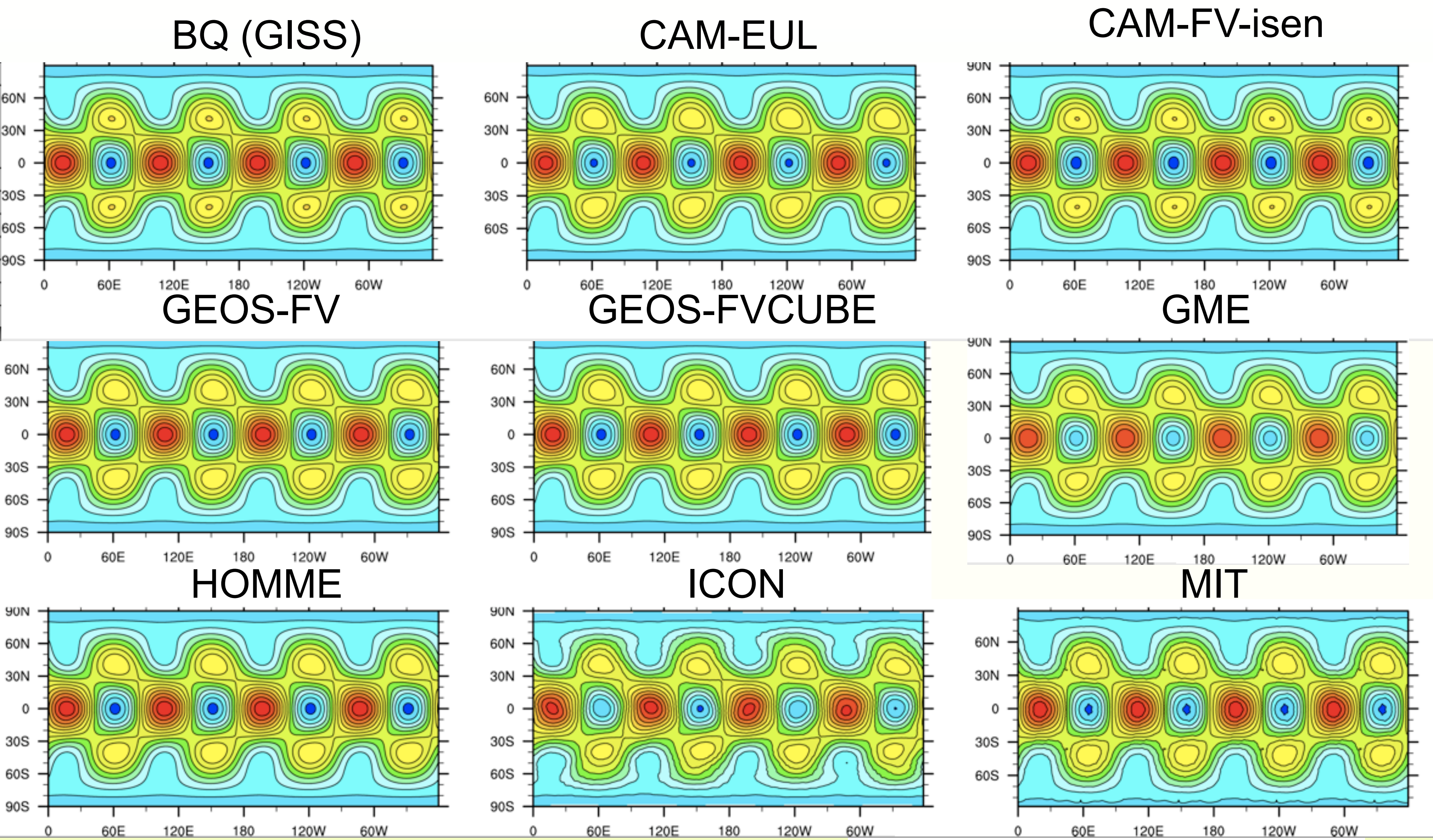
Rotation angles can matter

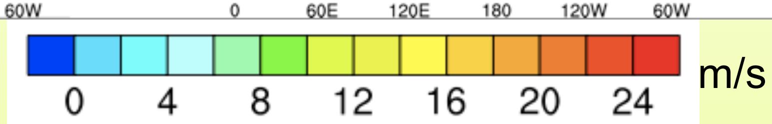
Most insensitive: models GISS-BQ, FVCUBE, HOMME



≈1° ×1° L60, dz=250 m

Test 4: 3D Rossby-Haurwitz Wave

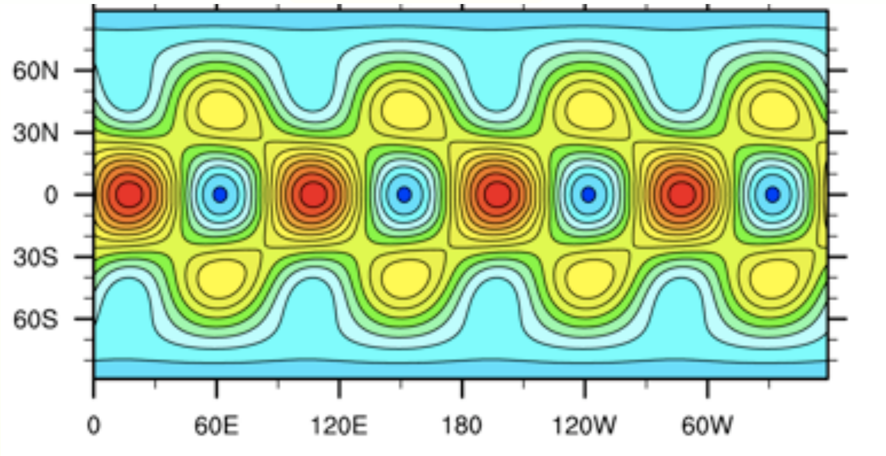




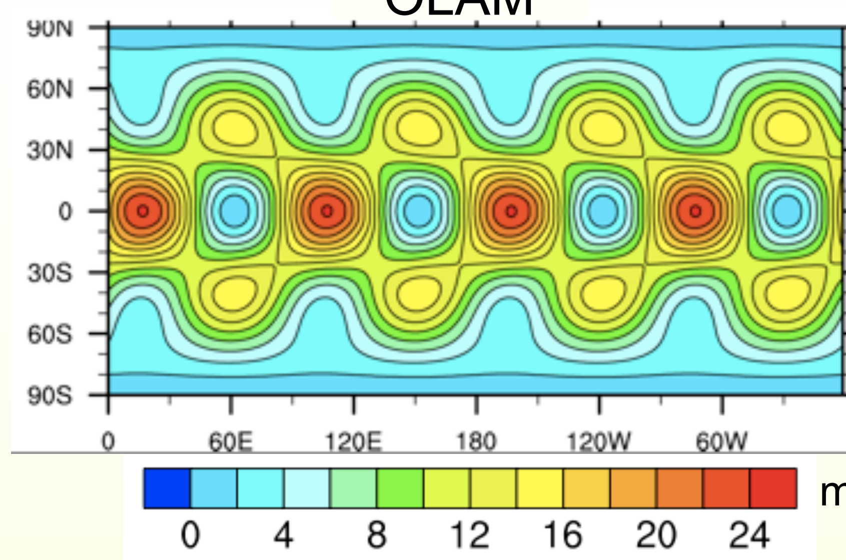
Zonal wind at day 15 (≈1° ×1° L26)

Test 4: Assess diffusion and symmetry

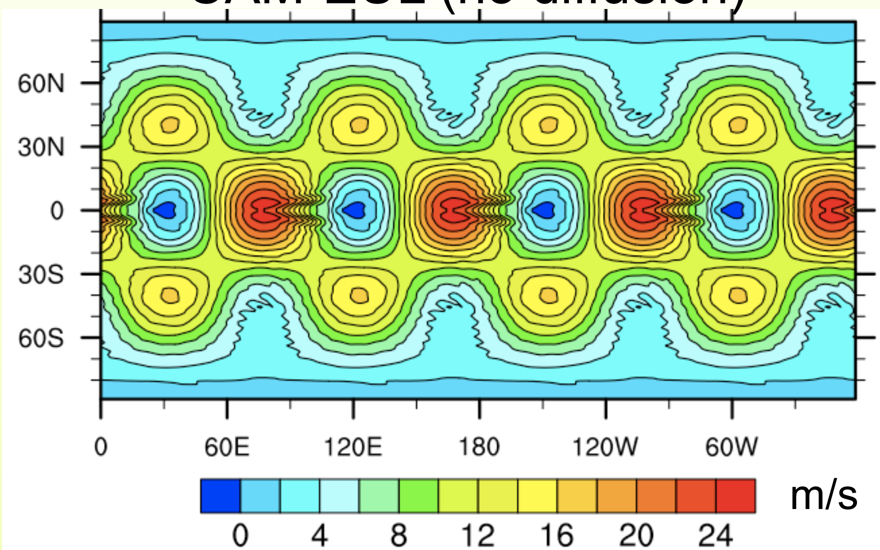
CAM-EUL



OLAM



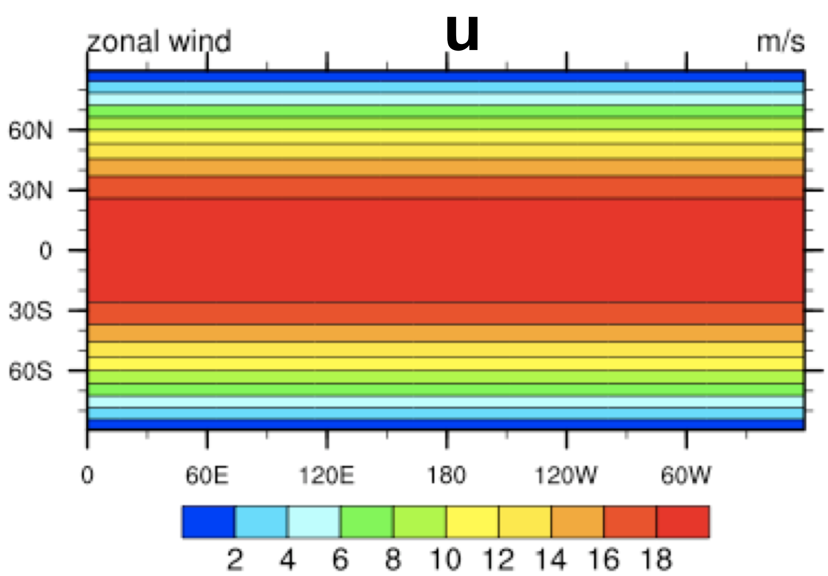
CAM-EUL (no diffusion)

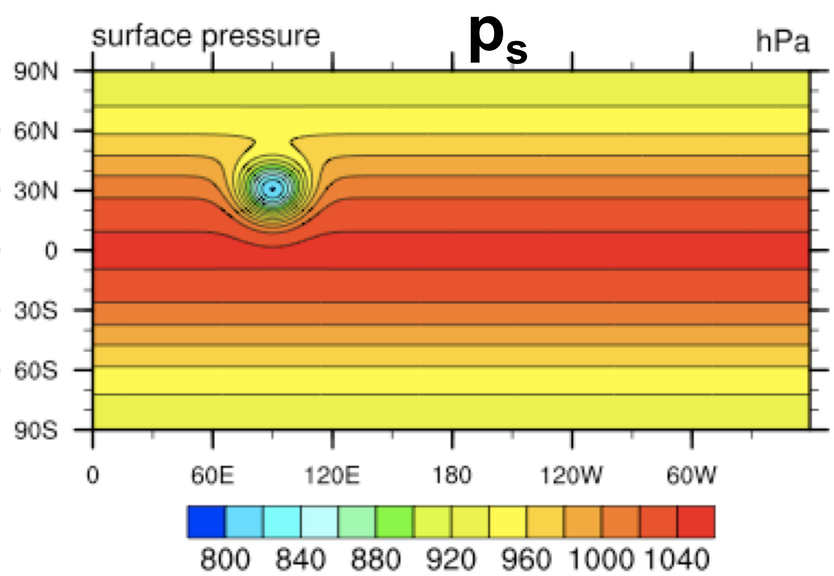


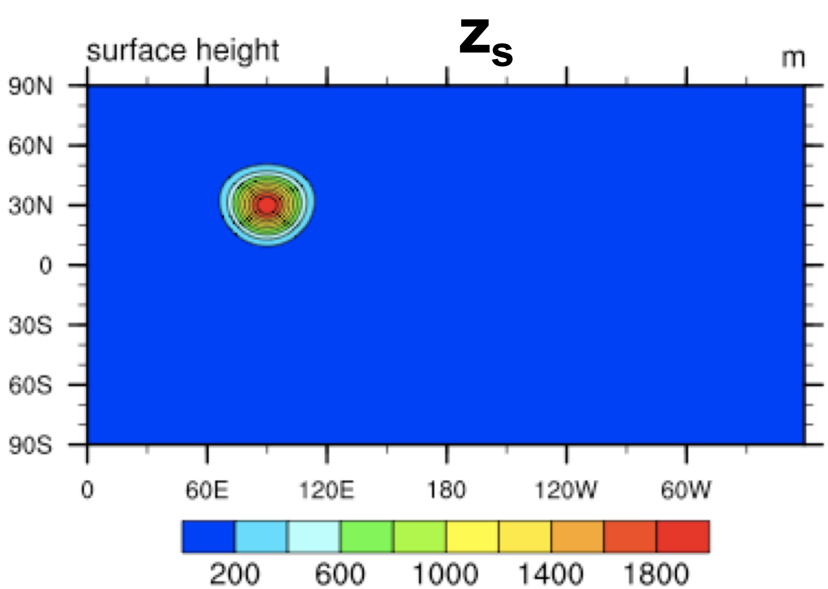
- Diffusion is needed for stability in EUL
- OLAM shows reduced amplitudes

Zonal wind at day 15
(≈1° ×1° L26)

Test 5) Mountain-induced Rossby waves



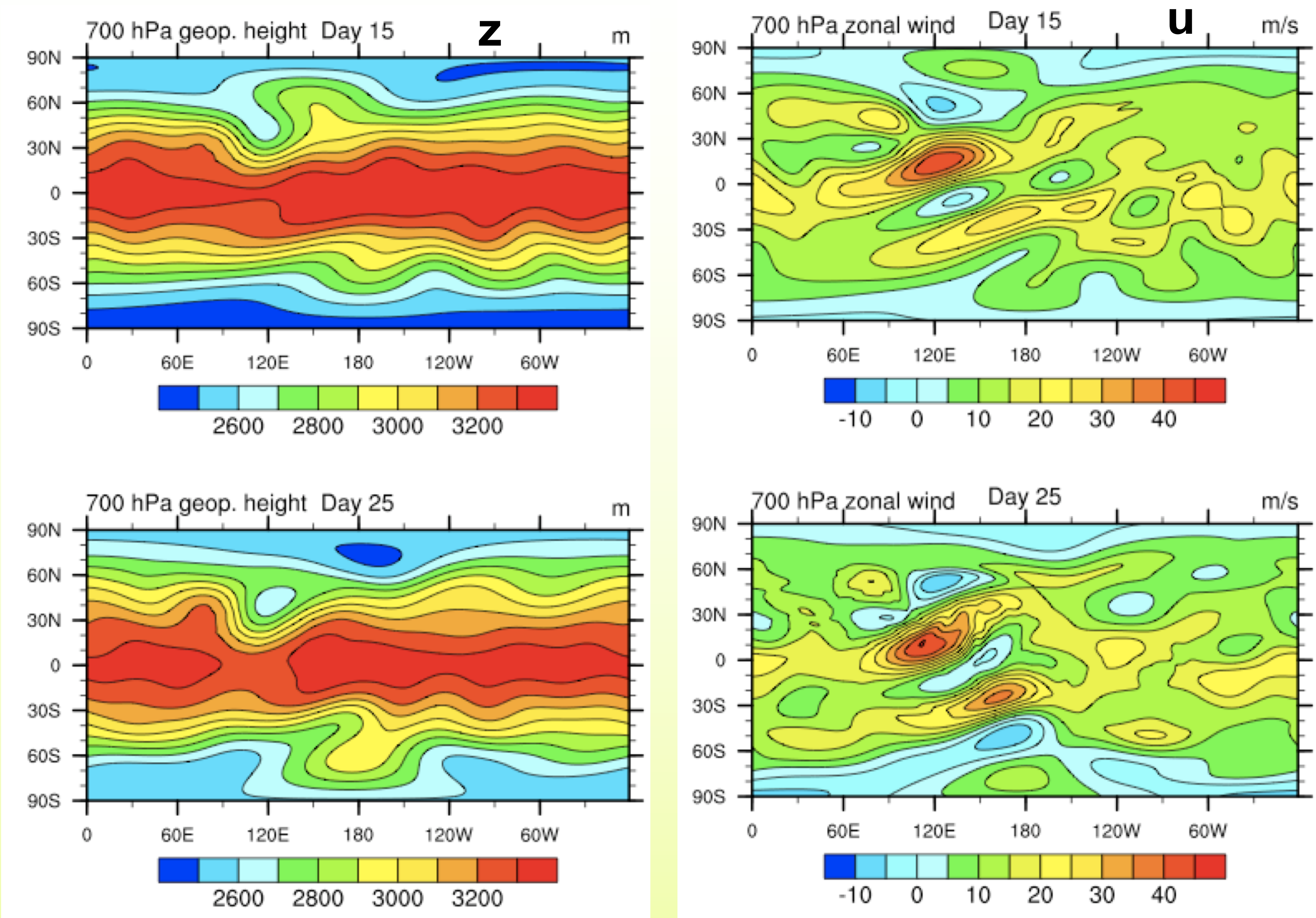




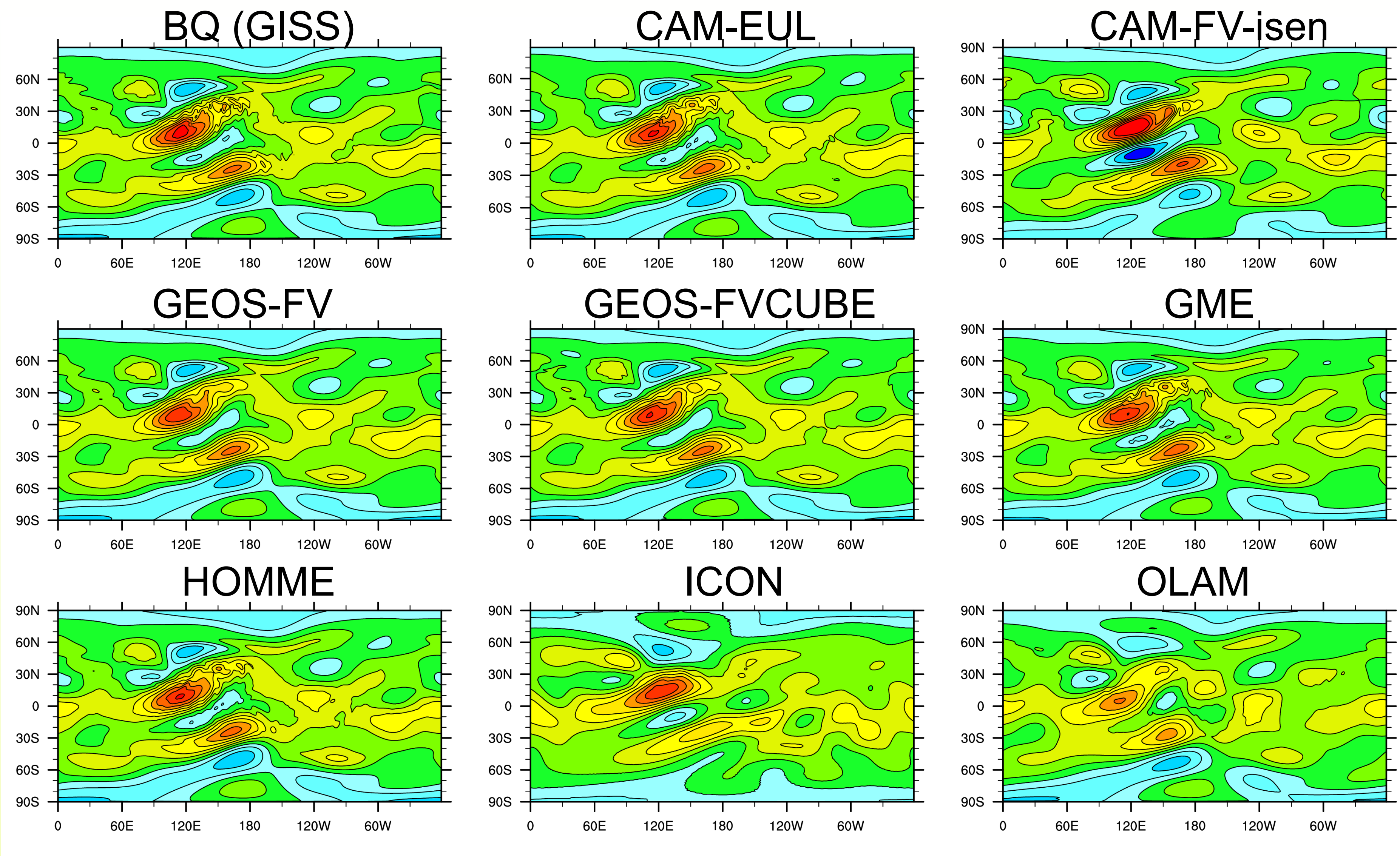
- Initial u, p_s, z_s fields, isothermal, v=0 m/s, balanced
- Mountain triggers the evolution of Rossby waves
- Hydrostatic, nonlinear regime

Days 15 & 25: Mountain-induced waves

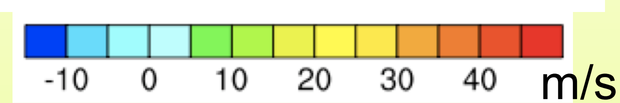
CAM-FV 180x360L26



Test 5: Noise or Physical Nonlinear Effects?

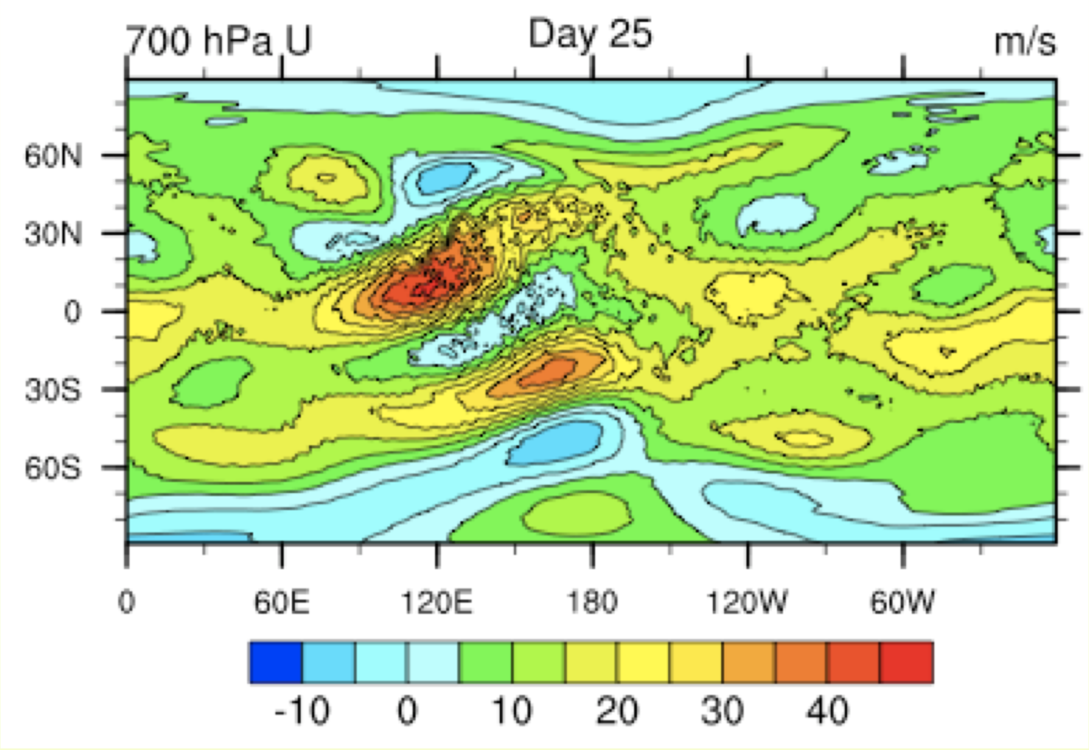


700 hPa zonal wind at day 15
(≈1° ×1° L26)



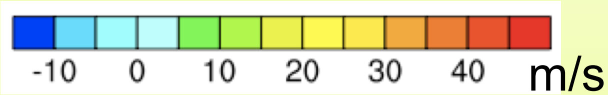
Test 5: Noise or Physical Nonlinear Effects?

CAM-EUL

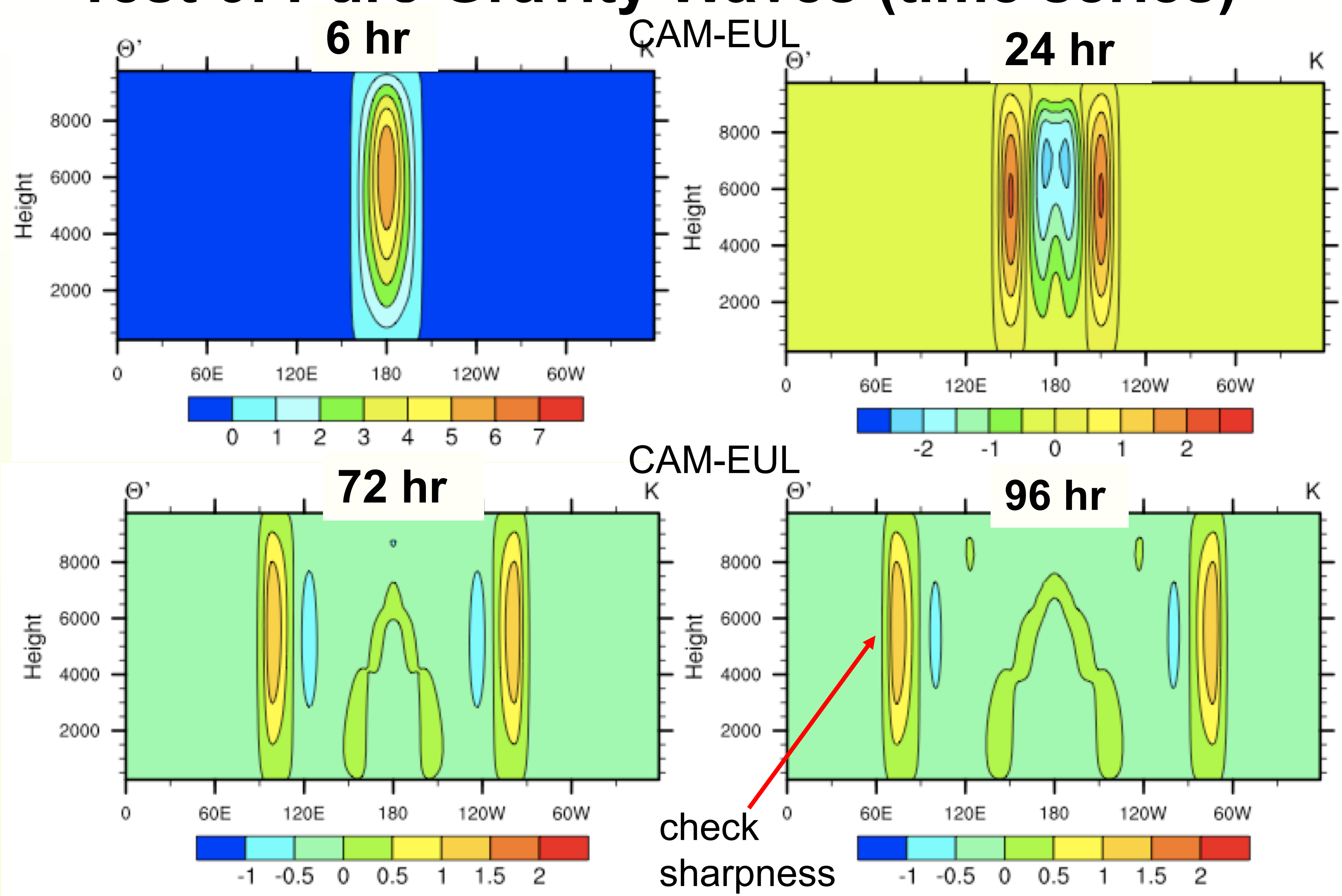


Noise, underdiffused

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

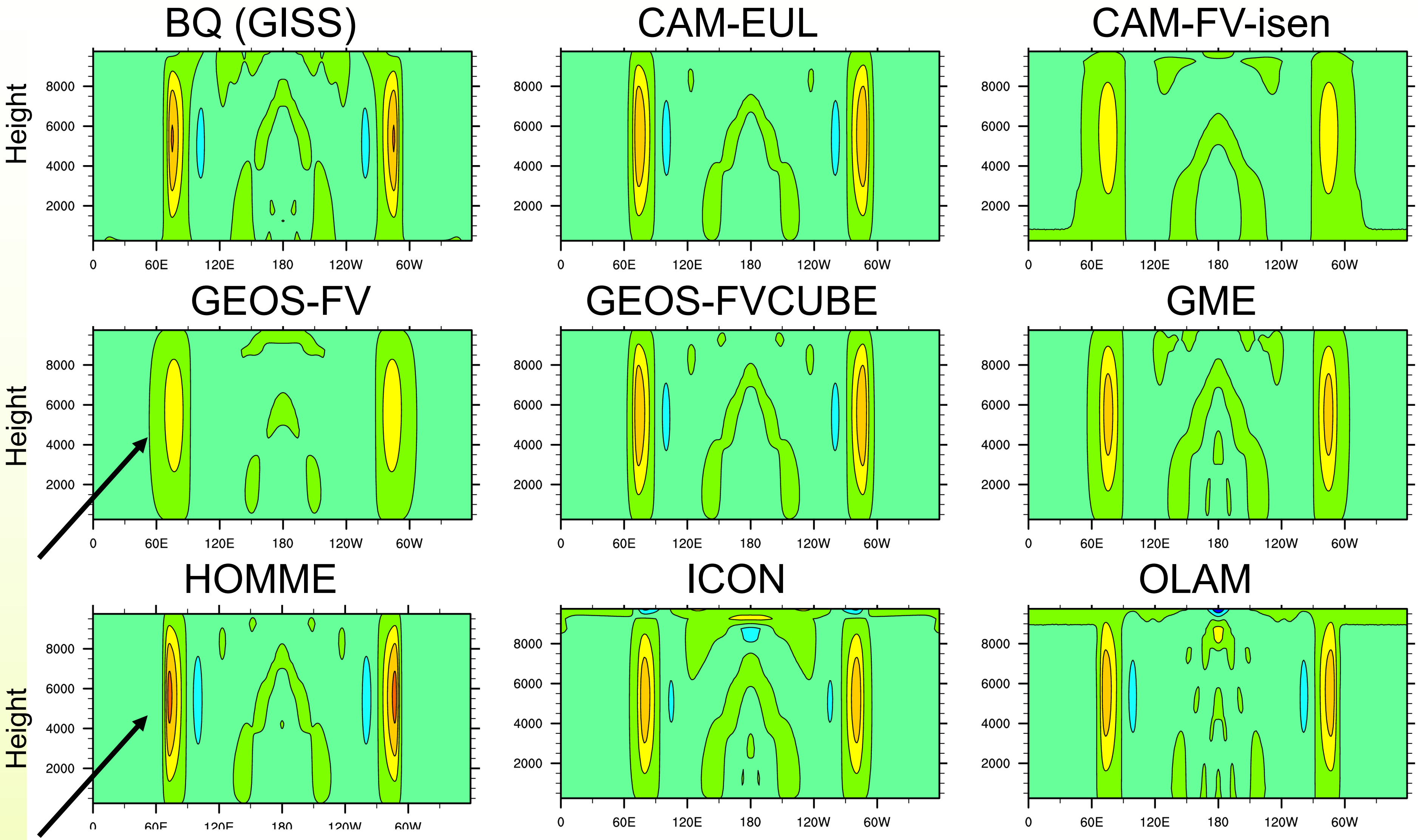


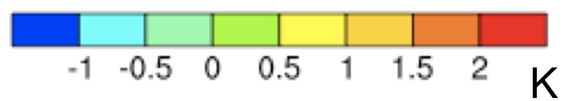
Test 6: Pure Gravity Waves (time series)



CAM-EUL T106 L20 with standard diffusion, Θ' cross section along equator

Test 6: Θ’ cross section along the equator





Day 4, (≈1° ×1° L20)

Check sharpness
amplitude, speed

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 had increasing 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 models
  - Simplified physics?

Future candidates

- 3D Mountain Waves (irrotational) on the sphere: hydrostatic & non-hydrostatic, linear & non-linear
- Acoustic Waves (non-hydrostatic)
- Dycore tests with real orography

- Moist dycore tests with intermediate complexity:
- Moist baroclinic waves
- Idealized tropical cyclones:
  - Prescribed tropical vortex
  - Balanced initial data, ocean-covered surface with specified (e.g. constant) SST