Model Evaluations I:
How to think about and what to expect from dynamical core and GCM tests

Christiane Jablonowski

University of Michigan, Ann Arbor

July 31, 2012 Dynamical Core Model Intercomparison Project (DCMIP) Summer School

Overview & Questions

- What are the sources of uncertainty in General Circulation Models (GCMs) and dynamical core experiments?
- Review of the typical test hierarchy for GCMs
- What is the particular impact of the dynamical core on the flow, illustrated via a tropical cyclone test
- Review of dry dynamical core tests with examples from the 2008 Dynamical Core Summer Colloquium
- Overview of the DCMIP test cases and example results

Sources of Uncertainty in GCMs

Structural:
choice of physical parameterizations and dynamical cores, model resolution, …

Data:
Initial data, boundary data (e.g. SSTs, …)

Parameter: physics tuning, physical constants, diffusion coefficients, …

GCM Test Hierarchy

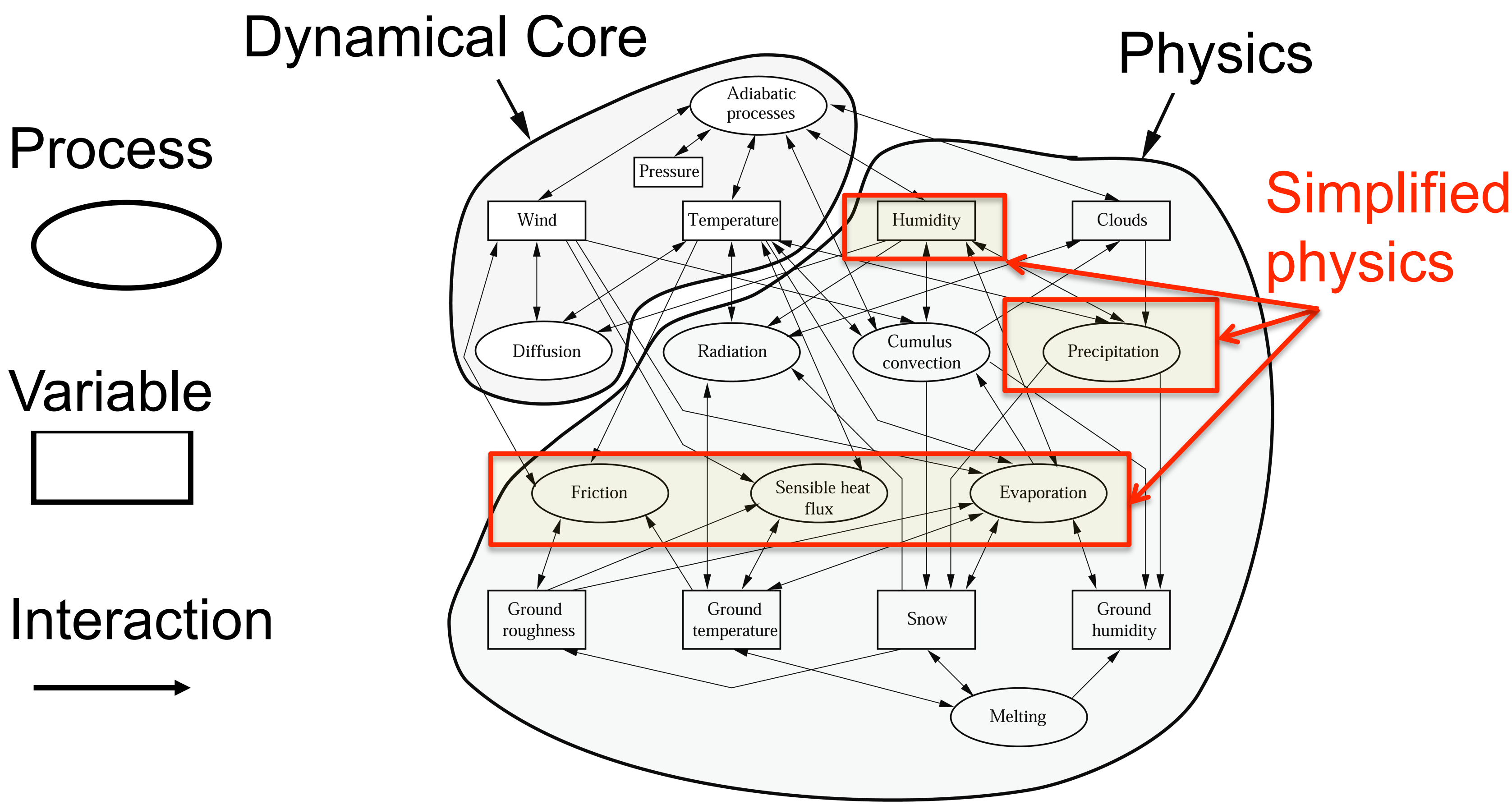
- Typical evaluation hierarchy for Dynamical Core and GCMs assessments

Increasing Complexity →

2D Shallow Water Test Cases → 3D Dry Dynamical Core Test Cases → 3D Dynamical Core + Moist Simple-Physics Test Cases → 3D Aqua-Planet Experiment (APE) → 3D Atmospheric Model Intercomparison Project (AMIP)

Mainly **deterministic** tests, with the exception of the Held-Suarez experiment → Tests of the **statistical** behavior (model 'climate')

Dynamics & Physics: How to think about simplified physics



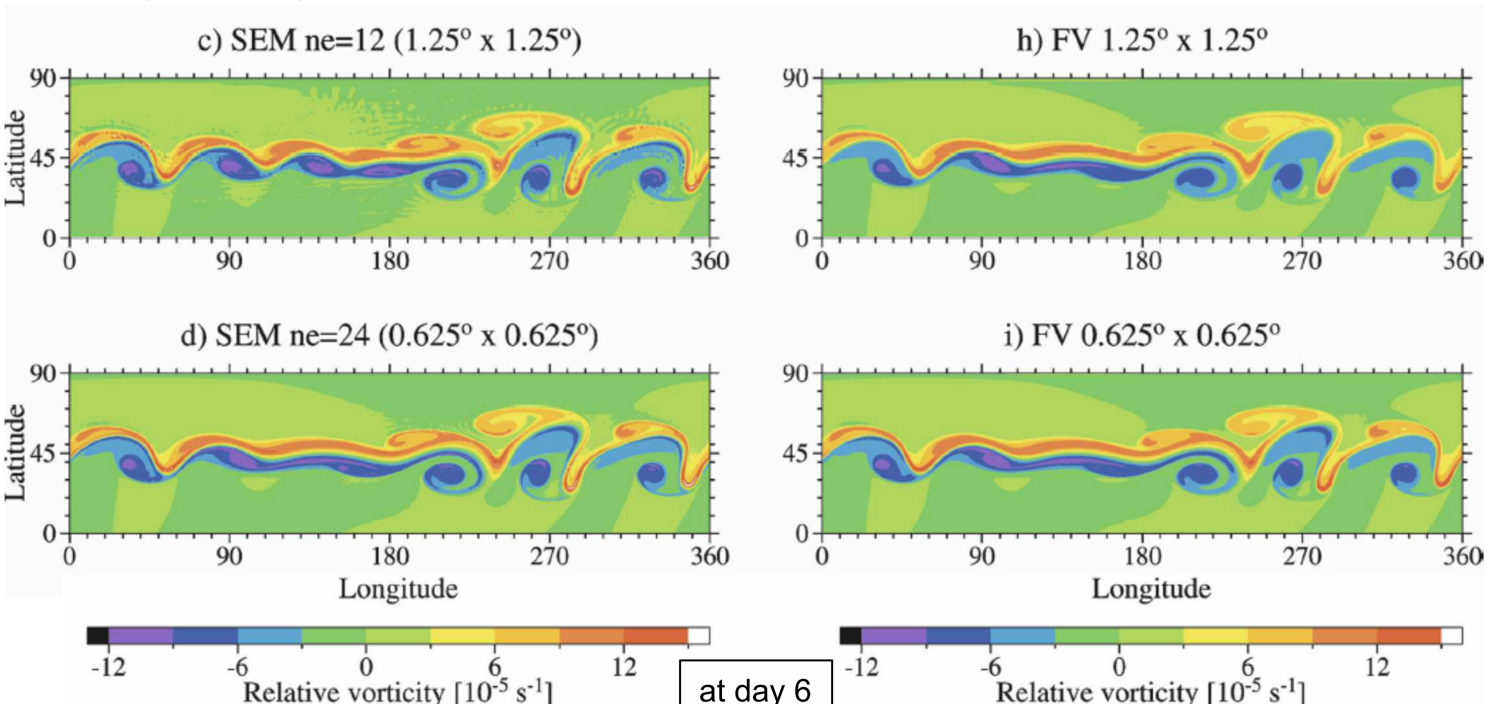
Replace the physics package: use only simple surface fluxes, large-scale condensation and vertical diffusion in BL

GCM Test Hierarchy: 2D SW

- 2D shallow water (SW) tests evaluate the characteristics of the horizontal and temporal discretizations
- An example is the barotropic wave test by Galewsky et al., Tellus (2004), here shown for two SW models SEM and FV

Coarse grid

Double resolution



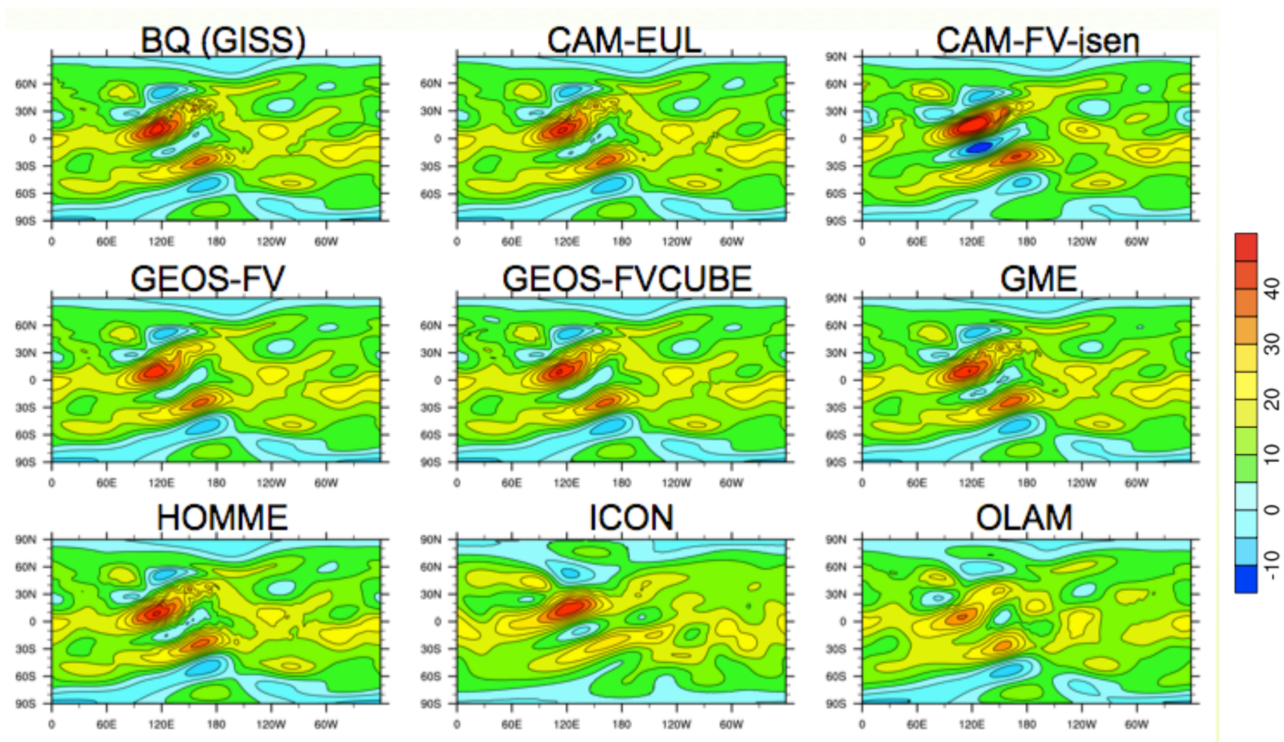
at day 6

from St-Cyr, Jablonowski, et al., MWR, 2008

GCM Test Hierarchy: 3D dry

- 3D dry dynamical core tests evaluate the characteristics of the horizontal, vertical and temporal discretizations

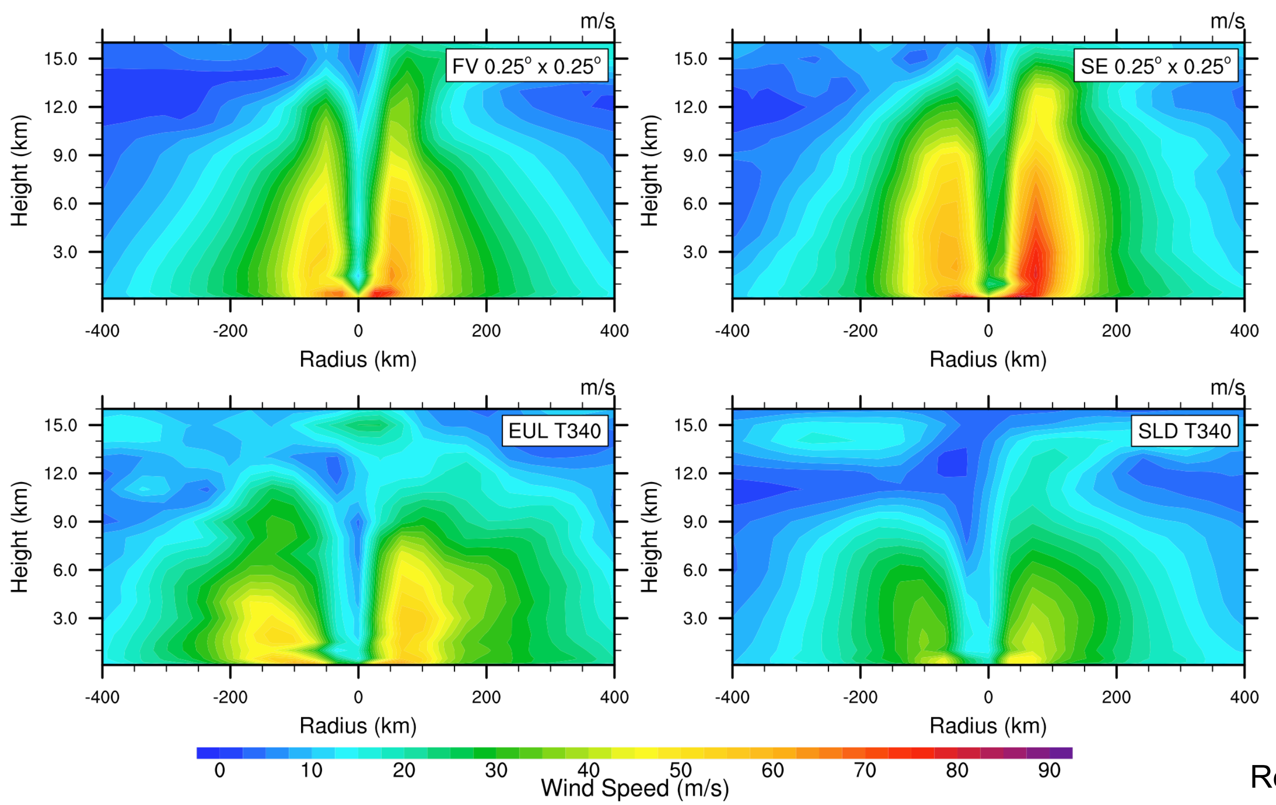
9 different dynamical cores



Example from the 2008 Dynamical Core Intercomparison during the NCAR ASP Summer Colloquium: Mountain-generated Rossby waves, 700 hPa zonal wind (m/s) at day 15

GCM Test Hierarchy: 3D moist

- 3D (simplified)-moist dynamical core tests evaluate the characteristics of the horizontal, vertical and temporal discretizations, and their interaction with simple physical parameterizations: tropical cyclone example with CAM



Wind Speed (m/s) at day 10

4 dynamical cores of the NCAR Community Atmosphere Model CAM:

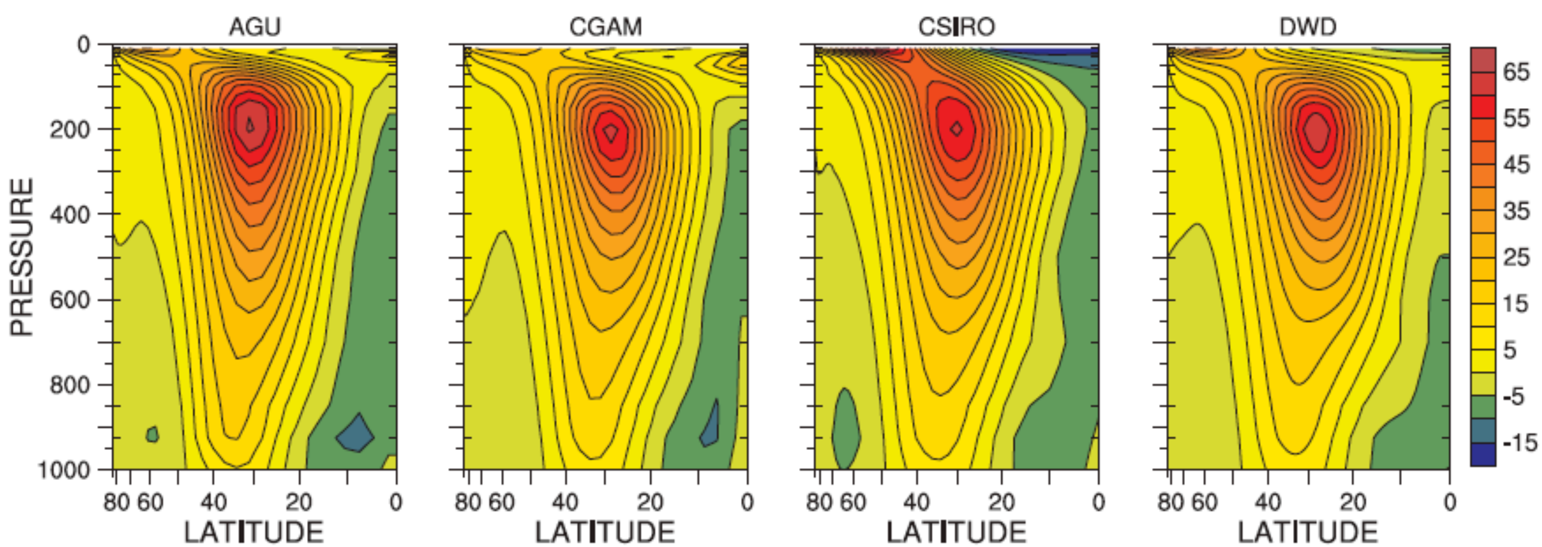
FV & SE at 0.25°
(≈ 28 km)

EUL & SLD at T340
(≈ 39 km)

Reed and Jablonowski, JAMES (2012)

GCM Test Hierarchy: Aqua-planet

- 3D aqua-planet tests evaluate the interaction between the dynamical core with complex physical parameterizations using a simplified lower boundary (flat ocean-covered Earth with analytically prescribed sea surface temperatures (SSTs))

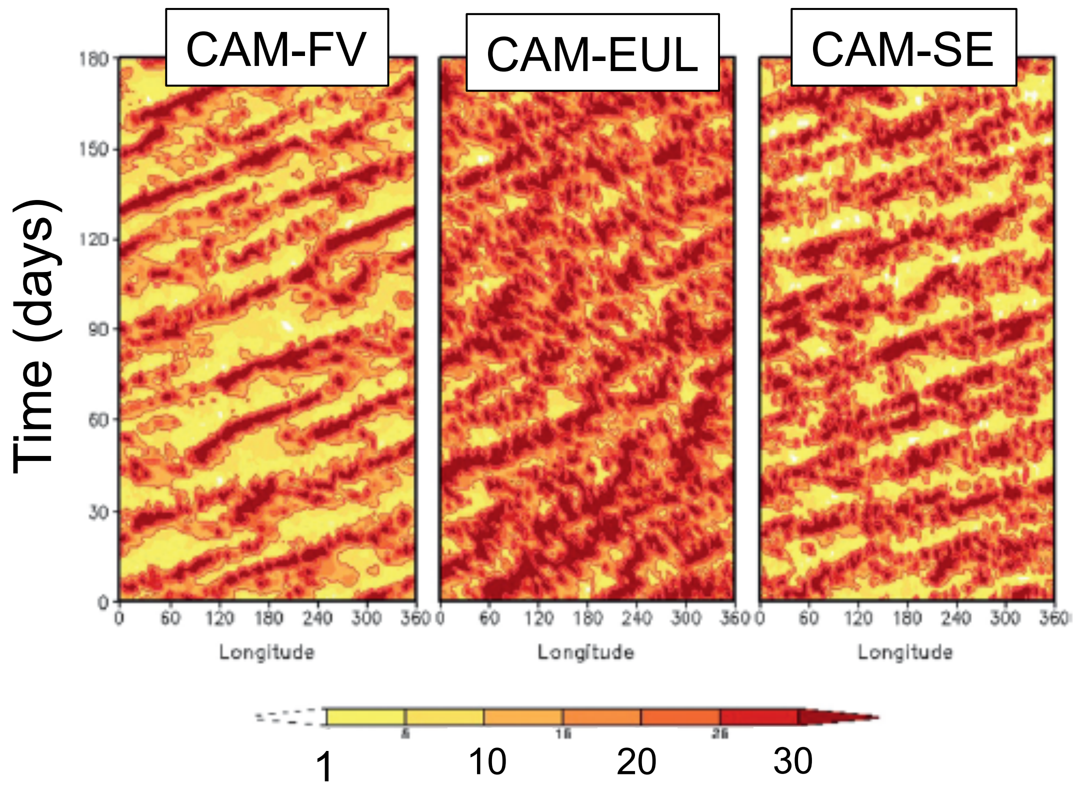


Zonal-mean 3-year-mean zonal wind: Snapshots of 4 GCMs that participated in the Aqua-Planet Experiment (APE)

Williamson et al., NCAR Technical Note TN-484+STR (2012)

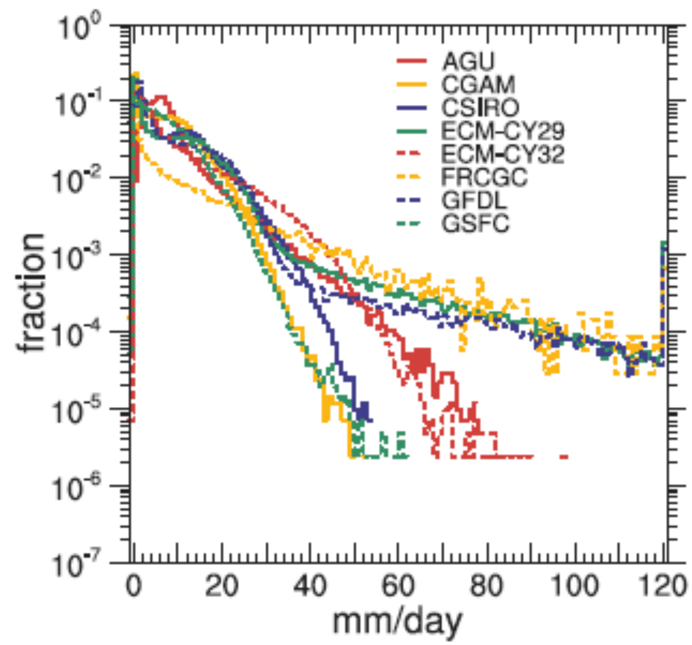
GCM Test Hierarchy: Aqua-planet

- 3D aqua-planet tests give insights into the characteristics of moisture processes, what drives these differences?



Daily rainfall rate (mm/day) in the tropics

Mishra et al., J. Climate (2011)

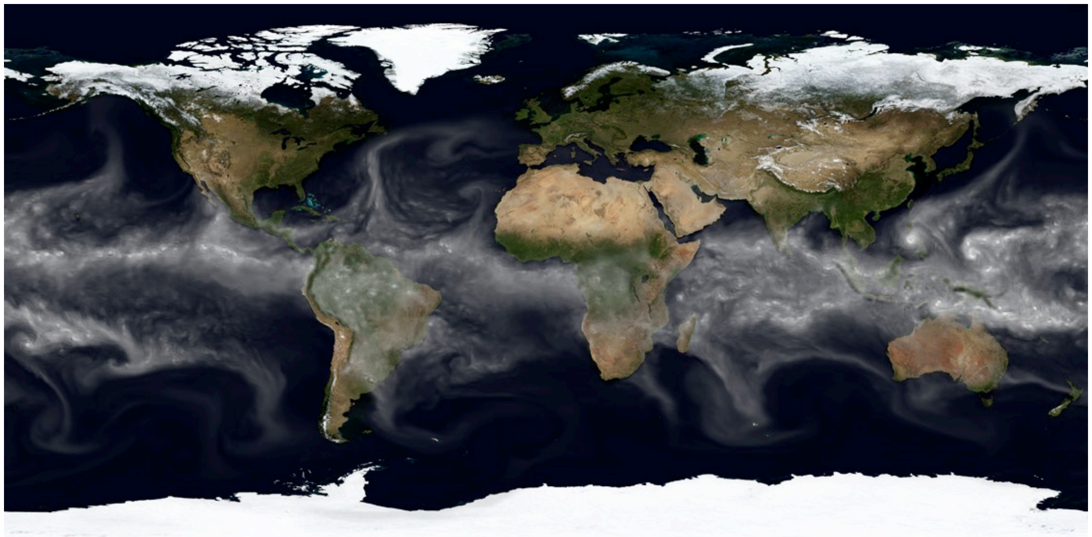


Fraction of time precipitation in the tropics is between 0-120 mm/day

Williamson et al., NCAR Technical Note TN-484+STR (2012)

GCM Test Hierarchy: AMIP

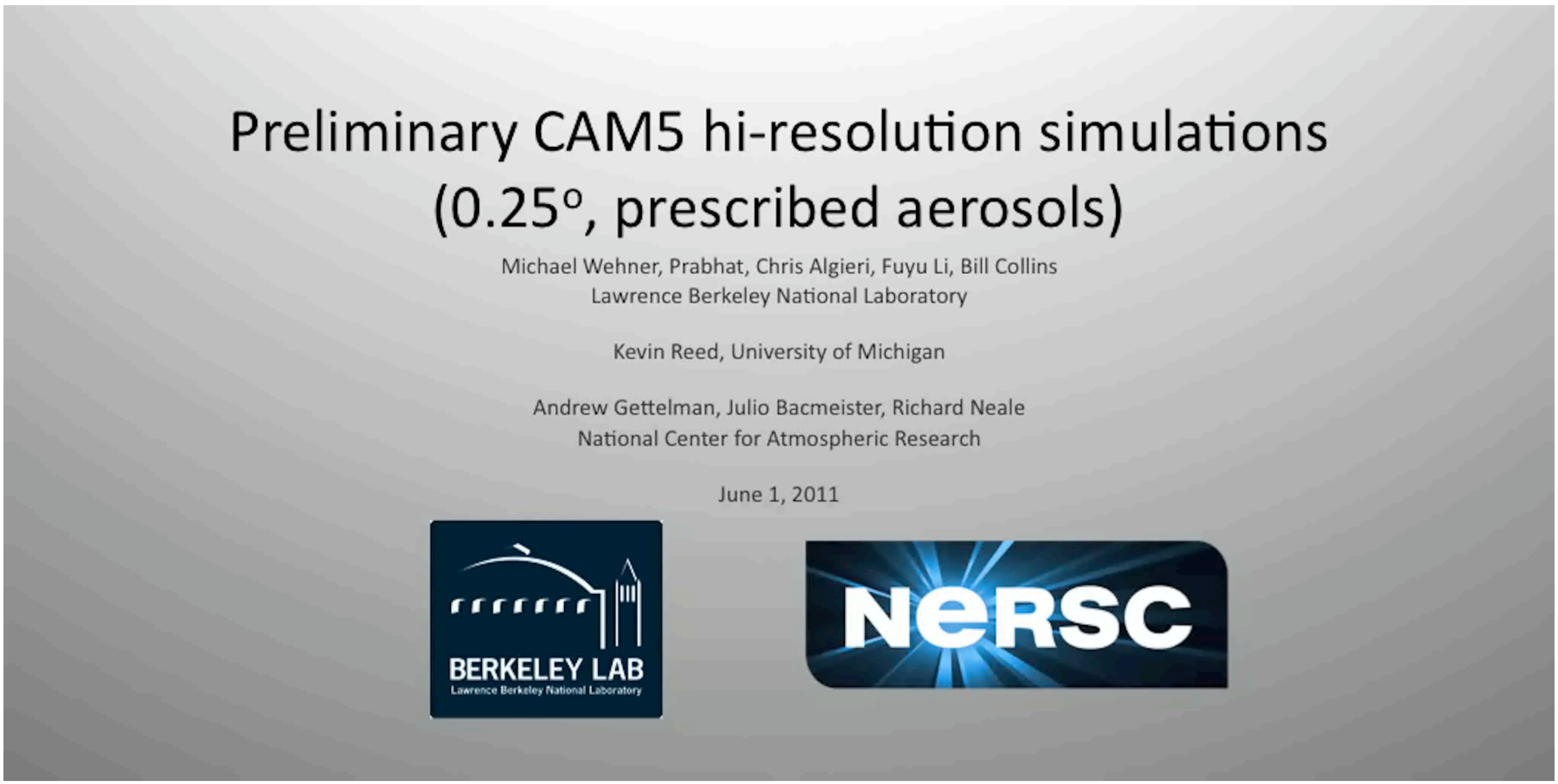
- 3D AMIP tests evaluate the interaction between the dynamical core with complex physical parameterizations (maybe even including chemistry packages) using a complex but prescribed lower boundary (orography, prescribed observation-based SSTs and sea ice) over 25-year time frames



Snapshot of the precipitable water in a CAM-FV (25 km) AMIP simulation conducted by Kevin Reed (University of Michigan) and Michael Wehner (LBNL)

GCM Test Hierarchy: AMIP

- Time-loop of the precipitable water in the CAM-FV (25 km) AMIP simulation (produced by the Lawrence Berkeley Lab)



GCM Test Hierarchy: Fully coupled

- The most complex GCM evaluations utilize fully coupled atmosphere—ocean—ice—land—chemistry—carbon-cycle Earth System Models,
  sometimes prescribed greenhouse gas concentrations are used
- Fully coupled simulations of past time periods are typically compared against observations, sometimes in form of re-analysis data
- Differences between simulations are very hard to understand due to the complexity and nonlinear interactions
- Fully coupled GCMs are used for the assessment of future climate scenarios, e.g. for the Intergovernmental Panel on Climate Change (IPCC) assessments

Measures of 'Truth'

- What is truth? How can we judge whether GCM model simulations are robust, reliable and accurate?
- The higher we go up in the test hierarchy the more difficult it is to understand the causes and effects, and to determine the accuracy of a simulation.
- Only very idealized test cases have analytic solutions.
- In non-linear dry dynamical core test cases we rely on ensembles of high-resolution references solutions to determine the perceived 'truth' and its uncertainty.
- Dry dynamical core tests converge within some uncertainty with increasing resolution.
- Moist dynamical cores and GCMs do not converge when resolution is increased.

Ensembles

- Ensembles are one way to assess the robustness of the simulations, and to gain insight into the uncertainty of the model simulations

There are three types of ensembles

- Perturbed parameter ensembles, e.g. variations of
  - empirical tuning factors in the physical parametrizations
  - diffusion coefficients or physical constants in the dynamical core
- Initial data and boundary value ensembles, e.g.
  - slight variations of the initial data
  - different topography data set, different SSTs
- Multi-model ensembles, e.g. different
  - GCMs or different versions of the same GCM

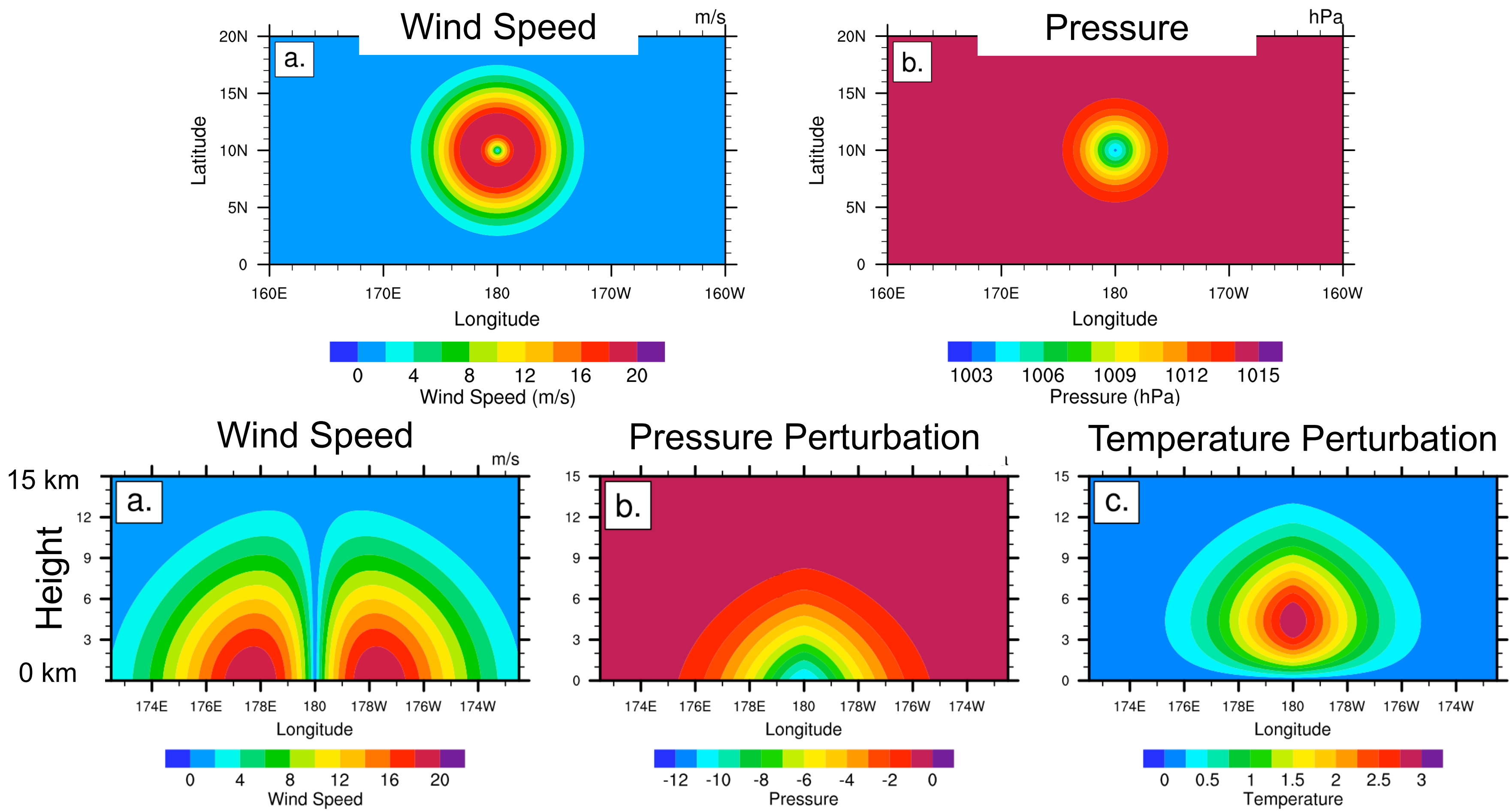
Ensembles: Some Examples

- Use the idealized tropical cyclone (TC) test case from DCMIP (test 52 setup)
- Utilize 4 dynamical cores from NCAR's CAM 5 model:
  - Finite-Volume (FV)
  - Spectral Element (SE)
  - Eulerian Spectral Transform (EUL)
  - Semi-Lagrangian Spectral Transform (SLD)
- Dycores use the same hydrostatic equation set, but there are many differences in the numerical methods, computational grids, staggering, choice of prognostic variables, and the dissipation mechanisms

Ensembles: Experimental Design

- Use idealized initial conditions to spin up an idealized TC over 10 simulation days in an aqua-planet configuration (SST = 29 °C) of CAM
- Quick look at initial data and structural uncertainty in CAM-FV due to
  - slightly (2%) perturbed initial conditions, modified physical constants and longitude-position of vortex
  - CAM 4 physics versus CAM 5 physics
- Quick look at structural uncertainty due to different dynamical cores with the same CAM 5 physics package

Tropical Cyclone (TC) Test Case: Analytic Initial Conditions



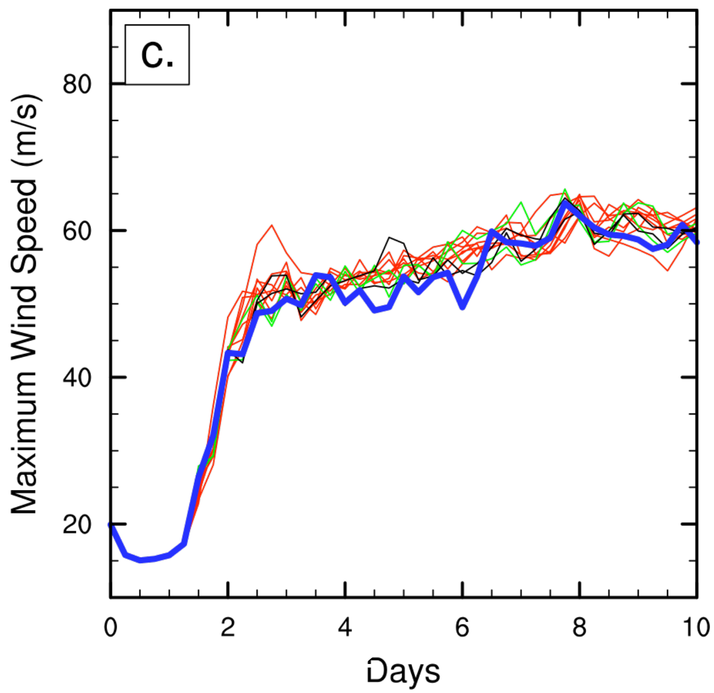
The vortex is centered at 10° N and 180° E.

Reed and Jablonowski, MWR (2011a)

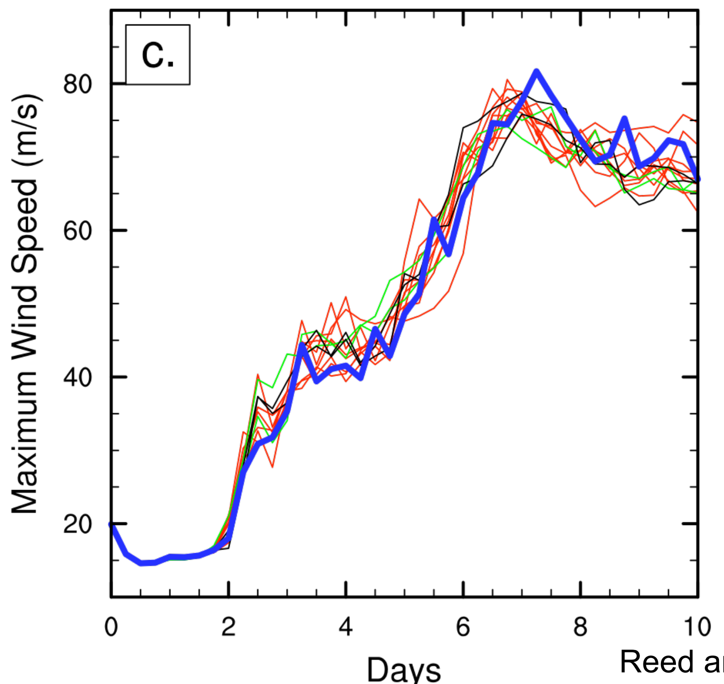
TC Test: CAM-FV 4 / CAM-FV 5

- Initial data (colored lines, blue is unperturbed) and structural (physical parameterization, left/right) uncertainties: Structural uncertainty is large

FV (28 km) with CAM 4 physics



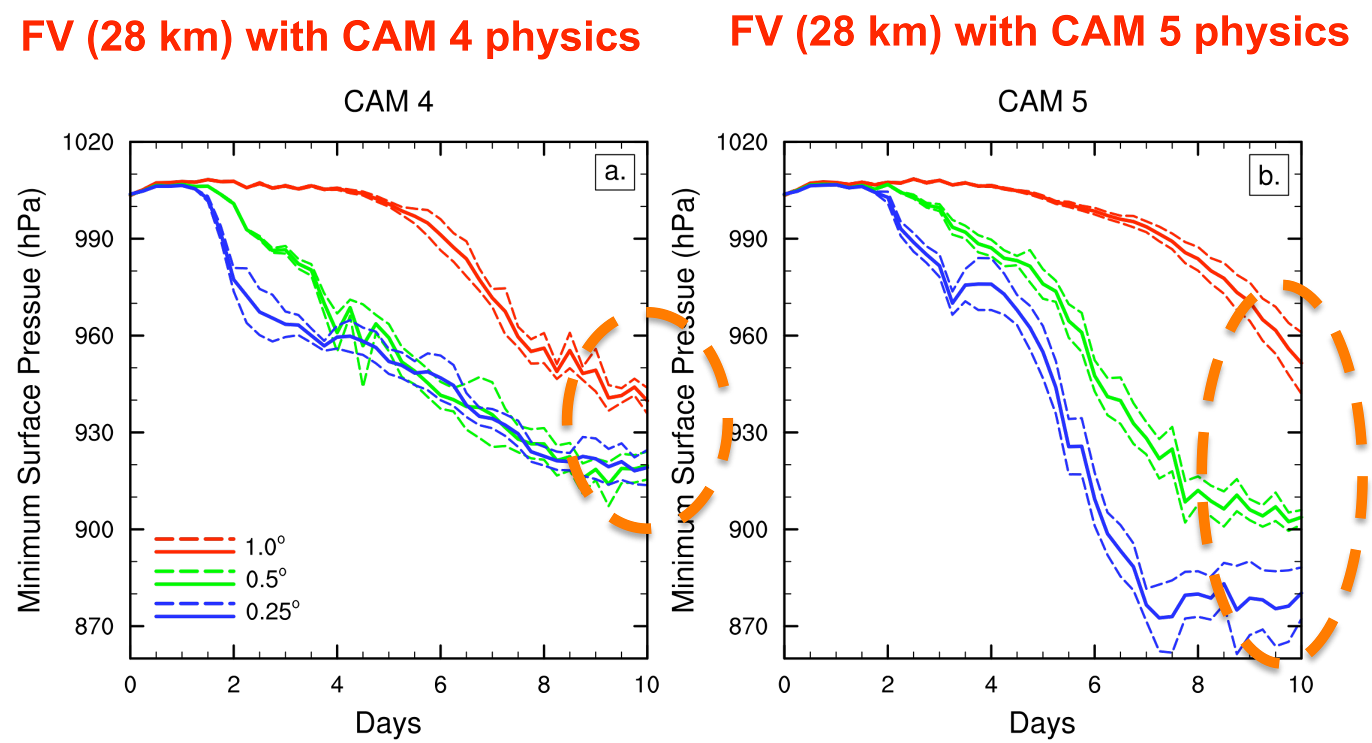
FV (28 km) with CAM 5 physics



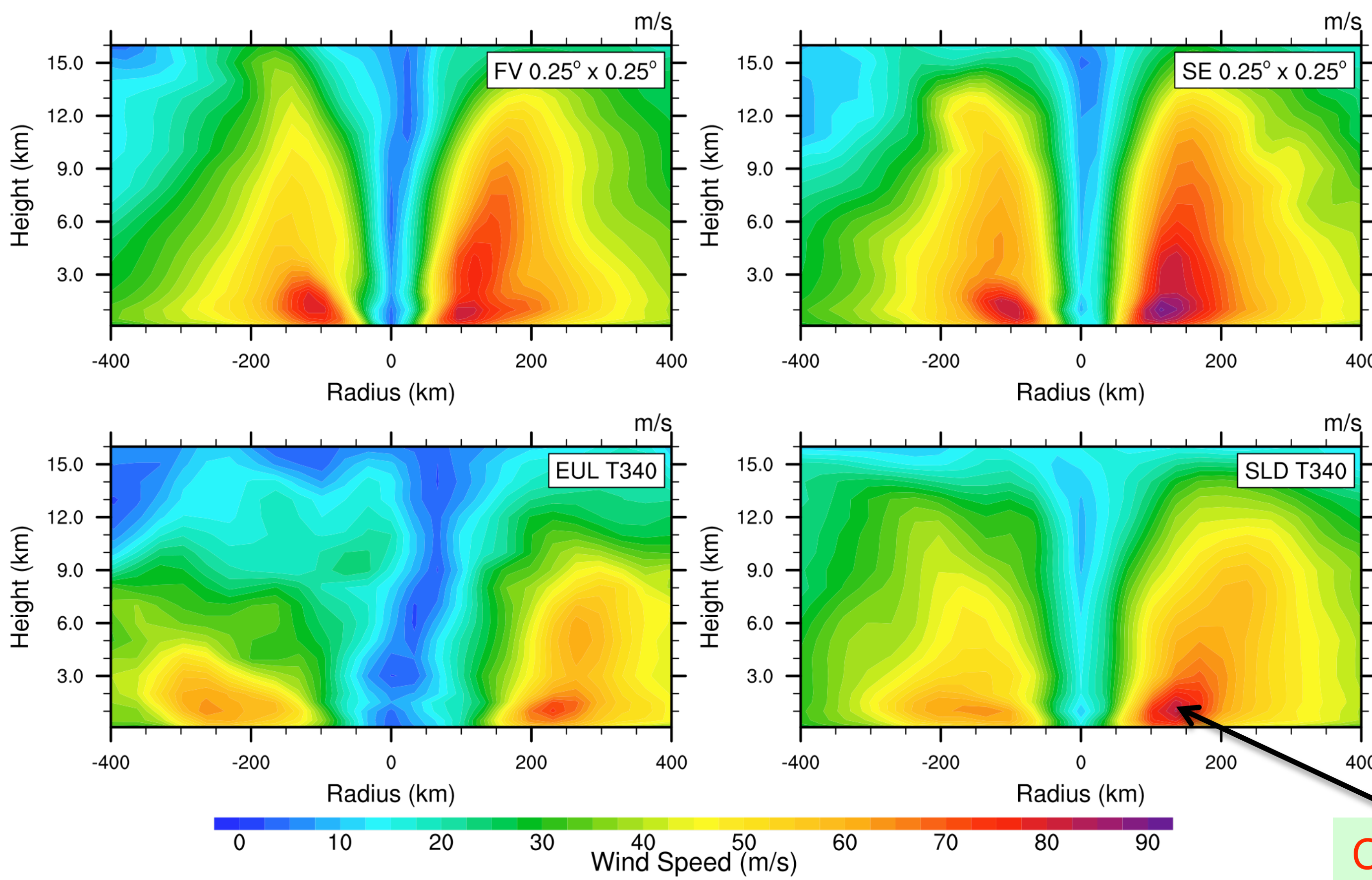
Reed and Jablonowski, JAMES (2011c)

TC Test: CAM-FV 4 / CAM-FV 5

- Initial data (solid, dashed lines are uncertainty estimates) and structural (horizontal resolution, colors) uncertainties: Structural uncertainty is large



Impact of the Dynamical Core: CAM 5 Full Physics Simulations



Wind Speed (m/s)
At Day 10

Differing strengths and shapes of the tropical cyclone:

FV & SE
at 0.25^o
(≈ 28 km)

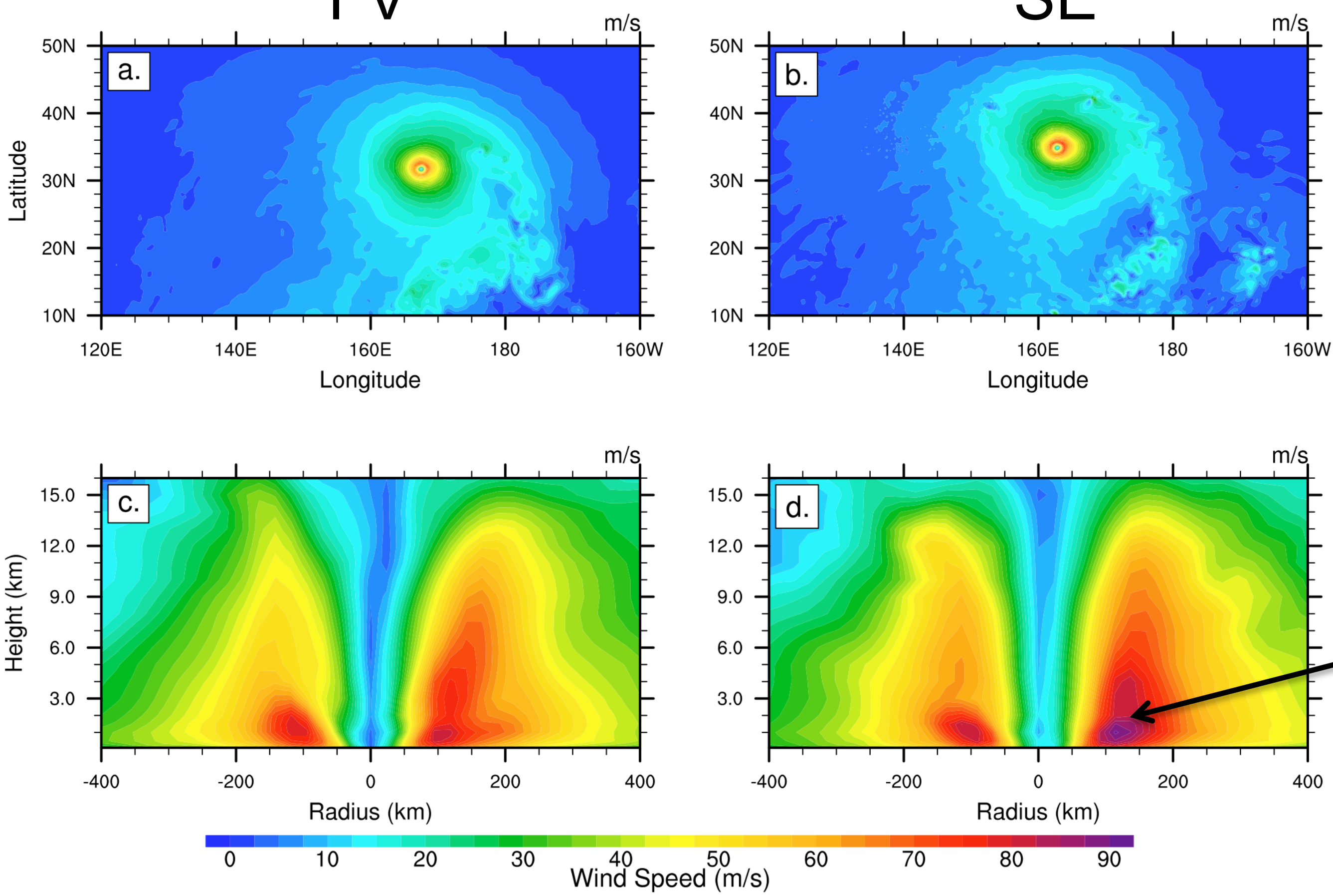
EUL & SLD
at T340
9 km)

Category-4 cyclone

EUL and SLD: weaker and broader storms

Reed and Jablonowski, JAMES (2012)

Impact of the Dynamical Core: CAM 5 Full Physics Simulations



Wind Speed (m/s)
At Day 10

$0.25^o \approx 28$ km

Category-5 cyclone

FV and SE: similar in strength and TC characteristics

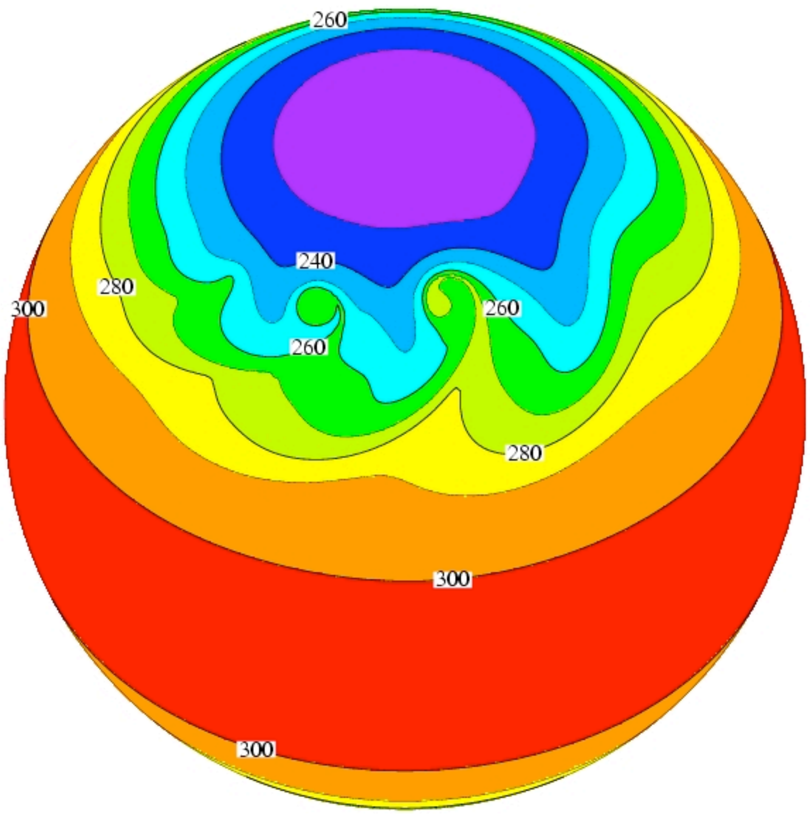
Reed and Jablonowski, JAMES (2012)

Review: Examples of Dry Dynamical Core Tests

- In 2008 we organized a 2-week NCAR Summer Colloquium on Dynamical Cores and collected & designed a suite of dry dynamical core test cases
- All had analytic initial conditions

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

Review: Dry Baroclinic Wave Test (DCMIP test 410)



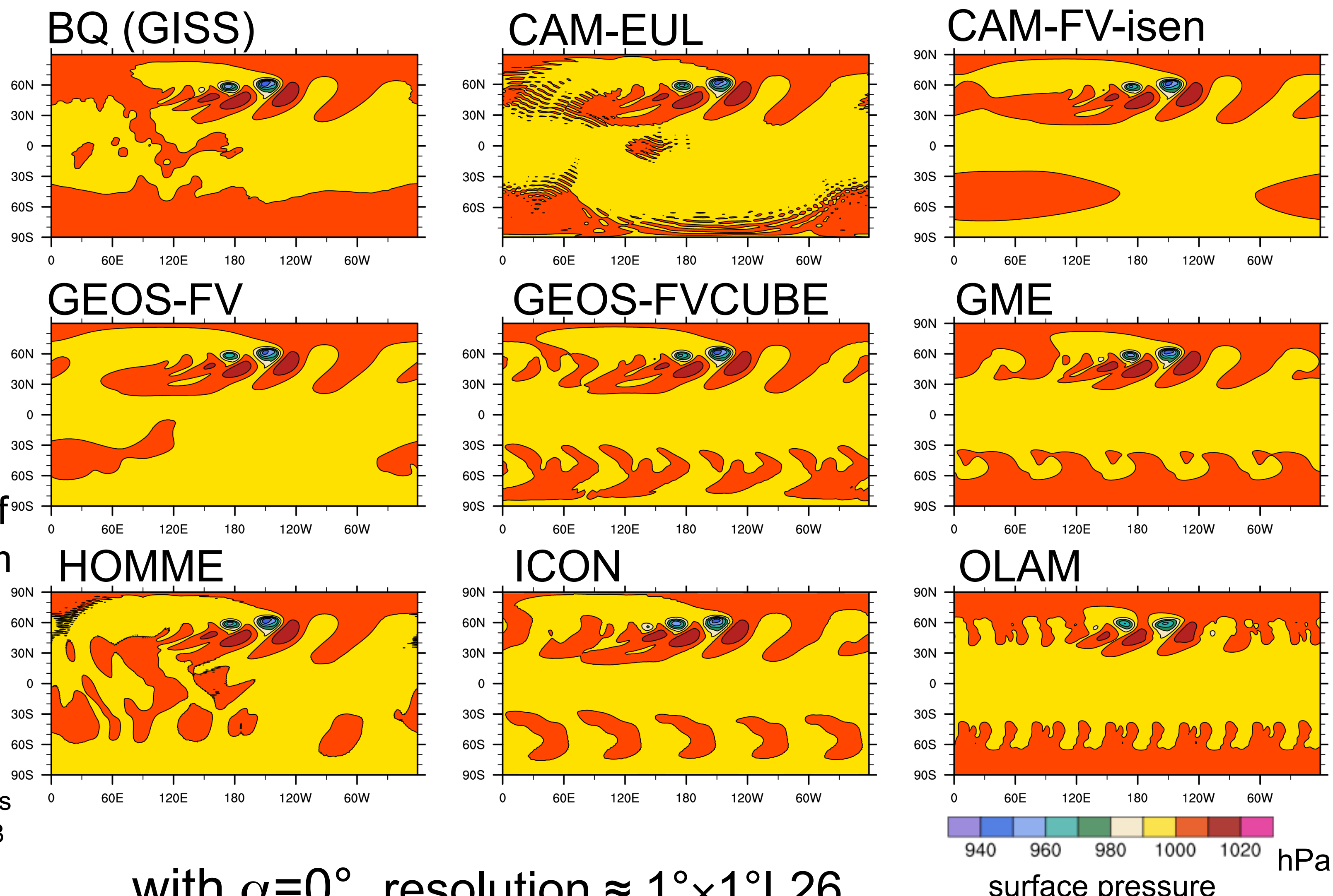
- 850 hPa temperature field (in K) of an idealized baroclinic wave at model day 9
- Initially smooth temperature field develops strong gradients
- Explosive cyclogenesis after day 7
- Baroclinic wave breaks after day 9
- Models start converging at 1°

Jablonowski and Williamson, QJ (2006)

DCMIP

Dry Baroclinic Wave Test: p_s

Look for grid imprinting, numerical noise like spectral ringing, strength of the system

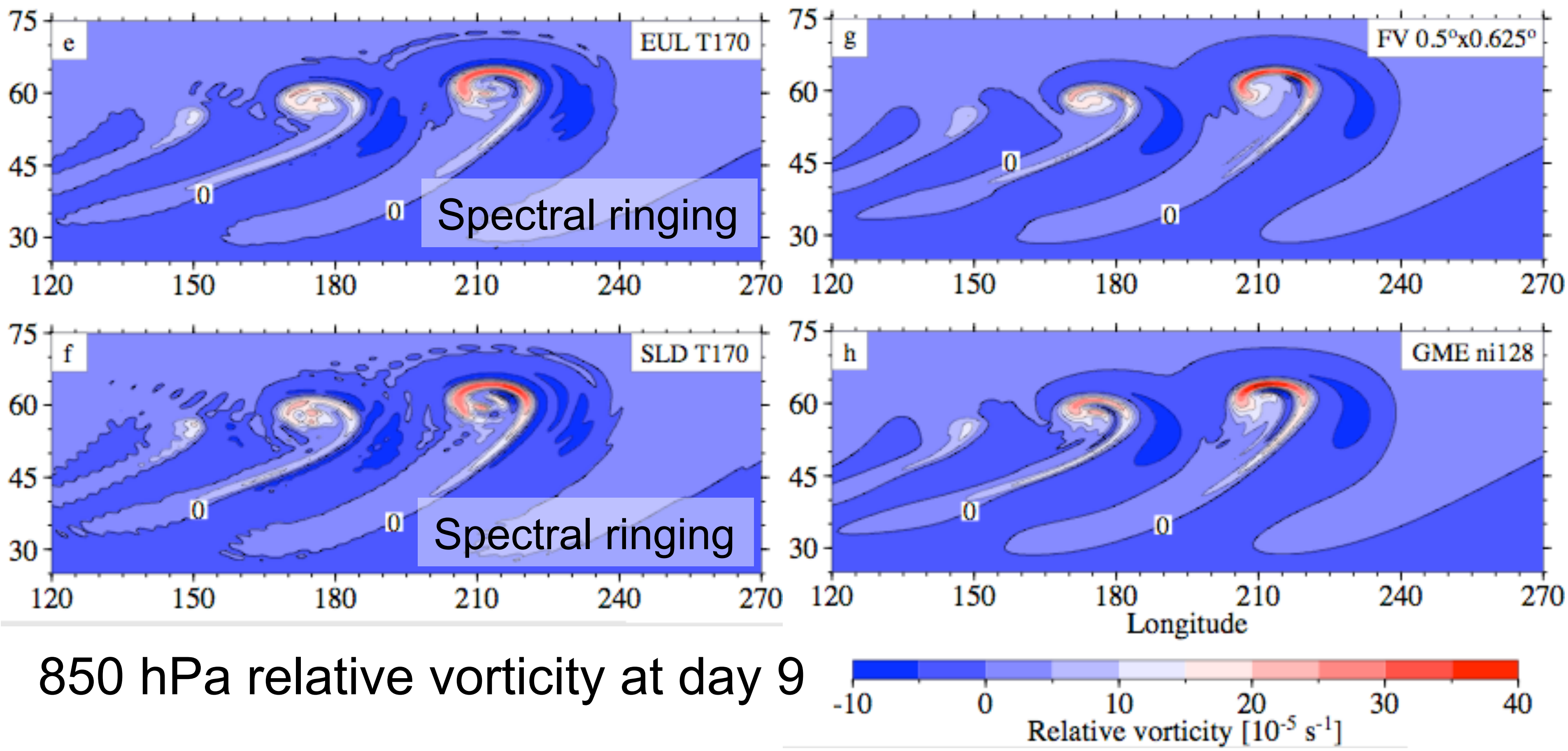


Results from 9 dynamical cores during the 2008 NCAR Colloquium

with α=0°, resolution ≈ 1°×1°L26

Dry Baroclinic Wave Test: ζ_{850hPa}

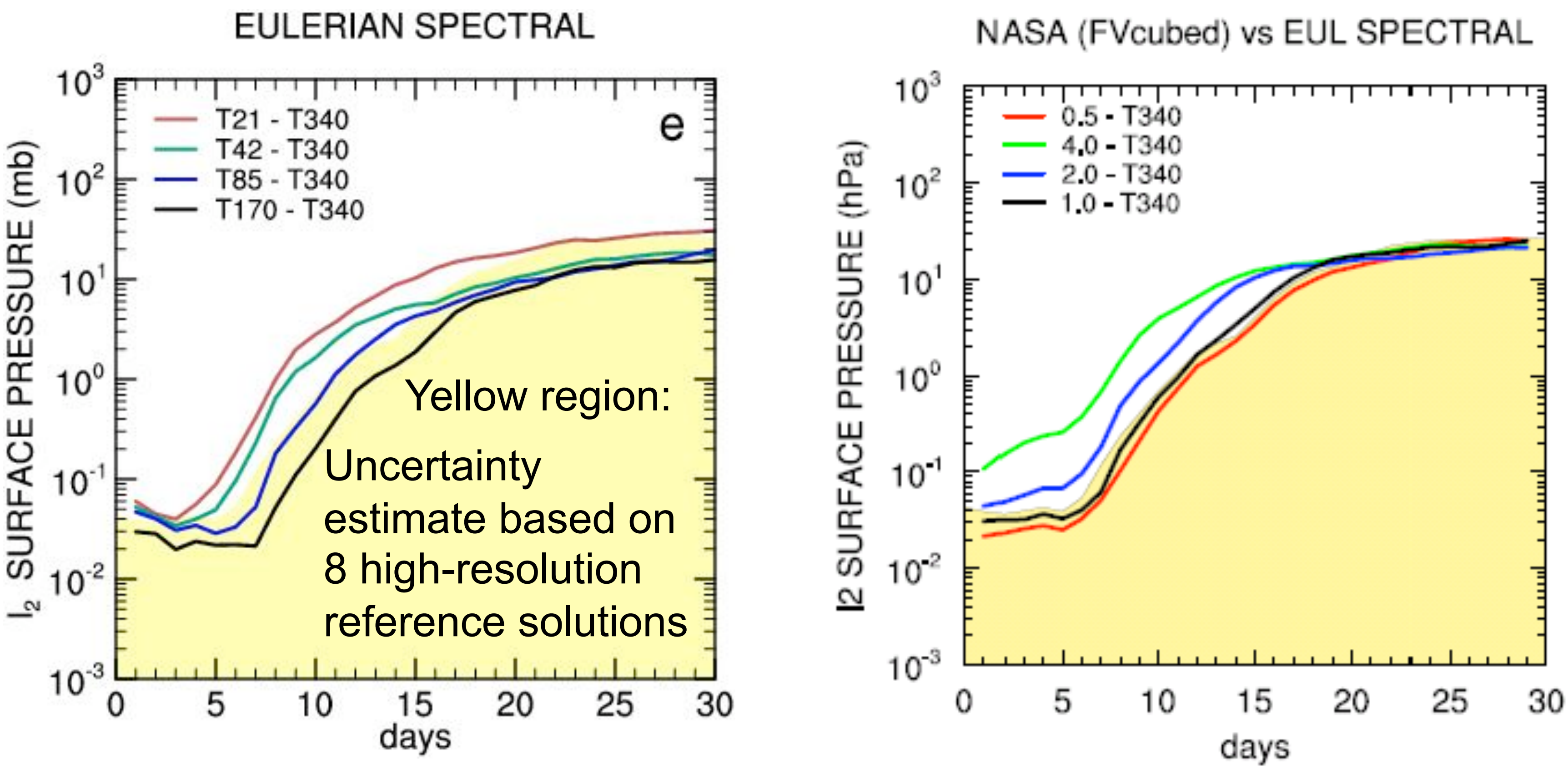
- Differences in the vorticity fields grow faster than p_s diff.
- Small-scale differences easily influenced by diffusion



850 hPa relative vorticity at day 9

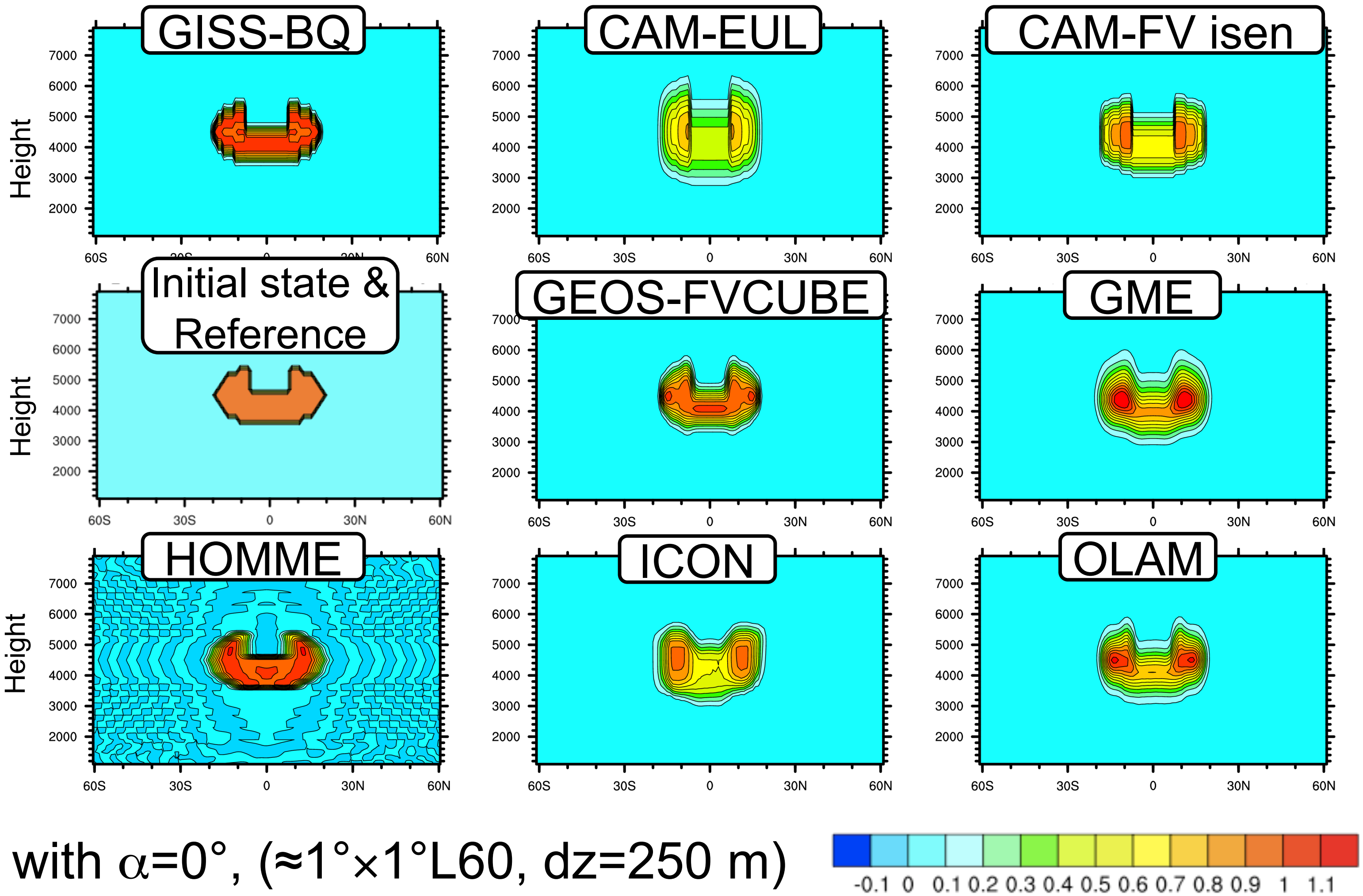
Convergence & Uncertainty

- l_2 error norms: Dry baroclinic wave simulations converge within the uncertainty estimate for the resolutions T85 (EUL & SLD), around 1º (FV), GME (55km / ni=128)



3D Tracer Transport with Prescribed Winds

Results from 8 dynamical cores during the 2008 NCAR Colloquium



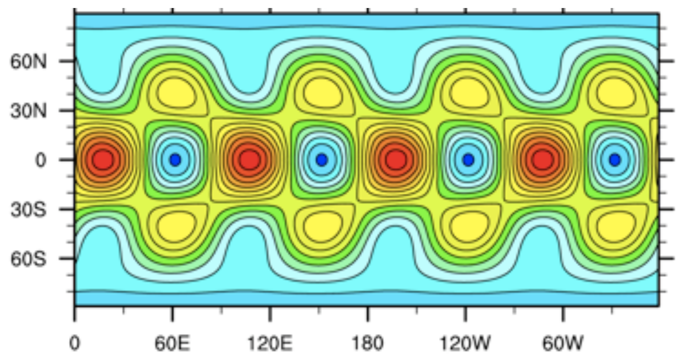
Test case description in Jablonowski et al. (2008), similar to DCMIP 11

with α=0°, (≈1°×1°L60, dz=250 m)

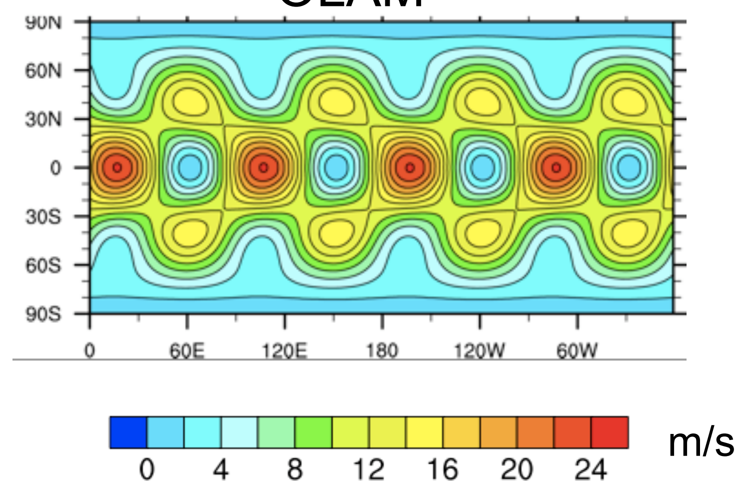
3D Rossby-Haurwitz Wave

Zonal wind at day 15 (≈1°×1°L26)

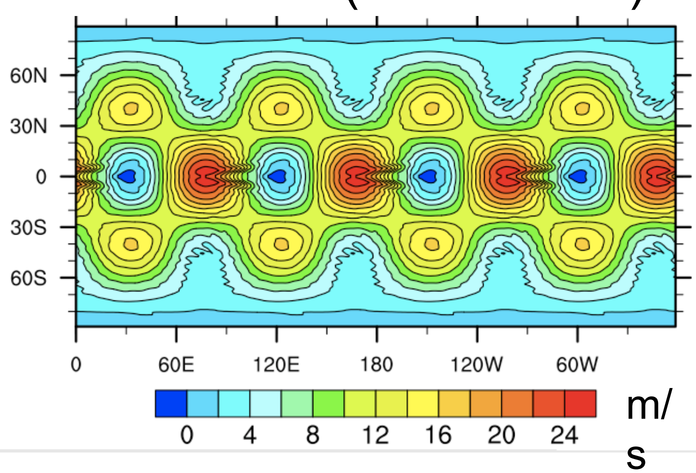
CAM-EUL



OLAM



CAM-EUL (no diffusion)



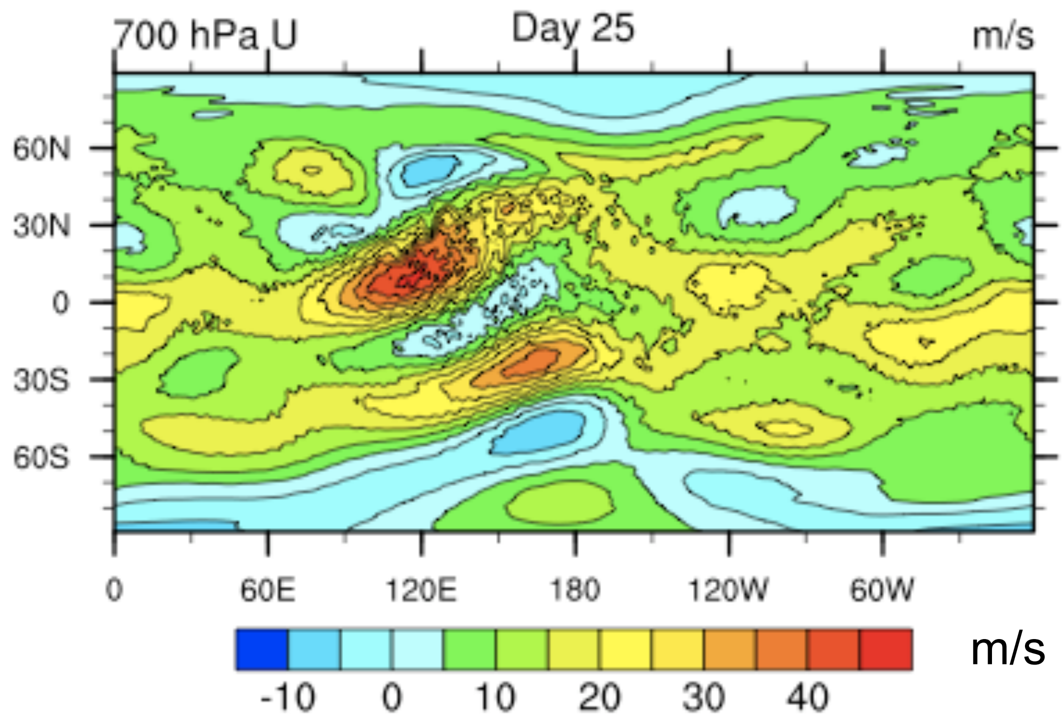
- Diffusion needed for stability in EUL
- OLAM shows reduced amplitudes

Test case description in Jablonowski et al. (2008)

Mountain-Induced Rossby Wave

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

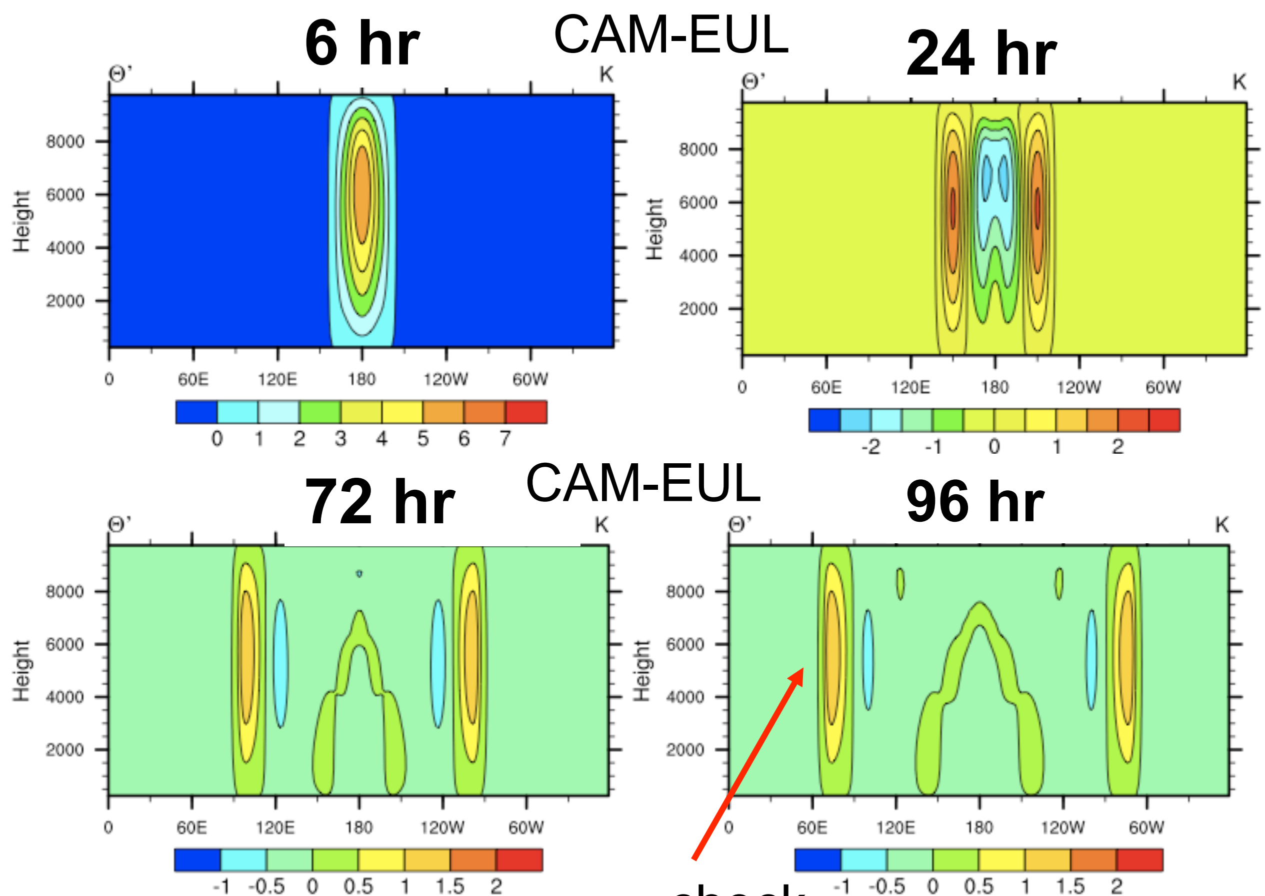
CAM-EUL



As modeler evaluators, we need to judge what we see: Numerical noise or physical nonlinear effects?

Irrotational Gravity Waves

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



check
sharpness, propagation speed

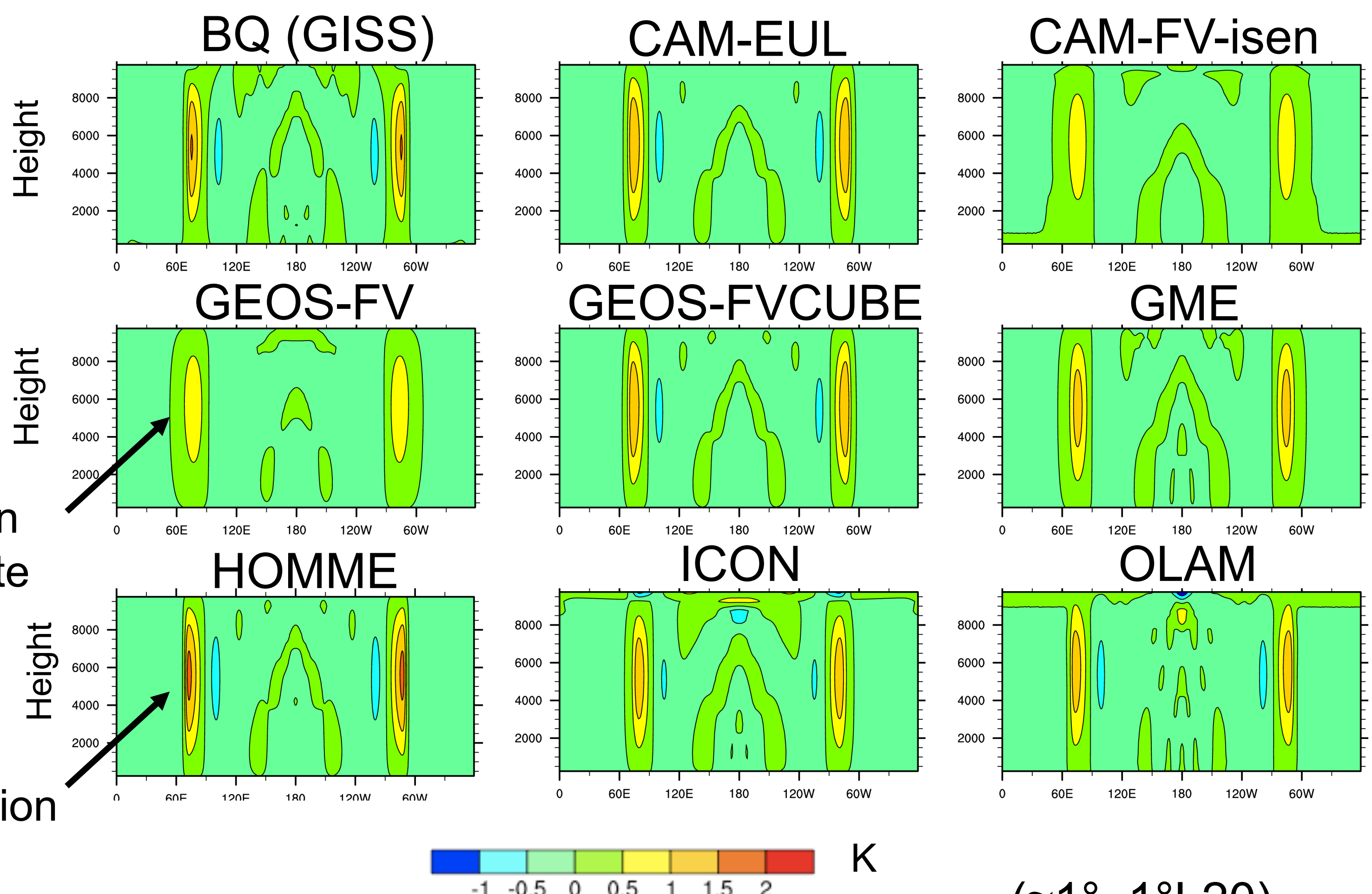
Test case description in Jablonowski et al. (2008)
similar to DCMIP 31

Irrotational Gravity Waves

Θ' cross section along the equator at day 4

This extreme diffusion was due to explicit diffusion with an inadequate coefficient.

sharp, low diffusion



(≈1°×1°L20)

Results from 9 dynamical cores during the 2008 NCAR Summer Colloquium.

The DCMIP Test Case Hierarchy

- Advection
  - Pure 3D advection without orography
  - Pure 3D advection in the presence of orography
- Dry dynamical core without rotation
  - Stability of a steady-state at rest in presence of a mountain
  - Mountain-induced gravity waves on small planets
  - Thermally induced gravity waves on small planets
- Dry dynamical core with the Earth's rotation
  - From large (hydrostatic) to small (nonhydrostatic) scales, nonlinear baroclinic waves on a shrinking planet
- Simple moisture feedbacks
  - Moist baroclinic waves with large-scale condensation
  - Moist baroclinic waves with simplified physics (simple-physics)
  - Idealized tropical cyclones with simple- and full-physics

For descriptions see http://earthsystemcog.org/projects/dcmip-2012/test_cases

The DCMIP Test Case Hierarchy

Table 1: Overview of all DCMIP test cases

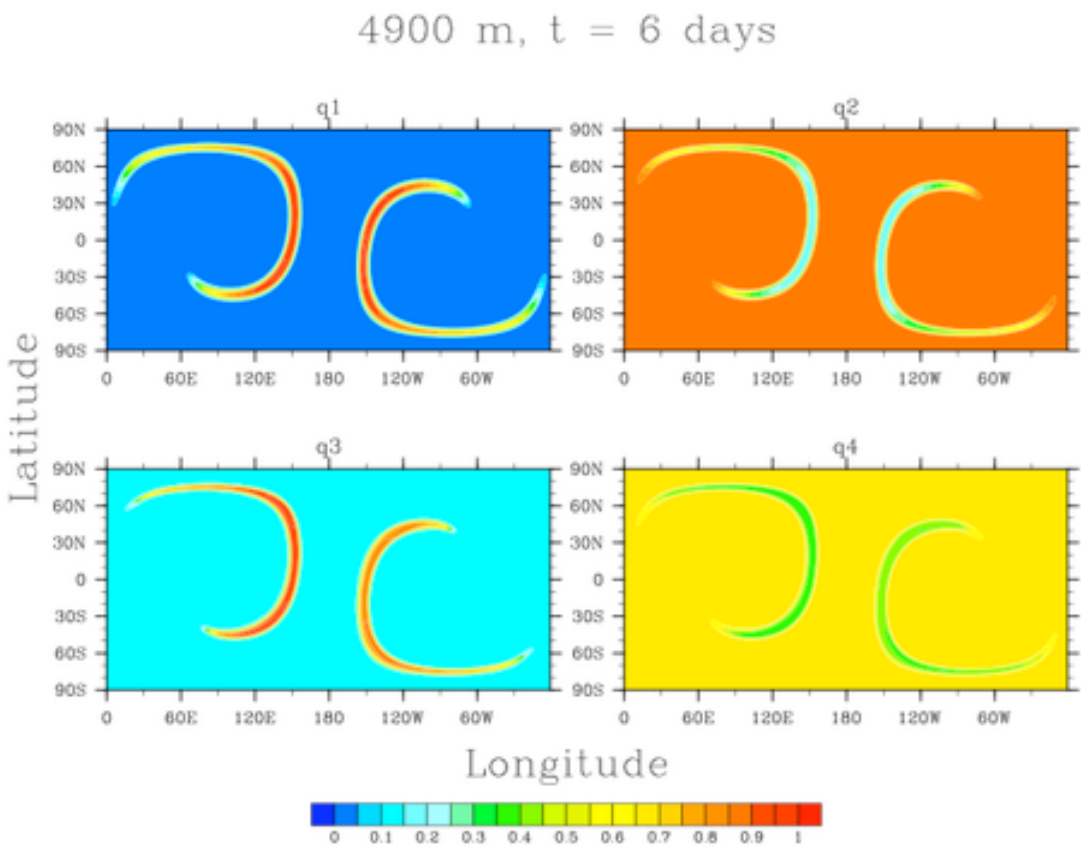
11	3D deformational flow
12	3D Hadley-like meridional circulation
13	2D transport of thin cloud-like tracers in the presence of orography
200	optional: Steady-state at rest in the presence of moderatley-steep orography
201	optional: Steady-state at rest in the presence of steep orography on a small planet (X=500)
21	Mountain waves over a Schaer-type mountain on a small planet without shear (X=500)
22	Mountain waves over a Schaer-type mountain on a small planet with shear (X=500)
31	Gravity wave on a small planet, along the equator (X=125)
410	Dry baroclinic instability with dynamic tracers EPV and Θ and X=1
411	Dry baroclinic instability with dynamic tracers EPV and Θ and X=10 (scaled small planet)
412	Dry baroclinic instability with dynamic tracers EPV and Θ and X=100 (scaled small planet)
413	Dry baroclinic instability with dynamic tracers EPV and Θ and X=1000 (scaled small planet)
42	Moist baroclinic instability (with large-scale condensation)
43	optional: Moist baroclinic instability (with simplified physics forcing)
51	Idealized tropical cyclone (with simplified physics forcing)
52	optional: Idealized tropical cyclone (with full physics forcing)

Check the DCMIP-2012 web page

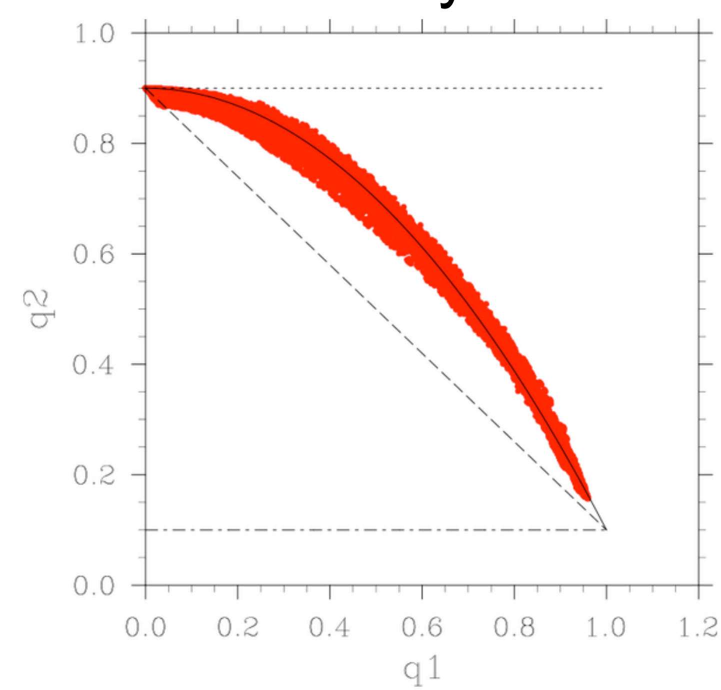
DCMIP 3D Advection Tests

Test 11: Correlated tracers in a reversing sheared flow

4 tracers at time of flow reversal



Mixing diagnostics at day 6

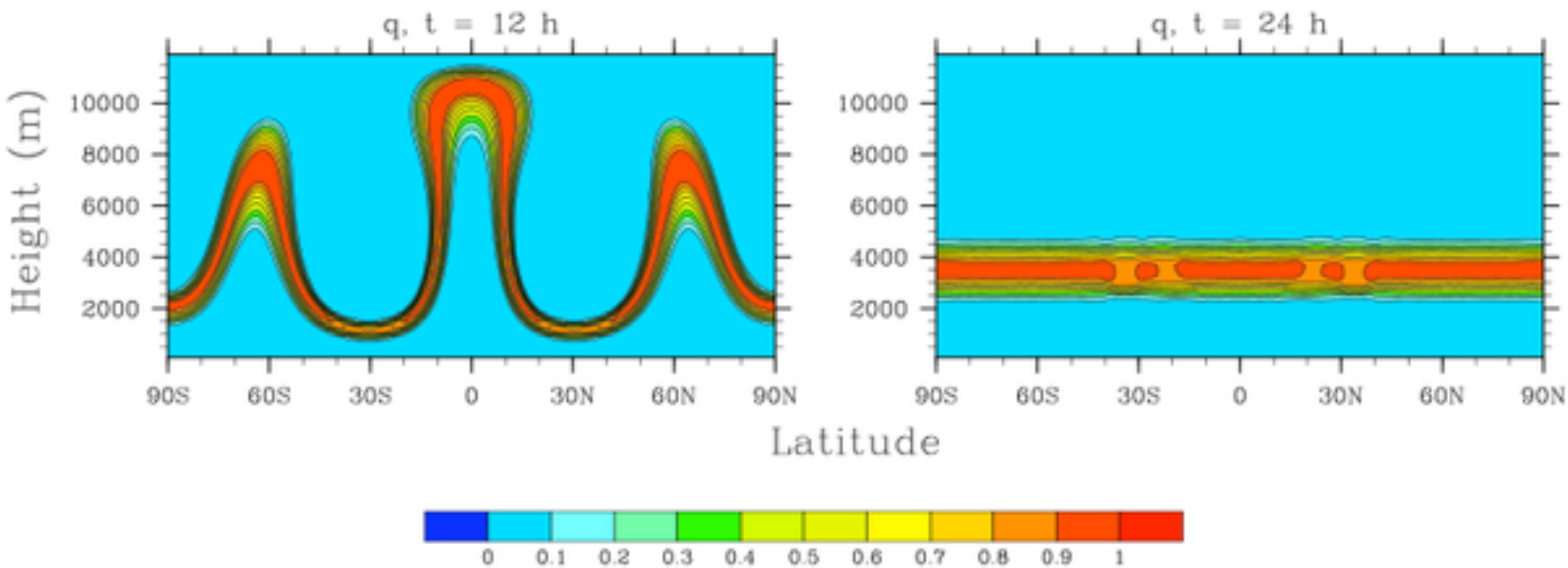


Initial state is the reference solution

DCMIP 3D Advection Tests

Test 12: Tracers in a Hadley-cell like meridional circulation

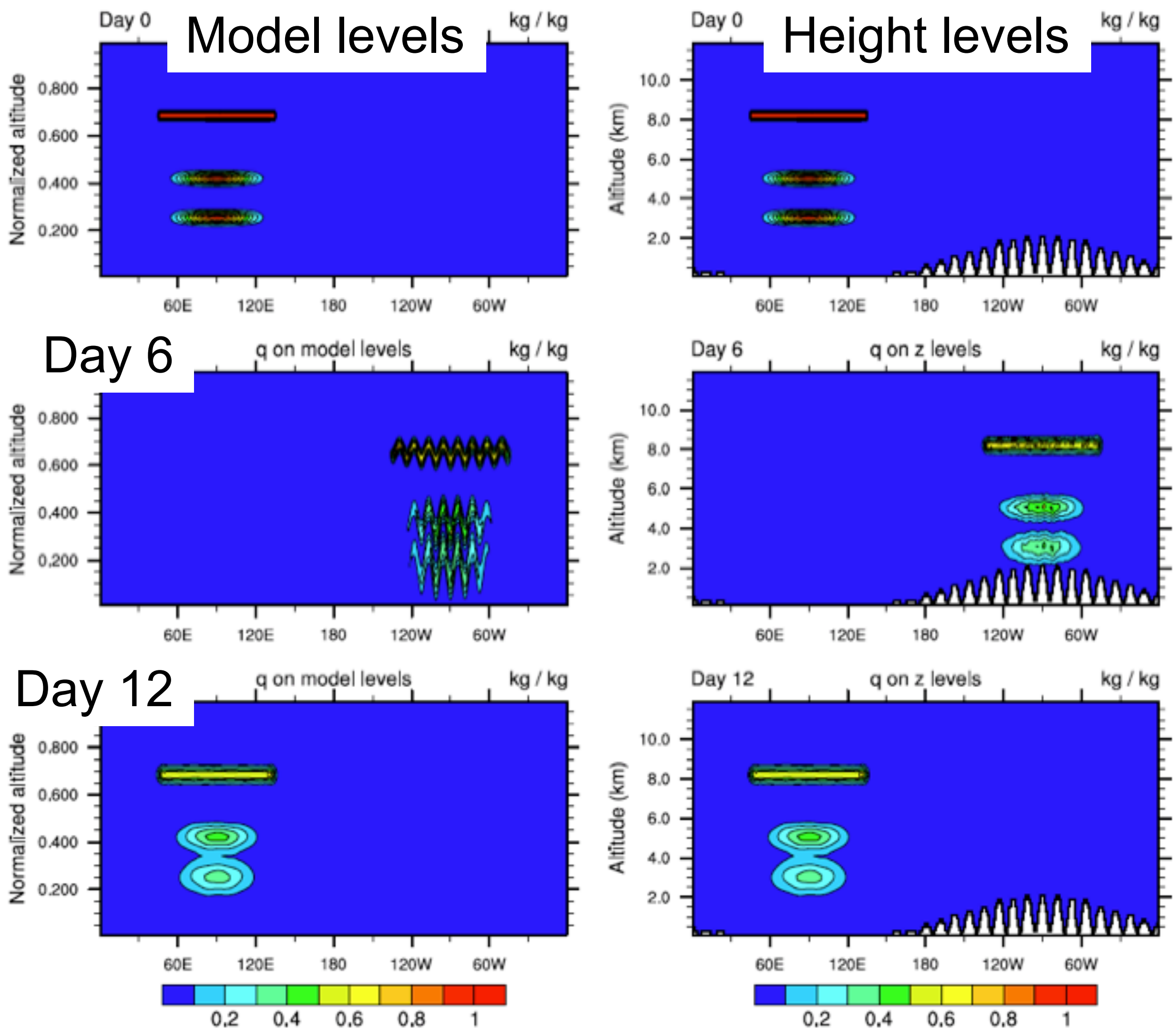
Tracer q is stretched thin, but is still resolved on a 1°x1° grid, comes back to its original position after 1 day



Initial state is the reference solution: check error norms

DCMIP 3D Advection Tests

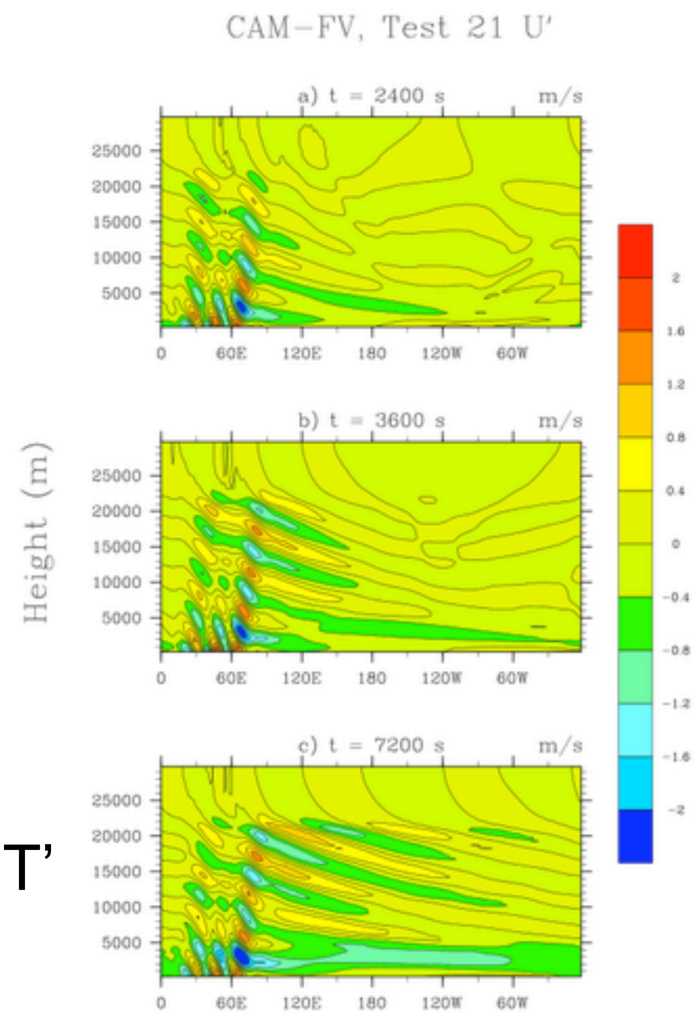
Test 13: Horizontal advection of thin cloud-like tracers (at a 30° angle to the equator) in the presence of orography



Model: MCORE

DCMIP: Flow over Topography and Gravity Waves

Test 21 on a reduced-size Earth with a circumference at the equator of 80 km distinguishes between hydrostatic and nonhydrostatic responses



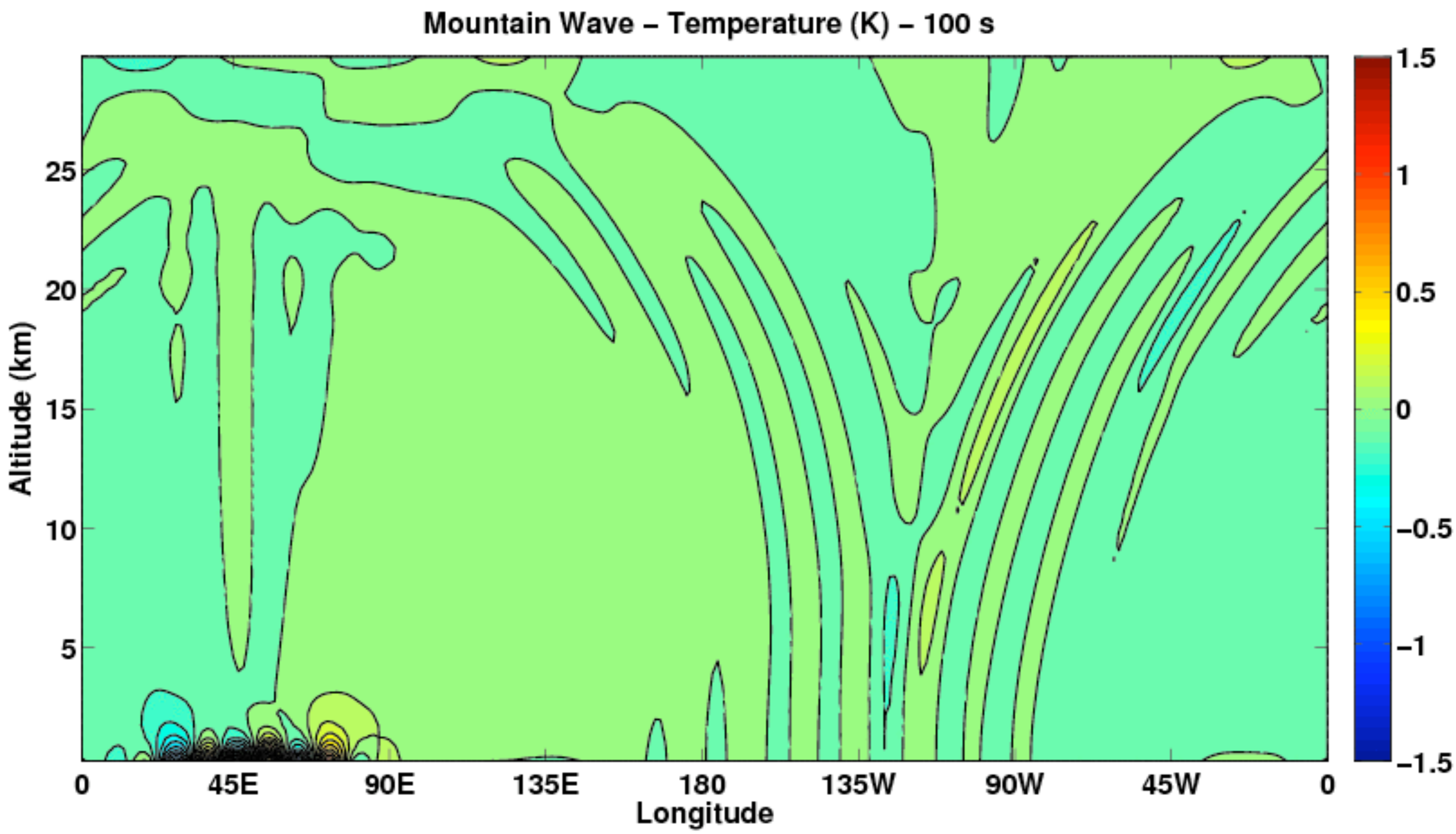
Test 21 without vertical wind shear: **Hydrostatic response** in the zonal wind perturbation u' in CAM-FV at the scaled times 2400 s, 3600 s, 7200 s, the temperature perturbation T' looks similar

The nonhydrostatic solution is very different.

DCMIP: Flow over Topography and Gravity Waves

Test 22 on a reduced-size Earth:

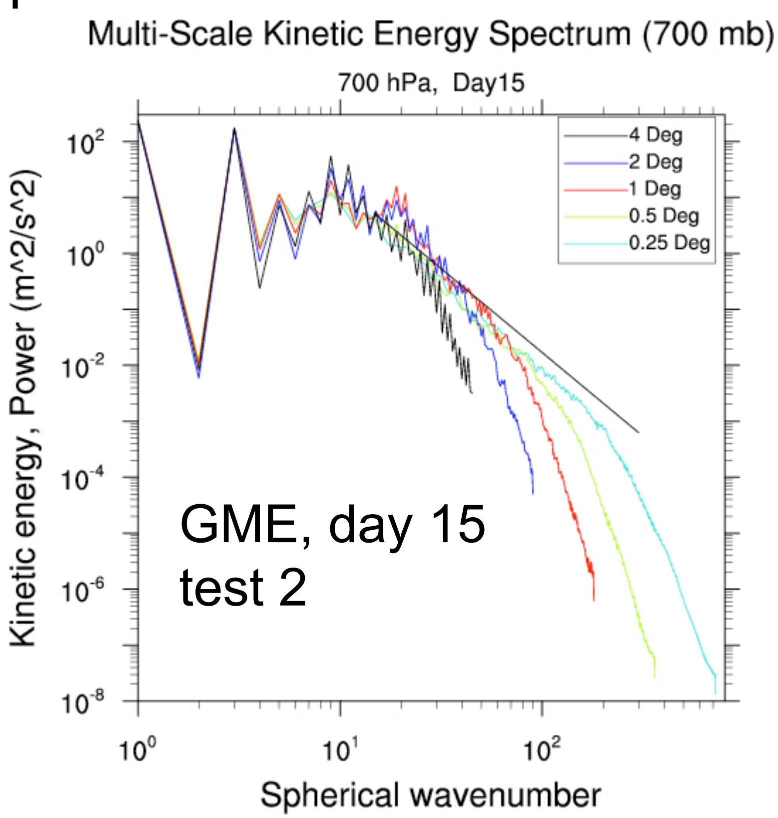
with vertical wind shear: Example of nonhydrostatic response in the temperature perturbation field T' (model MCORE, animation)



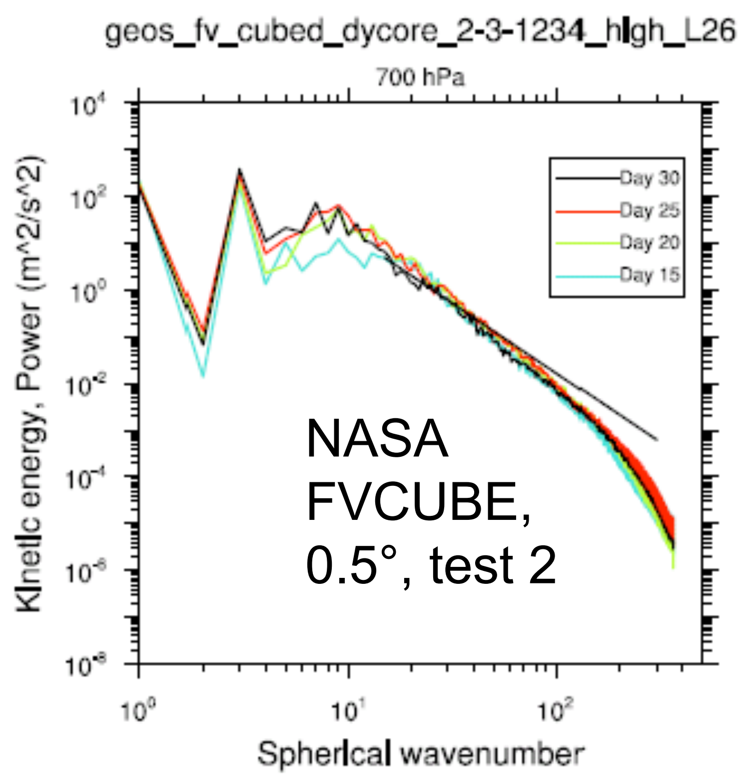
DCMIP Test 41X: KE spectra

Test 41X: Baroclinic wave KE spectra as diagnostic tools, Diffusion characteristics are expressed by steepness of tail

Optional: Variation with resolution

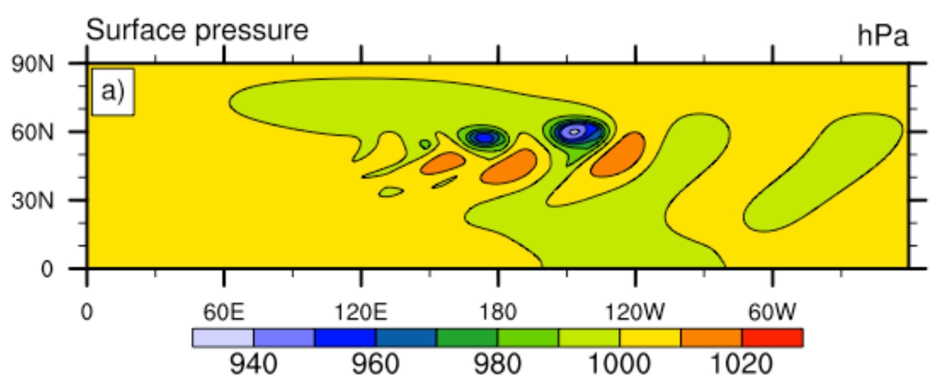


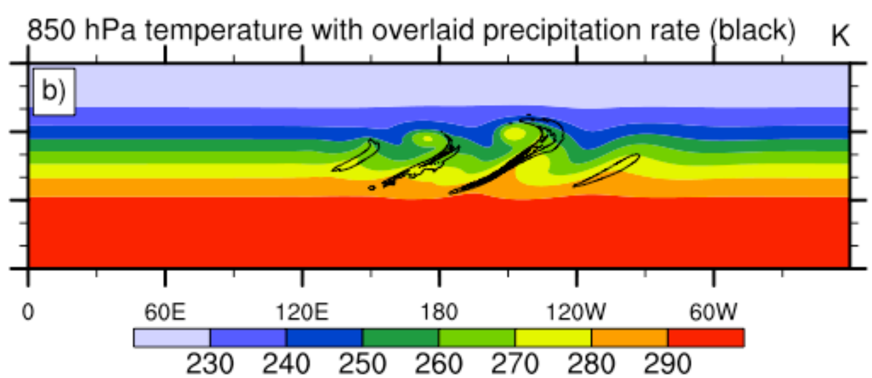
Variation with time



DCMIP Test 42: Moisture and Large-Scale Condensation

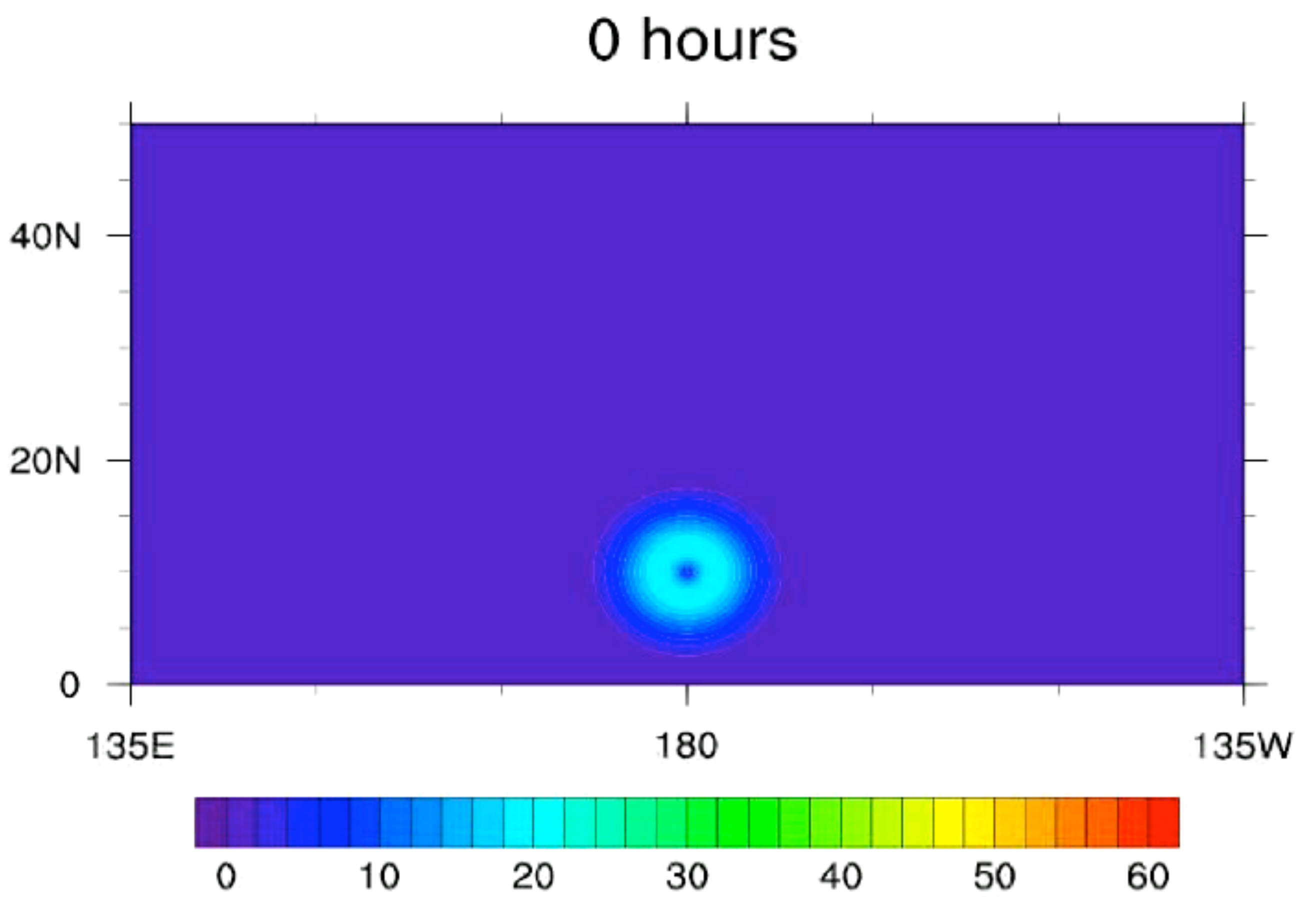
Test 42:
Large-scale condensation in the moist baroclinic wave leads to an intensification of the baroclinic wave in CAM-FV (1°x1° L30), here at day 9





DCMIP Test 51: Tropical Cyclone with Simple-Physics

Idealized TC: Aqua-planet Simulations with Simple-Physics (here including a Betts-Miller-type convective adjustment)



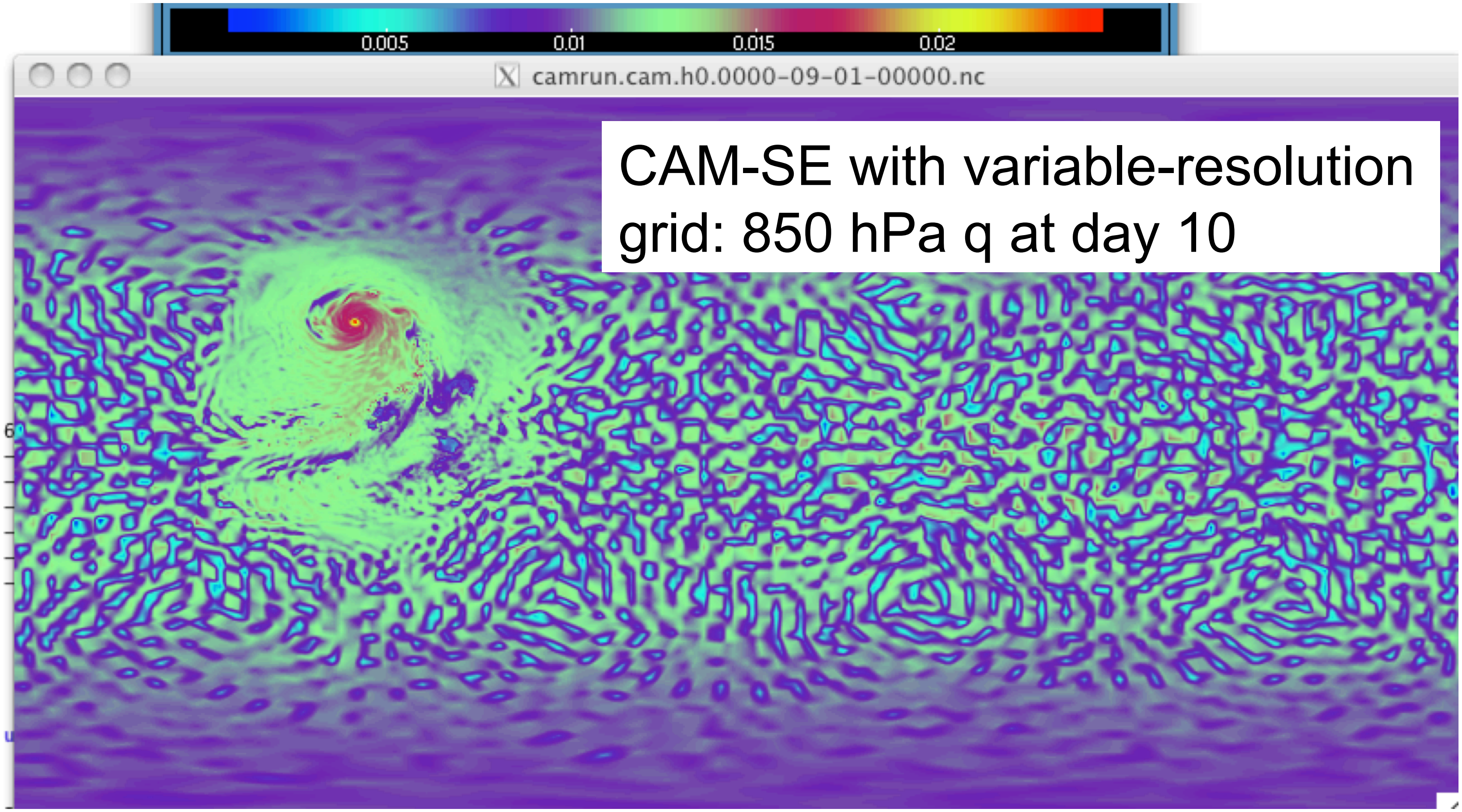
Wind speed at 100 m (animation)

CAM 3.1 FV at 0.5x0.5 L26

≈ 55 km grid spacing

DCMIP Test 52: Tropical Cyclone with Full Physics

Test 52: Check grid imprinting signatures in the moisture field q



Some Final Thoughts

- Component testing like the test of the dynamical core is a crucial stepping stone in the GCM evaluation hierarchy.
- We (the dynamical core community) just started testing our dynamical cores in a systematic way, assessing **model ensembles and uncertainties** will become standard.
- Let's close the gap between dry dynamical cores and full-physics simulations in the evaluation hierarchy by assessing **simple moisture feedbacks**.
- We hope that DCMIP contributes valuable ideas towards a **standardized test case suite** for dry and moist dycores. Feedback is appreciated.

References

- Reed, K. A., and C. Jablonowski (2011a), An analytic vortex initialization technique for idealized tropical cyclone studies in AGCMs, Mon. Wea. Rev., 139, 689–710, doi:10.1175/2010MWR3488.1.
- Reed, K. A., and C. Jablonowski (2011b), Impact of physical parameterizations on idealized tropical cyclones in the Community Atmosphere Model, Geophys. Res. Lett., 38, L04 805, doi: 10.1029/2010GL046297.
- Reed, K. A., and C. Jablonowski (2011c), Assessing the Uncertainty of Tropical Cyclone Simulations in NCAR's Community Atmosphere Model, J. Adv. Model. Earth Syst., 3, M08002, 16, doi:10.1029/2011MS000076.
- Reed, K. A., and C. Jablonowski (2012), Idealized tropical cyclone simulations of intermediate complexity: a test case for AGCMs, , J. Adv. Model. Earth Syst., Vol. 4, M04001, doi:10.1029/2011MS000099
- Reed, K. A., C. Jablonowski and M. A. Taylor (2012), Tropical cyclones in the spectral element configuration of the Community Atmosphere Model, Atmos. Sci. Lett., in press.

References

- Jablonowski, C., P. H. Lauritzen, R. D. Nair and M. Taylor (2008),Idealized test cases for the dynamical cores of Atmospheric General Circulation Models: A proposal for the NCAR ASP 2008 summer colloquium, Technical Report May/29/2008 (download at http://esse.engin.umich.edu/groups/admg/publications.php)
- Jablonowski, C., and D. L. Williamson (2006), A Baroclinic Instability Test Case for Atmospheric Model Dynamical Cores, Quart. J. Roy. Met. Soc., Vol. 132, 2943-2975
- Jablonowski, C., and D. L. Williamson (2006), A Baroclinic Wave Test Case for Dynamical Cores of General Circulation Models: Model Intercomparisons, NCAR Technical Note NCAR/TN-469+STR, Boulder, CO, 89 pp.
- St-Cyr, A., C. Jablonowski, J. M. Dennis, H. M. Tufo and S. J. Thomas (2008), A Comparison of Two Shallow Water Models with Non-Conforming Adaptive Grids, Mon. Wea. Rev., Vol. 136, 1898-1922
- DCMIP shared workspace and DCMIP test case document: http://earthsystemcog.org/projects/dcmip-2012/

References

- Williamson, D. L., et al. (2012), The APE Atlas, NCAR Technical Note NCAR/TN-484+STR, Boulder, CO, 146 pp.
- Mishra, S. K., M. A. Taylor, R. D. Nair, P. H. Lauritzen, H. M Tufo and J. J. Tribbia (2011), Evaluation of the HOMME Dynamical Core in the Aquaplanet Configuration of NCAR CAM4: Rainfall, Journal of Climate, Vol. 24, 4037-4055
- Galewsky, J., R. K. Scott, L. M. Polvani (2004), An initial value problem for testing numerical models of the global shallow-water equations, Tellus, Vol. 56A, 429-440