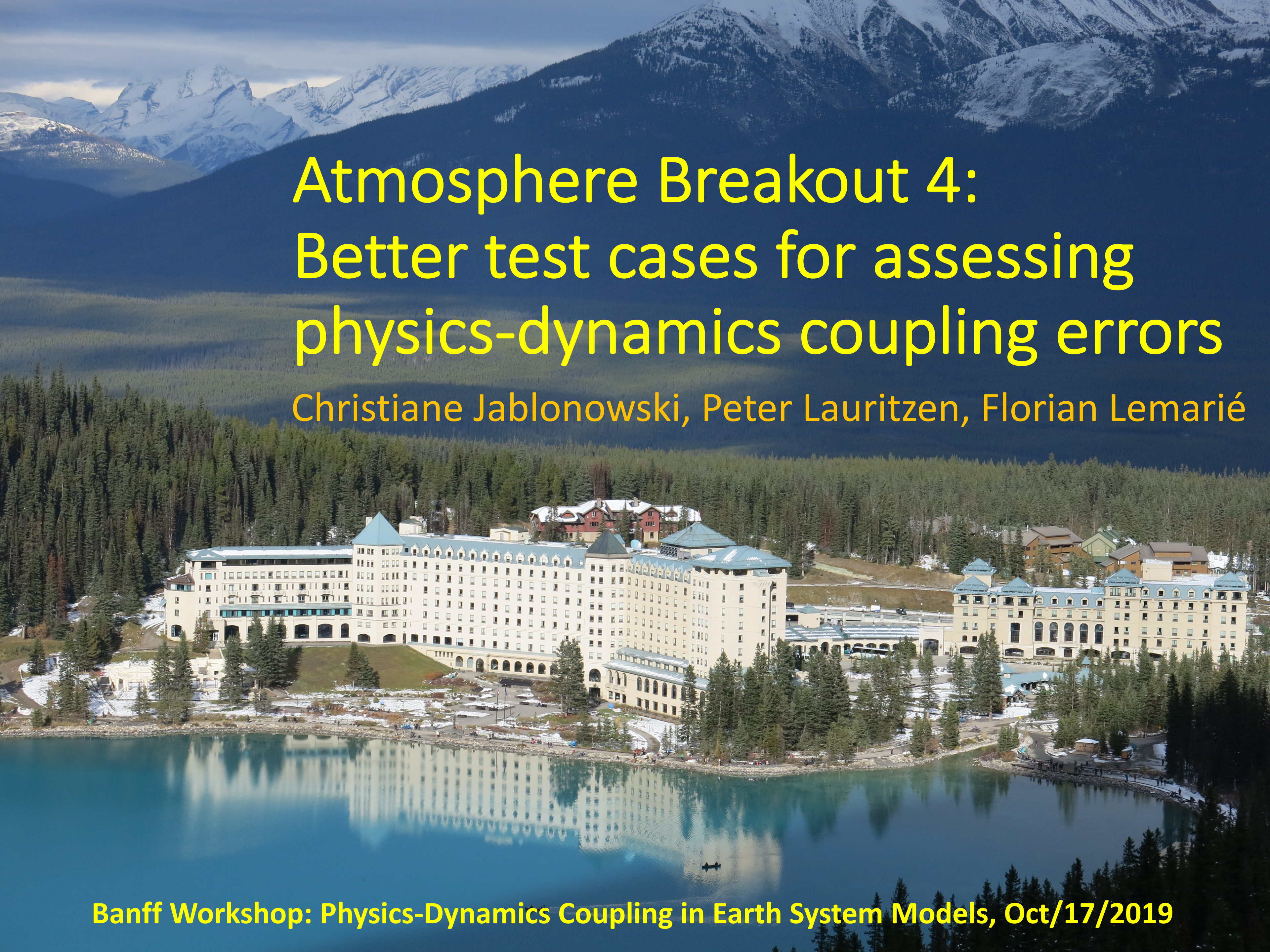
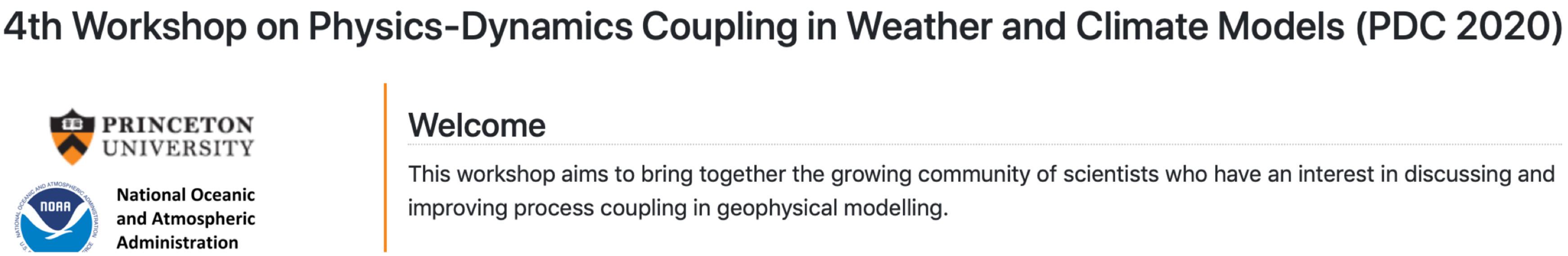


Atmosphere Breakout 4: Better test cases for assessing physics-dynamics coupling errors

Christiane Jablonowski, Peter Lauritzen, Florian Lemarié

Banff Workshop: Physics-Dynamics Coupling in Earth System Models, Oct/17/2019

Advertisement: Save the Date for PDC2020



4th Workshop on Physics-Dynamics Coupling in Weather and Climate Models (PDC 2020)

Welcome

This workshop aims to bring together the growing community of scientists who have an interest in discussing and improving process coupling in geophysical modelling.

- Dates: June/23-26/2020
- Host: NOAA’s Geophysical Fluid Dynamics Laboratory (GFDL)
- Location: Princeton, NJ, USA
- Official announcement and call for abstracts will follow in the next few weeks
- Similar format as PDC2014 (CICESE, Mexico), PDC2016 (PNNL, U.S.) and PDC2018 (ECMWF, U.K.) with 1-hour keynote talks and 30-minute contributed talks

Design Aspects of (Atmospheric) Test Cases

Dry or moist test cases

- Debugging purposes
- Model intercomparisons (e.g. DCMIP)
- Numerical properties/consistency of dynamical cores (e.g. conservation properties, diffusion characteristics, impact of fixers, properties of tracer advection schemes)

Moist test cases

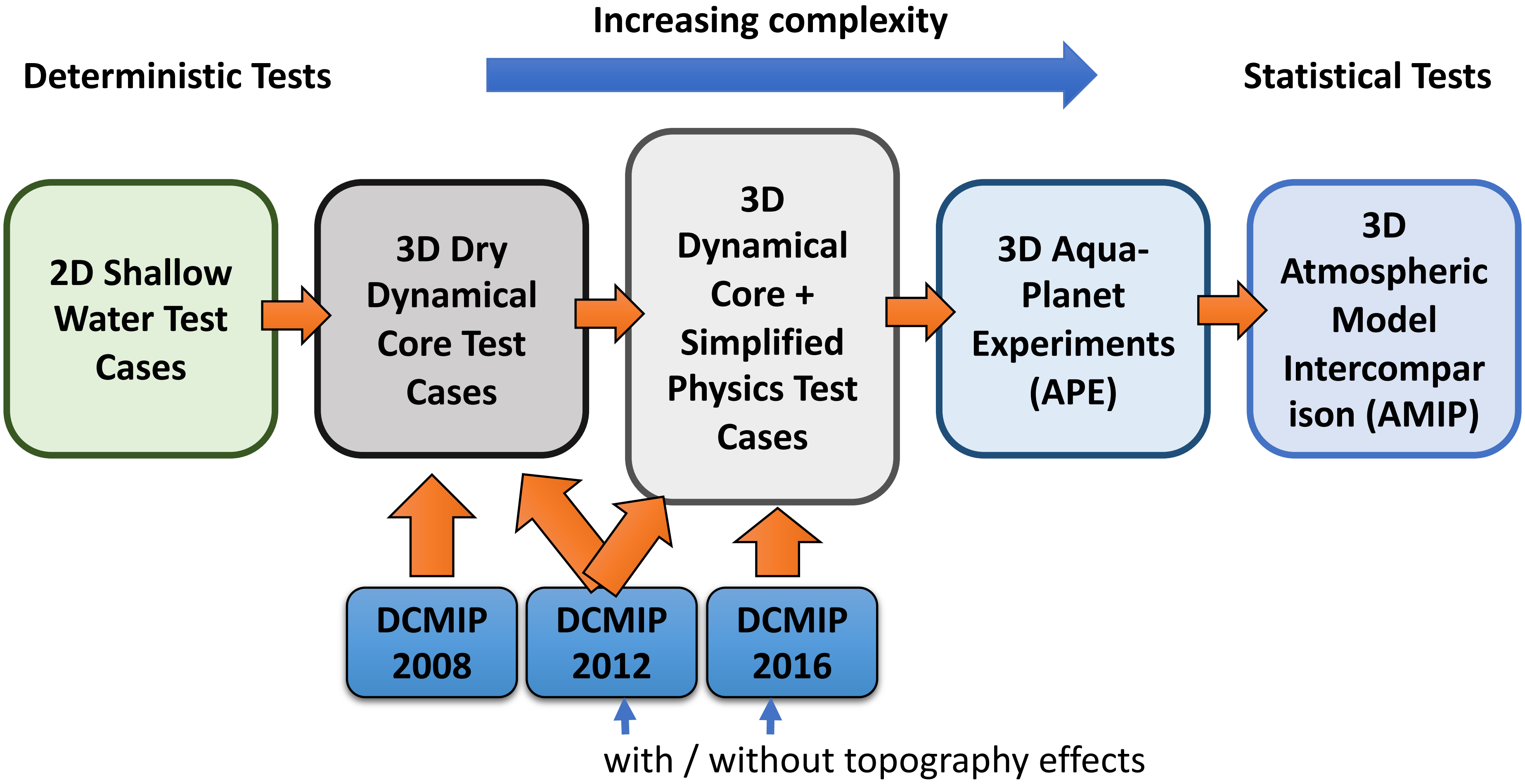
- Technical aspects of the physics-dynamics coupling strategy (e.g. coupling frequency, dribbling versus full updates, convergence)
- Better understanding of the physics-dynamics interplay (and how simplified models can mimic complex models)
- Not explored yet: Atmosphere – Ocean coupling test cases, so far only aqua-planet configurations have been used

DCMIP Resources

- The Dynamical Core Model Intercomparison Project (DCMIP)
  - 2008: https://www.earthsystemcog.org/projects/dycore-2008/
  - 2012: https://www.earthsystemcog.org/projects/dcmip-2012/
  - 2016: https://www.earthsystemcog.org/projects/dcmip-2016/
- Description of all **three DCMIP test case suites** are also available from: http://clasp-research.engin.umich.edu/groups/admg/publications.php (under 'The DCMIP Test Case Suites: 2008, 2012 and 2016' header) with examples of the DCMIP-2008, DCMIP-2012 and DCMIP-2016 intercomparisons (download pdf files (conference presentations))
- Book (also available as an E-book) published after the 2008 Workshop: Lauritzen, P. H., C. Jablonowski, M. A. Taylor and R. D. Nair (Eds.) (2011), **Numerical Techniques for Global Atmospheric Models**, Lecture Notes in Computational Science and Engineering, Springer, Vol. 80, 572 pp.

DCMIP Test Suites & Model Hierarchies

Define and establish a collection of easy-to-use idealized test cases for different flow scenarios to foster objective dynamical core intercomparisons.



Increasing complexity

Deterministic Tests

Statistical Tests

2D Shallow Water Test Cases

3D Dry Dynamical Core Test Cases

3D Dynamical Core + Simplified Physics Test Cases

3D Aqua-Planet Experiments (APE)

3D Atmospheric Model Intercomparison (AMIP)

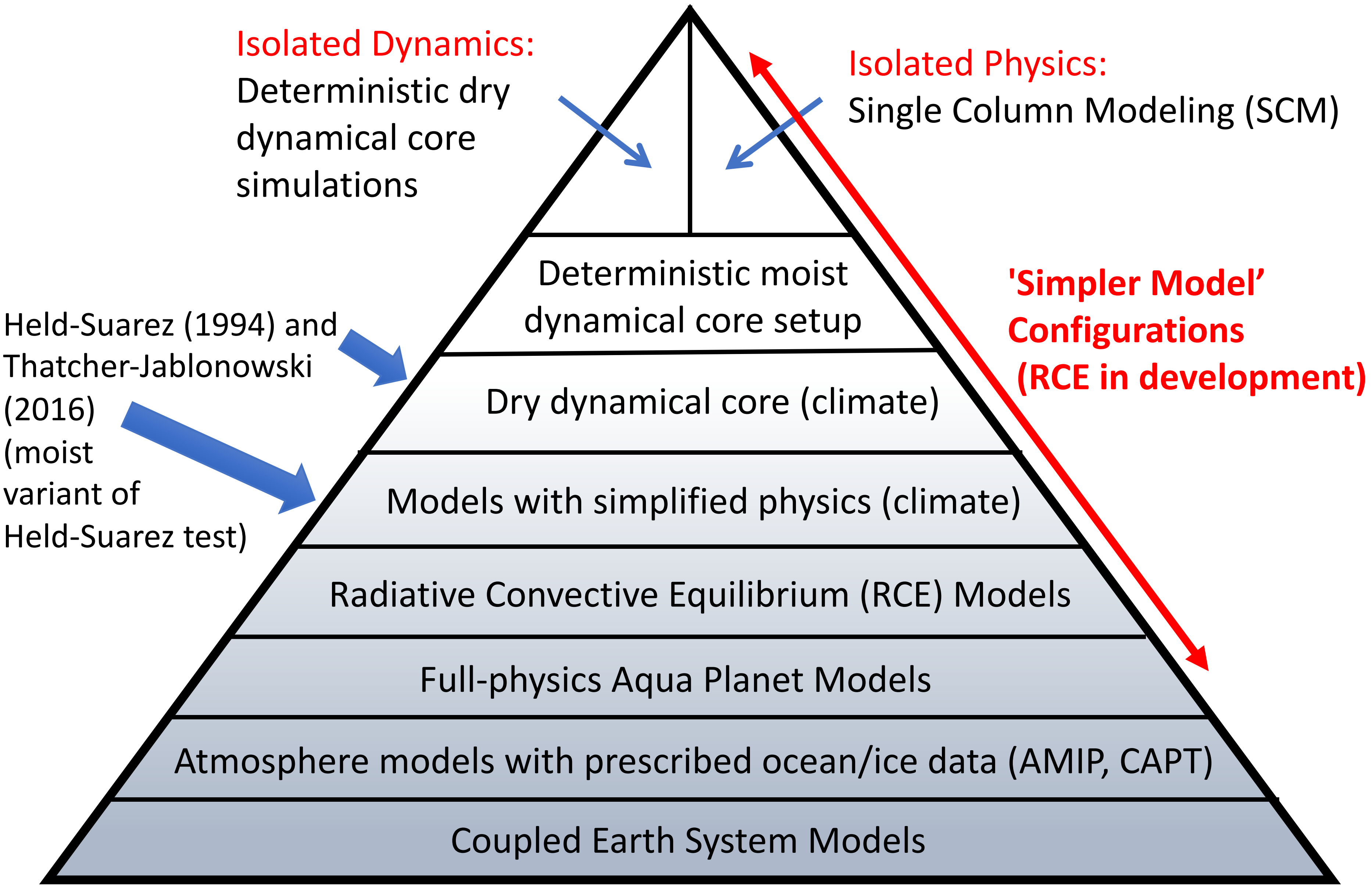
DCMIP 2008

DCMIP 2012

DCMIP 2016

with / without topography effects

Model Hierarchy in NCAR’s CESM



Isolated Dynamics:
Deterministic dry dynamical core simulations

Isolated Physics:
Single Column Modeling (SCM)

Deterministic moist dynamical core setup

Dry dynamical core (climate)

Models with simplified physics (climate)

Radiative Convective Equilibrium (RCE) Models

Full-physics Aqua Planet Models

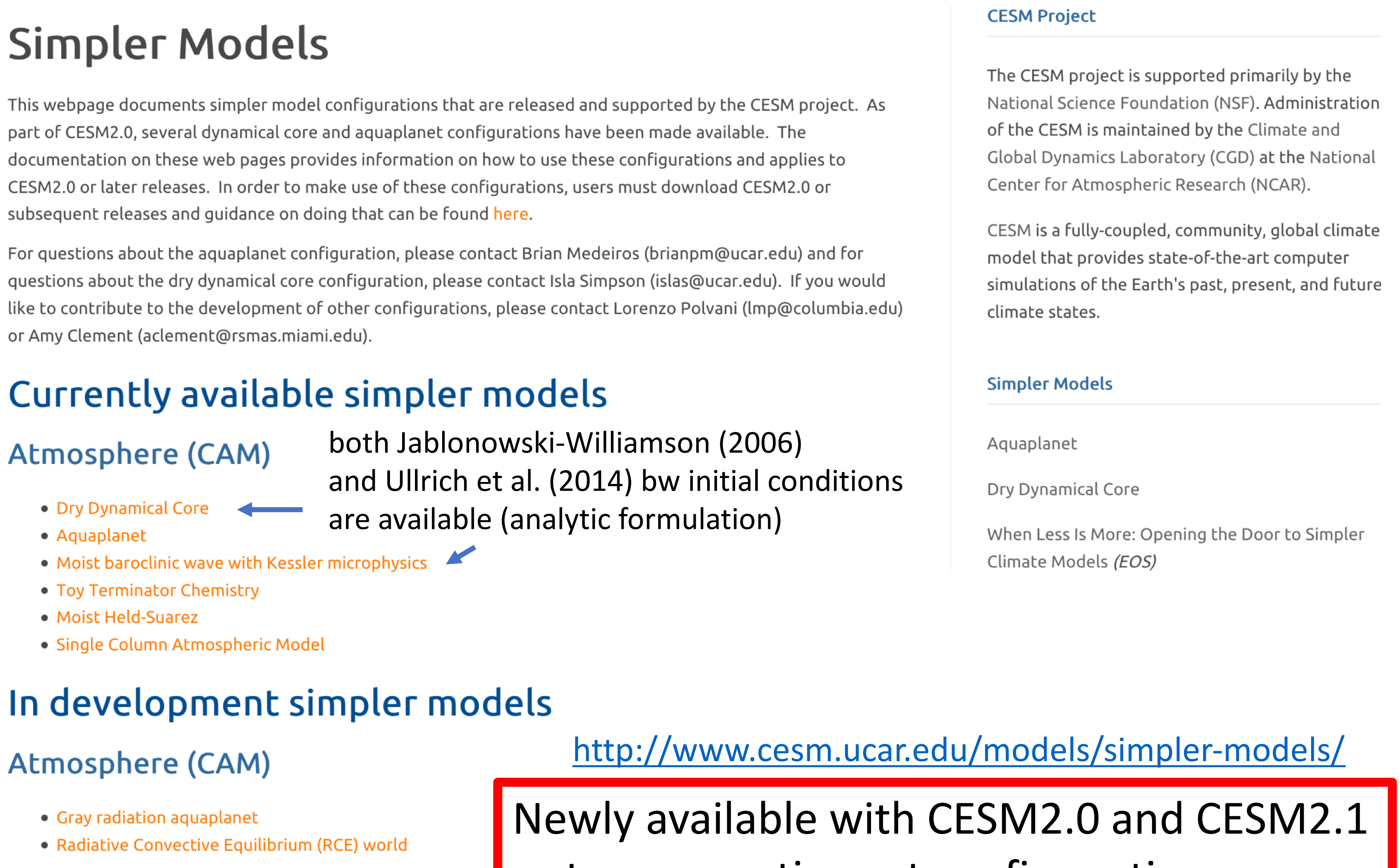
Atmosphere models with prescribed ocean/ice data (AMIP, CAPT)

Coupled Earth System Models

Held-Suarez (1994) and Thatcher-Jablonowski (2016) (moist variant of Held-Suarez test)

'Simpler Model’ Configurations (RCE in development)

CESM ‘Simpler Model’ Webpage



Simpler Models

This webpage documents simpler model configurations that are released and supported by the CESM project. As part of CESM2.0, several dynamical core and aquaplanet configurations have been made available. The documentation on these web pages provides information on how to use these configurations and applies to CESM2.0 or later releases. In order to make use of these configurations, users must download CESM2.0 or subsequent releases and guidance on doing that can be found here.

For questions about the aquaplanet configuration, please contact Brian Medeiros (brianpm@ucar.edu) and for questions about the dry dynamical core configuration, please contact Isla Simpson (islas@ucar.edu). If you would like to contribute to the development of other configurations, please contact Lorenzo Polvani (lmp@columbia.edu) or Amy Clement (aclement@rsmas.miami.edu).

Currently available simpler models

Atmosphere (CAM)

- Dry Dynamical Core
- Aquaplanet
- Moist baroclinic wave with Kessler microphysics
- Toy Terminator Chemistry
- Moist Held-Suarez
- Single Column Atmospheric Model

both Jablonowski-Williamson (2006) and Ullrich et al. (2014) bw initial conditions are available (analytic formulation)

In development simpler models

Atmosphere (CAM)

- Gray radiation aquaplanet
- Radiative Convective Equilibrium (RCE) world

CESM Project

The CESM project is supported primarily by the National Science Foundation (NSF). Administration of the CESM is maintained by the Climate and Global Dynamics Laboratory (CGD) at the National Center for Atmospheric Research (NCAR).

CESM is a fully-coupled, community, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states.

Simpler Models

Aquaplanet

Dry Dynamical Core

When Less Is More: Opening the Door to Simpler Climate Models *(EOS)*

http://www.cesm.ucar.edu/models/simpler-models/

Newly available with CESM2.0 and CESM2.1 as turn-on options at configure time

Goals and Wish-List for the DCMIP Test Suite

Test cases should

- be designed for **hydrostatic** and **non-hydrostatic** dynamical cores on the sphere,
  ideally: 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 as easy as possible, but as complex as necessary
- be cheap and 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
- deal with (simple) moisture: shed light on physics-dynamics coupling
- include topographic effects (with and without moisture)

The Architecture of the DCMIP Test Suites

Tests cases with increasing degrees of complexity:

- **Pure 3D advection tests (with prescribed velocities)**
  - Advection without orography
  - Advection in the presence of orography
  - Advection of correlated tracers
- **Dry dynamical core tests 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 tests with the Earth's rotation**
  - Steady-state test case with various rotation angles
  - Mountain-induced Rossby waves (3D extension of shallow water test)
  - Rossby-Haurwitz wave with wavenumber 4 (extension of shallow water test)
  - Baroclinic waves
    - with and without underlying topography, Jablonowski-Williamson (2006), Ullrich et al. (2014)
    - with and without passive or dynamic tracers (e.g. PV or θ) or toy chemistry interactions
    - on full-size or reduced-size planets (capture nonhydrostatic scales cheaply)

The Architecture of the DCMIP Test Suites

Tests cases with increasing degree of complexity:

- **Simple moisture feedbacks**
  - Moist baroclinic waves with
    - large-scale condensation (1 water species)
    - Kessler warm rain physics (3 water species)
    - simple-physics package (rain plus surface fluxes and planetary boundary layer (PBL) mixing)
  - Idealized tropical cyclones with simple-physics package (either with large-scale condensation or Kessler physics to represent rain)
  - Super cell storm with Kessler warm rain physics on a small planet

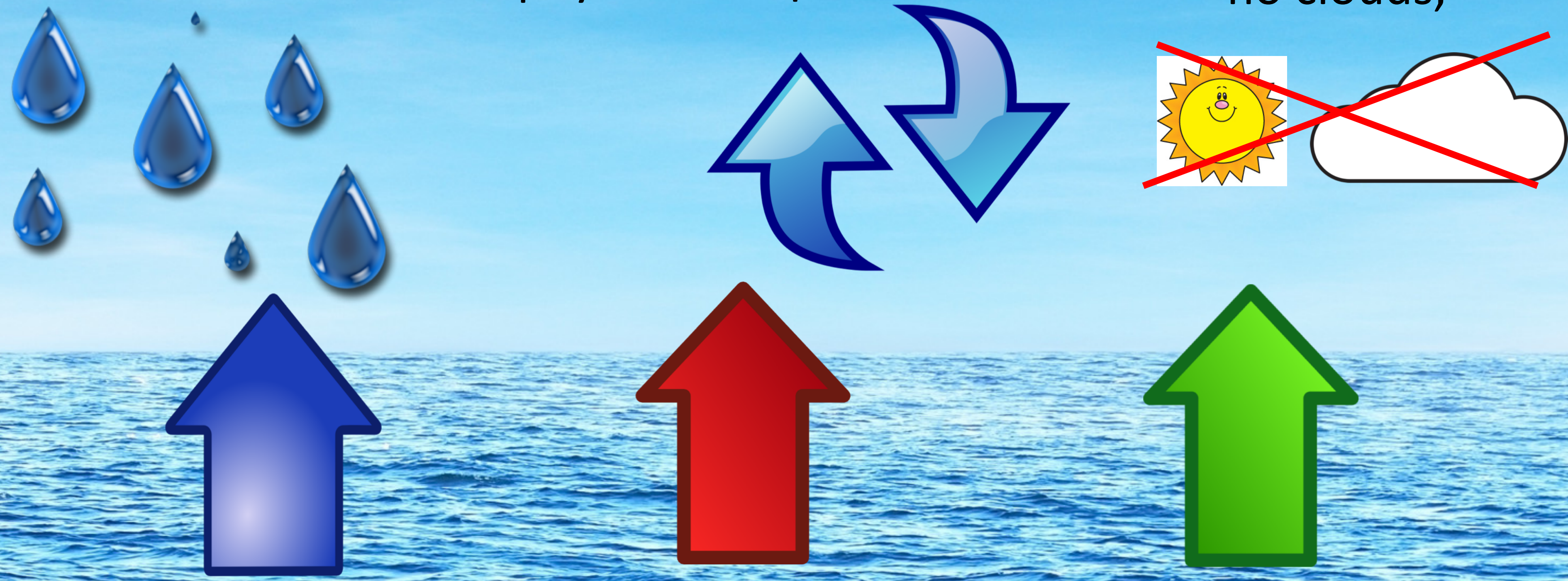
- **Other test configurations (not yet part of DCMIP)**
  - Moist baroclinic waves with full-complexity physics package (but without surface fluxes, no radiation)
  - Moist flow over topography with large-scale condensation or Kessler physics
  - ‘Moist Held-Suarez’ configuration with simple-physics (climate time scales)
    - with optional simplified Betts-Miller convection scheme
  - Dry or moist Held-Suarez with simple gravity wave drag parameterization
  - Dry or moist Held-Suarez with topography

Building bridges towards full-complexity physics: Studying physics-dynamics coupling with simplified physics processes and test cases

Full complexity

Simple

Example: Design of Simple-Physics Processes



Large-scale condensation
or Kessler warm rain physics

PBL Mixing of pot.
T, q, u, v

No radiation,
no clouds,

Surface fluxes of sensible & latent heat, and momentum

Simple-Physics (Reed and Jablonowski 2012),
or Kessler physics (e.g. see Klemp et al., 2015)

Simplest configuration: Rainfall only

Large-scale condensation with 1 water species (water vapor)

The physics tendencies are

$$\frac{\partial T}{\partial t} = \frac{L}{c_p} C$$

$$\frac{\partial q}{\partial t} = -C\,.$$

In case of RH > 100% condensation is represented by

$$C = \frac{1}{\Delta t}\left(\frac{q - q_{sat}(T,p)}{1 + \frac{L}{c_p}\frac{\mathrm{d}q_{sat}(T,p)}{\mathrm{d}T}}\right)$$

$$\frac{\mathrm{d}q_{sat}(T,p)}{\mathrm{d}T} \approx \frac{\varepsilon}{p}\frac{\mathrm{d}e_s(T)}{\mathrm{d}T} = \frac{L q_{sat}(T,p)}{R_v T^2}$$

Instantaneous rainfall,
No cloud phase

More complex rain fall scheme: Kessler

Potential temperature

$$\frac{\Delta\theta}{\Delta t} = \frac{L}{c_p\pi}\left(\frac{\Delta q_{vs}}{\Delta t} - E_r\right)$$

vapor

$$\frac{\Delta q_v}{\Delta t} = -\frac{\Delta q_{vs}}{\Delta t} + E_r$$

cloud water

$$\frac{\Delta q_c}{\Delta t} = \frac{\Delta q_{vs}}{\Delta t} - A_r - C_r$$

rain water

$$\frac{\Delta q_r}{\Delta t} = -E_r + A_r + C_r - V_r\frac{\partial q_r}{\partial z}$$

3 prognostic hydrometeors

Condensation

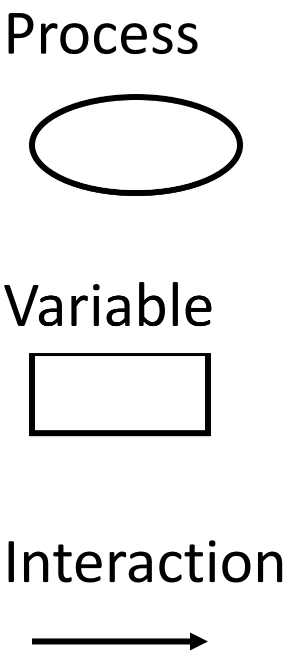
Rain water evaporation

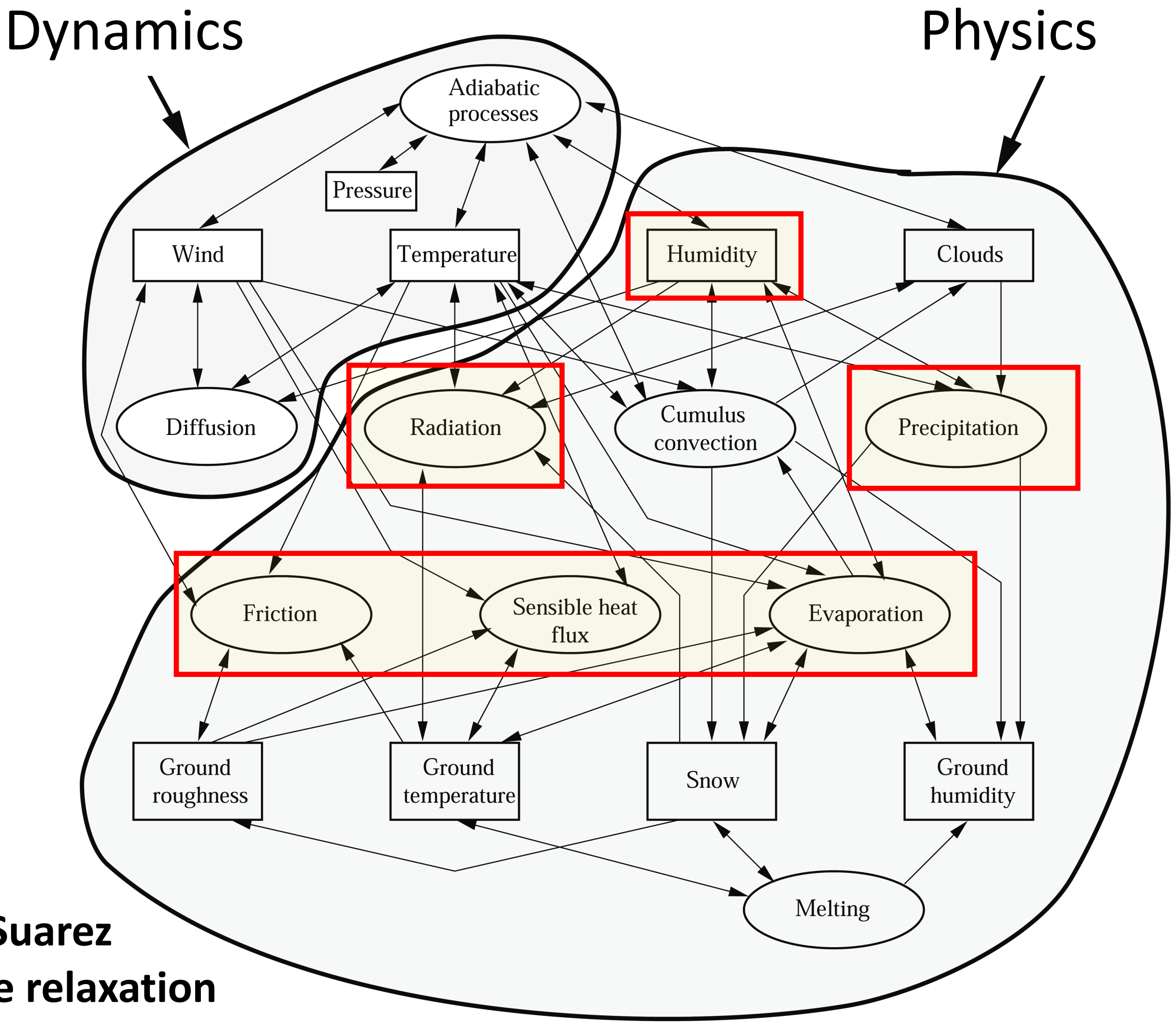
Auto-conversion

Collection rate of rain water

Precipitation

How Simple is a *Simple-Physics* Package for climate-like simulations ?

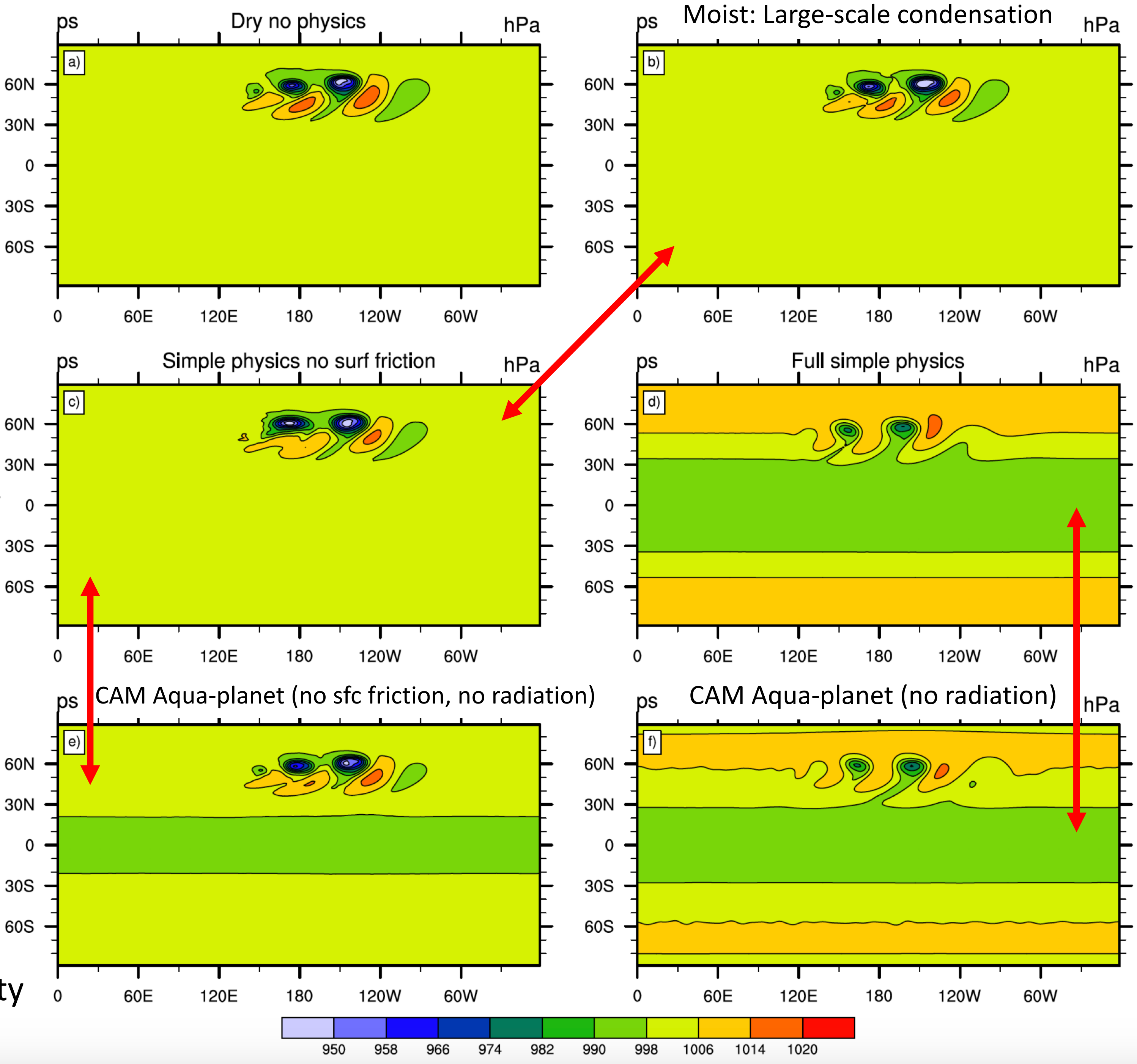




Thatcher and Jablonowski (GMD, 2016): moist Held-Suarez test case with temperature relaxation

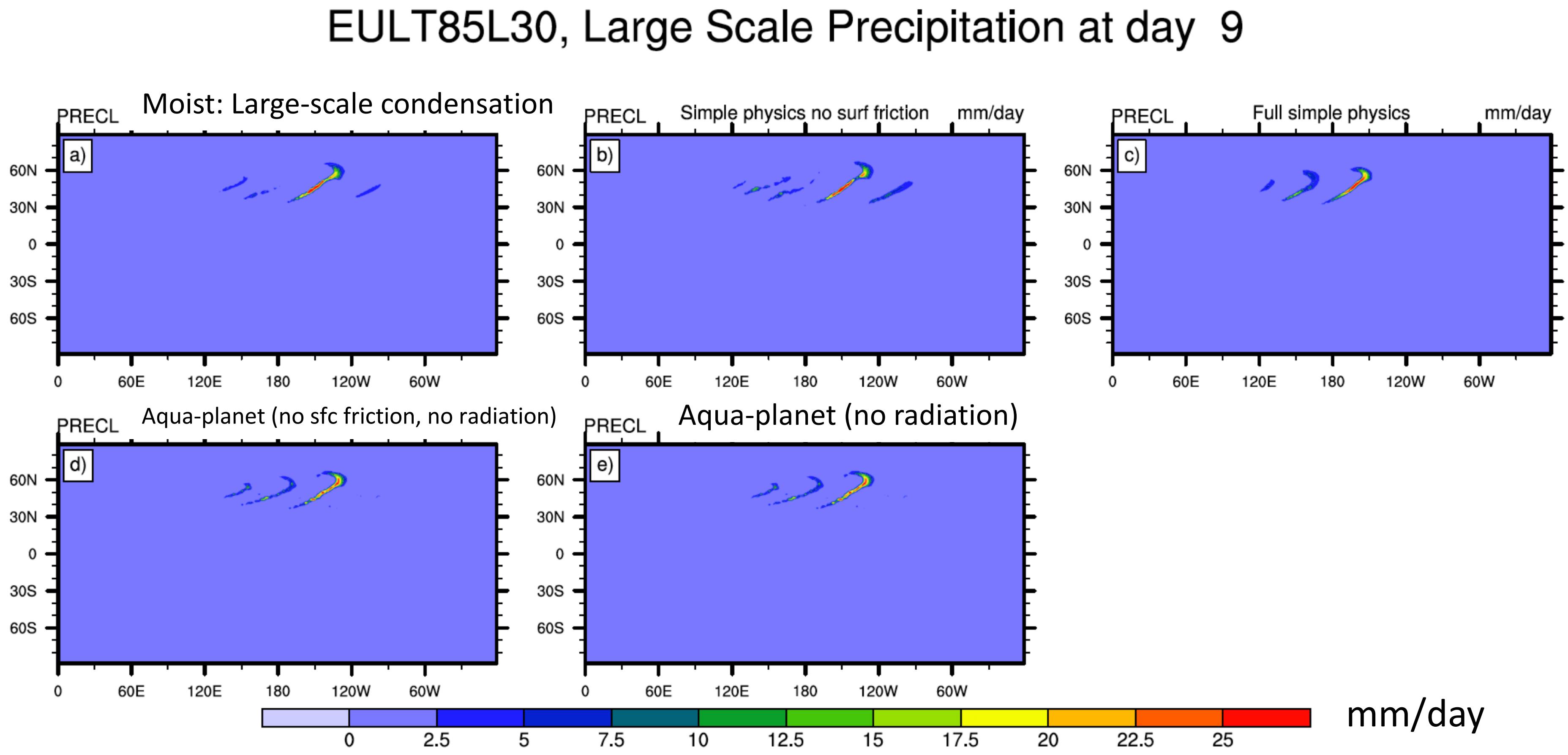
Can simple configurations mimic full-complexity simulations?

JW06 / DCMIP-2012 baroclinic wave simulation with the spectral-transform CAM-EUL T85L30 dycore at day 9



Simpler physics configurations can mimic full-complexity physics (here: CAM)

Can simple configurations mimic full-complexity simulations?



Precipitation patterns are similar: Aqua-planet uses full-complexity microphysics and convection schemes to predict rain

JW06 / DCMIP-2012 baroclinic wave with the spectral-transform CAM-EUL T85L30 dycore

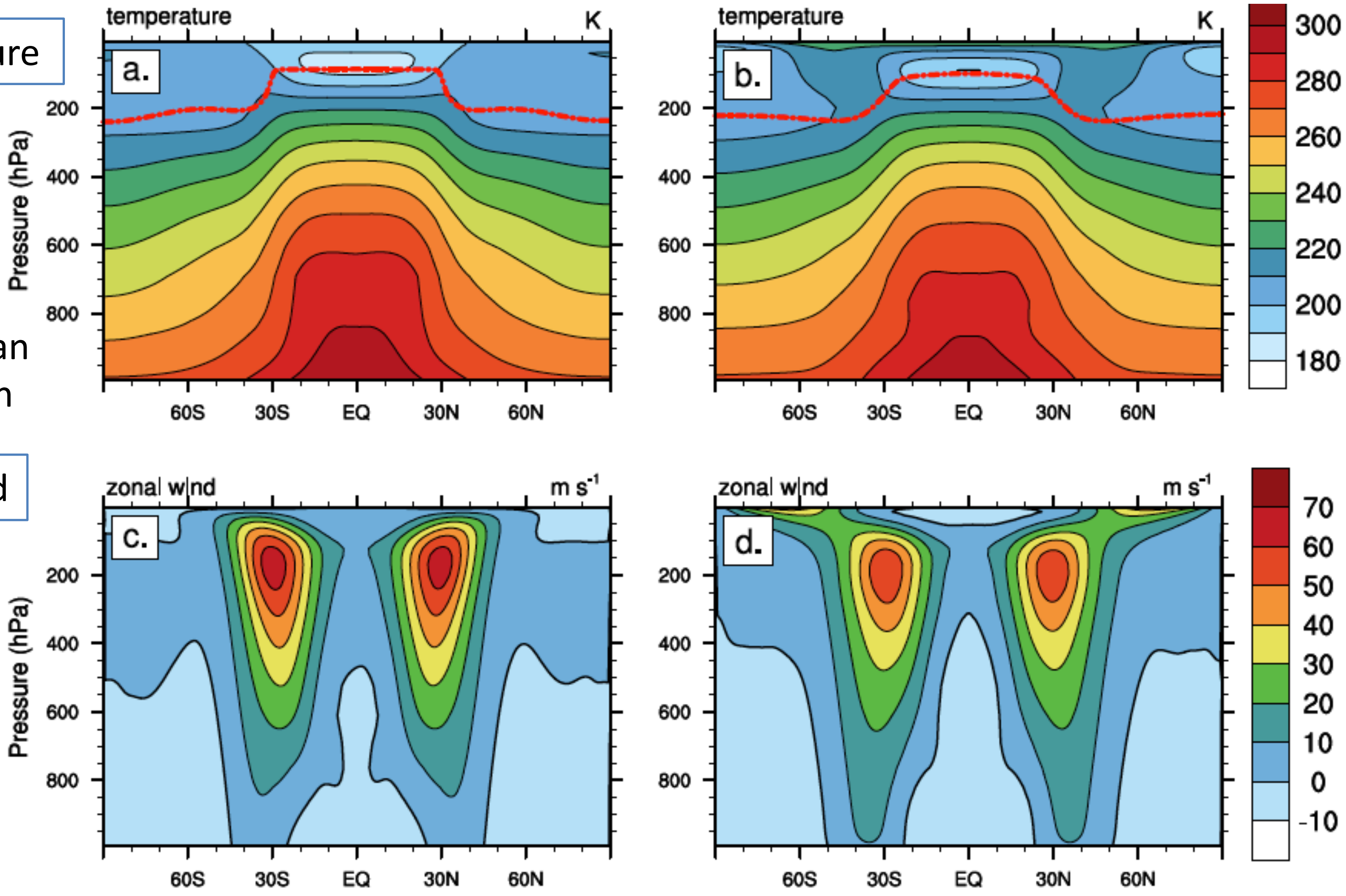
Comparison of TJ16 (‘moist Held-Suarez’) and Aqua-Planet

CAM5-SE 1° L30: Moist Held-Suarez mimics Aqua-Planet simulations

Moist Held-Suarez (TJ16)

Aqua-Planet with complex CAM5 physics

Temperature



2-year-mean zonal-mean

Zonal wind

Thatcher, D. R. and C. Jablonowski (2016), A moist aquaplanet variant of the Held–Suarez test for atmospheric model dynamical cores, Geosci. Model Dev., 9, 1263-1292, https://doi.org/10.5194/gmd-9-1263-2016

Comparison of TJ16 (‘moist Held-Suarez’) and Aqua-Planet

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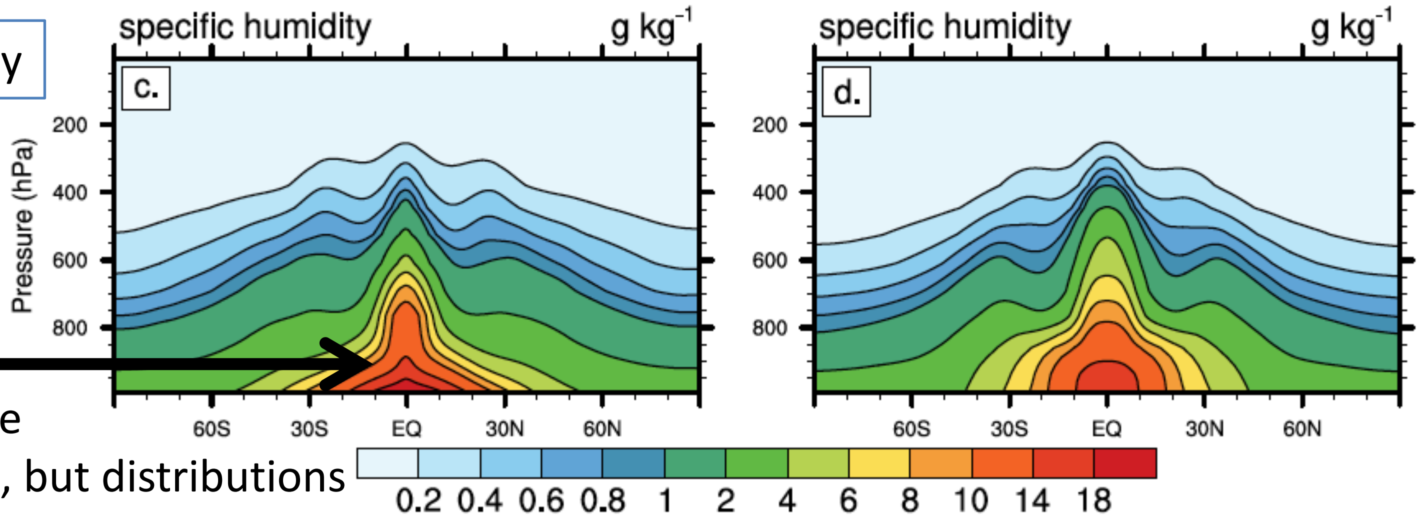
Moist Held-Suarez(TJ16)

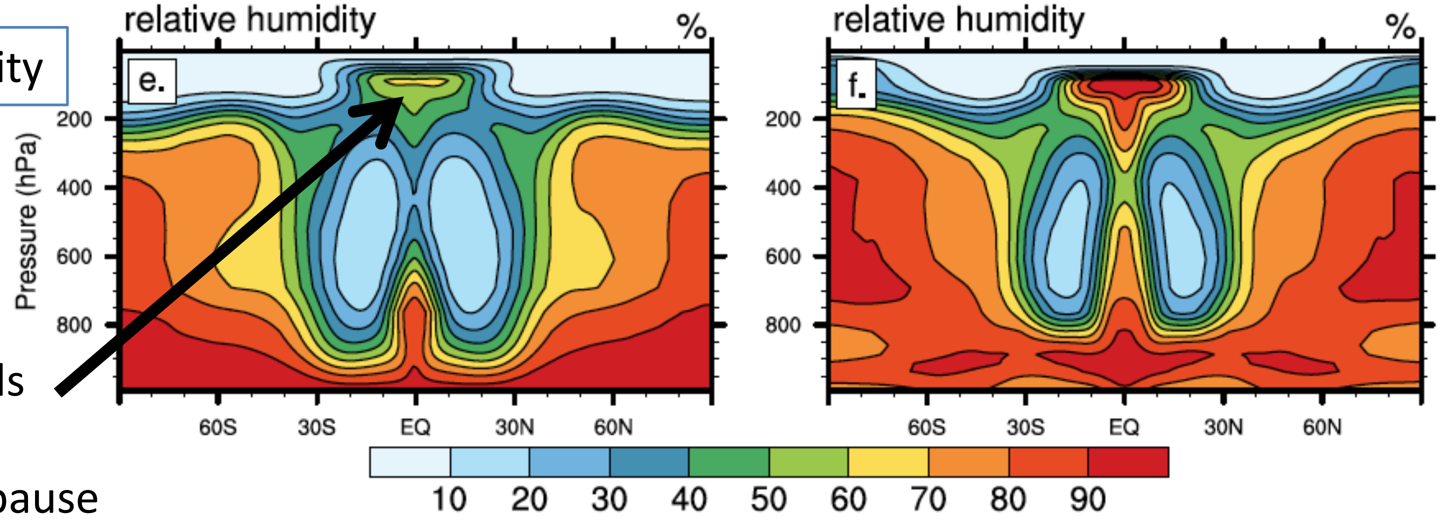
Aqua-Planet with complex CAM5 physics

Specific humidity



Less efficient upward moisture transport in PBL, but distributions are similar

Relative Humidity



Lack of deep convection leads to dryer areas near the tropopause

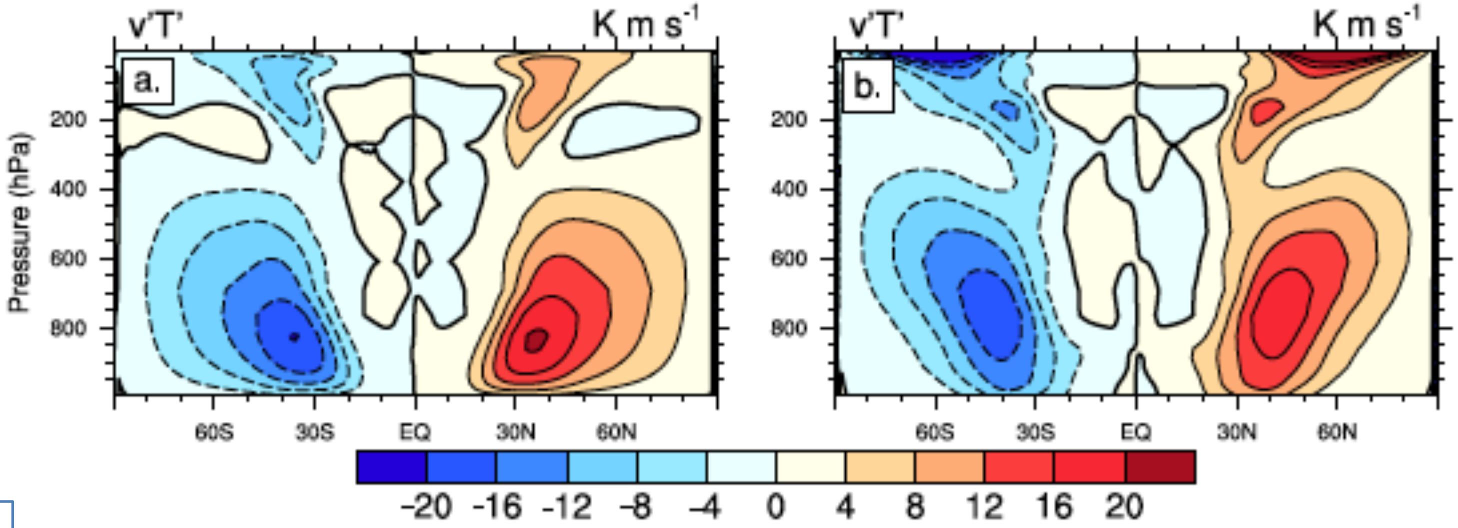
Moist Held-Suarez and Complex Aqua-Planet

CAM-SE 1° L30: Reasonable – Eddy transports are comparable

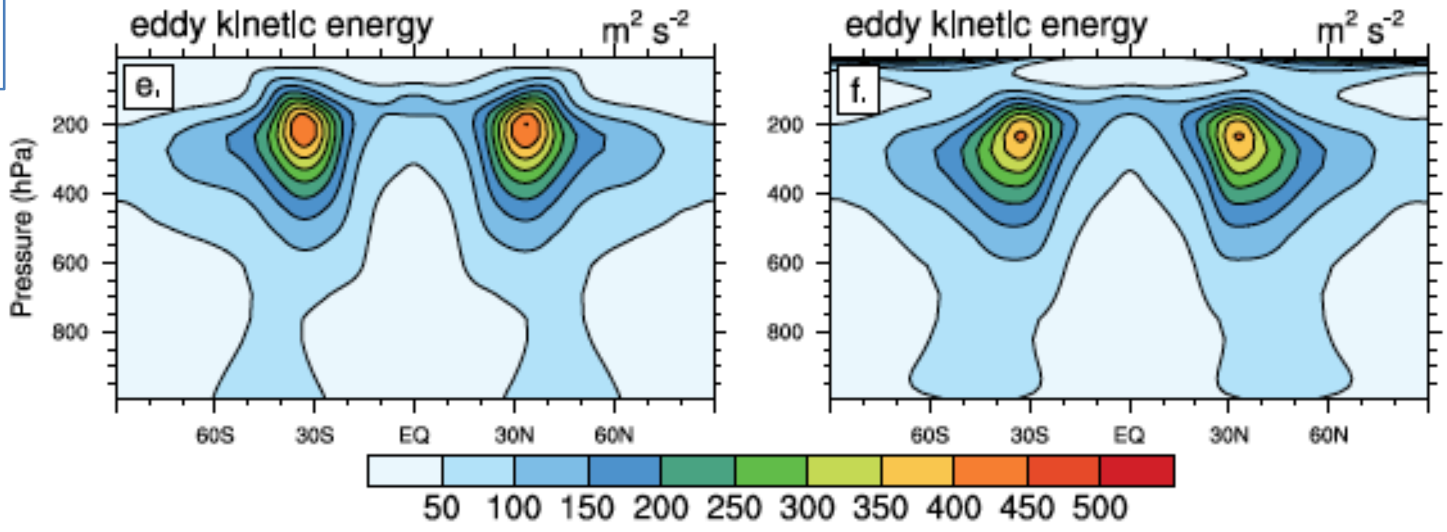
Moist Held-Suarez with simple-physics

Aqua-Planet with complex CAM5 physics

Eddy
Heat Flux

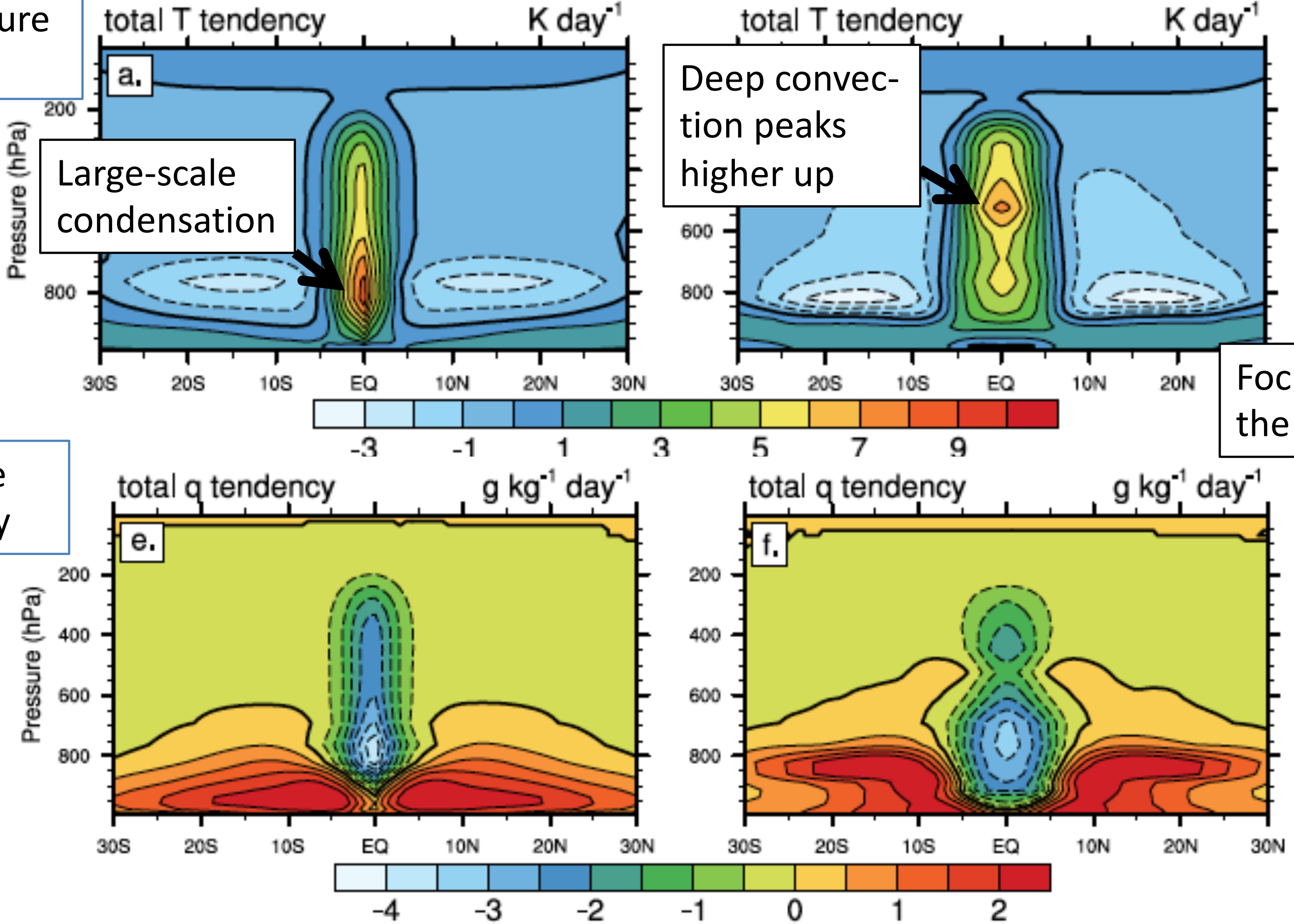


Eddy Kinetic
Energy



Moist Held-Suarez and Complex Aqua-Planet

CAM-SE 1° L30: Reasonable – Physics forcing magnitudes comparable



Moist Held-Suarez with simple-physics

Aqua-Planet with complex CAM5 physics

Temperature tendency

Large-scale condensation

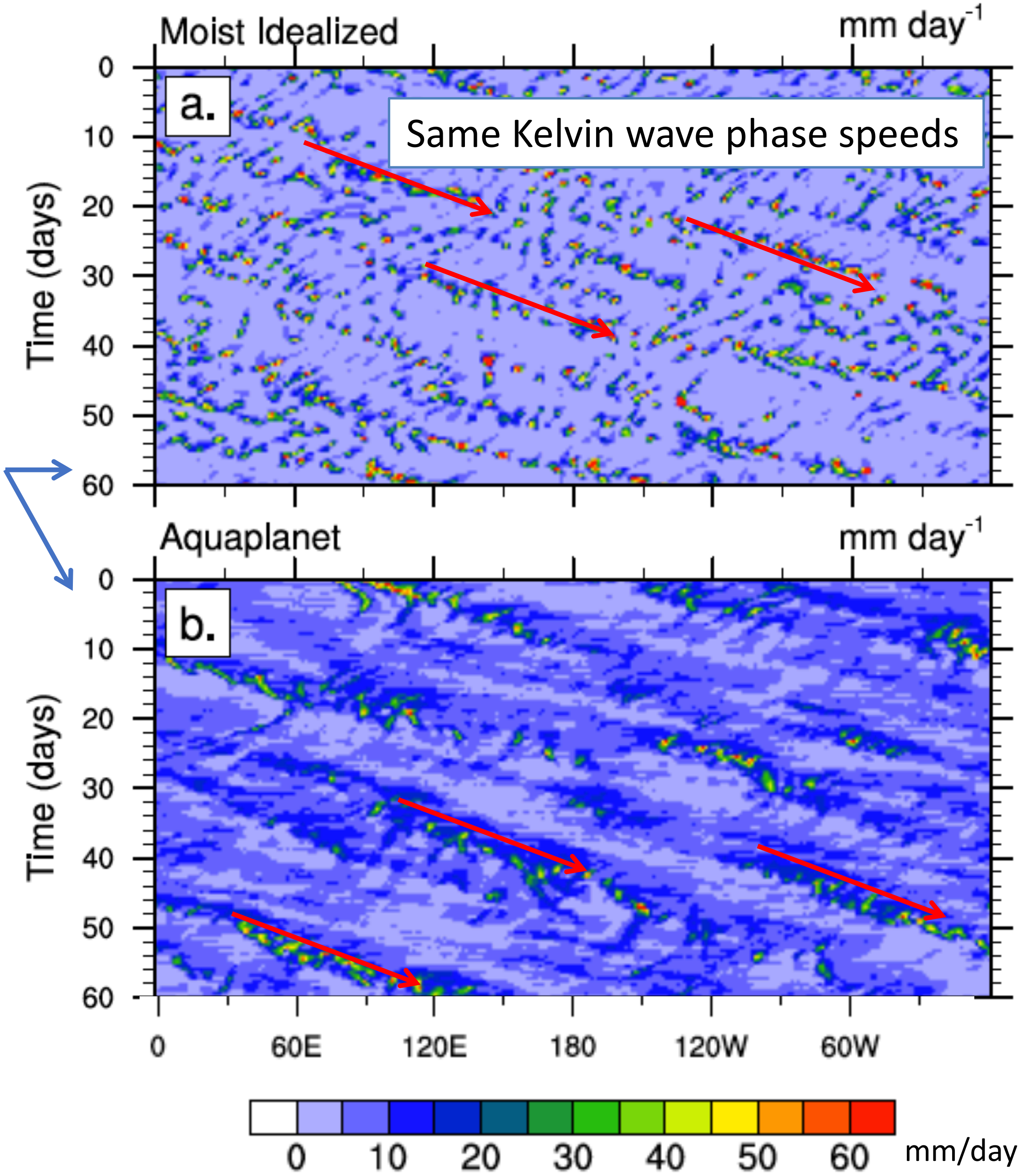
Deep convection peaks higher up

Focus on the tropics

Moisture tendency

Moist Held-Suarez and Complex Aqua-Planet

CAM-SE 1° L30:
Similar tropical waves are apparent in **the total precipitation rate (averaged between 5S-5N)** in moist Held-Suarez (top) and Aqua-Planet (bottom) runs (here eastward traveling Kelvin waves)

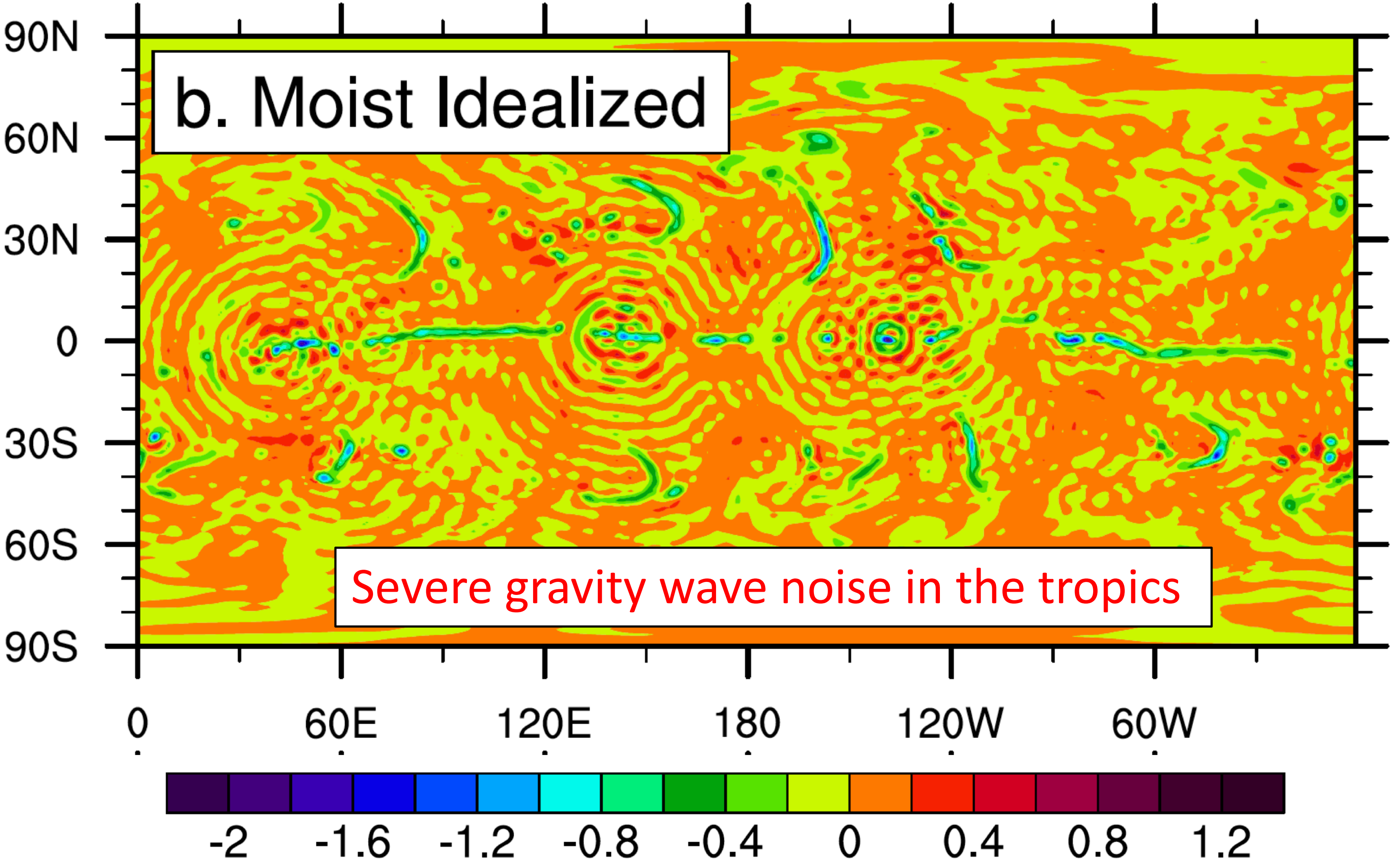


Same Kelvin wave phase speeds

Precipitation is less organized in the moist HS experiment due to simplicity of precipitation

Moist HS: Physics – Dynamics Coupling

Vertical pressure velocity snapshot at 850 hPa (Pa/s) in CAM-SE

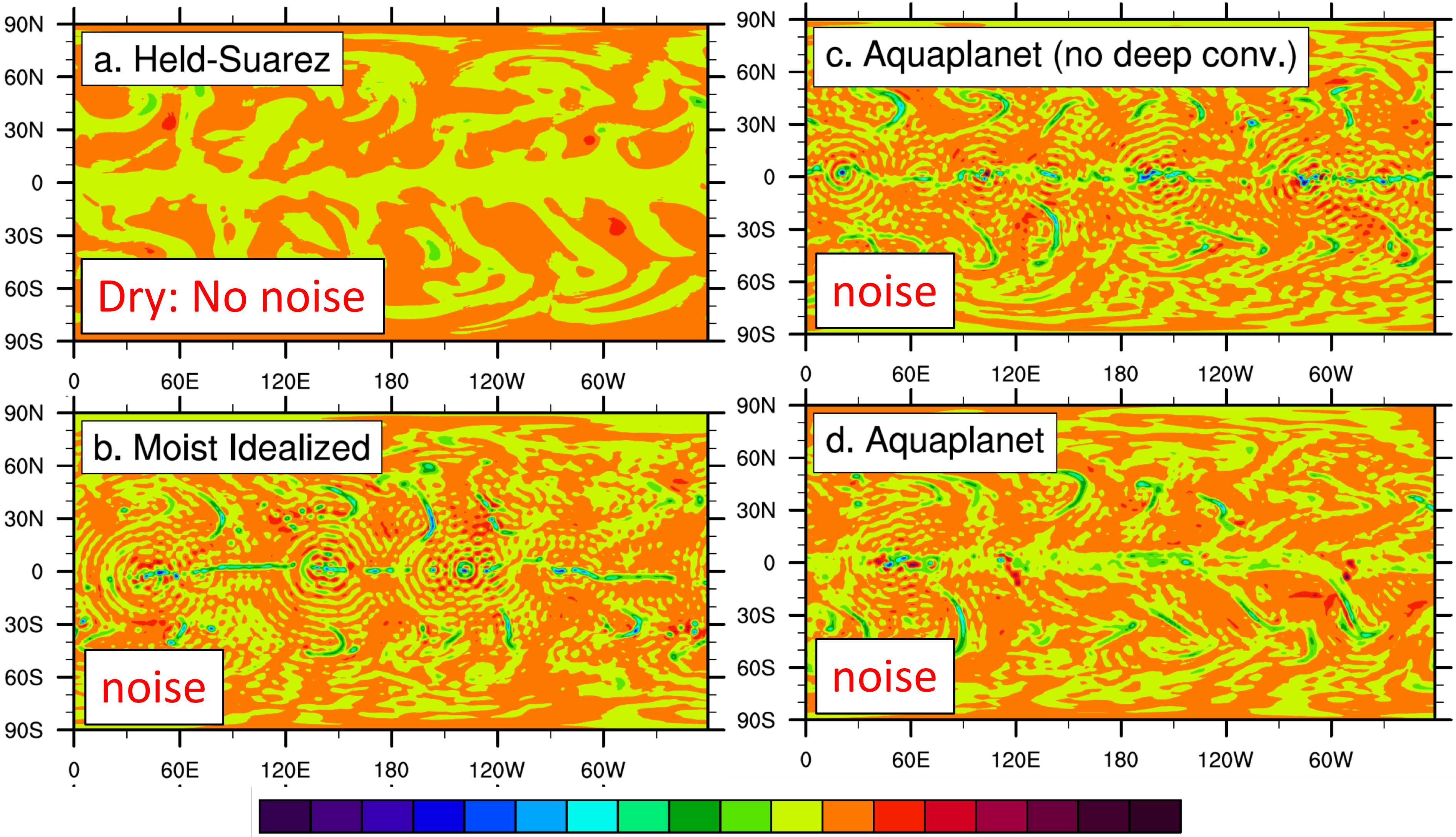


Severe gravity wave noise in the tropics

Resolution: 110 km, L30

Moist HS: Physics – Dynamics Coupling

Vertical pressure velocity snapshots at 850 hPa (Pa/s) in CAM-SE



Resolution: 110 km, L30

What Are the Possible Causes for the Gravity Wave Noise in CAM-SE?

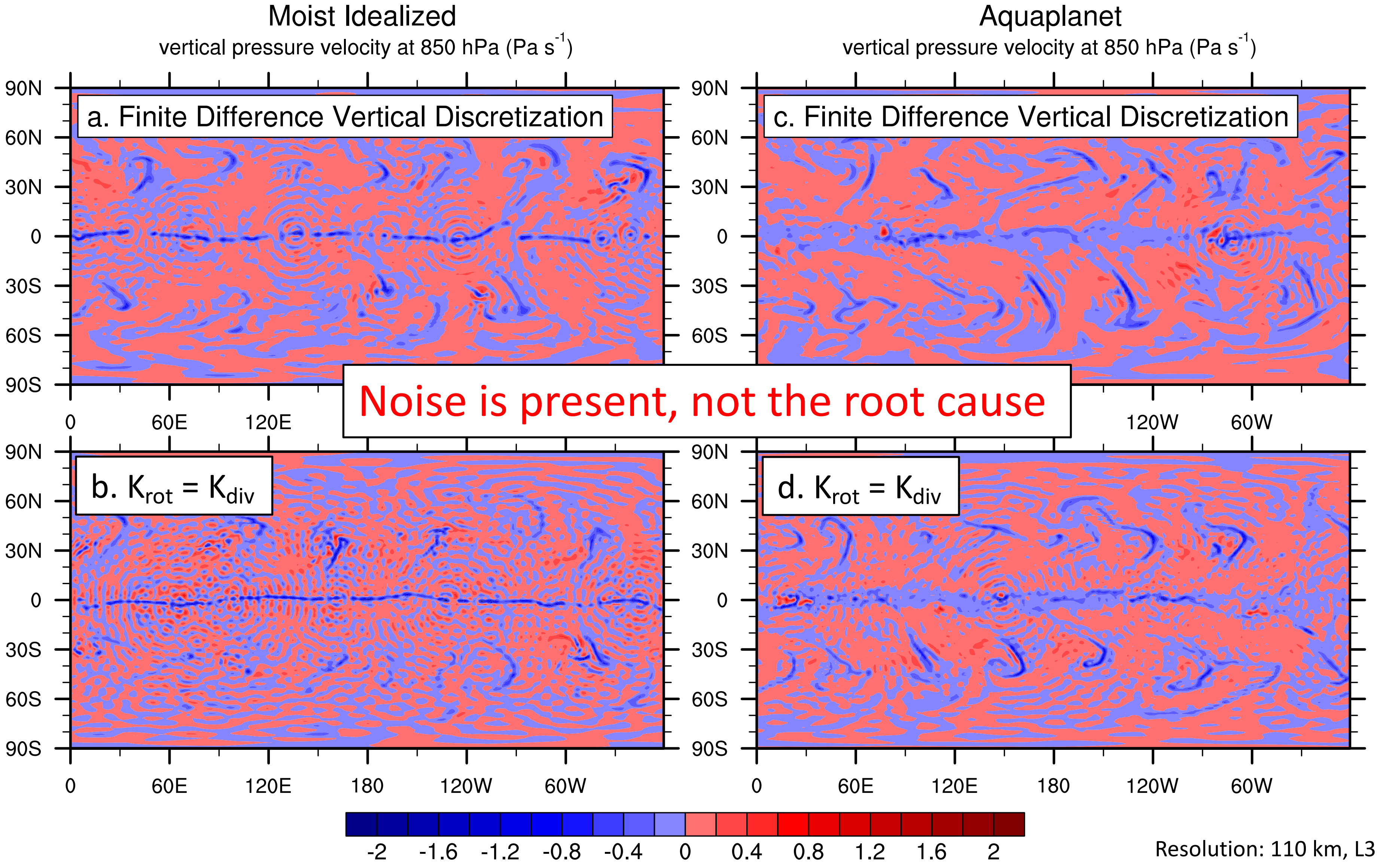
The SE dycore provides various options for

1. Vertical discretization (FD versus vertical floating Lagrangian)
2. Various options for the default floating Lagrangian coordinate (user-defined remap interval)
3. 4th-order hyperdiffusion coefficient for rotational and divergent motions can be different (default: $K_{div} = 2.5^2 \times K_{rot}$)
4. Various Runge-Kutta time stepping variants, complicated subcycling is present
5. Violation of stability constraints? Dynamics time steps too long?
6. Various options for the physics-dynamics coupling interval: sudden adjustment of the physics tendencies after long physics time steps (se_ftype = 1) or gradual application of the physics tendencies in the subcycled dycore (se_ftype = 0)

Moist HS: Physics – Dynamics Coupling

Try: Vertical Finite-Difference Scheme, Identical diffusion coefficients

model variants



Moist Idealized

vertical pressure velocity at 850 hPa (Pa s^{-1})

Aquaplanet

vertical pressure velocity at 850 hPa (Pa s^{-1})

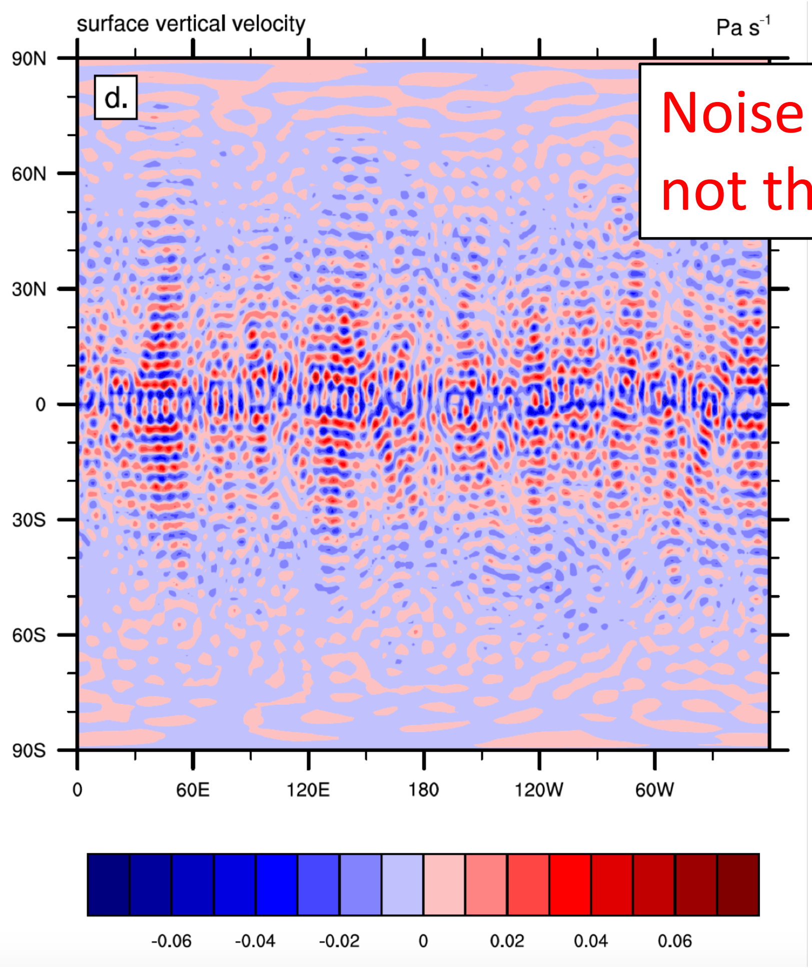
Noise is present, not the root cause

Resolution: 110 km, L30

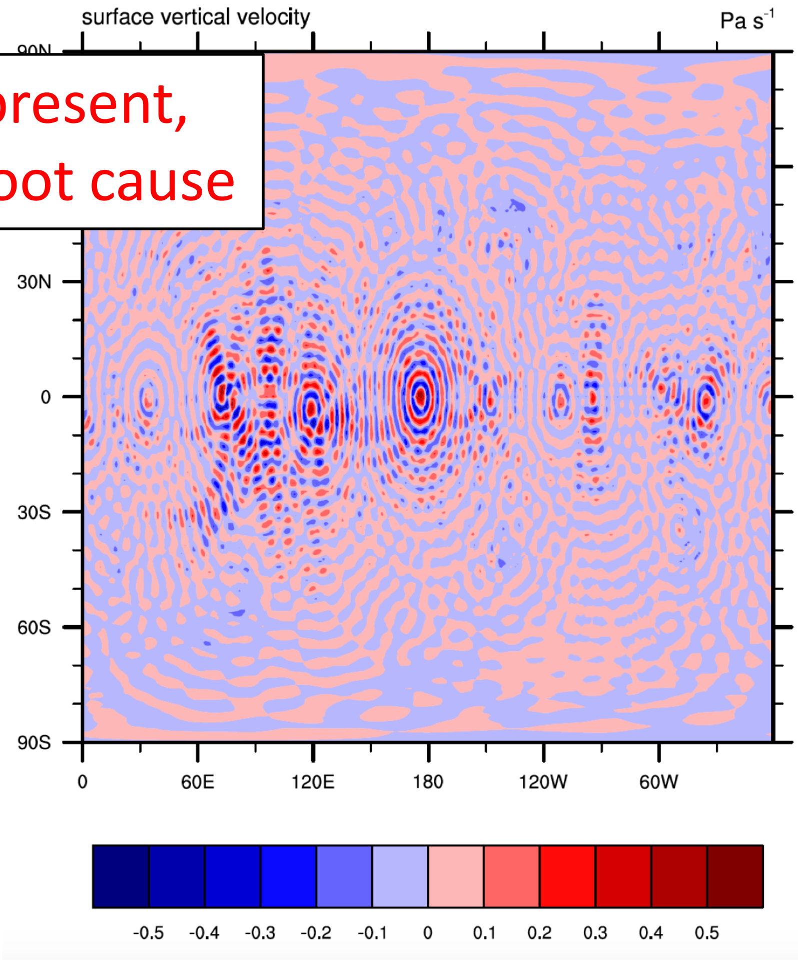
Moist HS: Physics – Dynamics Coupling

Try variants: Different dynamics time steps and vertical remap intervals

Default Time Step Settings
for the dynamics



Shorter dynamics time steps
Shorter remap interval

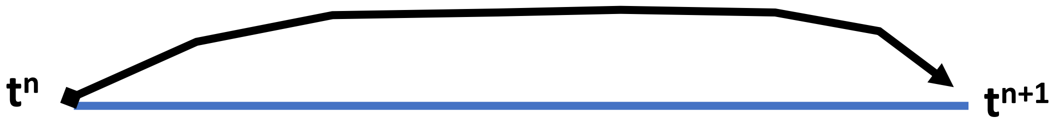


Noise is present,
not the root cause

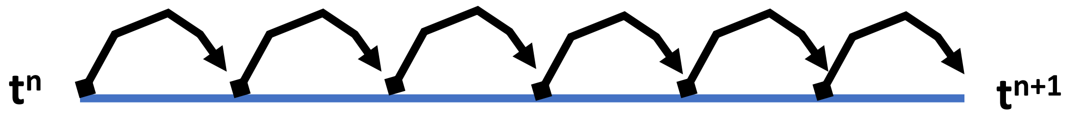
Resolution: 110 km, L30

CAM-SE: Physics – Dynamics Coupling Options

- CAM-SE time-split coupling: means that the physics package receives the updated state variables from the dynamical core.
- The physics and dynamics time steps are different. Dynamics time steps are subcycled (typically shorter by a factor of 6).
- Two available options, both compute the physics tendencies every 1800 s
  - se_ftype=1, sudden adjustment (default)
    Physics tendencies are immediately applied to update the state variables.



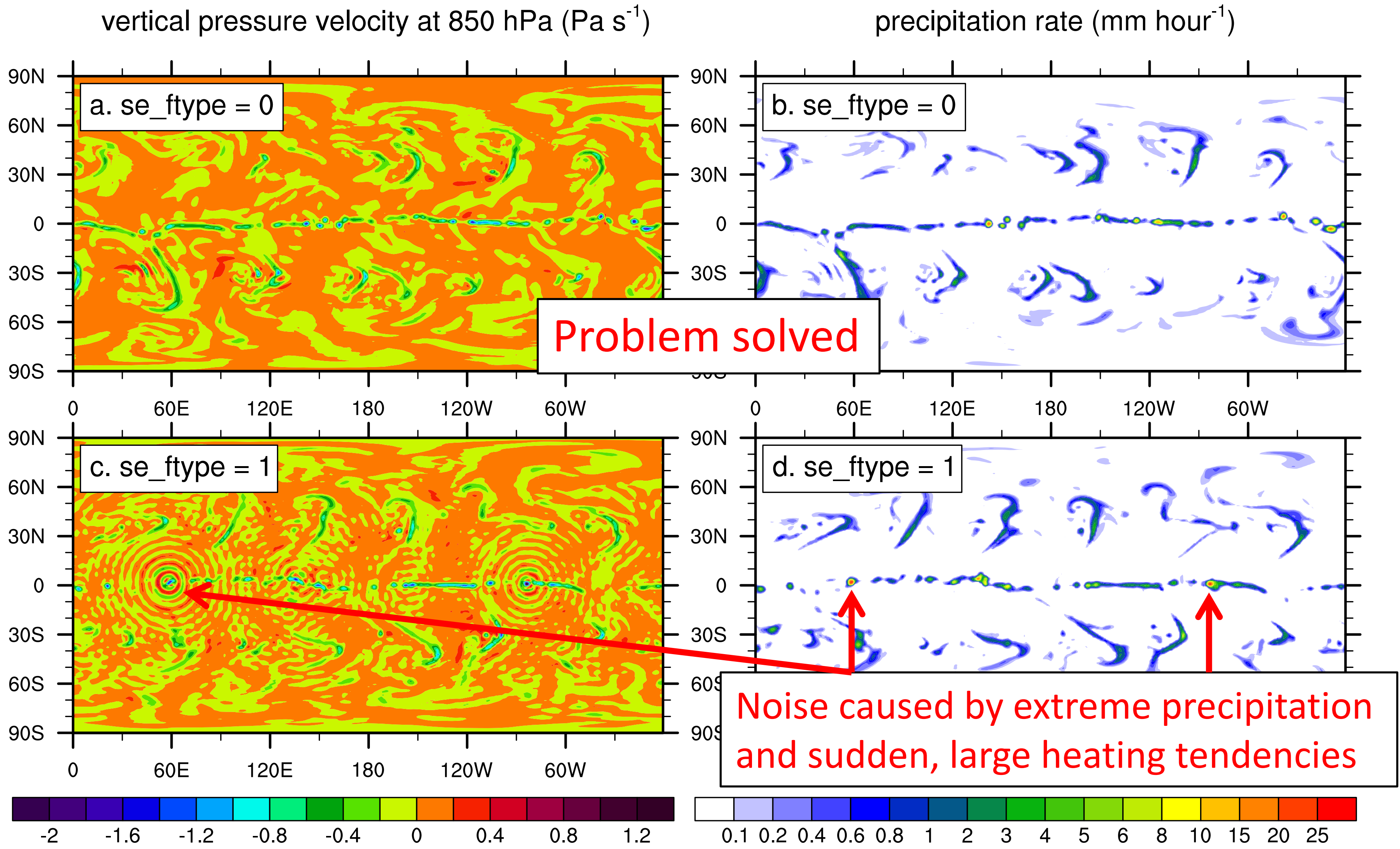
  - se_ftype=0 gradual adjustment (dribbling)
    Physics tendencies are divided by 6. They are not immediately applied but transferred to the dycore. The dycore applies them at each subcycled time step (6 times).



Moist HS: Physics – Dynamics Coupling

Try: Different physics-dynamics coupling strategy

se_ftype=1, sudden adjustment (default), se_ftype=0 gradual adjustm.



vertical pressure velocity at 850 hPa (Pa s^{-1})

precipitation rate (mm hour^{-1})

a. se_ftype = 0

b. se_ftype = 0

c. se_ftype = 1

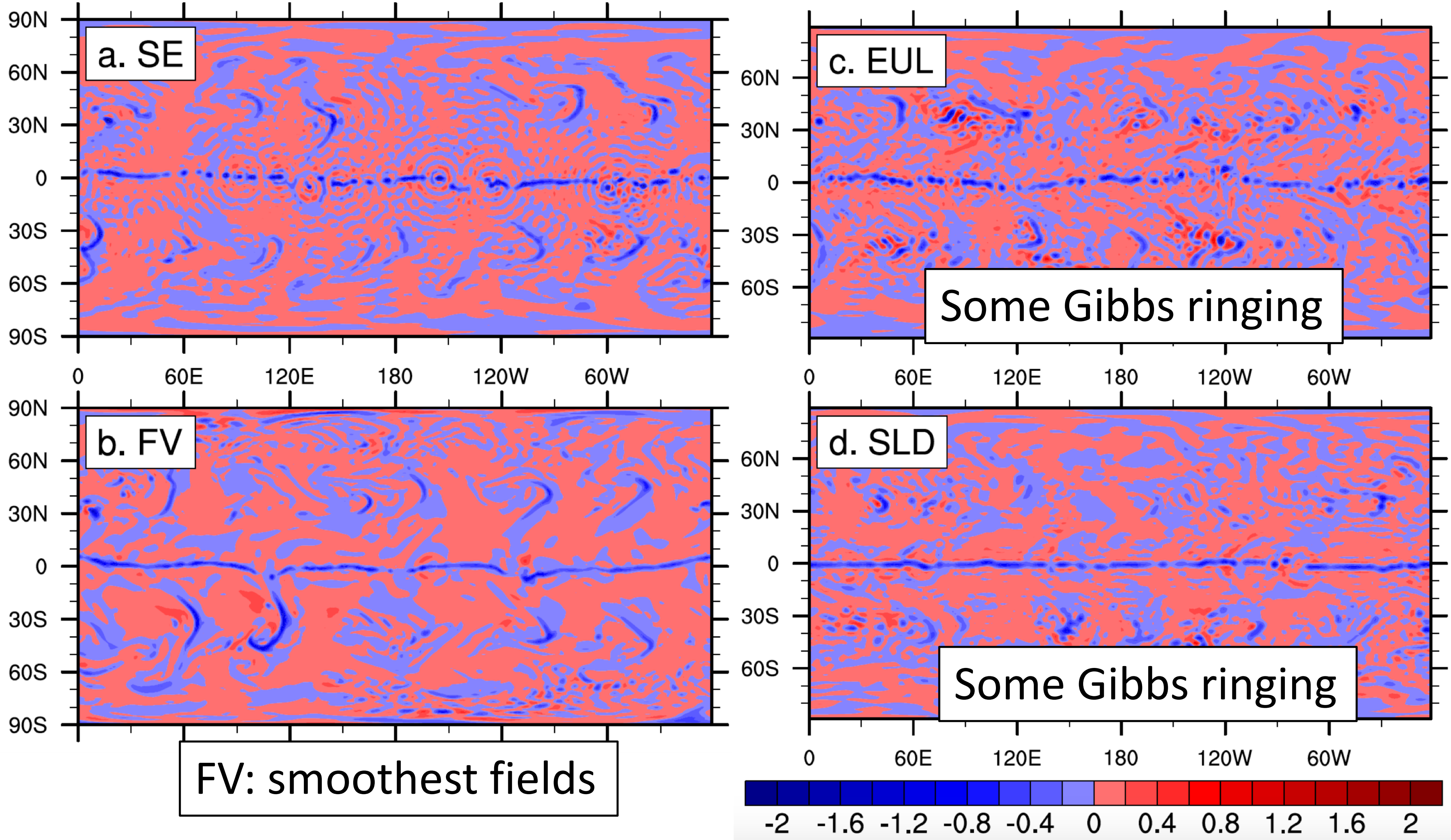
d. se_ftype = 1

Problem solved

Noise caused by extreme precipitation and sudden, large heating tendencies

Intercomparison: Physics – Dynamics Coupling

Instantaneous vertical pressure velocity at 850 hPa (Pa/s) in all CAM dycores with moist HS forcing



Some Gibbs ringing

Some Gibbs ringing

FV: smoothest fields

Intercomparisons: CAM5 dynamical cores

- The kinetic energy (KE) spectra of the moist HS experiments (solid) replicate the KE spectra of the complex CAM5 aqua-planet runs (dashed).

  Here with 110-150 km grid spacing.

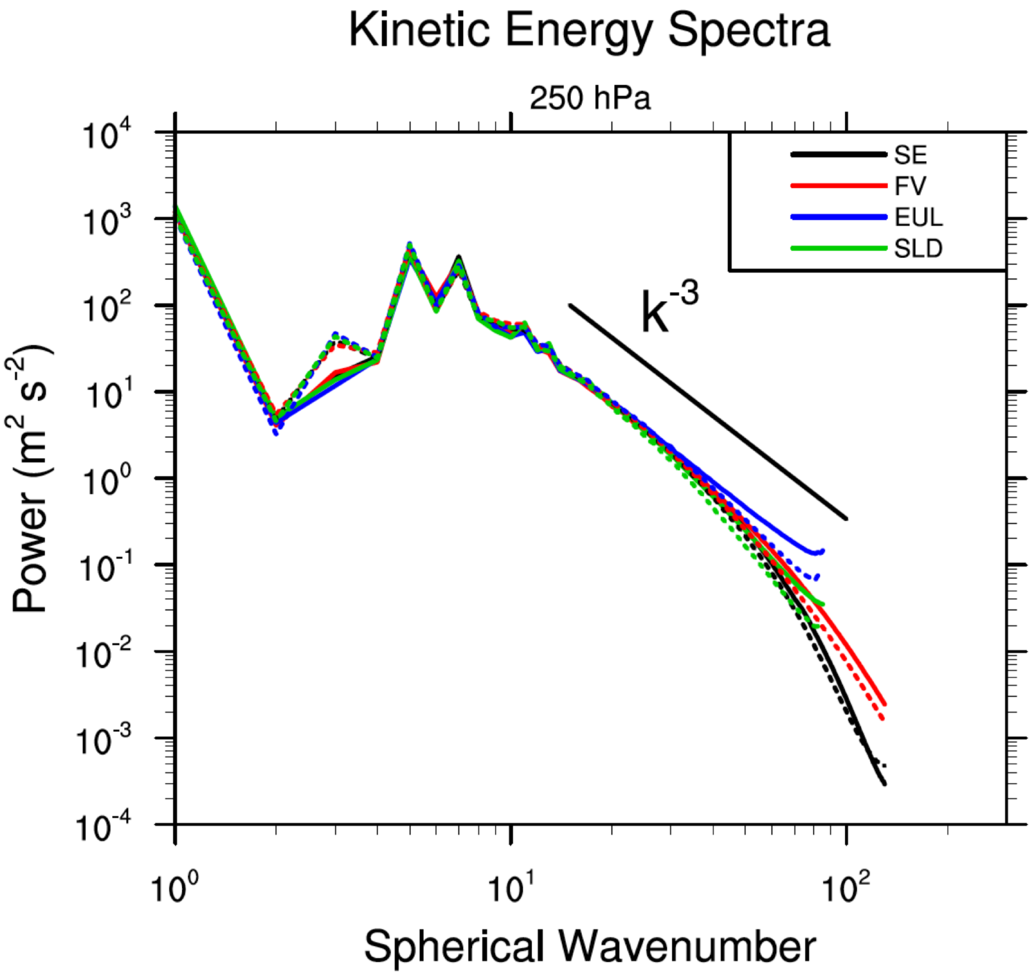
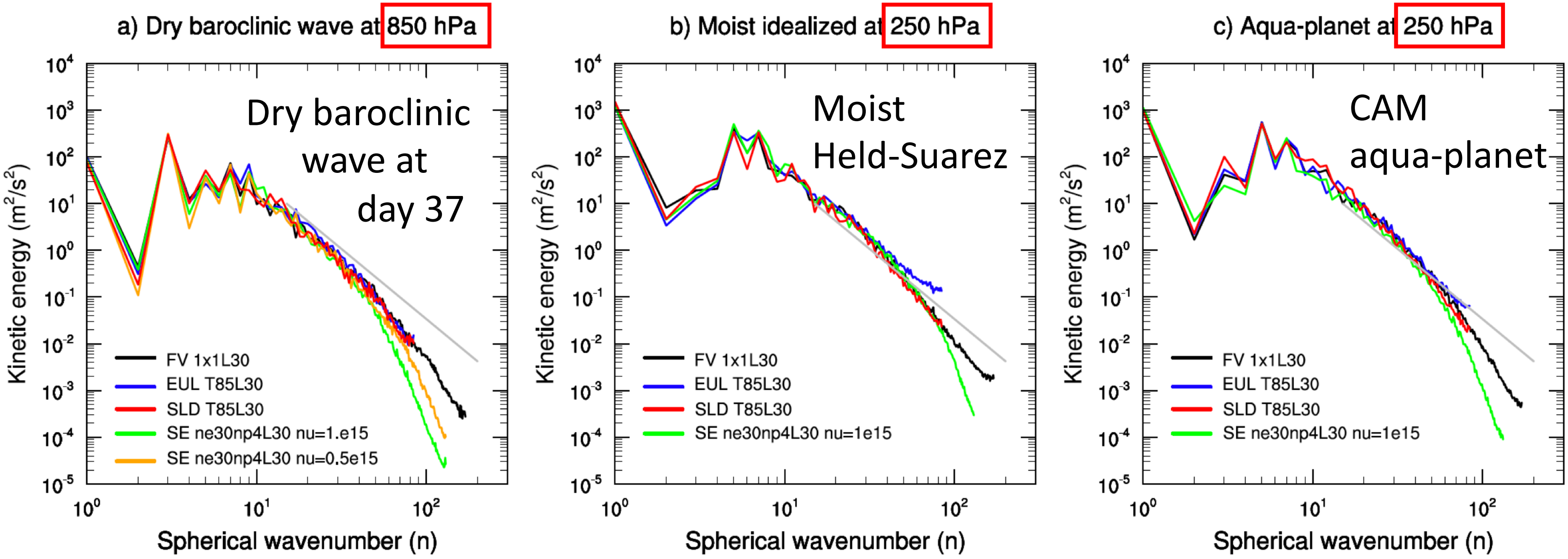


Figure 11. 250 hPa kinetic energy spectra for MITC (solid lines) and APS (dashed lines) simulations with SE (black), FV (red), EUL (blue), and SLD (green). The slopes can be compared to the theoretical k^{-3} slope.

Dry Dycore & Moist Held-Suarez & Aqua-Planet

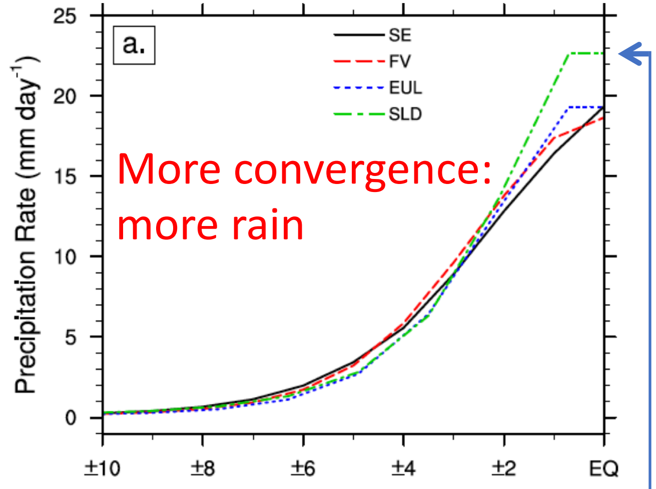


Even the KE spectrum of the dry baroclinic wave (at day 37) shows that CAM-SE (in green) diffuses the kinetic energy at the smallest scales the most

Intercomparisons: CAM5 dynamical cores

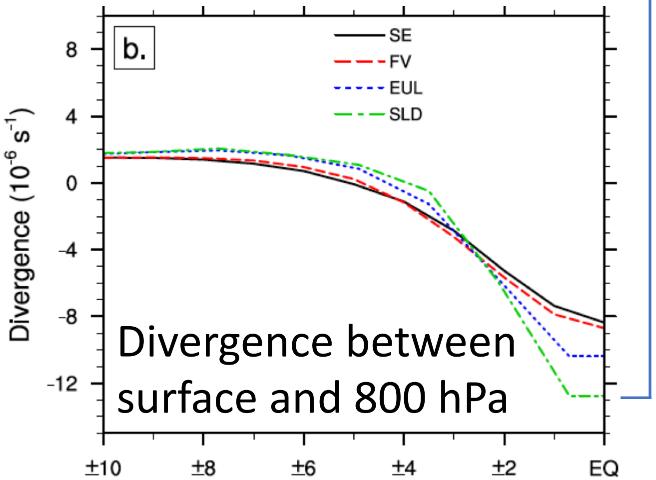
- Moist HS experiments highlight dynamical core differences in the tropics

Mean Precipitation Rate (mm/day)



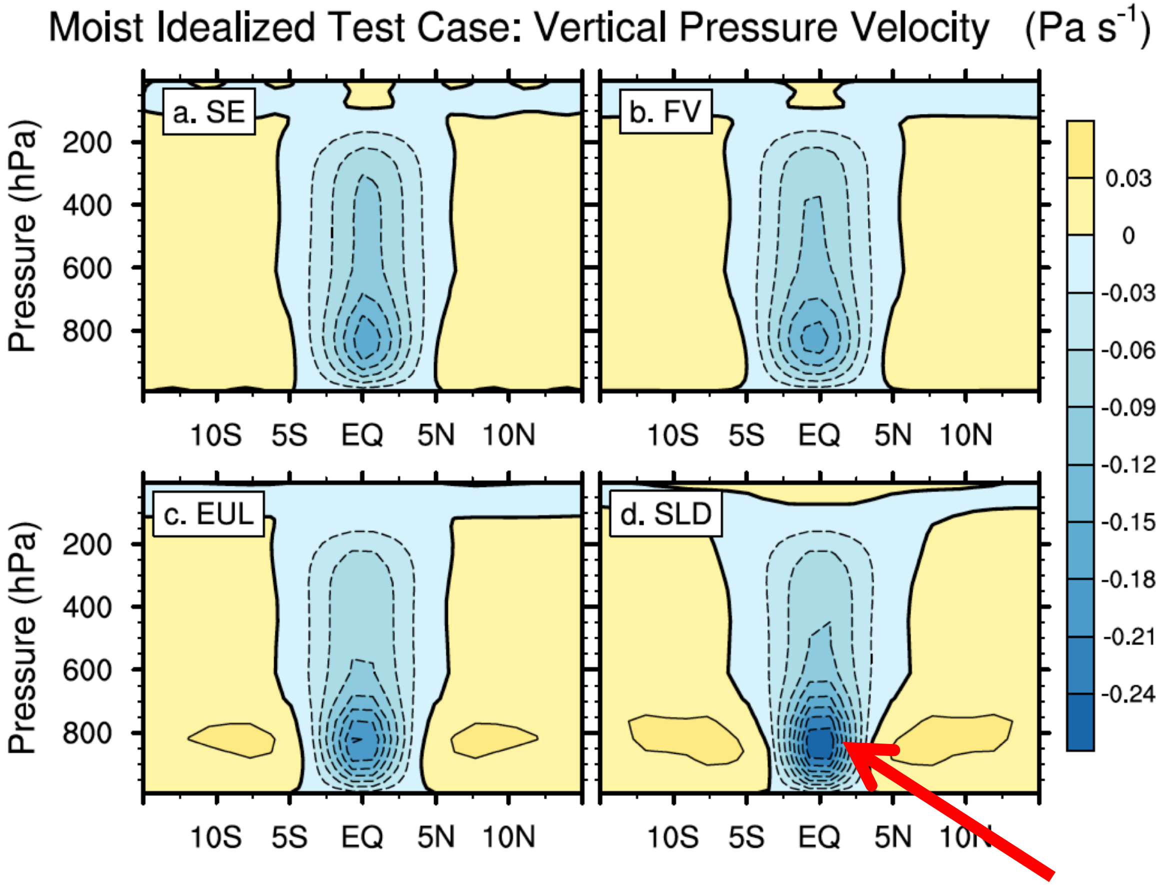
More convergence: more rain

Column-Integrated Divergence



Divergence between surface and 800 hPa

Latitude



Coupling: More precipitation & more latent heating lead to higher updraft speeds

Adding Complexity: Simple Convection

- Frierson (JAS, 2007) experimented with some simplified versions of a Betts-Miller-like convection scheme
- Simplified Betts-Miller (SBM): Relaxation towards a reference specific humidity (q_{ref}) and temperature (T_{ref}) profile over a time scale τ_{SBM}
- SBM provides δq and δT increments at each physics time step

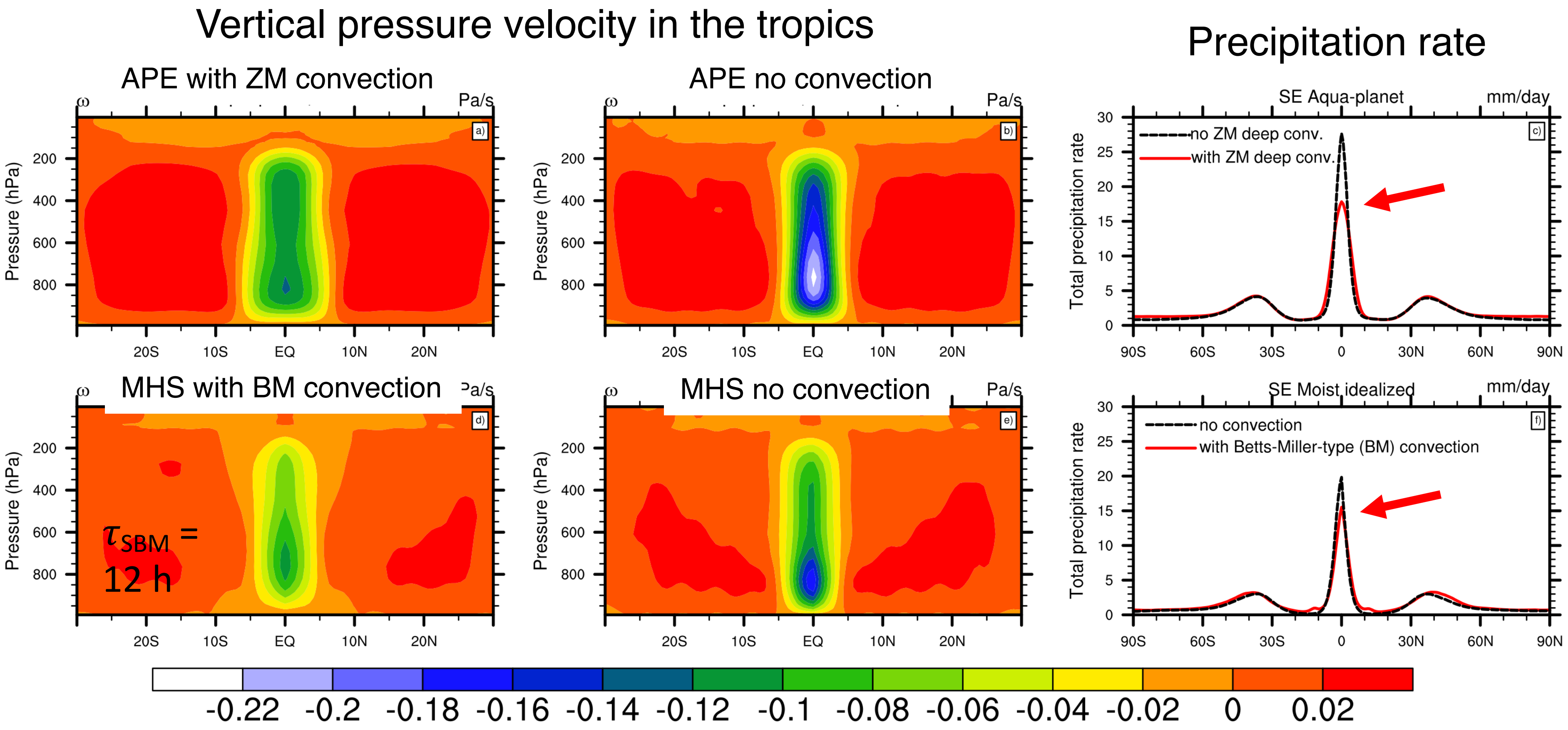
$$\delta q = -\frac{q - q_{\mathrm{ref}}}{\tau_{\mathrm{SBM}}}$$

$$\delta T = -\frac{T - T_{\mathrm{ref}}}{\tau_{\mathrm{SBM}}}$$

- Defaults: τ_{SBM} = 16 h, q_{ref} and T_{ref} reference profile specified for 80% relative humidity threshold

Adding Complexity: Simple Convection

How does the moist Held-Suarez (MHS) setup interact with a Betts-Miller-like convection scheme in CAM-SE (110 km L30)?


Vertical pressure velocity in the tropics

Precipitation rate

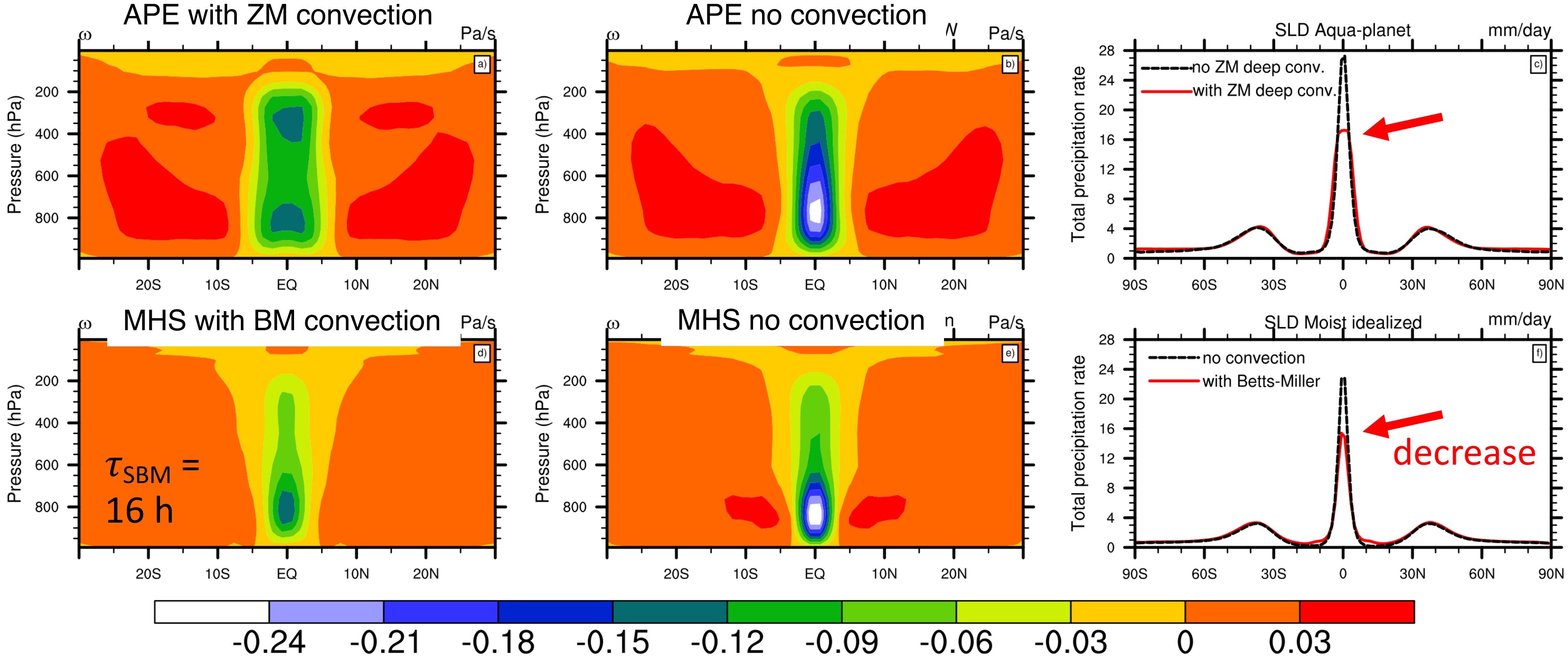
Convection (Zhang McFarlane (ZM) and simplified Betts-Miller (BM) both reduce the tropical precipitation rate (in red) as compared to configurations without convection (in black)

Adding Complexity: Simple Convection

How does the moist Held-Suarez (MHS) setup interact with a Betts-Miller-like convection scheme in CAM-SLDT85 (156 km L30)?

Vertical pressure velocity in the tropics

Precipitation rate


APE with ZM convection

APE no convection

MHS with BM convection

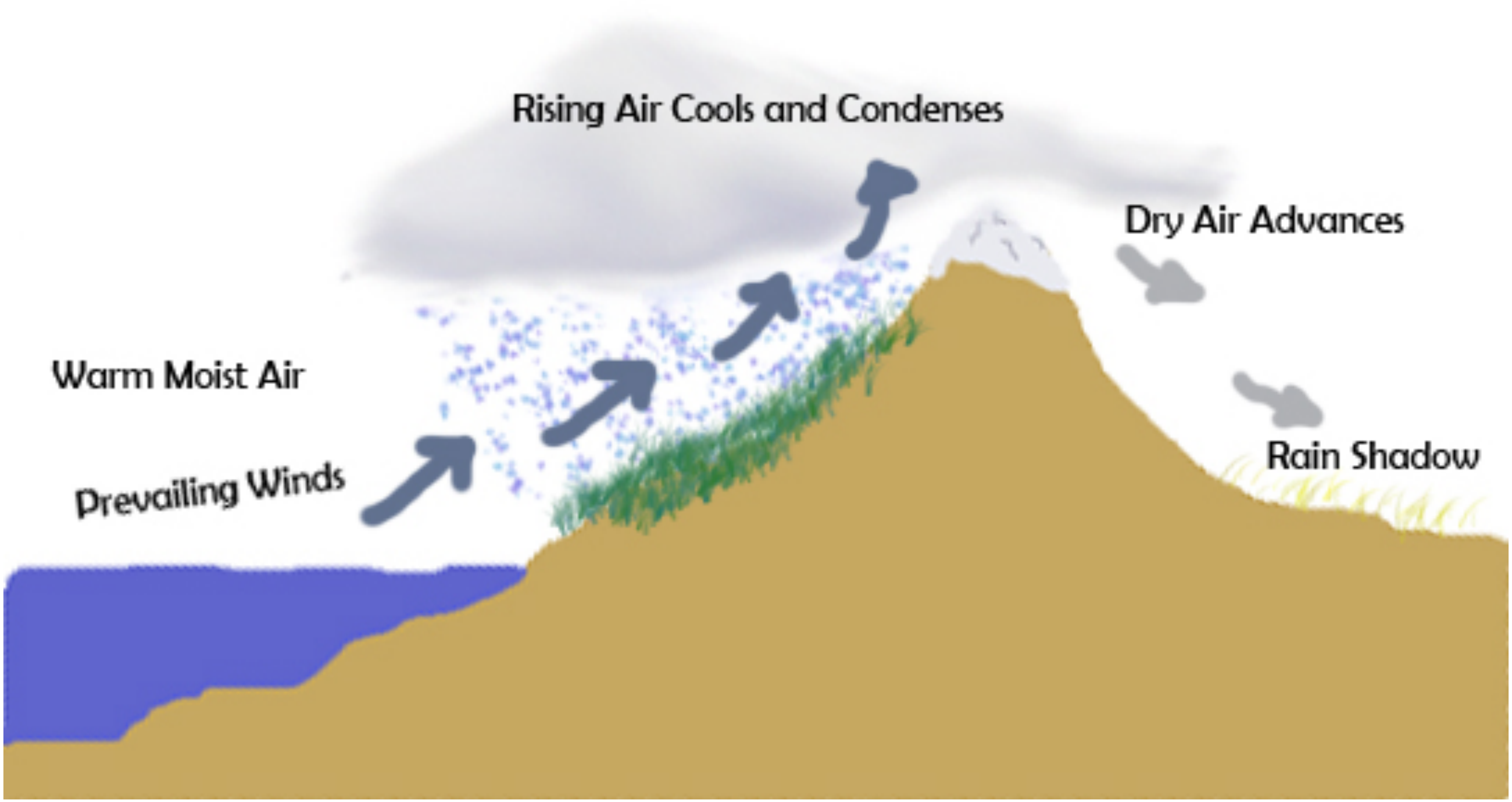
MHS no convection

τ_{SBM} = 16 h

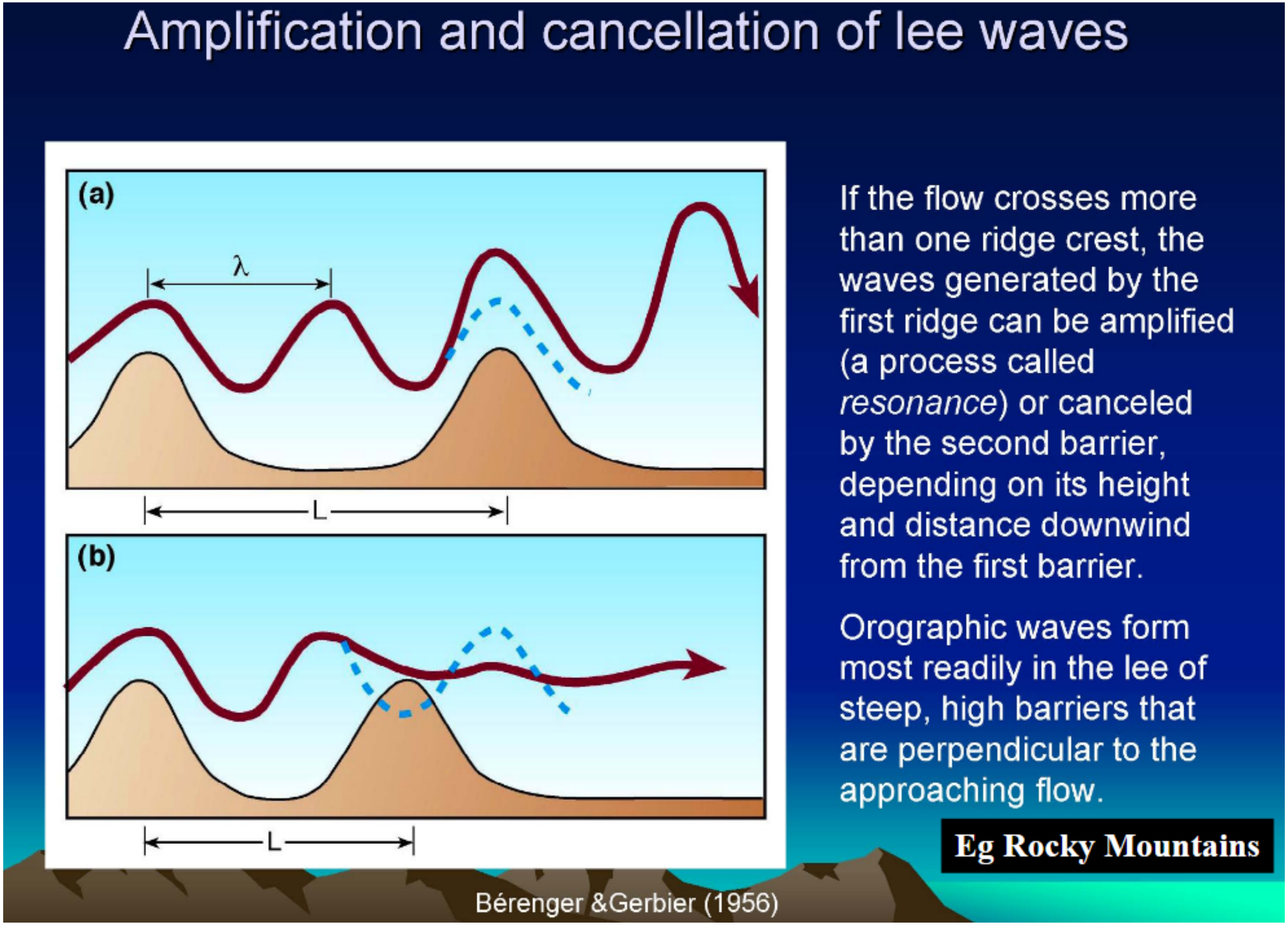
decrease

BM convection interacts in similar way with SLD, but the relaxation time scale τ_{SBM} = 16 h (tuning factor) needed to be longer (SE: 12 h), points to uncertainty in physics-dynamics coupling

Adding topography and moisture: Mountain-generated waves & precipitation



Adding topography and moisture: Mountain-generated waves & precipitation



Amplification and cancellation of lee waves

If the flow crosses more than one ridge crest, the waves generated by the first ridge can be amplified (a process called *resonance*) or canceled by the second barrier, depending on its height and distance downwind from the first barrier.

Orographic waves form most readily in the lee of steep, high barriers that are perpendicular to the approaching flow.

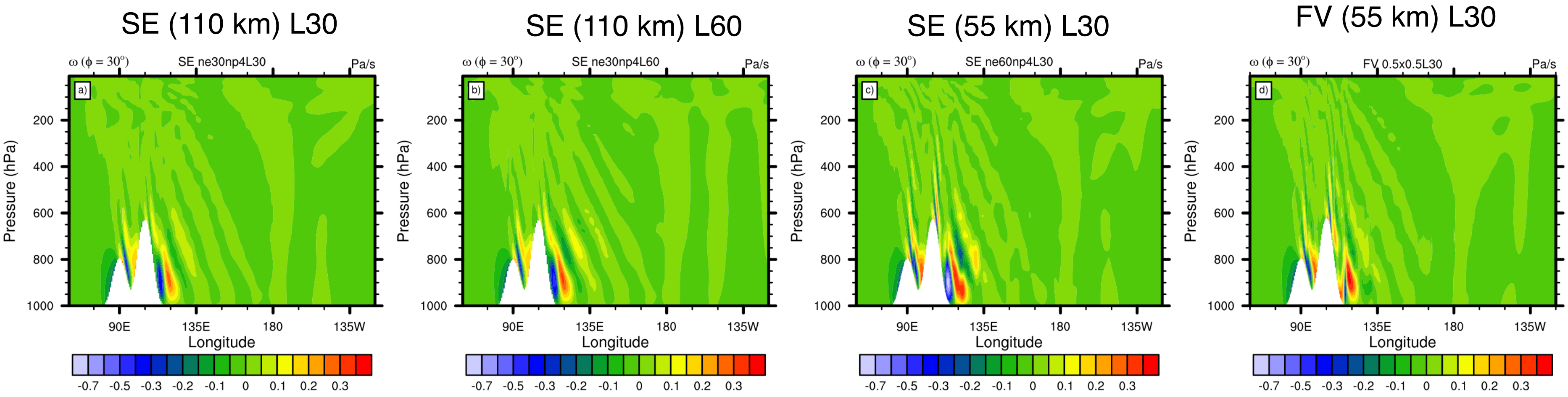
Eg Rocky Mountains

Bérenger &Gerbier (1956)

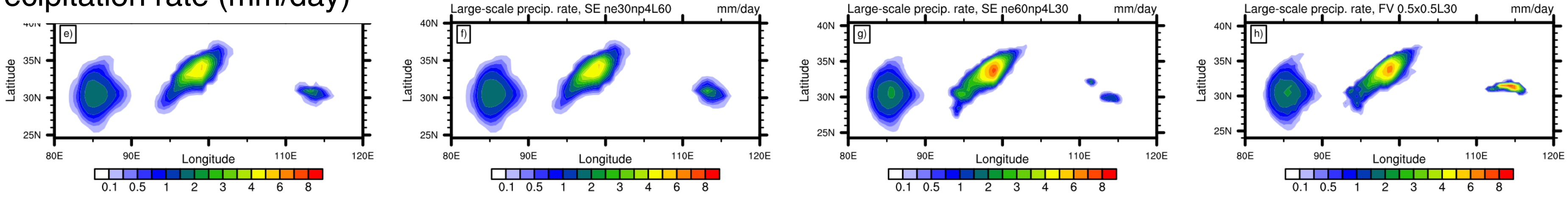
Adding topography and moisture: Mountain-generated gravity waves (GW) & precipitation

How do moisture and topography interact in dycores (here CAM) with large-scale condensation?

Vertical pressure velocity along 30N



Precipitation rate (mm/day)



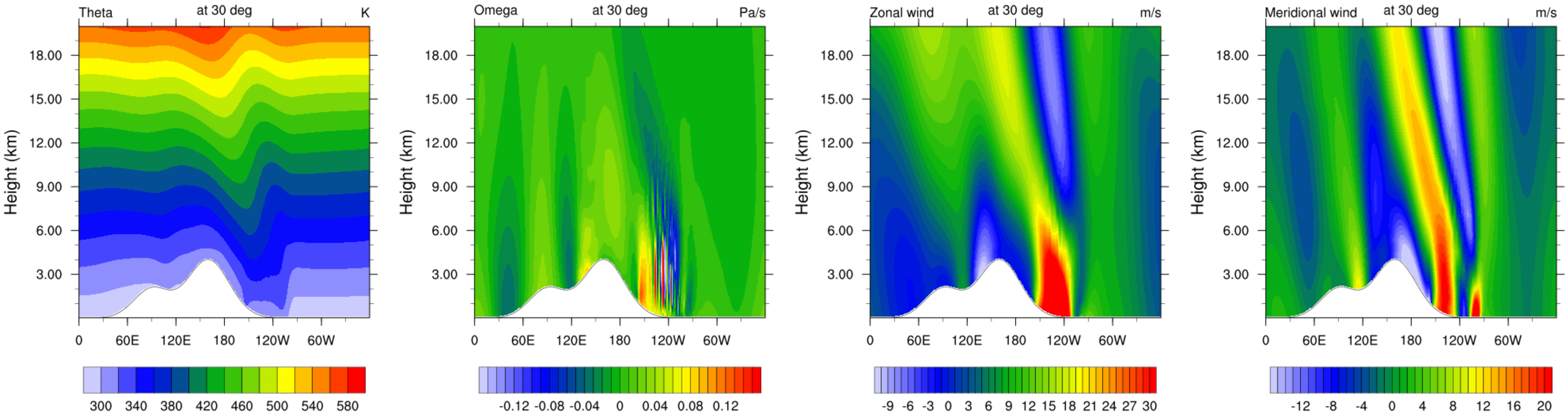
Precipitation rate mostly depends on horizontal resolution, less so on vertical resolution

Adding topography and moisture: Mountain-generated gravity waves (GW) & precipitation

How do moisture and topography interact in dycores with Kessler warm rain physics?

Lon-height cross sections of θ, ω, u and v along 30N at day 5 with CAM-SE (55 km L30)

Valley, Moist mountain-induced Rossby waves, Day: 5

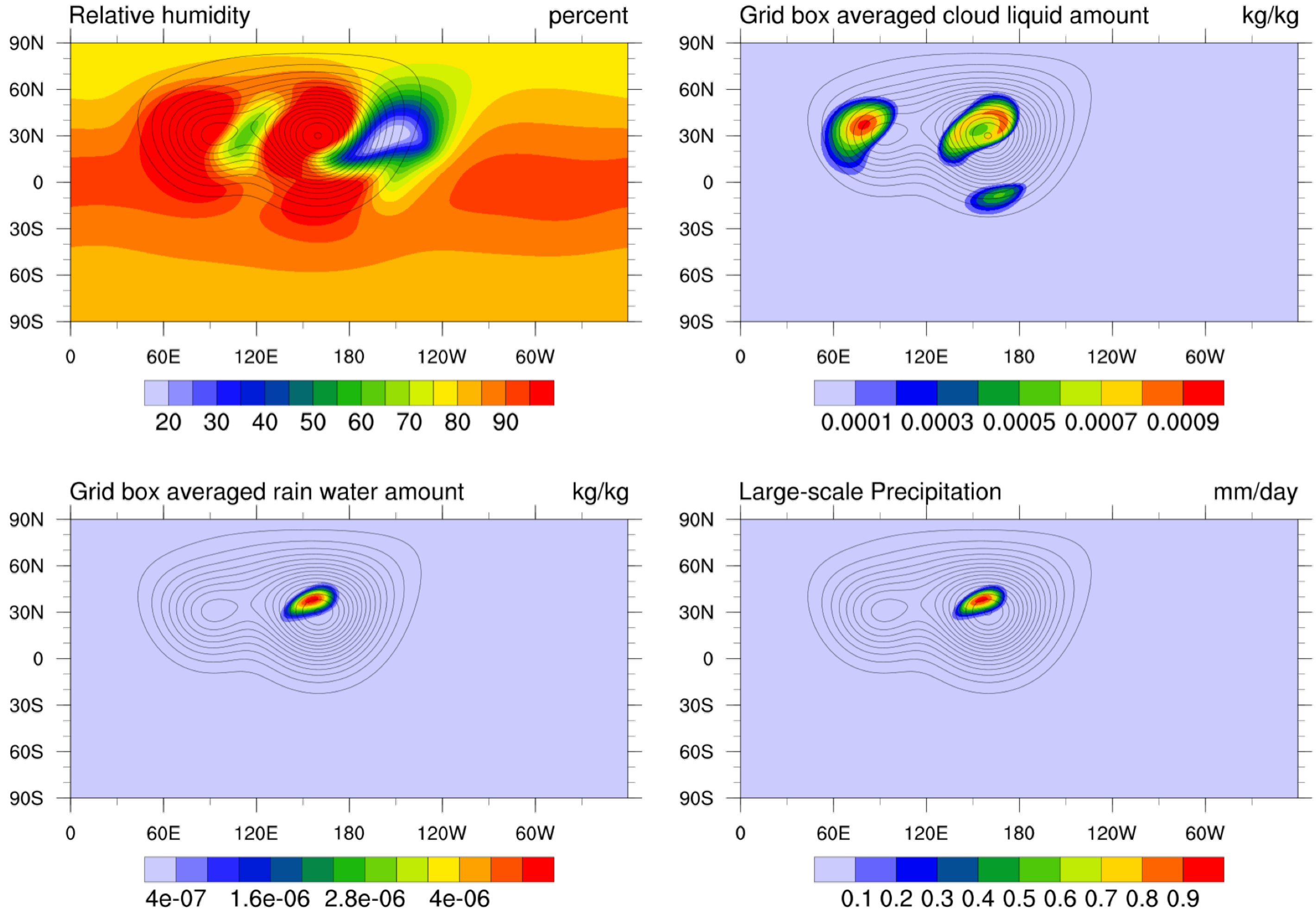


All topography/Kessler results provided by Samar Minallah (U. Michigan)

Adding topography and moisture: Mountain-generated gravity waves (GW) & precipitation

How do moisture and topography interact (with Kessler)?

Valley2, Moist mountain-induced Rossby waves, Day: 2 Lowest model level



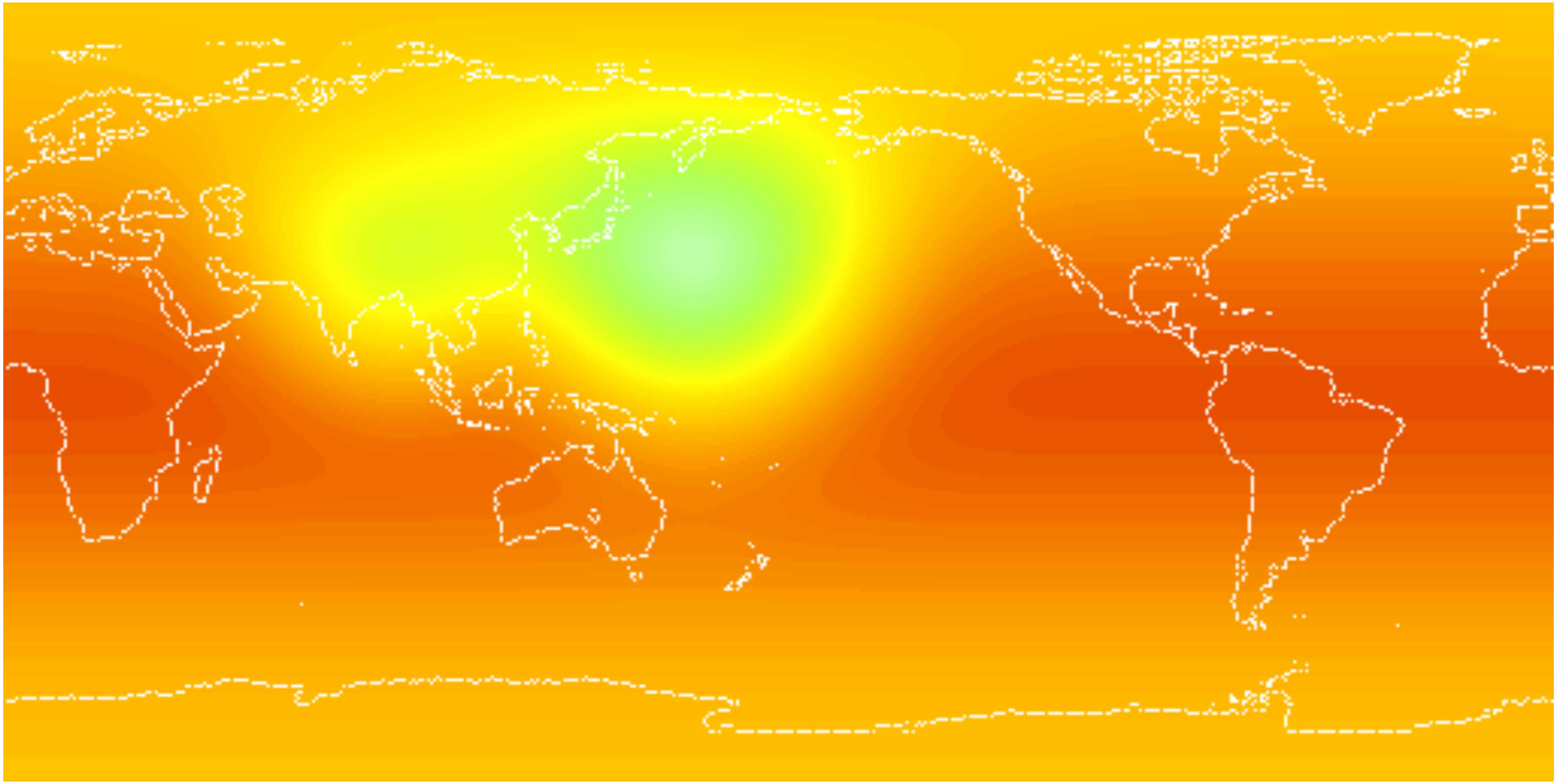
Moisture species of the Kessler scheme at day 2 (at the lowest model level)

CAM-SE (55 km L30)

Adding topography and moisture: Mountain-generated gravity waves (GW) & precipitation

How do moisture and topography interact (with Kessler)?

Evolution of relative humidity (CAM-SE 55 km lowest level), 30 days:

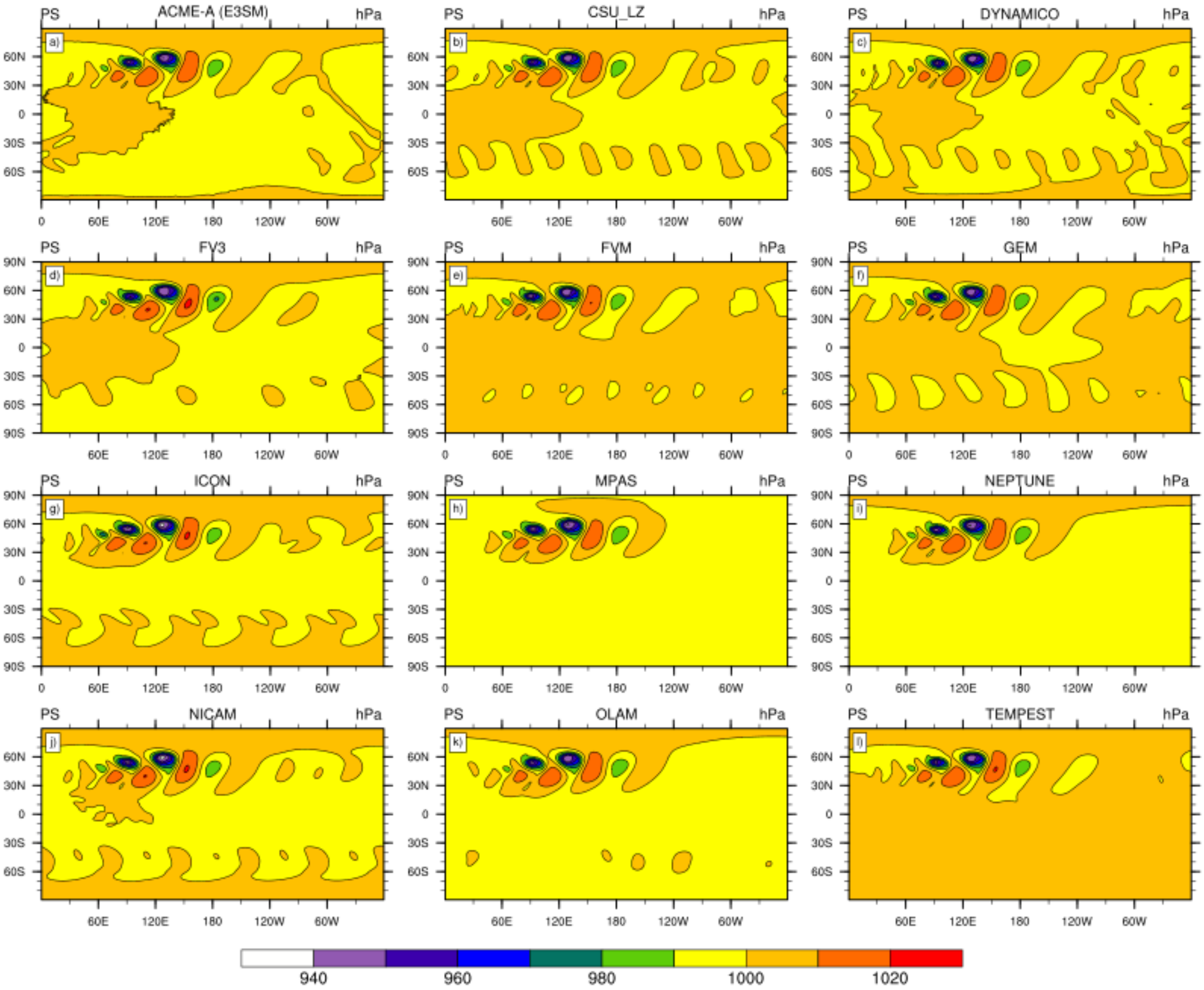


Adding topography and moisture: Mountain-generated gravity waves (GW) & precipitation

How do moisture and topography interact (with Kessler)?

Evolution of the precipitation rate (CAM-SE 55 km L30) over 30 days:

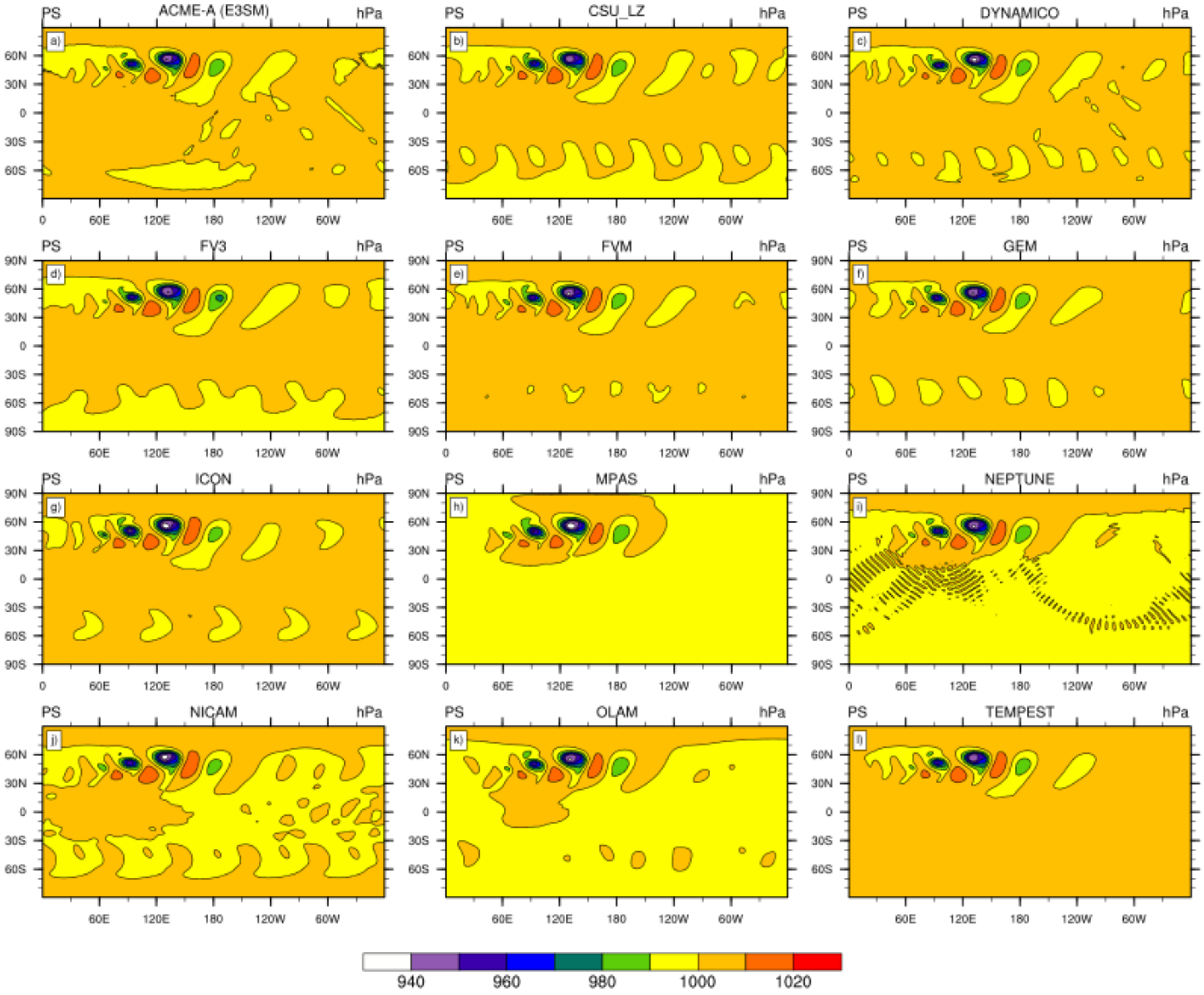
Snapshots of the DCMIP-2016 dry baroclinic wave



Ullrich et al.
(2014)
(DCMIP-2016)

Surface pressure at day 10 (Δx=110 km): overall patterns similar, details differ

Snapshots of the DCMIP-2016 moist baroclinic wave

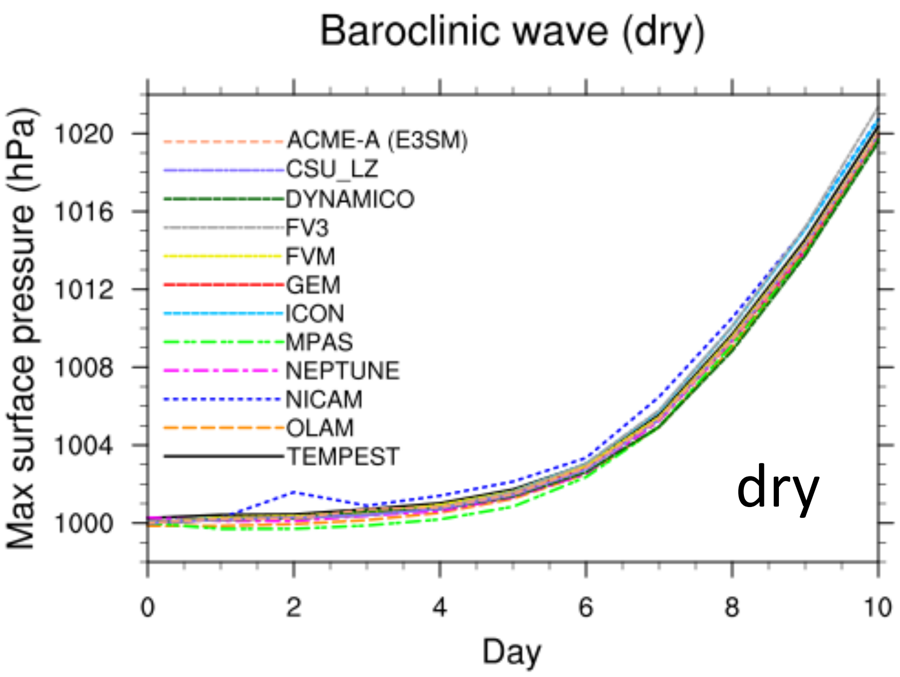


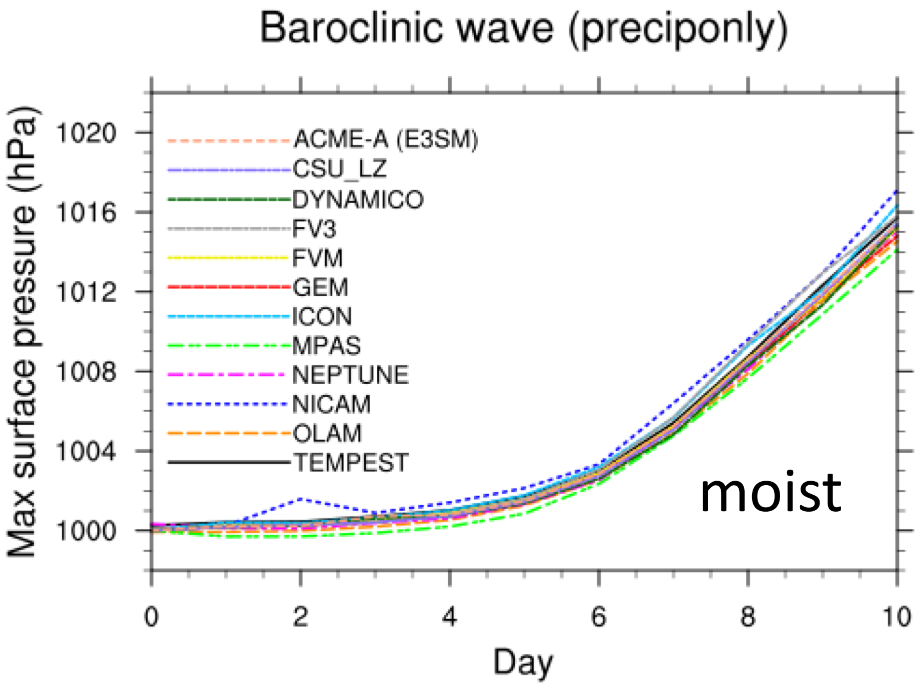
with Kessler
(DCMIP-2016)

Surface pressure at day 10 (Δx=110 km): overall patterns similar, details differ

Moisture effects weaken highs and strengthen lows

10-Day Time Series: dry and moist ps maxima

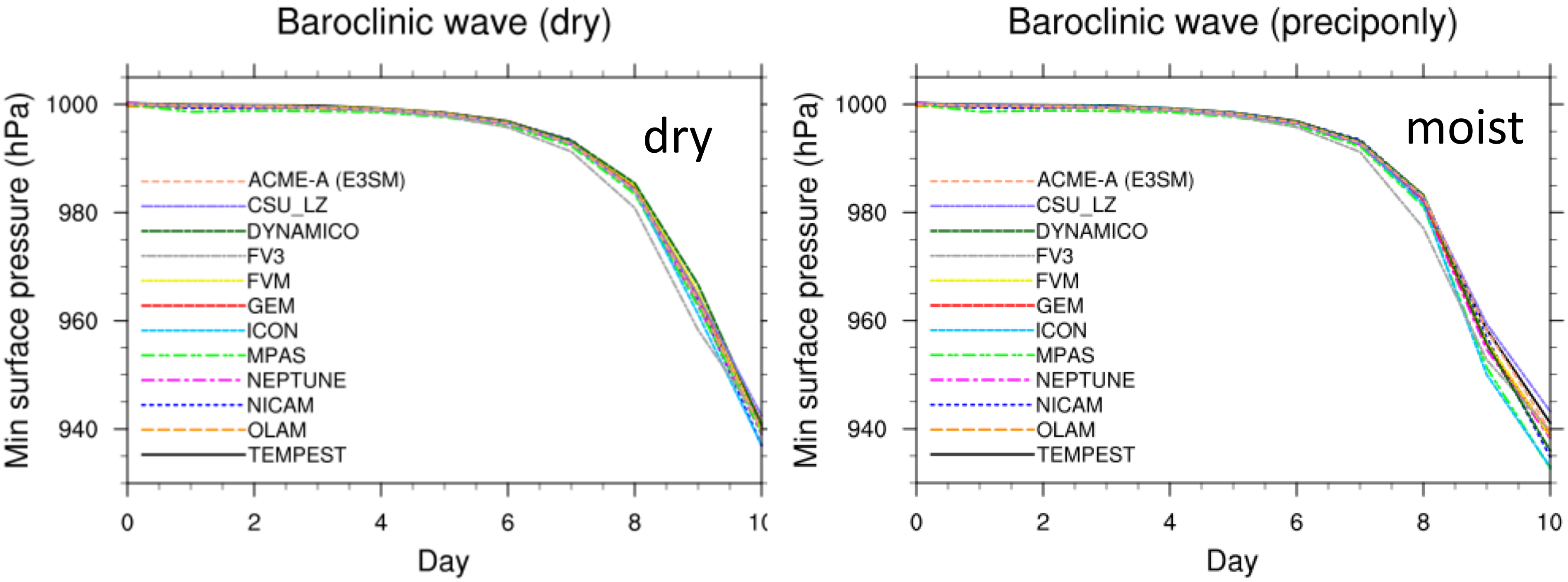




- Moisture effects **weaken high pressure** systems
- Presence of moisture and precip **widens the ensemble spread (similar magnitudes in dry and moist models)**
- Points to the uncertainties in the physics-dynamics interactions and the possible impact of effective resolutions

DCMIP-2016

15-Day Time Series: dry and moist ps minima

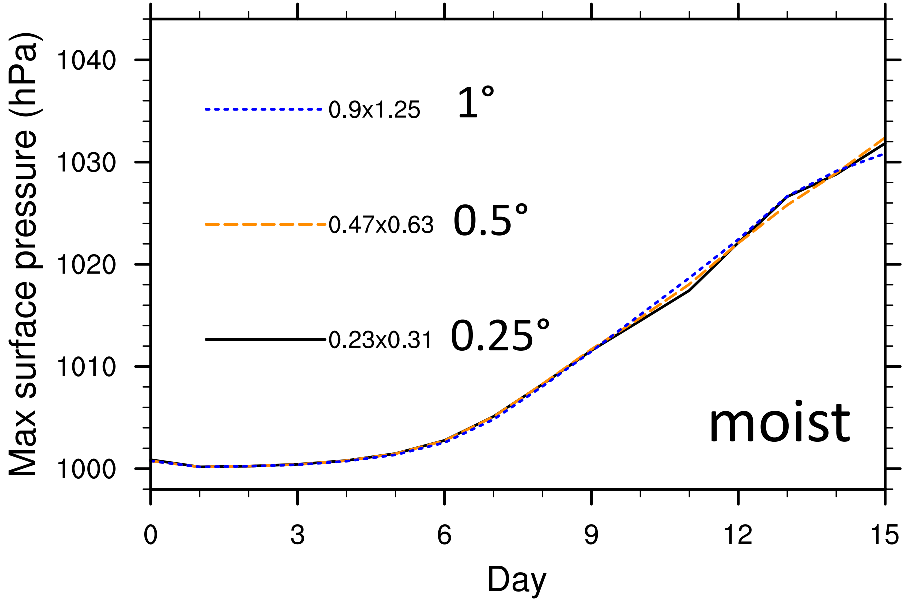


- Moisture effects: **tendency to strengthen low pressure** systems
- Presence of moisture **considerably widens the DCMIP ensemble spread**

DCMIP-2016

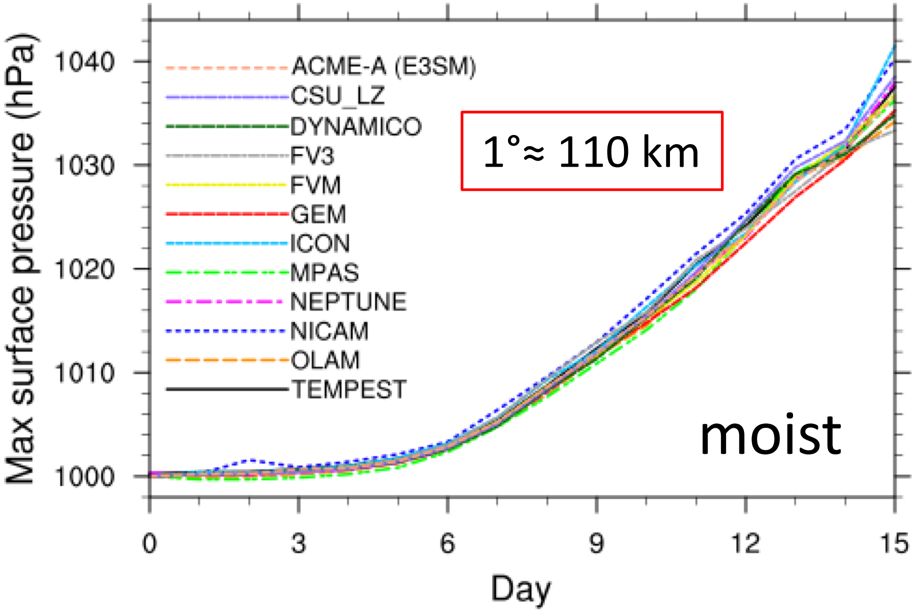
Impact of Resolution: Moist ps maxima

CAM FV Baroclinic wave (preciponly)



DCMIP models

Baroclinic wave (preciponly)

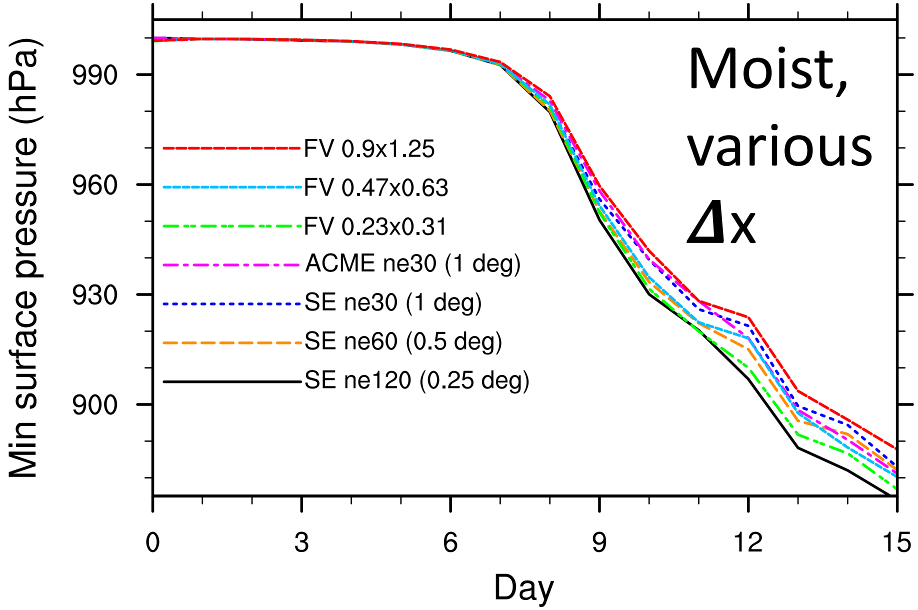


1° ≈ 110 km

- Moist CAM-FV: Impact of the horizontal resolution on the evolution of the ps_{max} is small
- However: ps_{max} in DCMIP models spreads wide
- ps_{min} spread in DCMIP models increases (next slide), physics-dynamics interactions most apparent in low pressure regions with precipitation and updraft

DCMIP-2016

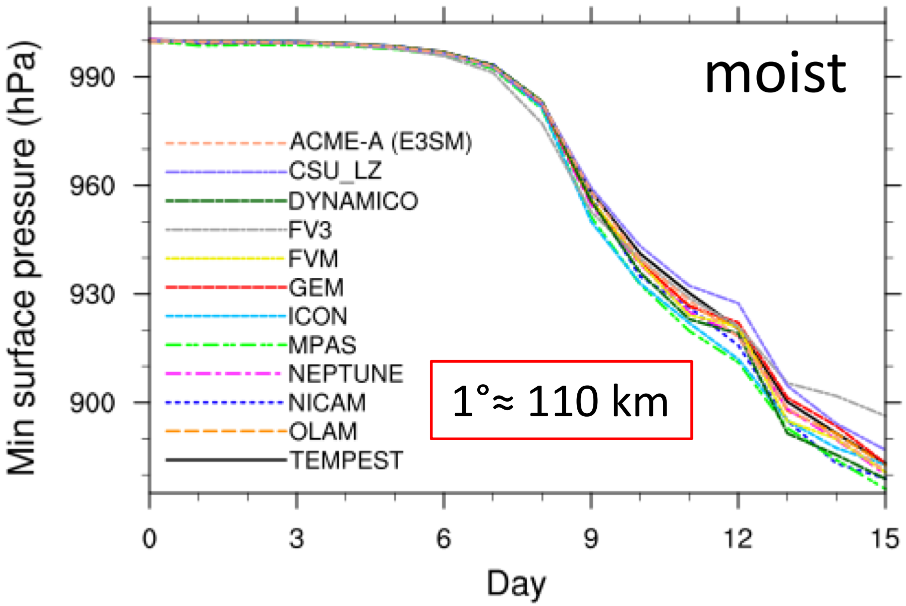
Impact of Resolution: Moist ps minima



CAM FV/SE Baroclinic wave (preciponly)

Moist, various Δx

DCMIP models



Baroclinic wave (preciponly)

moist

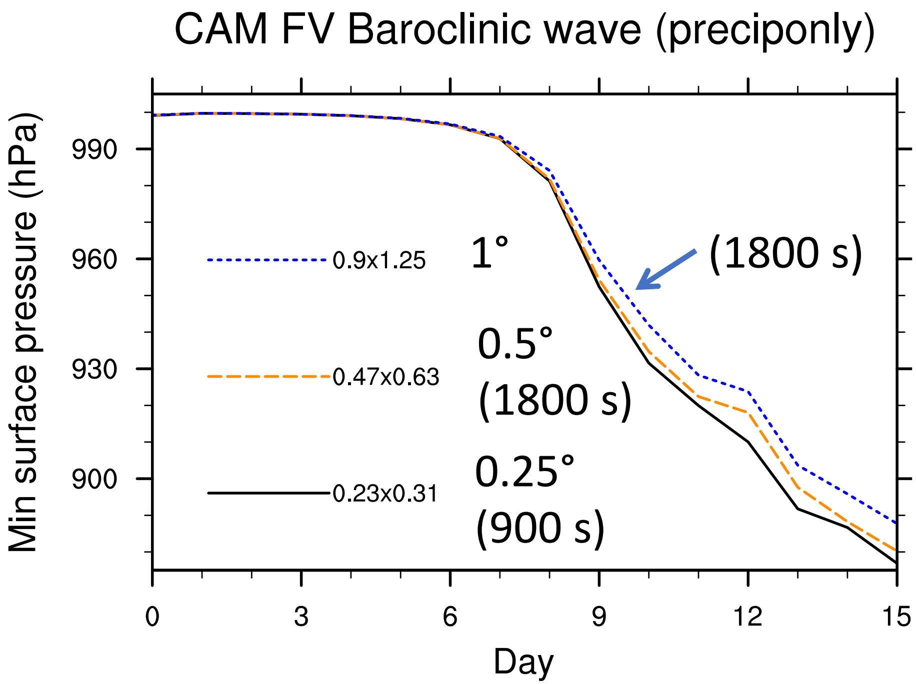
1°≈ 110 km

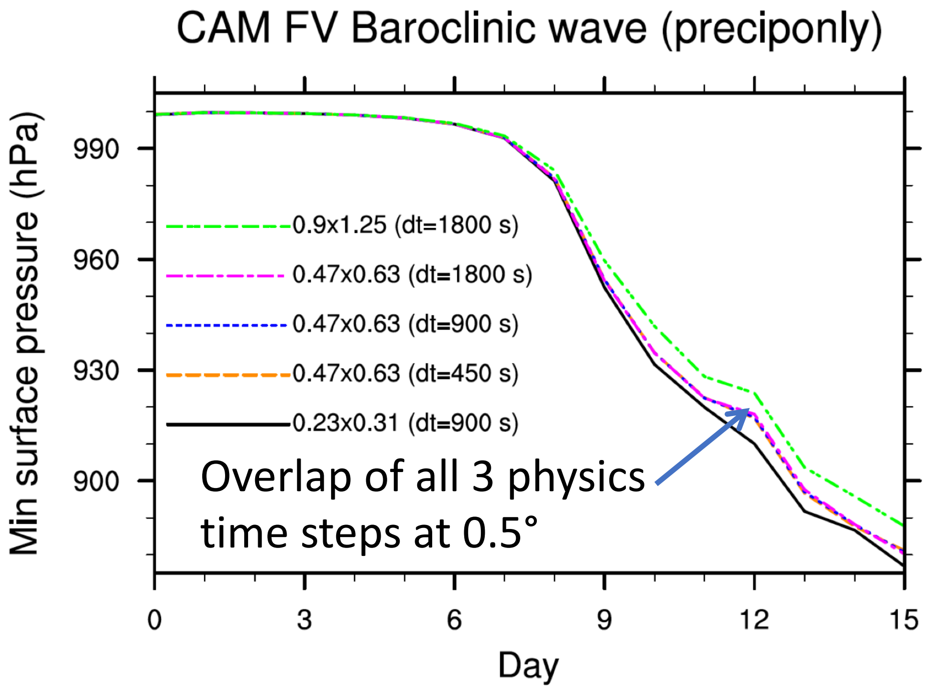
- **Increasing the horizontal resolutions** from 1° (110 km) to 0.5° /0.25° (55/28 km) **strengthens the surface pressure minima** in moist FV & SE, mimics spread of DCMIP models
- Possible pathway: higher precipitation rates force intensification
- ps_{min} spread in DCMIP models includes the effects of the effective resolutions

DCMIP-2016

Impact of Physics time step: Moist ps minima

Increased resolutions often come with decreased physics time steps


CAM FV Baroclinic wave (preciponly)

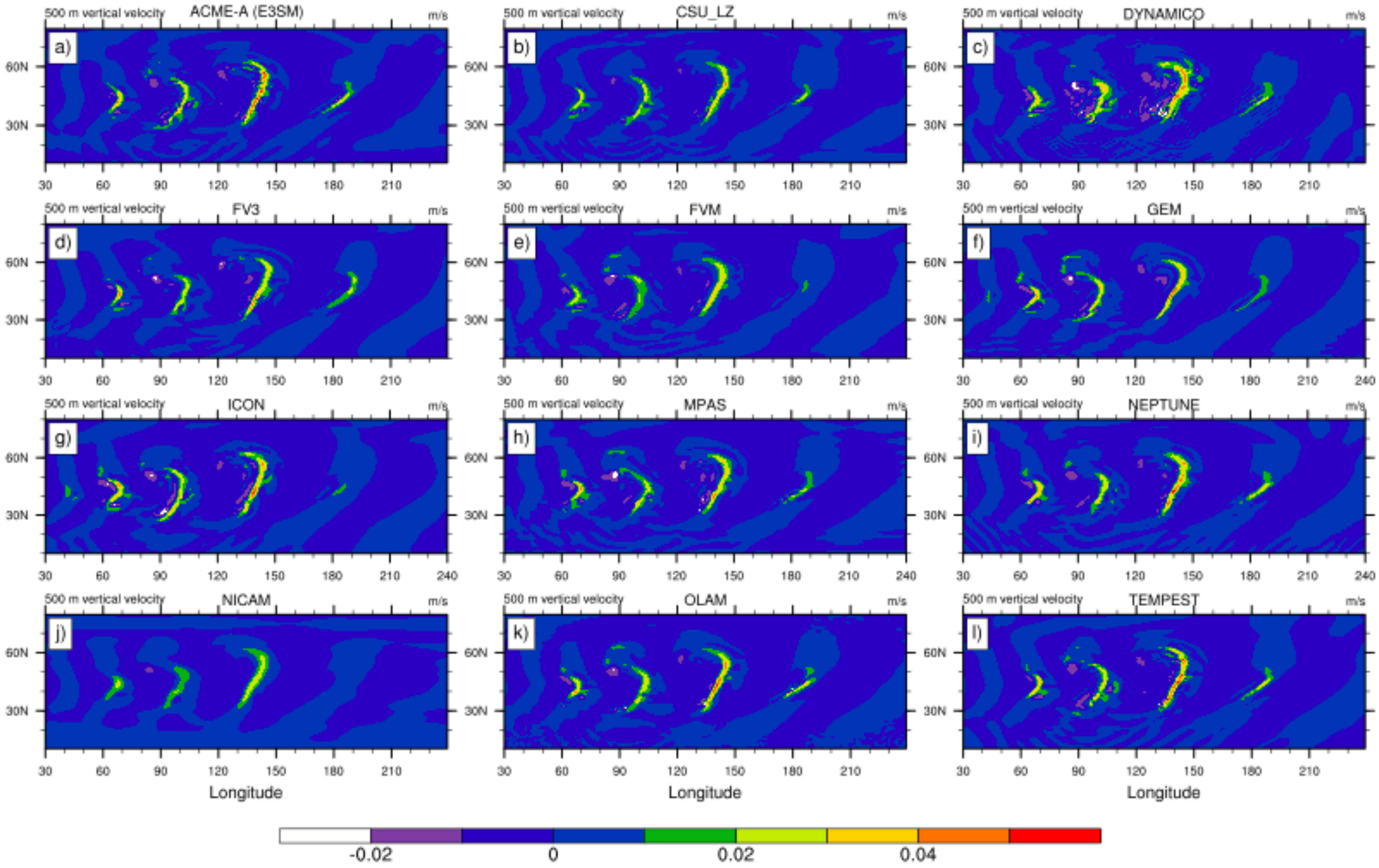

CAM FV Baroclinic wave (preciponly)

Overlap of all 3 physics time steps at 0.5°

- **Varying the physics time step** from 1800 s, 900 s to 450 s has **very little impact** on the minimum surface pressure evolution in CAM FV(0.5°)
- Suggests that physics time step is not the main driver for the model differences among DCMIP models

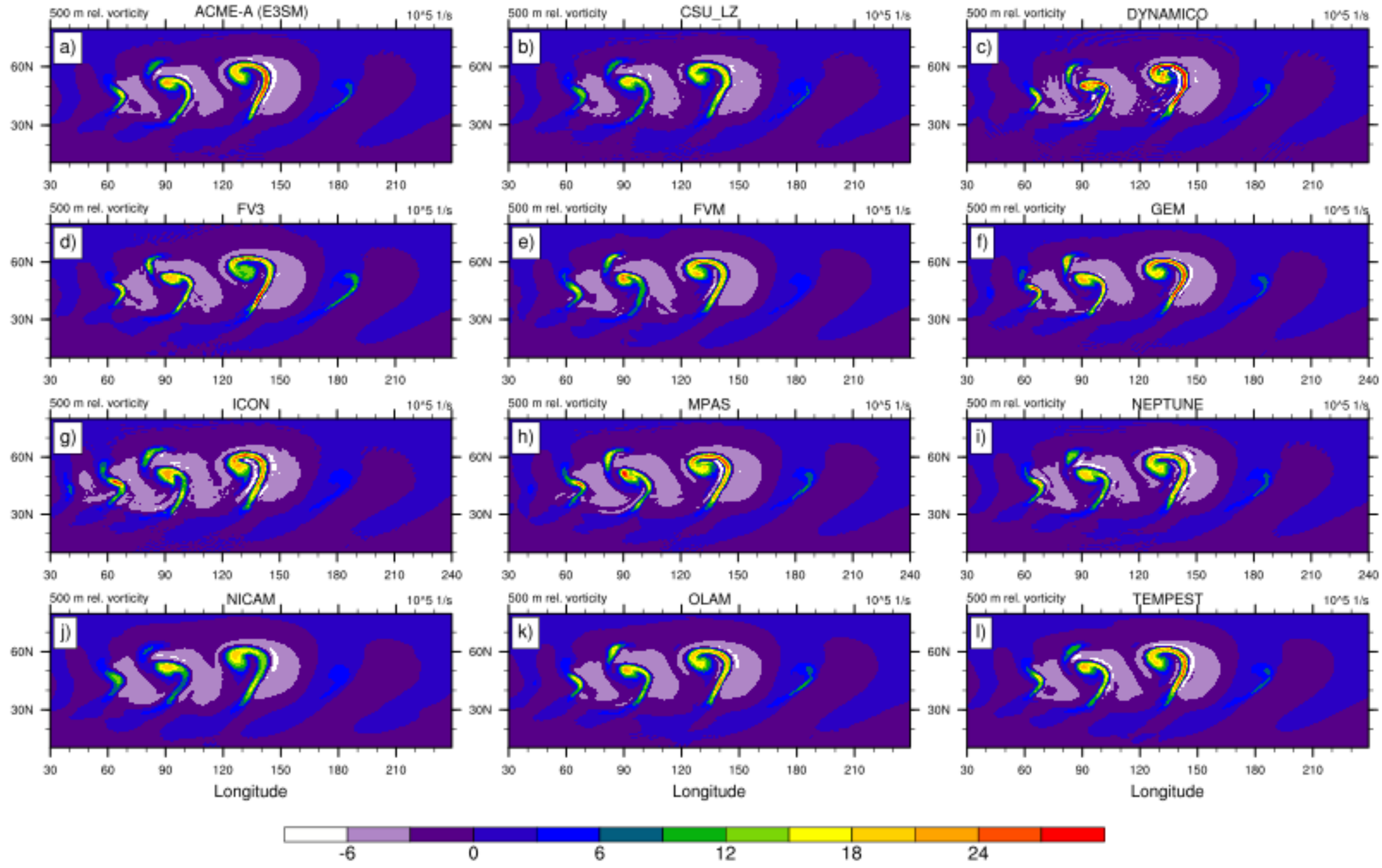
DCMIP-2016

500 m w: DCMIP-2016 moist baroclinic wave (day 10)



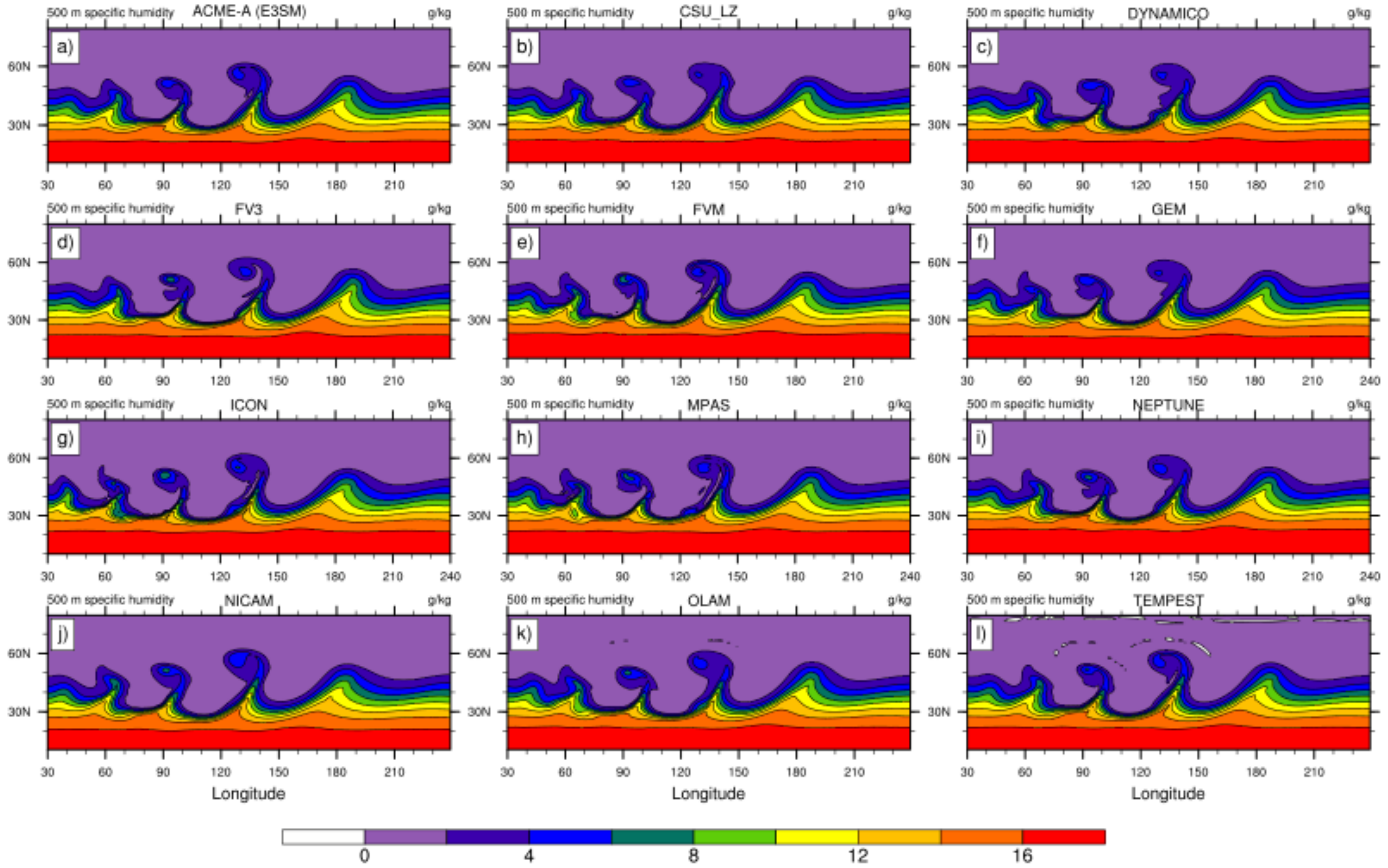
- Updraft regions and precipitation bands overlap

500 m rel. vorticity: DCMIP-2016 moist baroclinic wave (day 10)



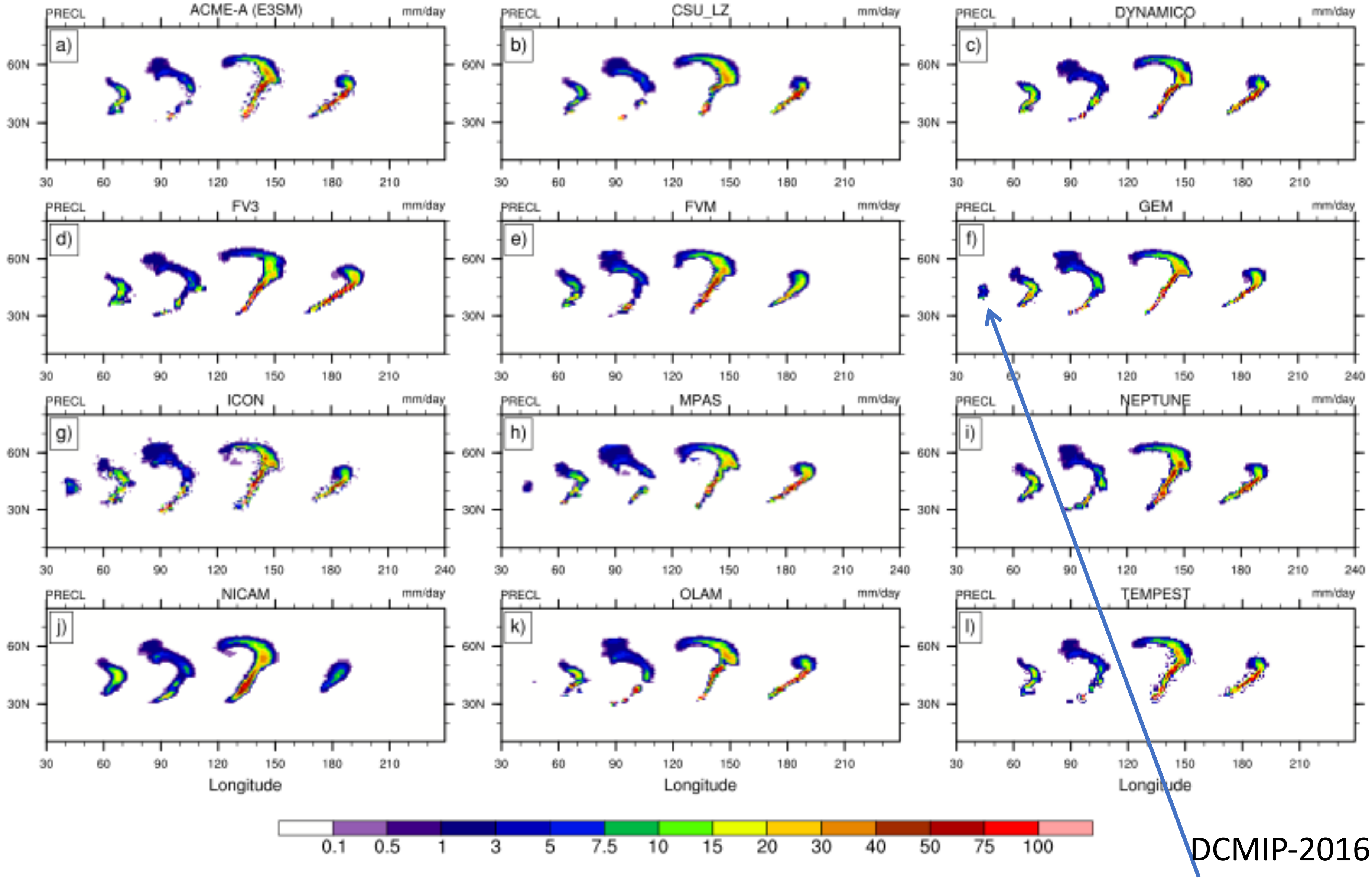
- Four main vortex structures, sharp vorticity gradients

500 m q: DCMIP-2016 moist baroclinic wave (day 10)



- Sharp specific humidity frontal zones, aligned with T fronts

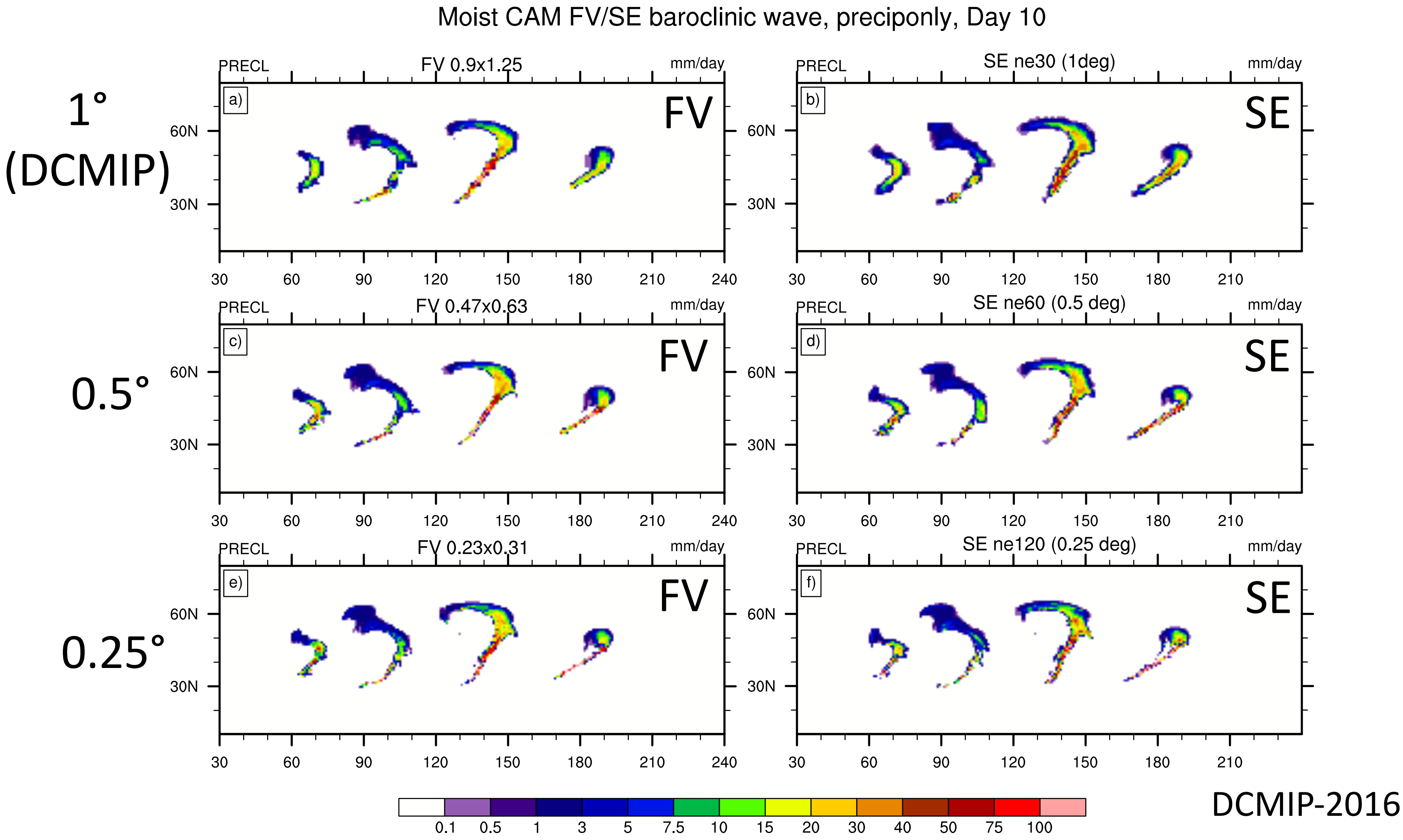
Precipitation rates in the moist baroclinic wave (day 10)



DCMIP-2016

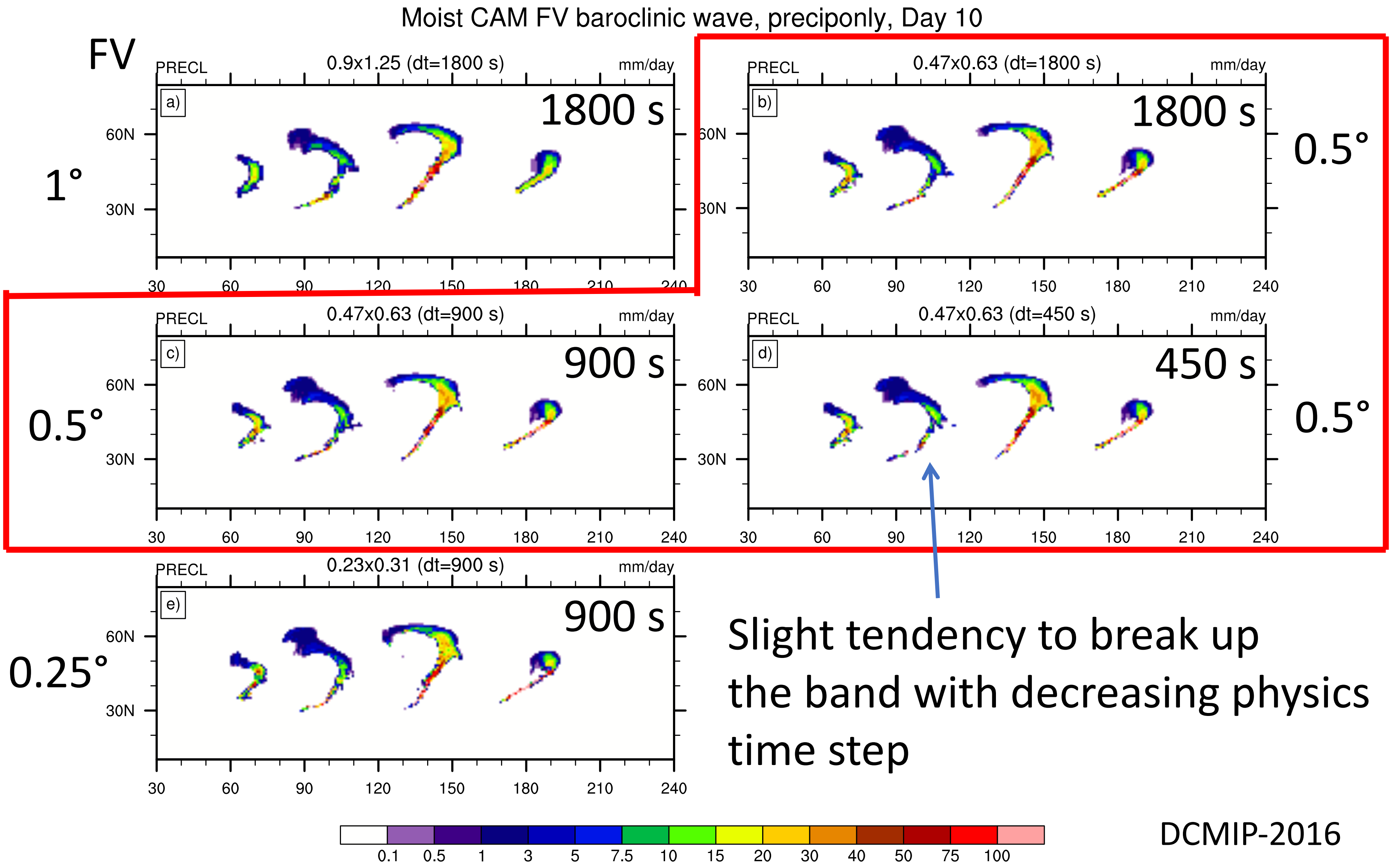
- Narrow precip bands, tend to break up, some: 5th precip band

Precipitation rates: Impact of Resolution



- Increasing horizontal resolution sharpens the precipitation patterns and increases the peaks in CAM FV and CAM SE

Precipitation rates: Impact of Physics Time Step

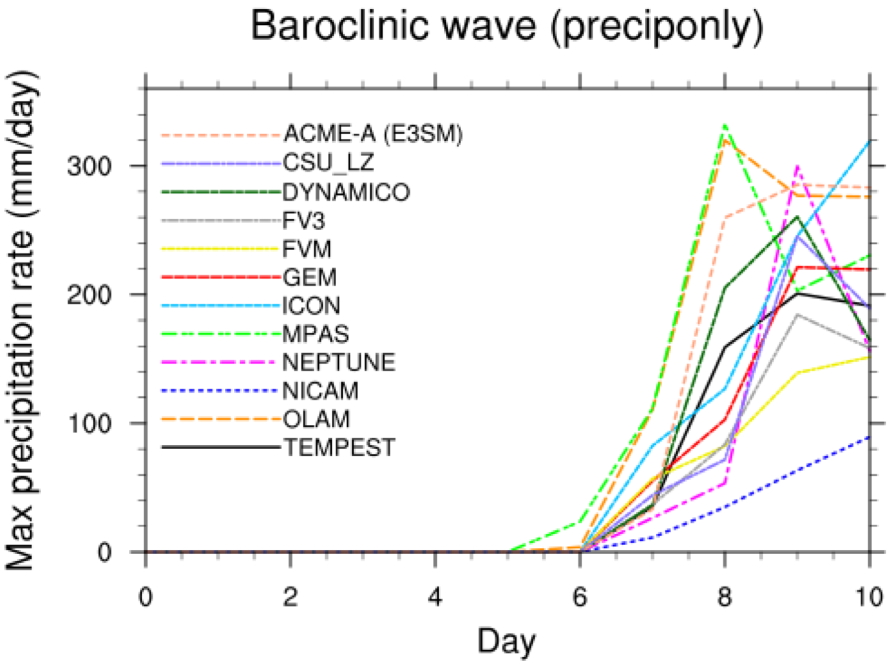


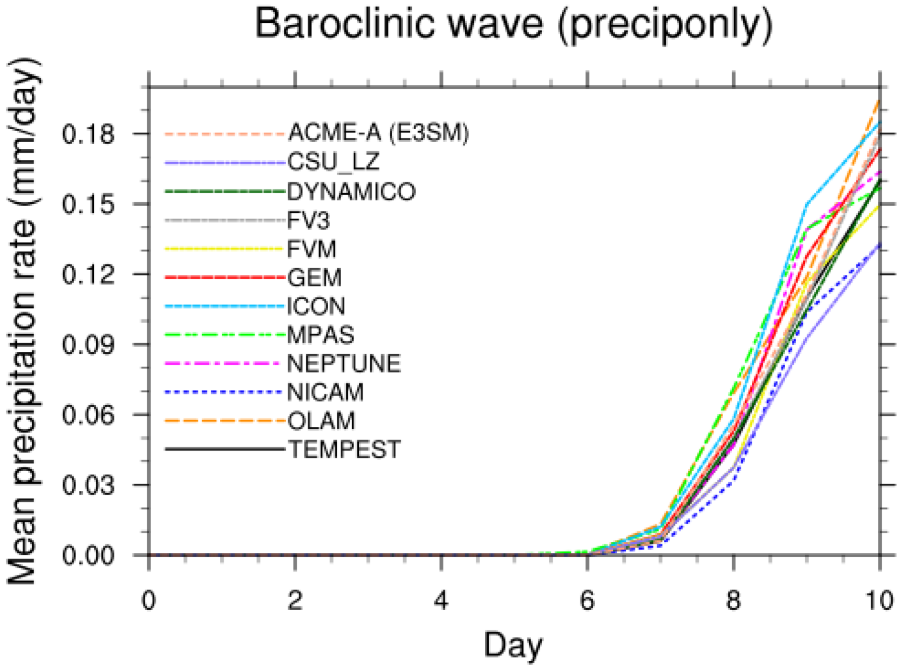
Slight tendency to break up the band with decreasing physics time step

DCMIP-2016

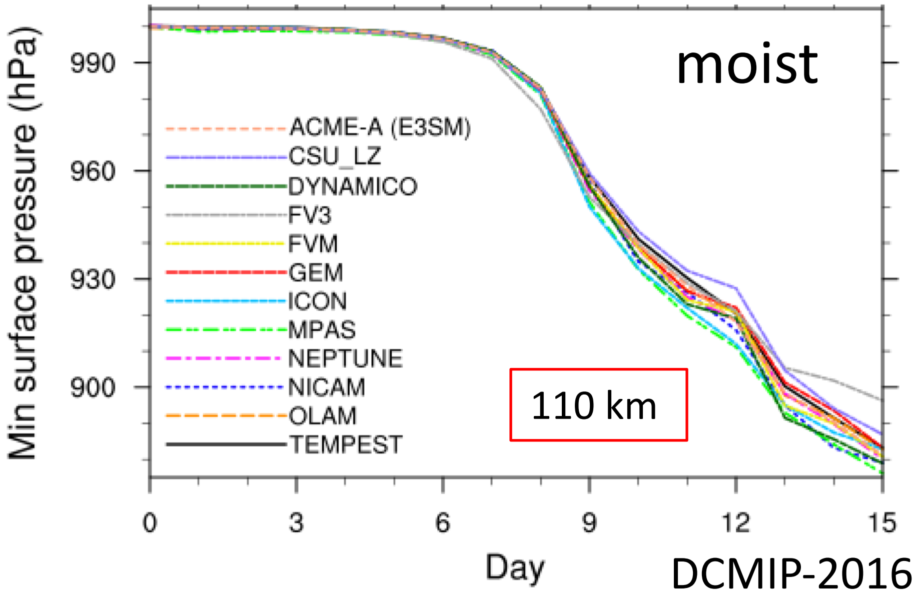
- Physics time steps in CAM FV have little effect on patterns

Precipitation rates: Max and Horizontal-Mean



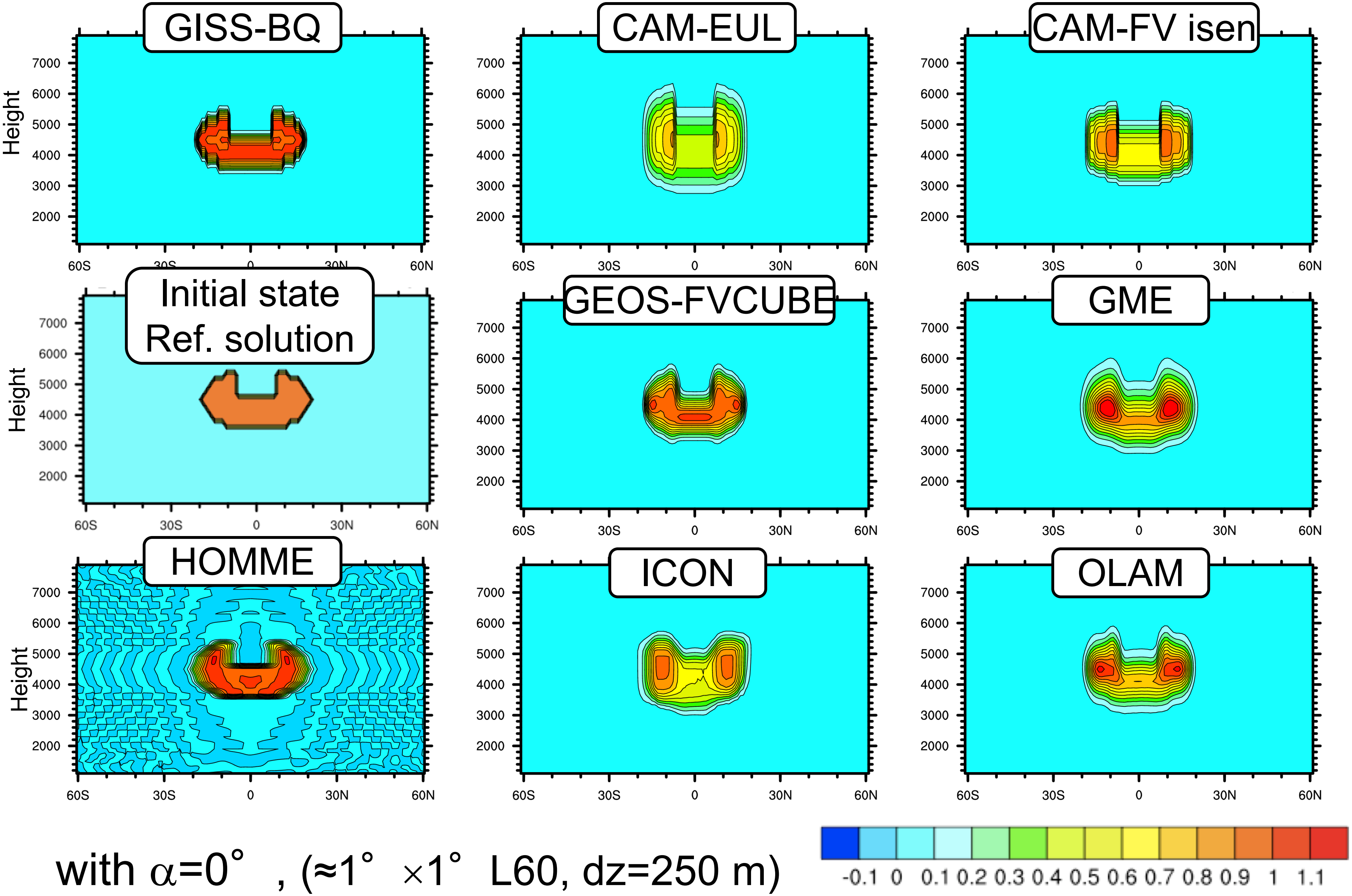


- Max precipitation rates vary widely
- Horizontal-means show systematic spread
- Evaluate whether this explains systematic ps_{min} spread, might not be enough (check advection properties)



DCMIP-2016

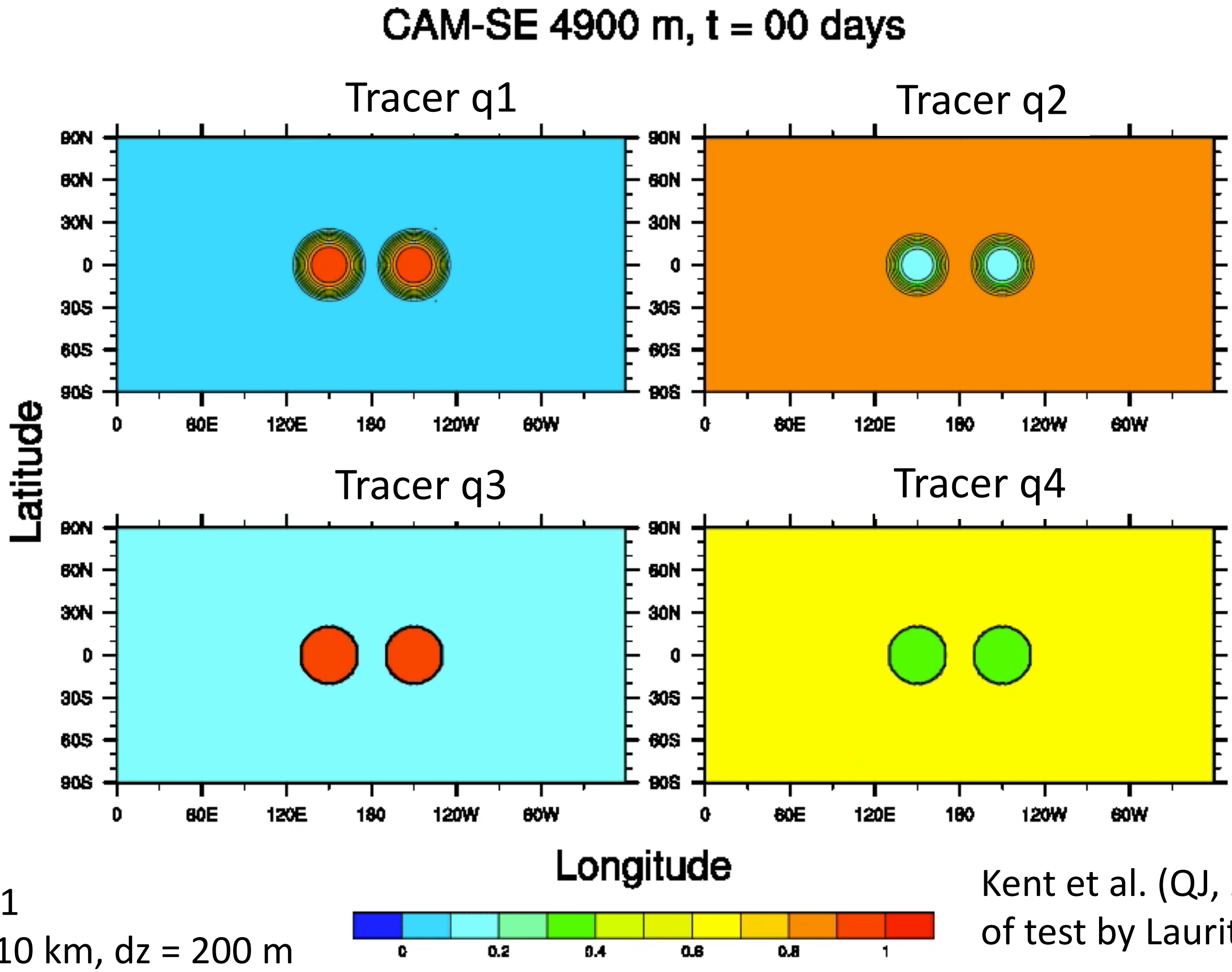
DCMIP-2008 advection: Slotted Ellipse after 12 Days, shows diffusive properties of advection scheme (important for moisture species)



with α=0°, (≈1° ×1° L60, dz=250 m)

DCMIP-2012
3D Advection: Deformational Flow

Test 11: 4 correlated tracers in a reversing sheared flow

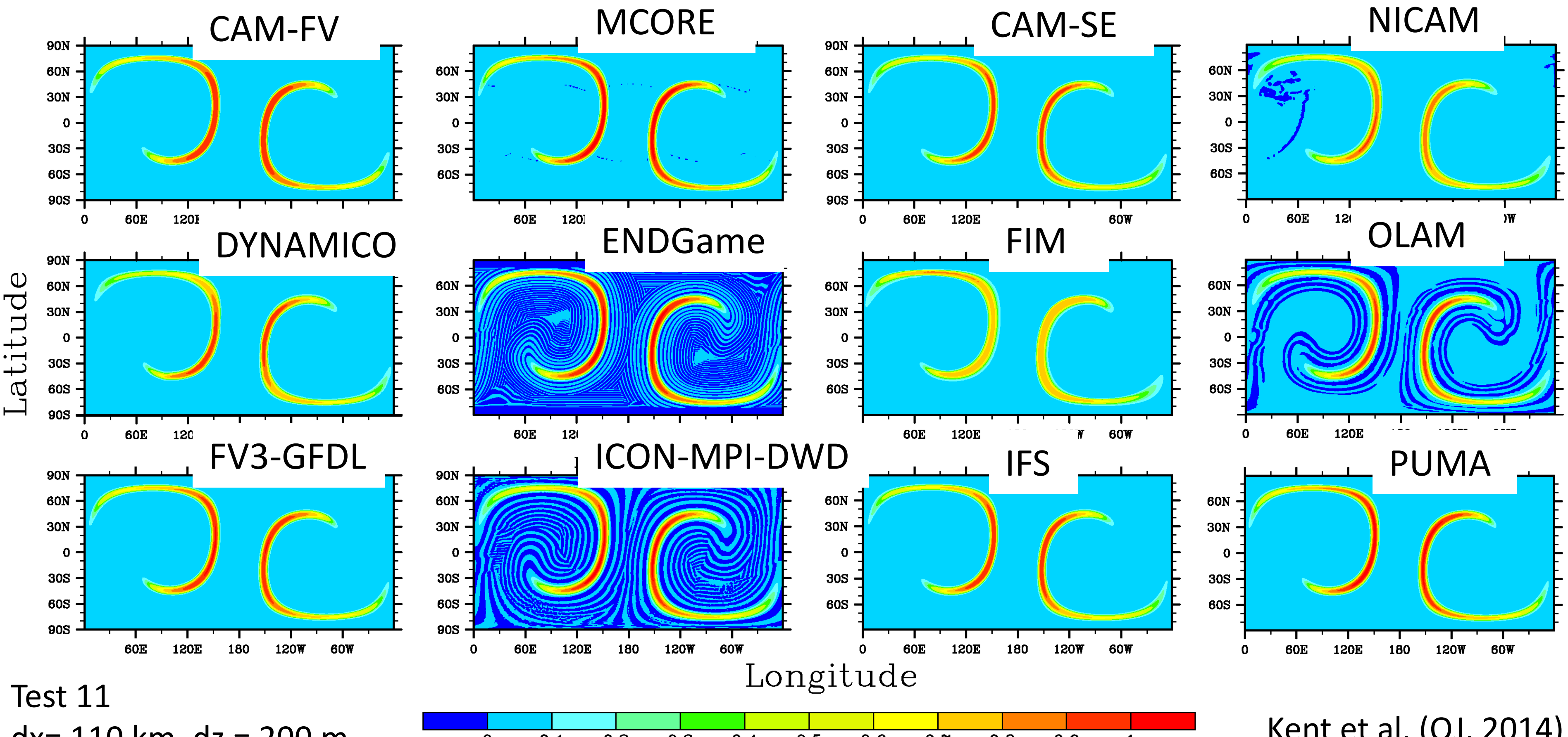


Test 11
dx= 110 km, dz = 200 m

Kent et al. (QJ, 2014): presents 3D version of test by Lauritzen and Thuburn (QJ, 2012)

DCMIP-2012
3D Advection: Deformational Flow

Test 11: Correlated tracers in a reversing sheared flow (tracer q1 at day 6)



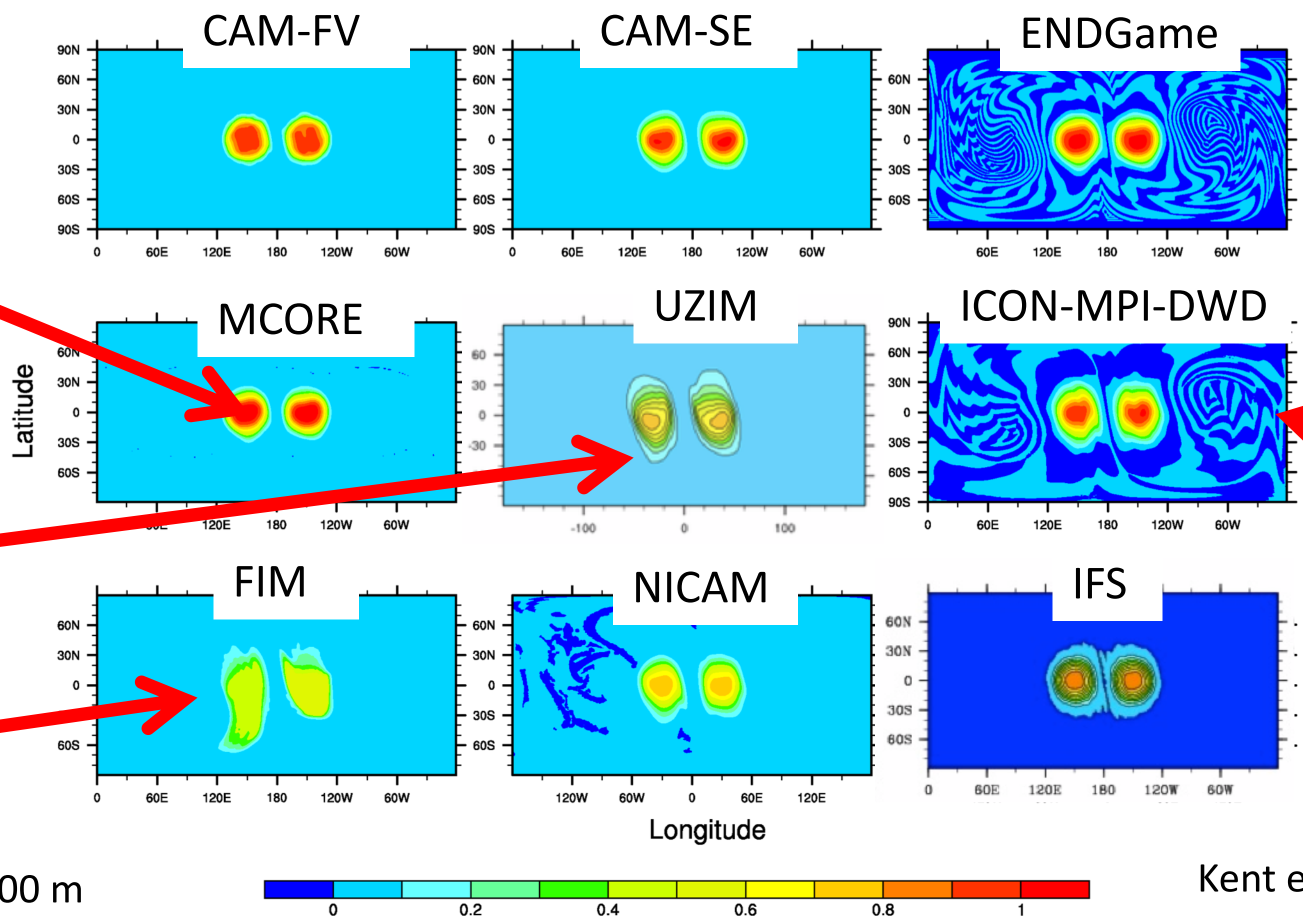
Test 11
dx= 110 km, dz = 200 m

Kent et al. (QJ, 2014)

DCMIP-2012
3D Advection: Deformational Flow

Test 11: Tracer q1 at day 12 after the flow reversed and tracer returned

Test 11 4900 m, t = 12 days



Overshoots

Degree of deformation

Diffusive properties

Under-shoots

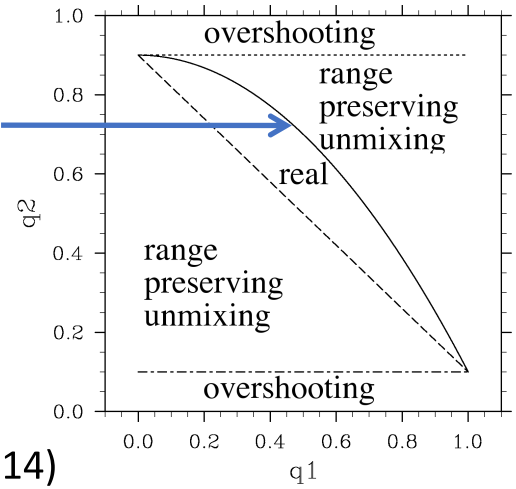
Test 11
dx= 110 km, dz = 200 m

Kent et al. (QJ, 2014)

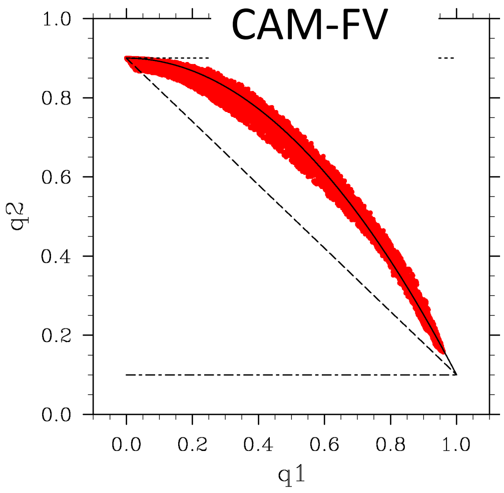
DCMIP-2012
3D Advection: Deformational Flow

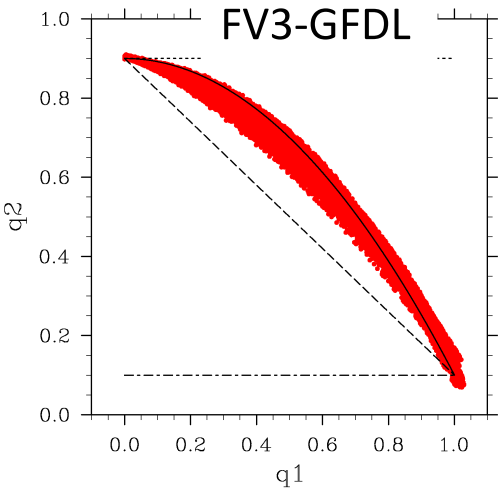
Test 11: Correlated tracers q1 & q2: Mixing diagnostics at day 6

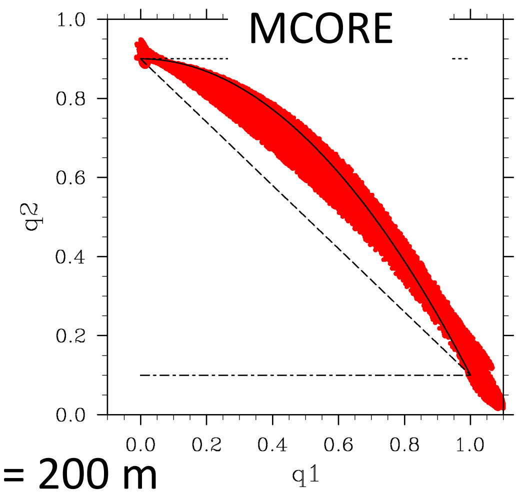
Functional relationship between q1 and q2

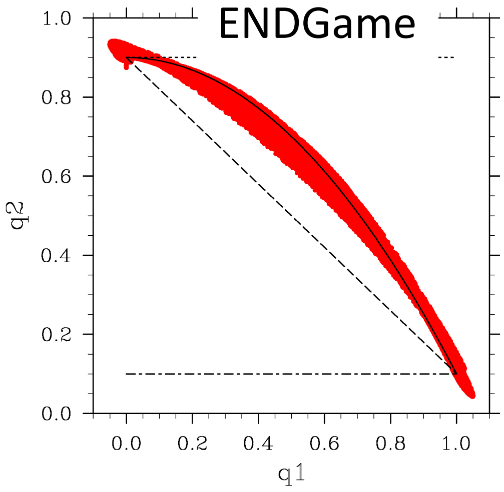


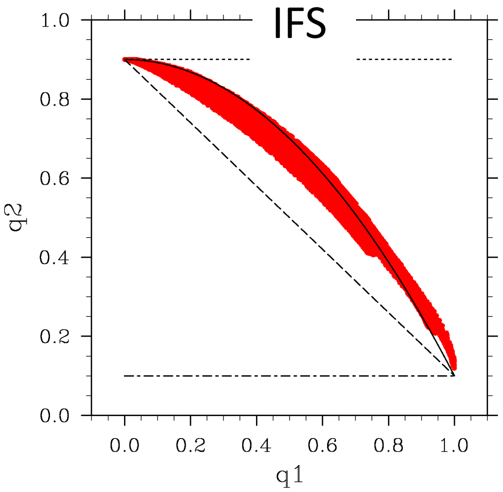
Kent et al. (QJ, 2014)


CAM-FV


FV3-GFDL

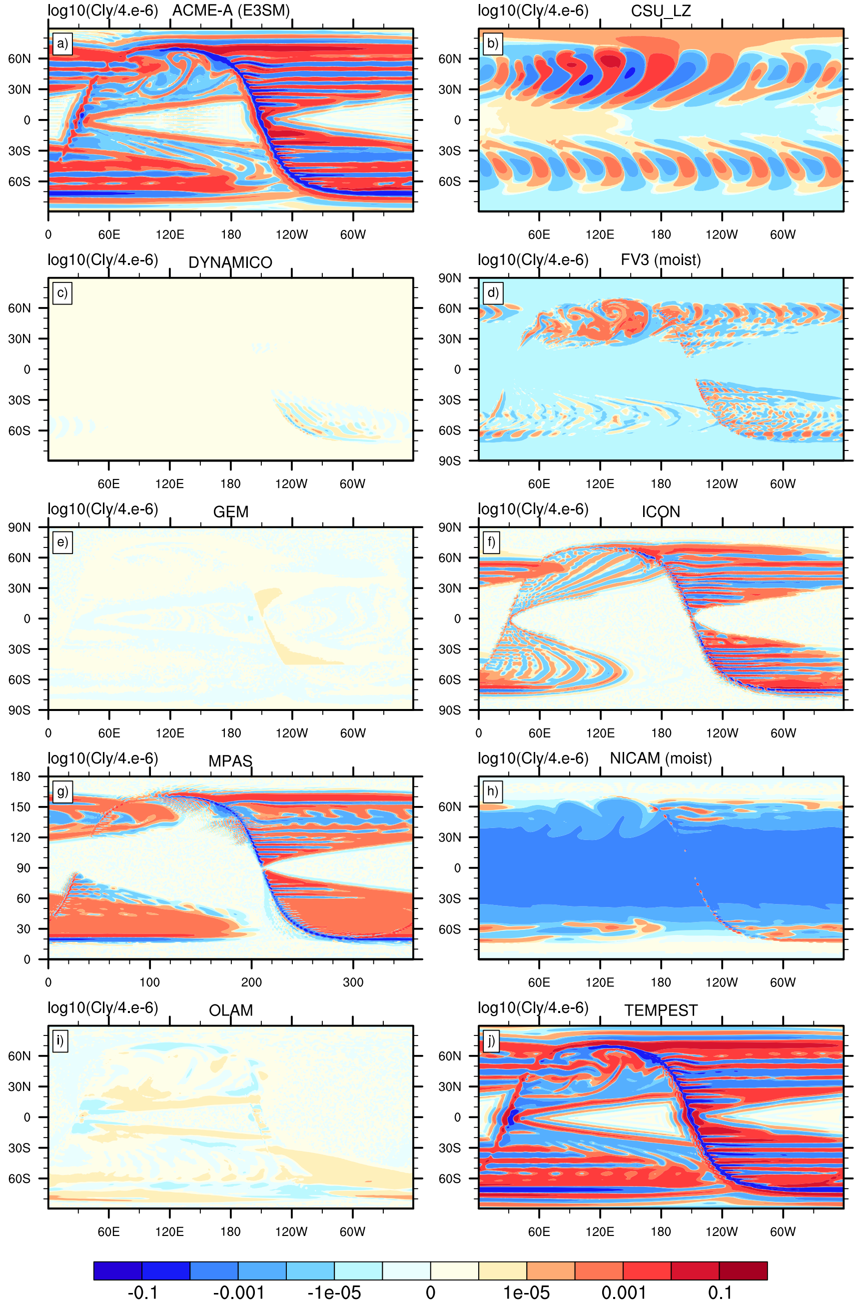

MCORE


ENDGame


IFS

dx= 110 km, dz = 200 m

DCMIP-2016: Toy chemistry & Tracer consistency



Dry baroclinic wave test (DCMIP-2016)

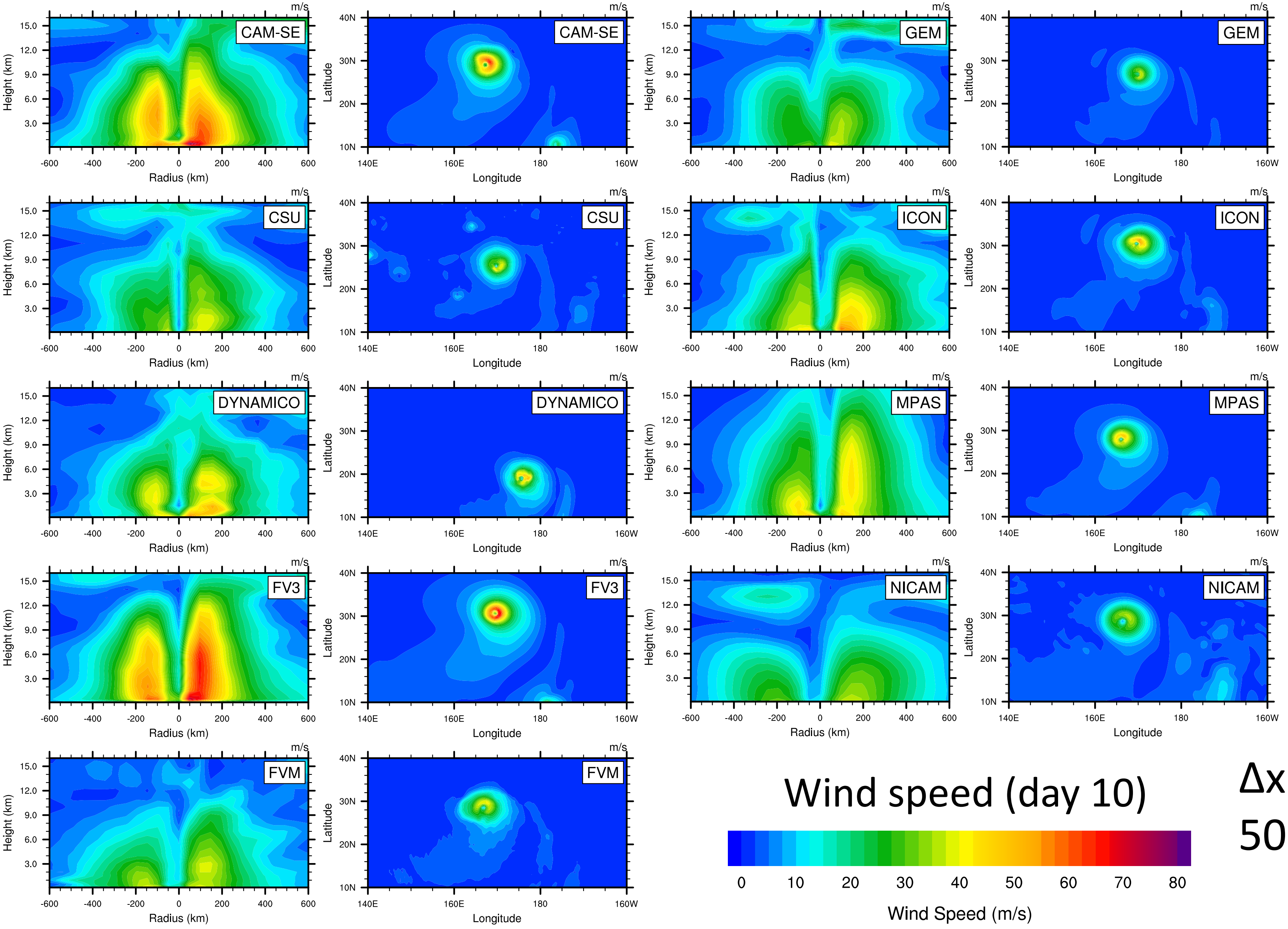
Vertically integrated tracers (weighted sum) at day 10

(Δx=110 km L30)

- Correlated tracer should stay perfectly correlated
- Analytical solution: zero variations
- Magnitudes of the tracer errors differ greatly ($10^{-1} – 10^{-6}$), caused by limiters, diffusion and monotonic constraints in the numerics

DCMIP-2016 Snapshots: Tropical Cyclone

at z=1km



Wind speed (day 10)

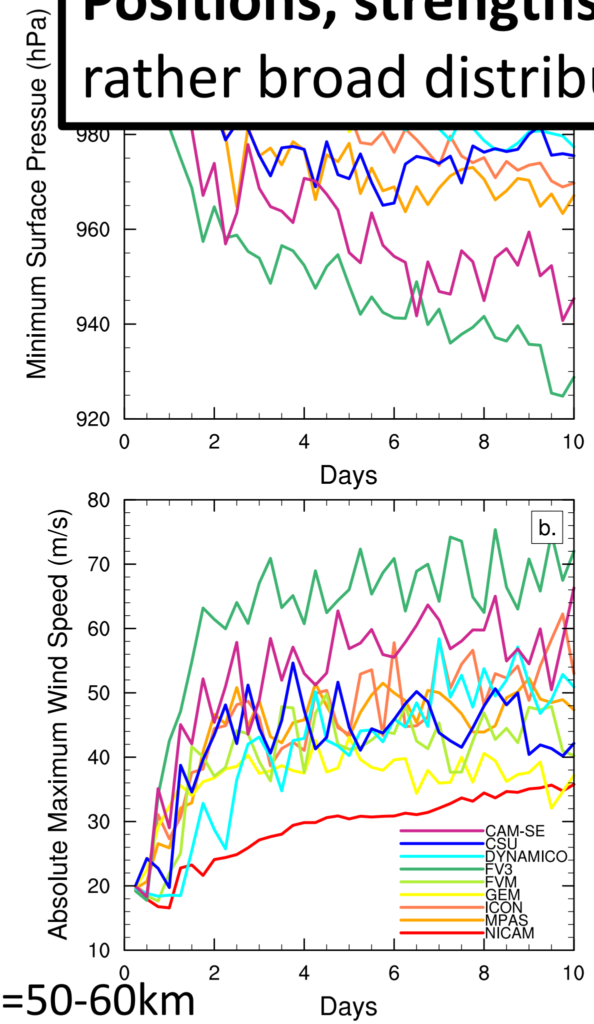
Δx=
50-60km

Description of the initial conditions and simple-physics: Reed and Jablonowski (2011, 2012)

Snapshots: Tropical Cyclone

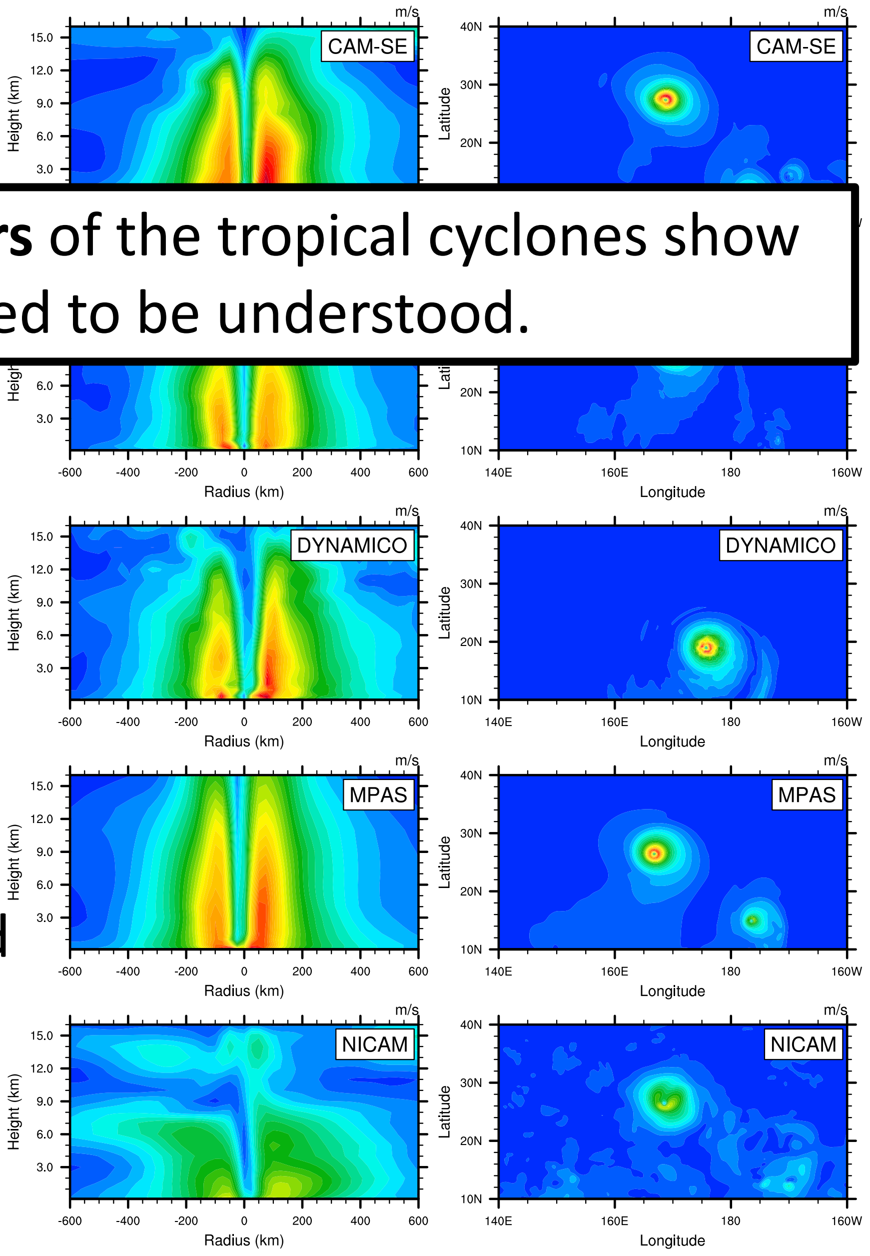
Wide spread: Evolution of the **minimum surface pressure** and **maximum wind speed**

Positions, strengths and diameters of the tropical cyclones show rather broad distributions that need to be understood.



Δx=50-60km

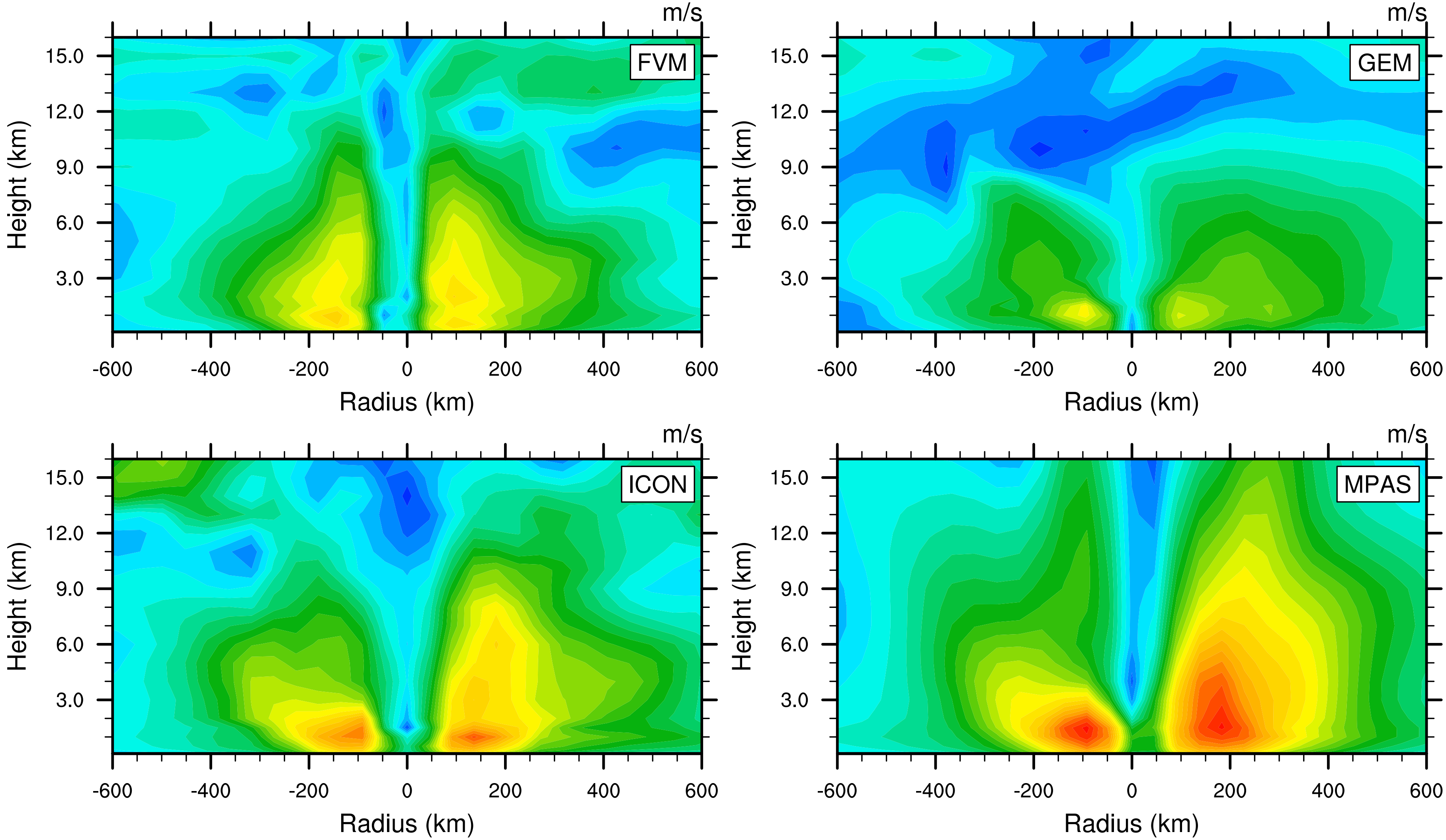
High resolutions (Δx=25-30 km)



Wind speed (day 10): Stronger, more structured cyclones (except NICAM)

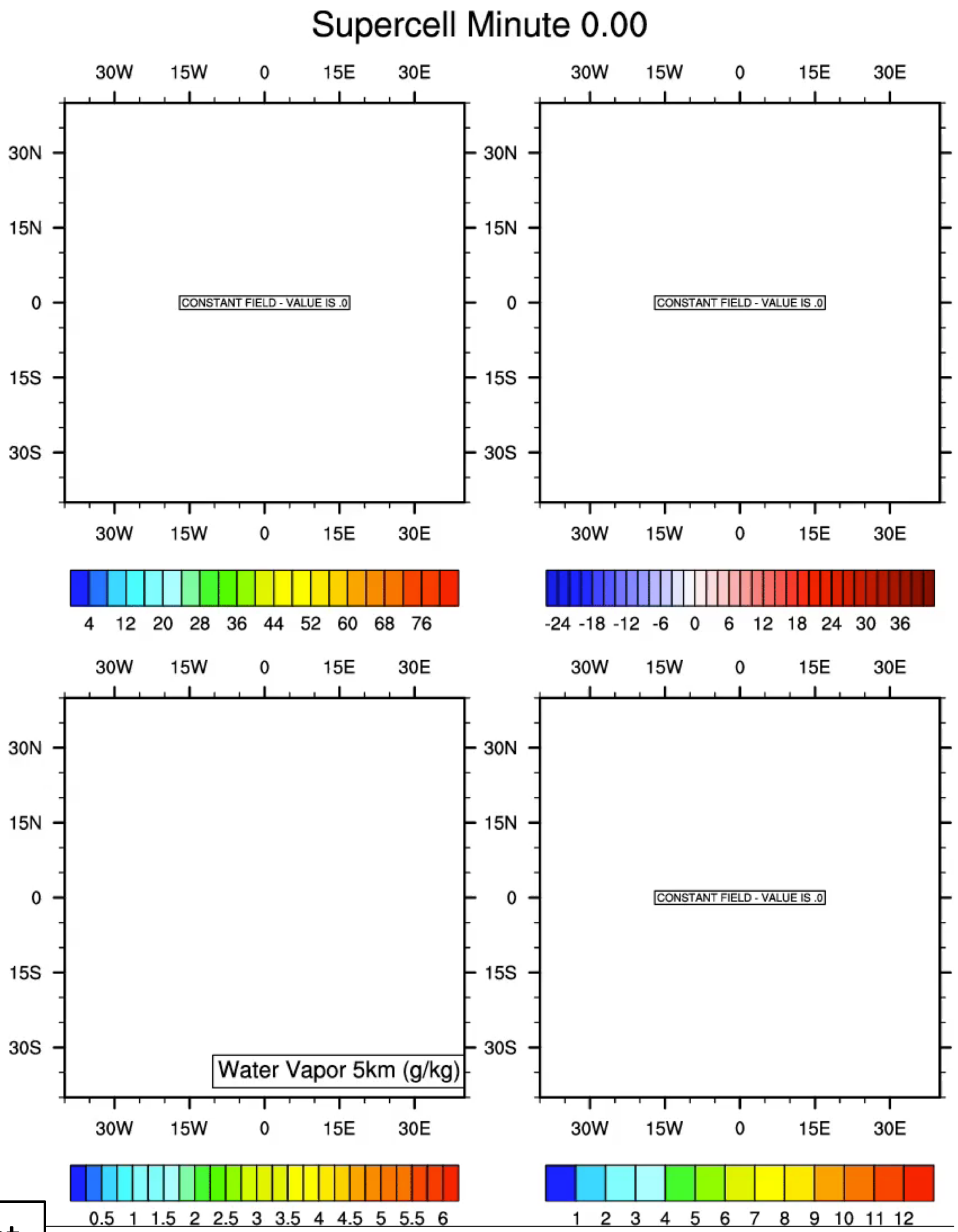
DCMIP-2016 Snapshots: Tropical Cyclone, wind at day 10

DCMIP encourages exploration of new test configurations: Alternative representation of the simplified planetary boundary layer (more mixing, by Bryan) modifies the shapes of the TC



DCMIP-2016 Snapshots: Supercell

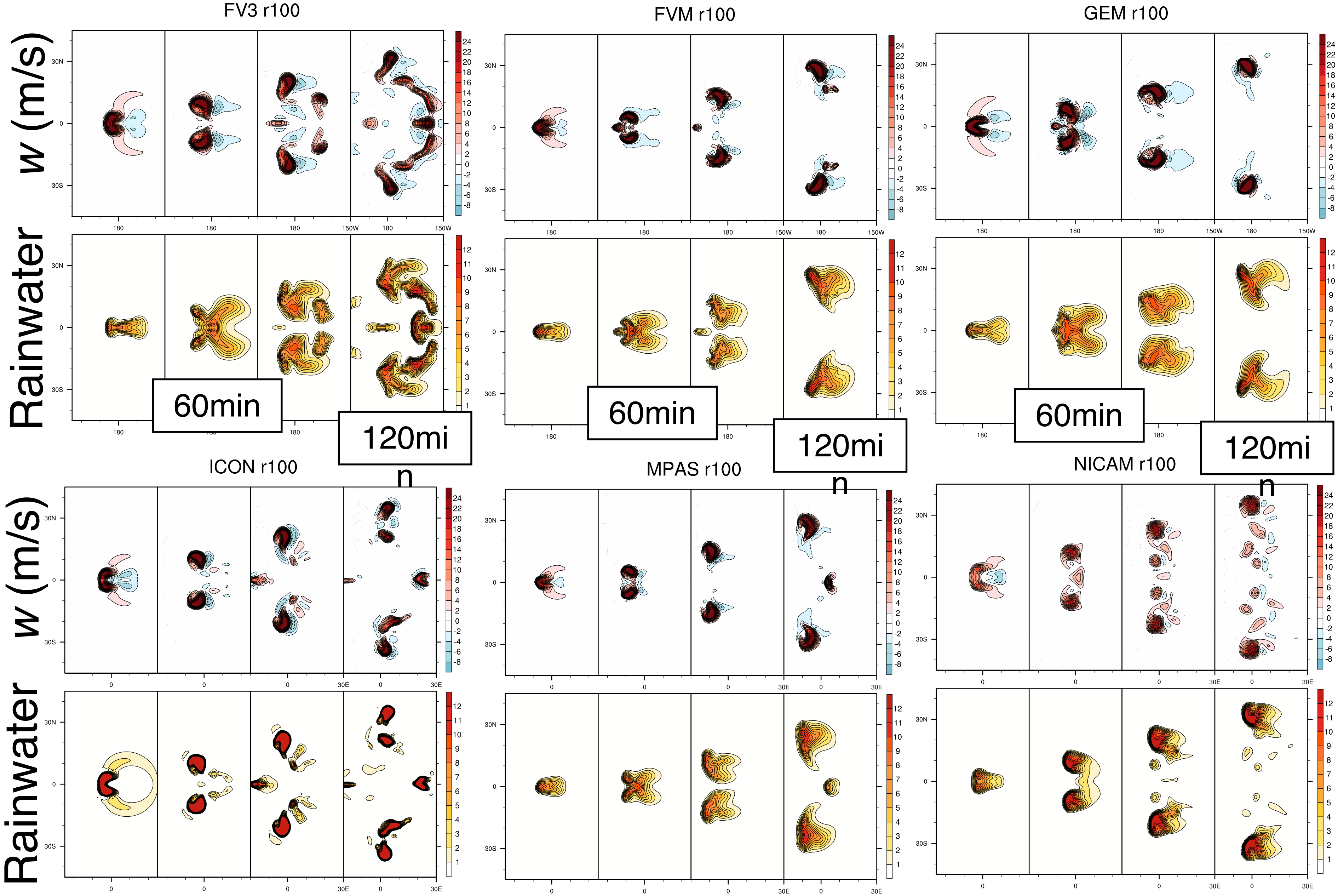
Computed on a reduced-size Earth at non-hydrostatic scales with Kessler precipitation (no PBL or surface fluxes): See Klemp et al. (2015)



Model Tempest

DCMIP-2016 Snapshots: Supercell with 1km grid spacing

Evolution of supercell (no rotation) at 5km: supercell always split, but shapes vary widely



DCMIP-2016 Snapshots: Supercell after 120 minutes

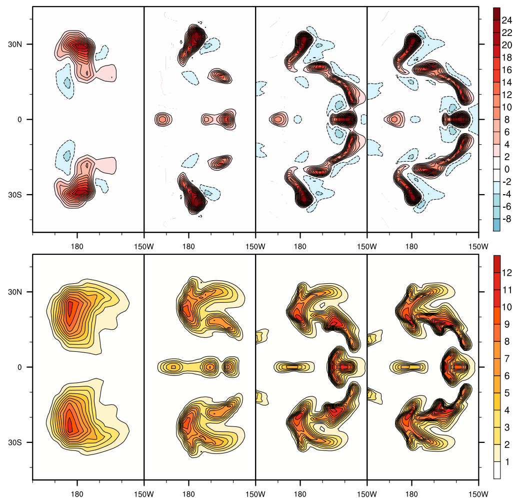
Dependence on resolution: some signs of convergence at 1km and finer

w (m/s)

Rainwater

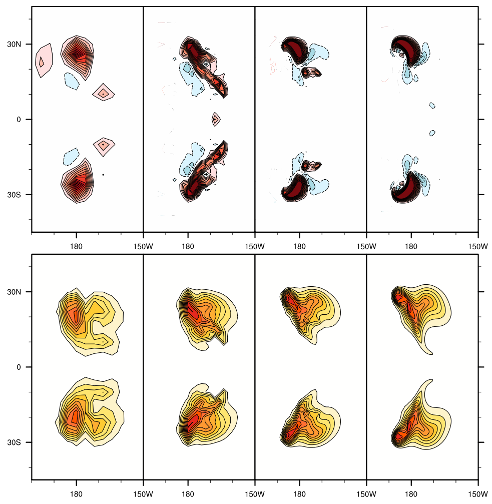
at z=5km

FV3, +7200s, r400 -> r50



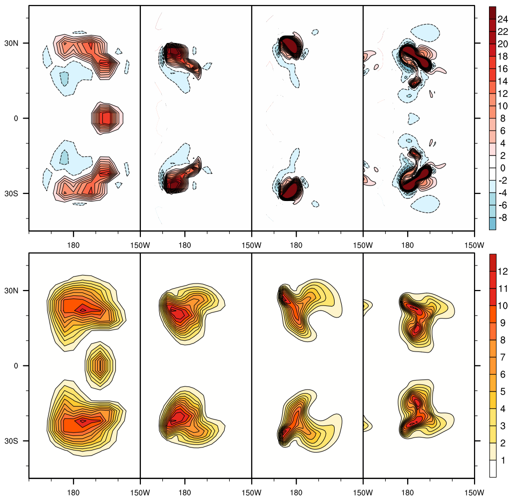
at z=5km

FVM, +7200s, r400 -> r50



at z=5km

GEM, +7200s, r400 -> r50



4km 2km 1km 0.5km

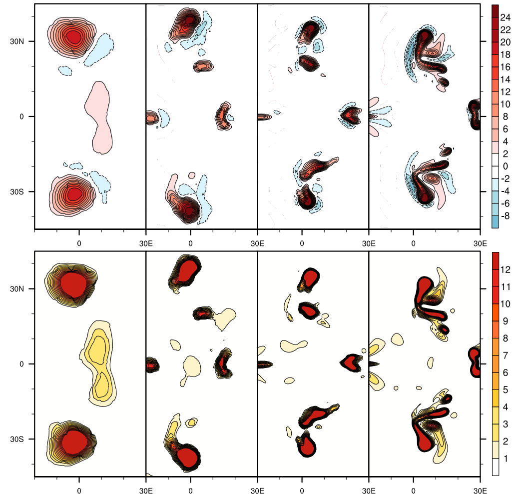
4km 2km 1km 0.5km

4km 2km 1km 0.5km

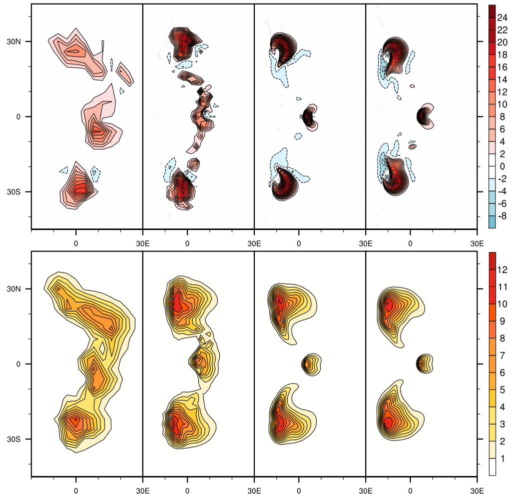
w (m/s)

Rainwater

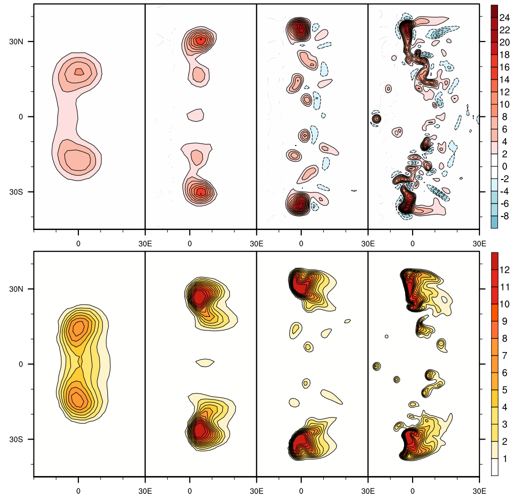
ICON, +7200s, r400 -> r50



MPAS, +7200s, r400 -> r50

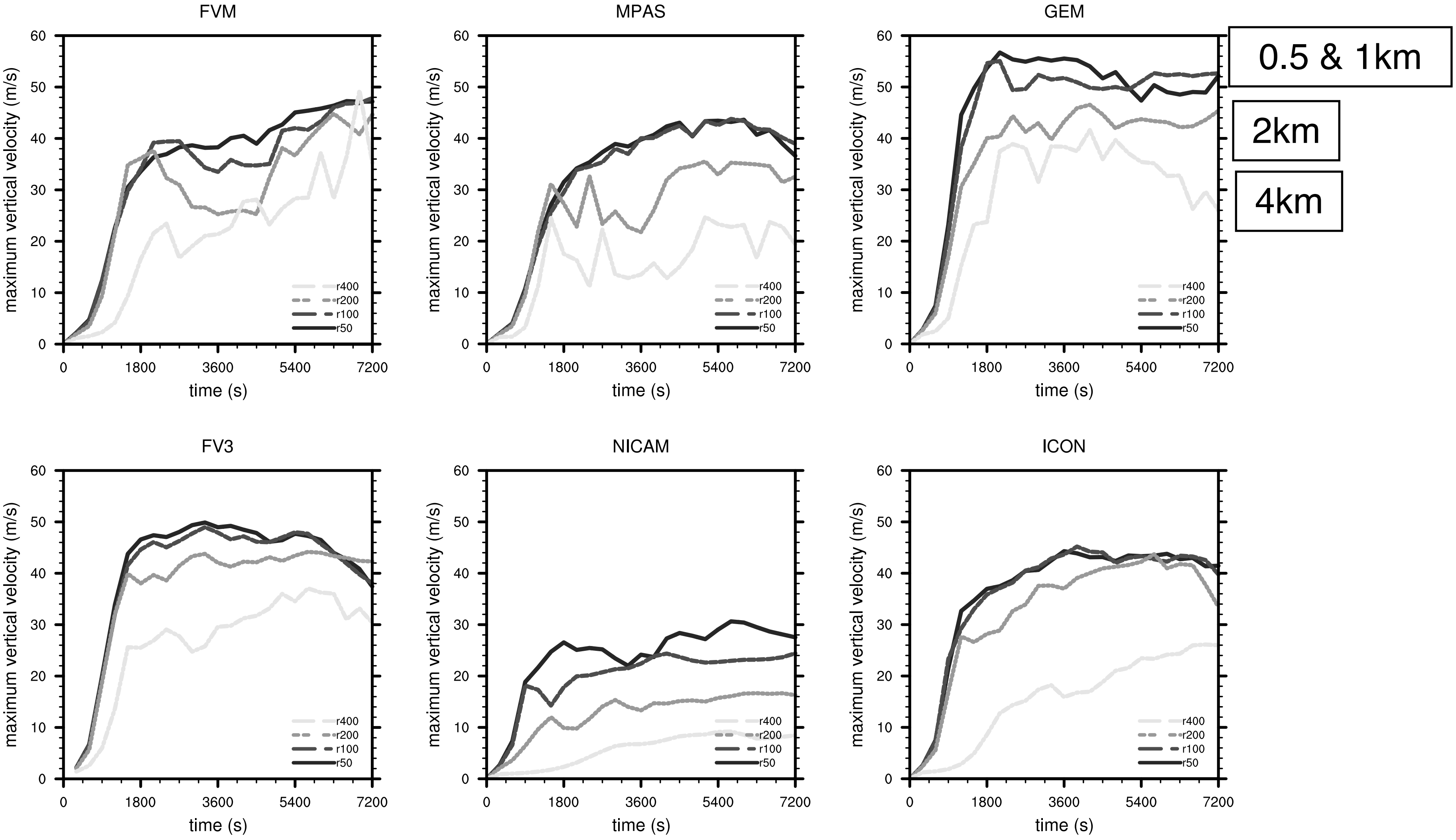


NICAM, +7200s, r400 -> r50



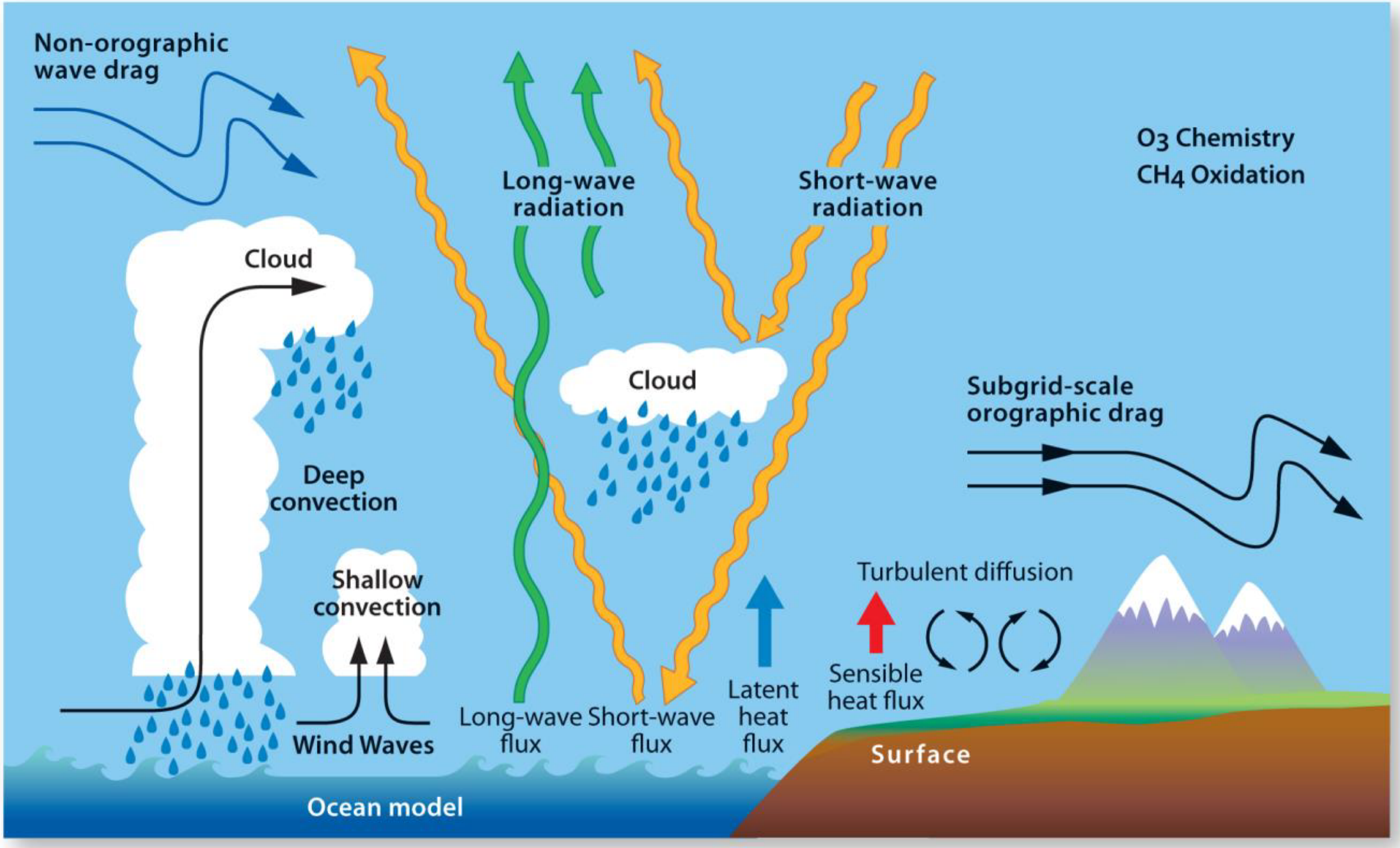
DCMIP-2016 Snapshots: Supercell at various resolutions

Maximum vertical velocities: single model shows signs of convergence at dx=dy=1 km spacing and finer, but inter-model spread is large



Gives insight into physics-dynamics coupling and the impact of diffusion

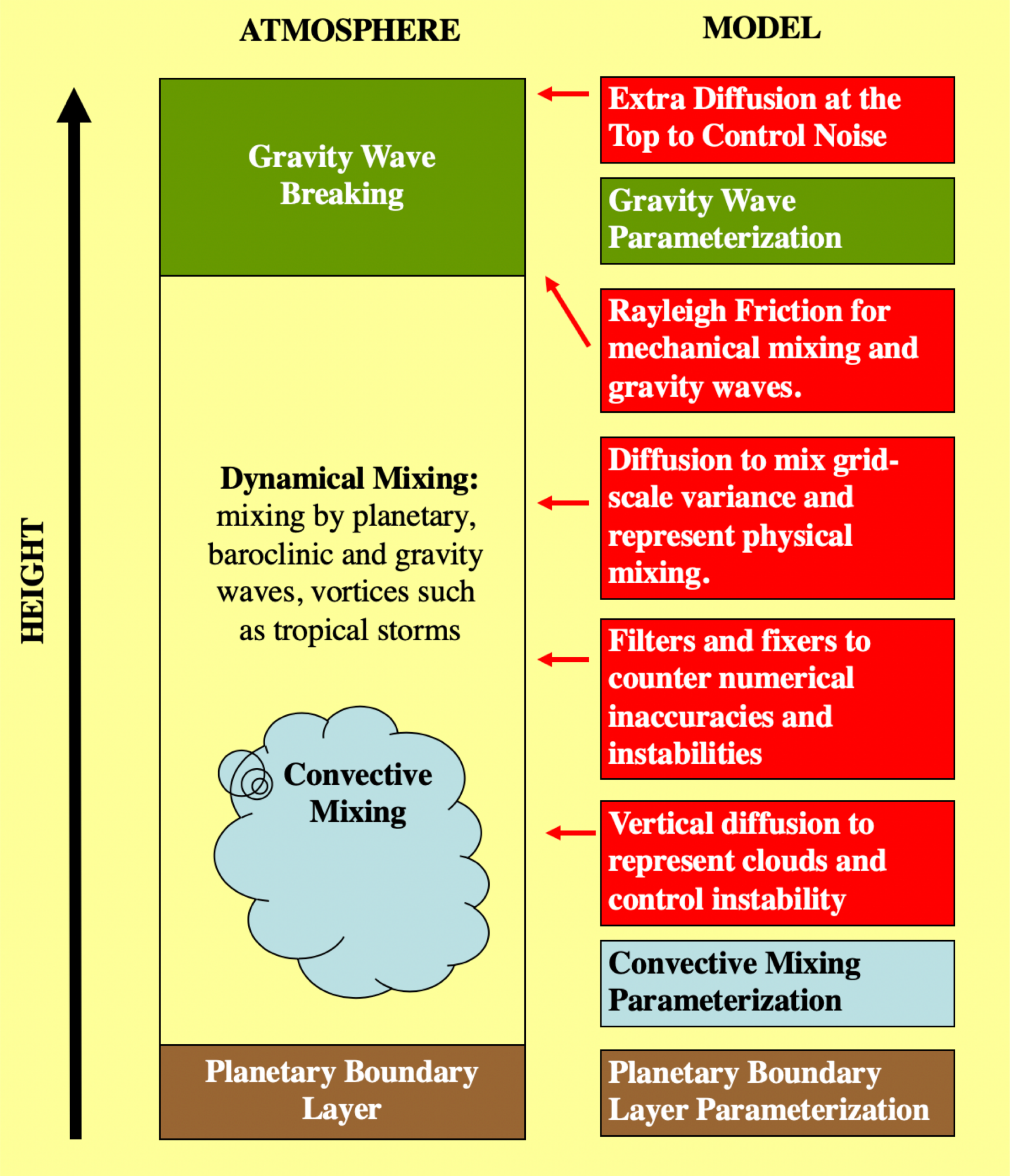
Ideas for other test cases: Processes



E.g.: Isolate impact of a simple non-orographic gravity wave drag scheme on circulation use prescribed gravity wave spectrum and a saturation condition to break waves

Danger zone:

Numerical mixing processes and physical mixing processes can be hard to disentangle (Numerical scheme might be used as a closure)



ATMOSPHERE

MODEL

HEIGHT

Gravity Wave Breaking

Dynamical Mixing: mixing by planetary, baroclinic and gravity waves, vortices such as tropical storms

Convective Mixing

Planetary Boundary Layer

Extra Diffusion at the Top to Control Noise

Gravity Wave Parameterization

Rayleigh Friction for mechanical mixing and gravity waves.

Diffusion to mix grid-scale variance and represent physical mixing.

Filters and fixers to counter numerical inaccuracies and instabilities

Vertical diffusion to represent clouds and control instability

Convective Mixing Parameterization

Planetary Boundary Layer Parameterization

Jablonowski and Williamson (2011)

Discussion

- How we understood all aspects of the existing **moist test cases** (moist baroclinic waves, tropical cyclone test, super cells, precipitation triggered by topography)
  - No, e.g. moist test cases often do not converge with resolution (at least not yet at dx=25 km), what is 'truth'?
  - Wide spread in DCMIP solutions should/needs to be better understood before we should make tests more complex

- What are the test cases that we need in the future?
  - Which aspects of the model and the physics-dynamics coupling should new tests focus on?
  - How should we modify existing test cases?
  - Ideas for coupled tests (atmosphere – ocean)?

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Selected references: Moist dynamical core test cases & intercomparisons

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