Analyzing Physics-Dynamics Coupling in an Ensemble of Simplified GCMs

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Organizing team

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What is DCMIP?

DCMIP: 2-week summer school and Dynamical Core Model Intercomparison Project (DCMIP): 2008, 2012, 2016
in 2016: use **idealized moist test cases** and focus on non-hydrostatic dynamical cores and their physics-dynamics coupling

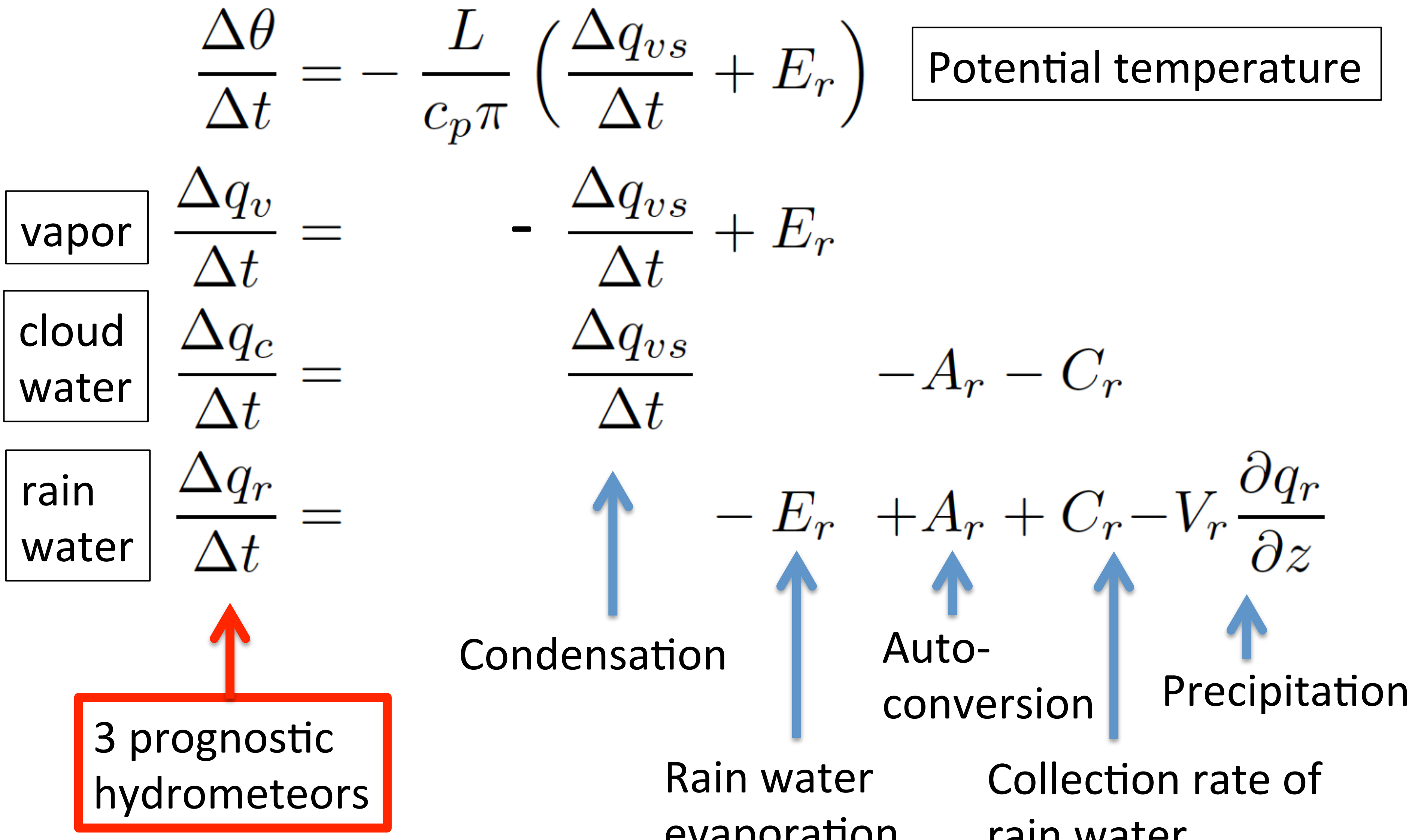
Three "core" test cases with idealized physics processes:

- **Test 1:** **Dry and moist (Kessler-physics) baroclinic instability test with "toy" terminator chemistry** (110 km, 30 vertical levels)
- **Test 2:** Moist tropical cyclone test
- **Test 3:** Moist mesoscale storm test (supercell)

Recent paper: "DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models", Ullrich et al. (2017) in GMD

"Living" Test case document and DCMIP-2016 web page:
https://github.com/ClimateGlobalChange/DCMIP2016
https://www.earthsystemcog.org/projects/dcmip-2016/

Warm-Rain Kessler Physics Scheme



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

Potential temperature

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

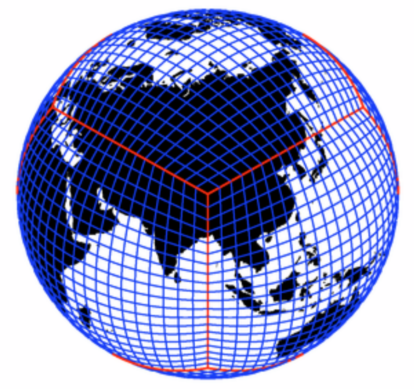
Rain water evaporation

Auto-conversion

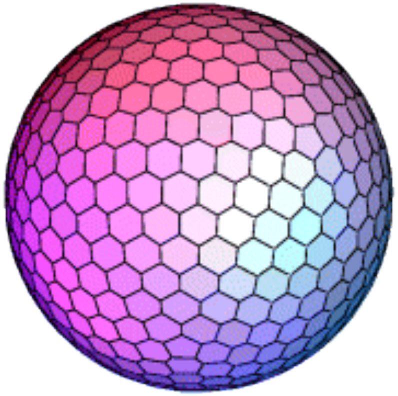
Collection rate of rain water

Precipitation

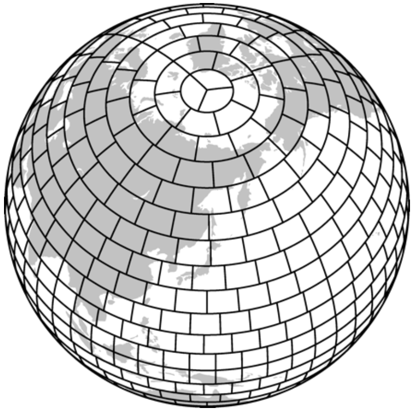
DCMIP-2016 Models (in blue: comparison models)



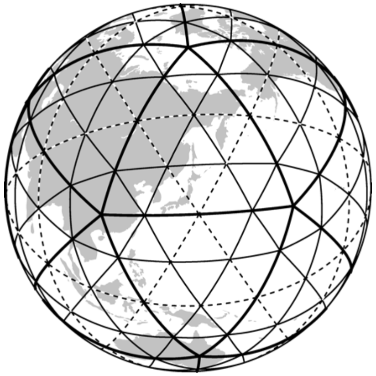
- ACME (E3SM) (DoE, CU)
- FV3 (GFDL)
- Tempest (UC Davis)
- CAM SE (NCAR), hydrost.



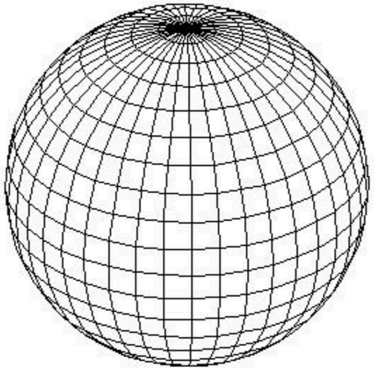
- CSU_LZ (CSU)
- OLAM (U. Miami)
- NICAM (Riken, U. Tokyo)
- MPAS (NCAR)



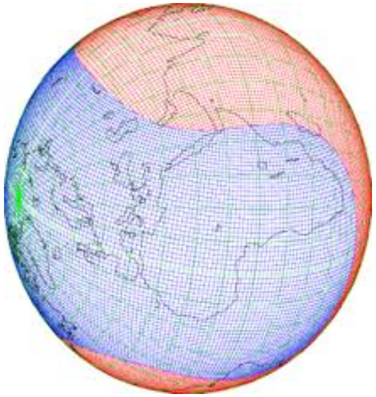
- FVM (ECMWF)



- ICON (DWD & MPI, Germany)
- DYNAMICO (LMD, IPSL, France), hydrostatic



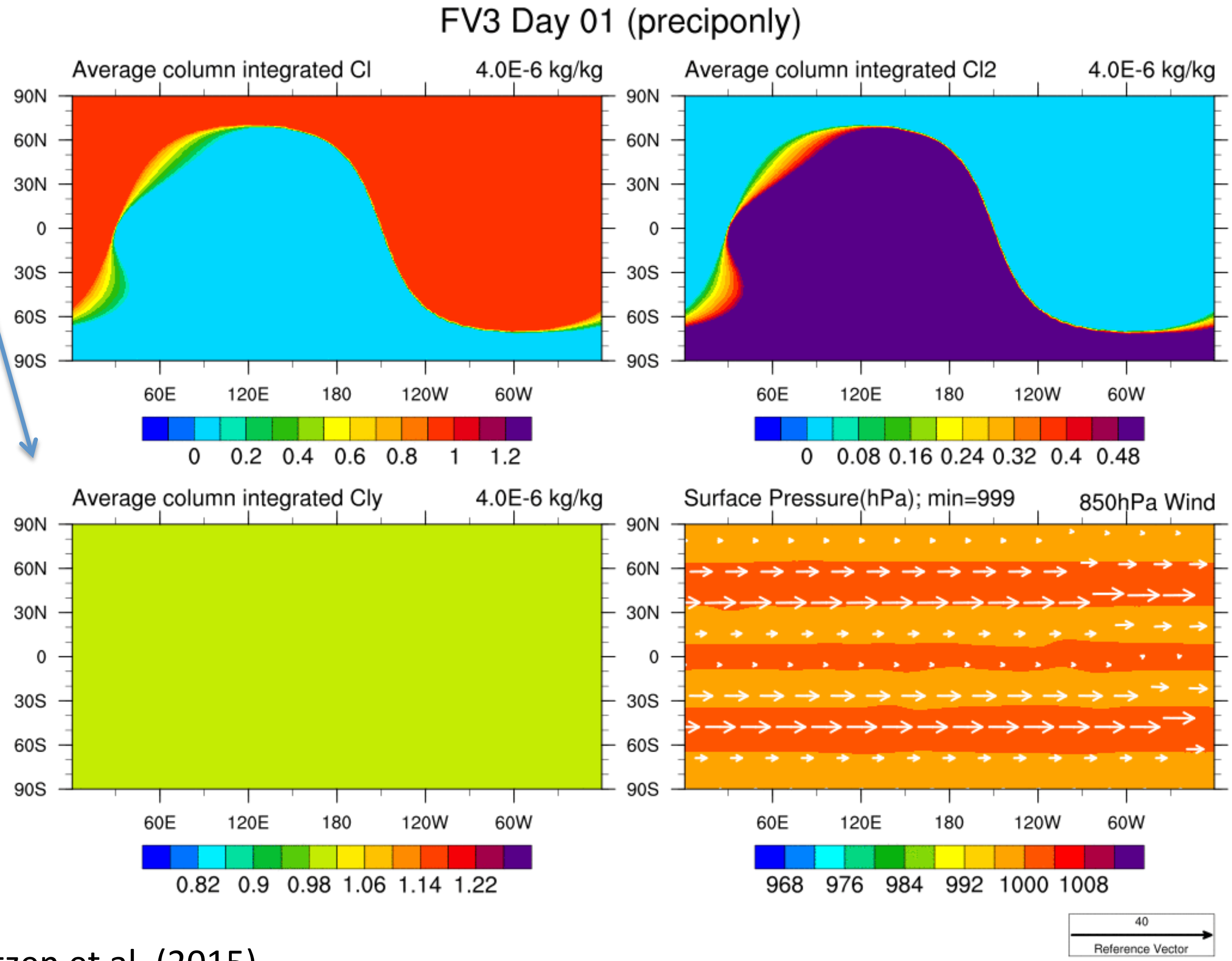
- CAM FV (NCAR), hydrostatic



- GEM (Environment Canada)

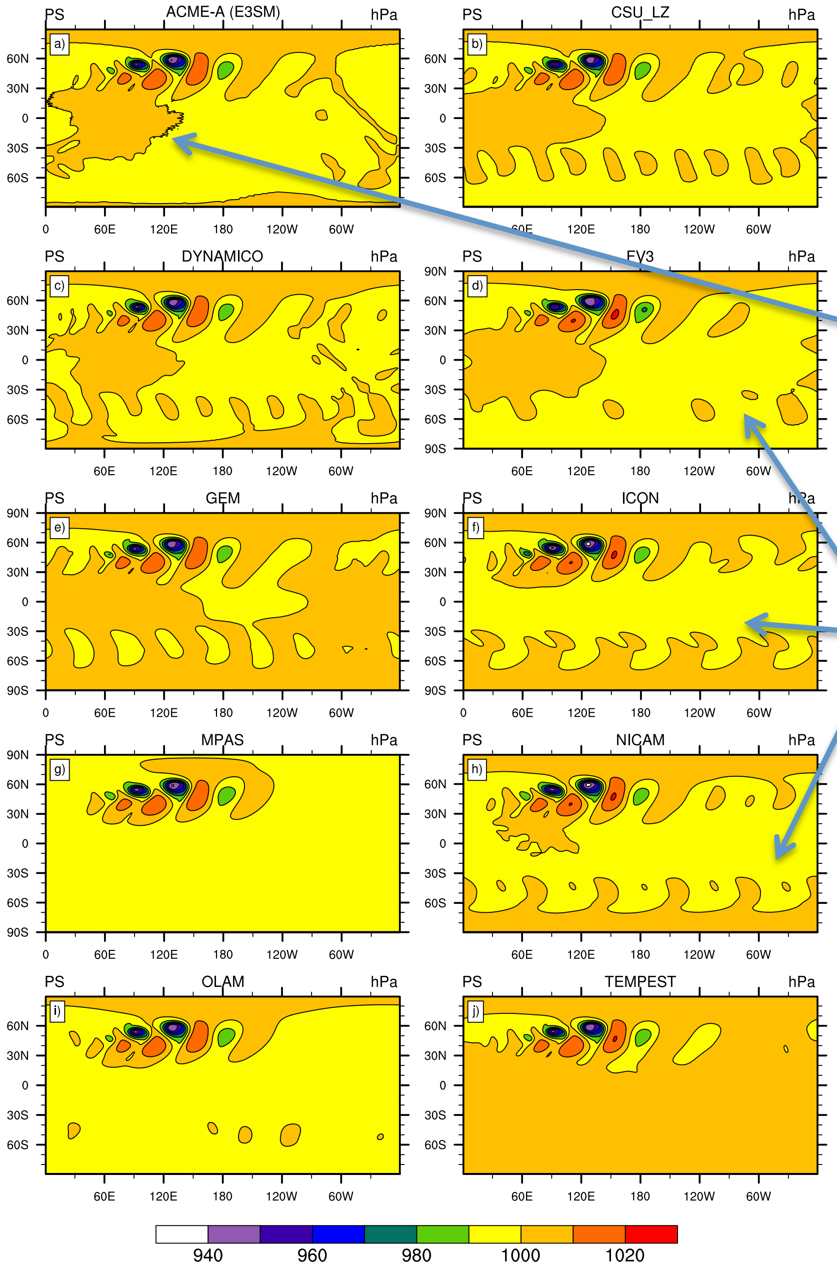
DCMIP-2016 Snapshots: "Toy" Terminator Chemistry

Tracer advection test with correlated tracers: Cly is the sum of Cl and Cl2 (needs to stay constant)



Lauritzen et al. (2015)

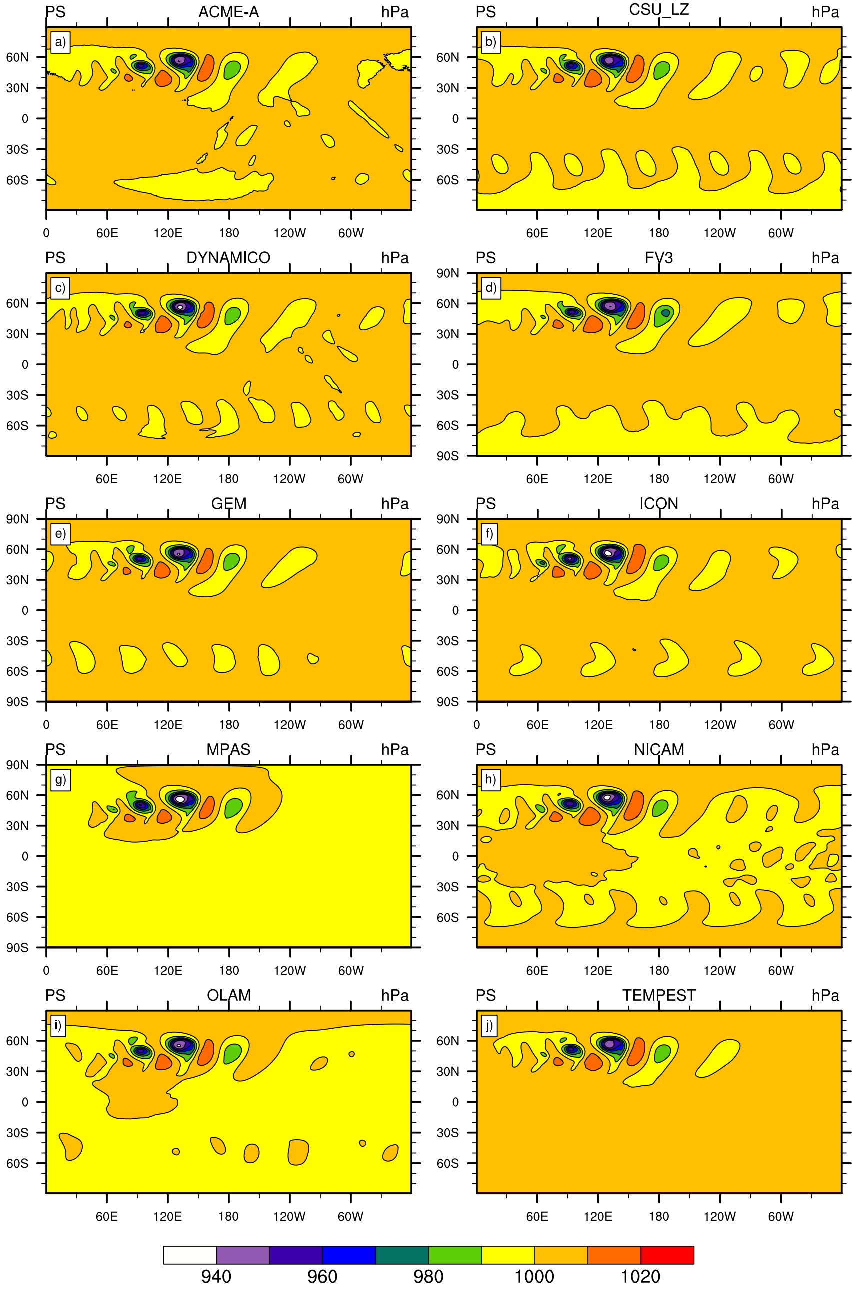
Snapshots of the dry baroclinic wave



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

- Some Gibb's ringing in ACME (spectral element model)
- Some grid imprinting (wave 4 and wave 5 signals) in CSU_LZ, DYNAMICO, FV3, ICON, NICAM, apparent in the Southern Hemispheres

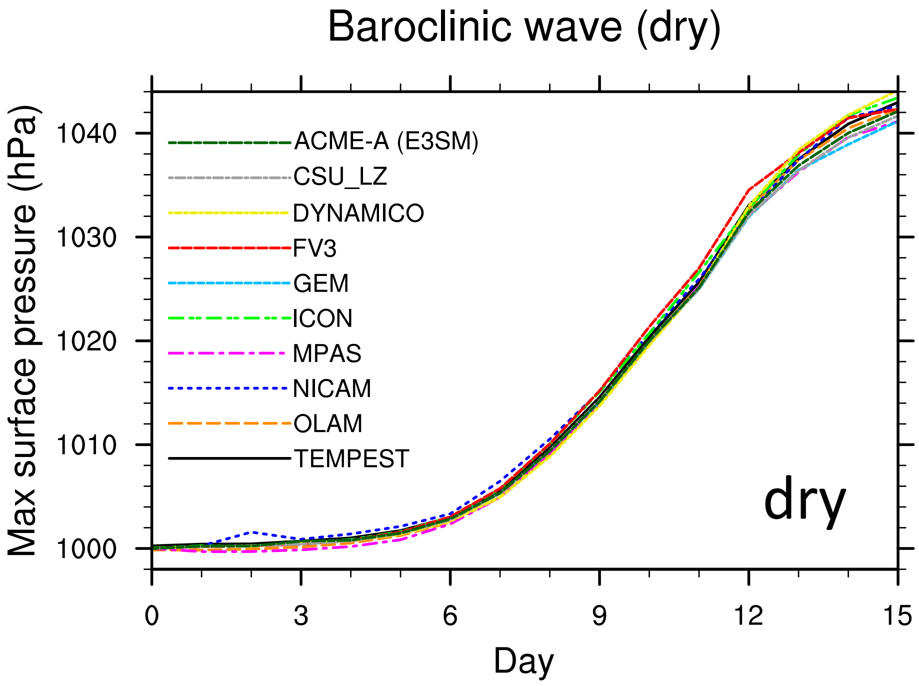
Snapshots of the moist baroclinic wave

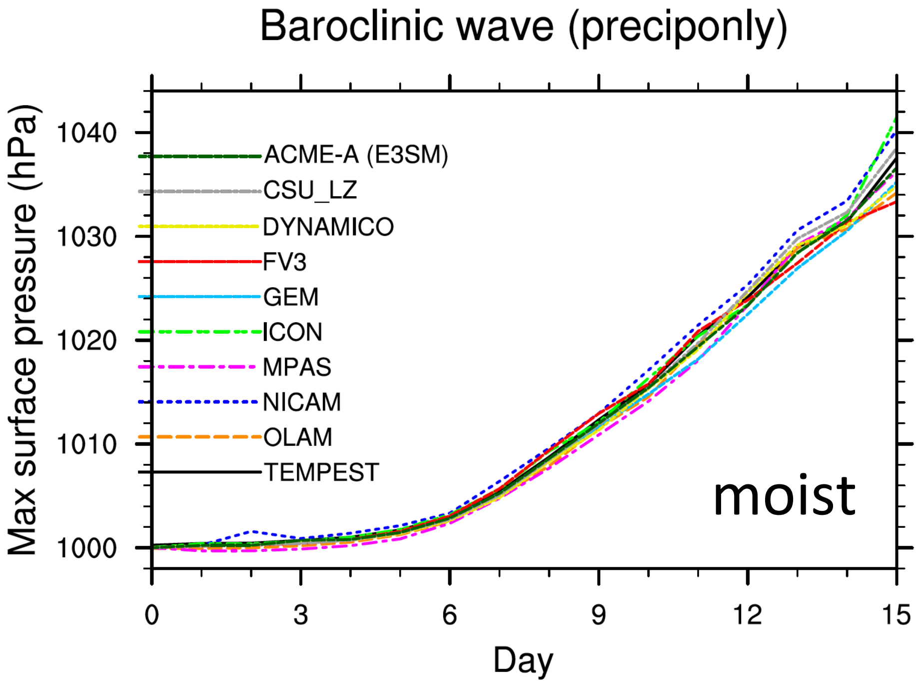


Surface pressure at day 10 (Δx=110 km): overall patterns similar, details differ

- Patterns look almost identical to the dry surface pressure patterns
- Moisture effects weaken high pressure systems and strengthen low pressure systems (e.g. visible in ICON and MPAS)

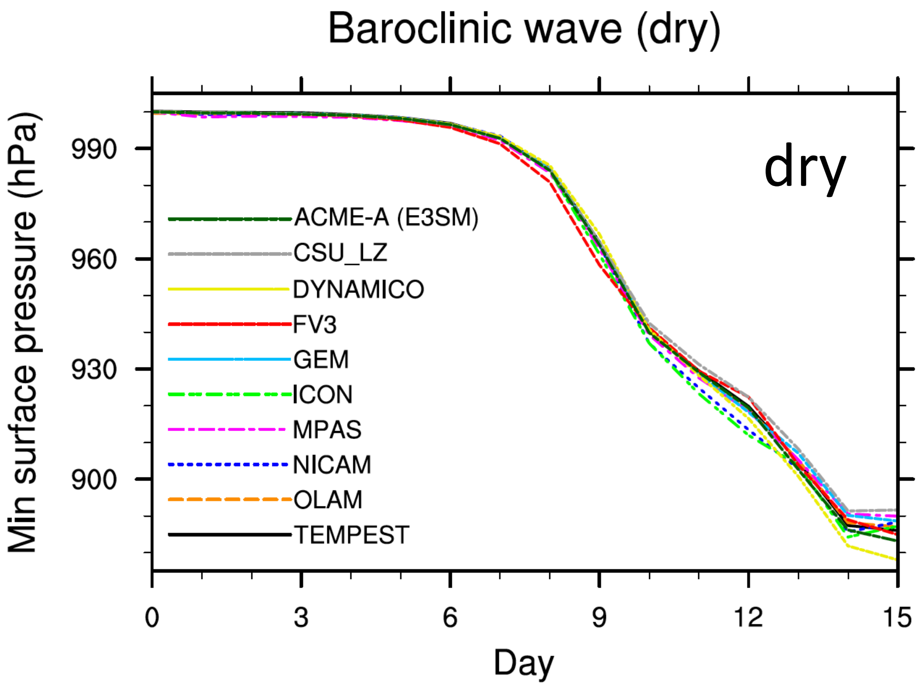
15-Day Time Series: **dry and moist** ps maxima

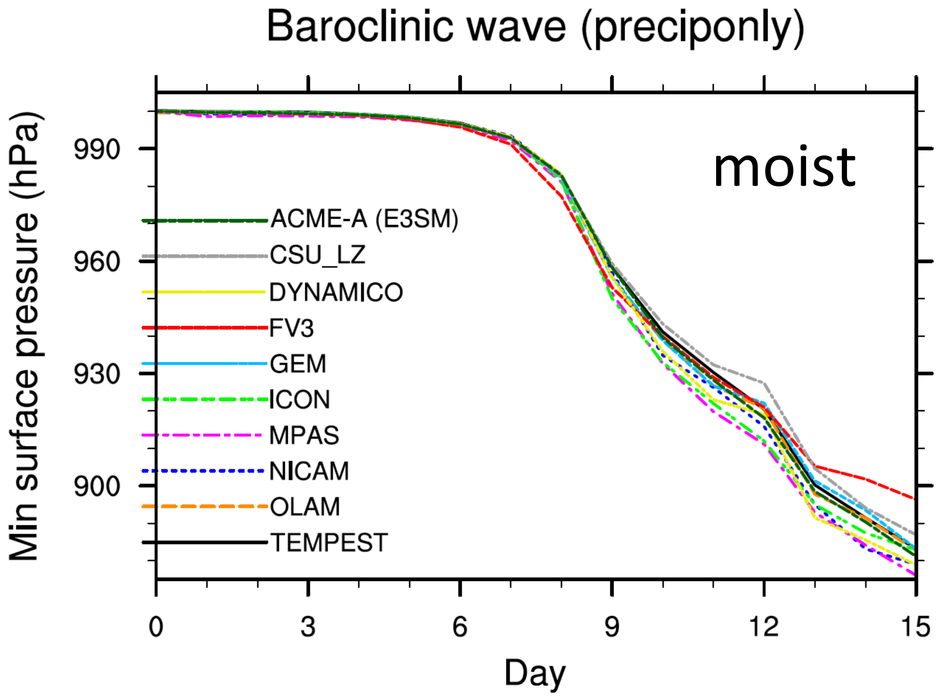

Baroclinic wave (dry)


Baroclinic wave (preciponly)

- Moisture effects **weaken high pressure** systems
- Presence of moisture **widens the ensemble spread** early in the simulations
- Points to the uncertainties in the physics-dynamics interactions and the possible impact of effective resolutions

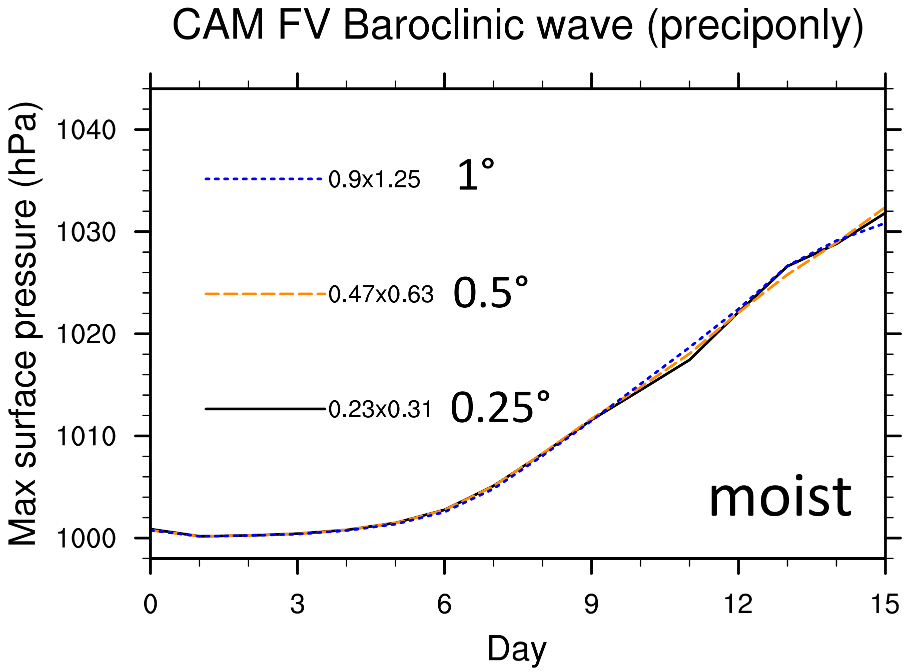
15-Day Time Series: **dry and moist** ps minima

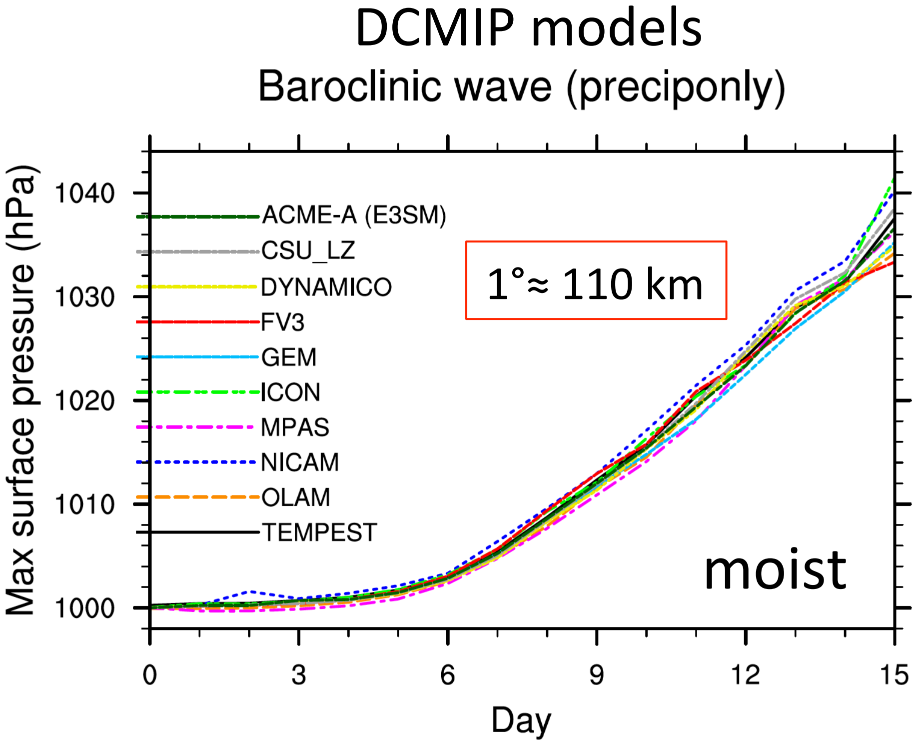




- Moisture effects: slight **tendency to strengthen low pressure** systems
- Presence of moisture **considerably widens the ensemble spread**
- Models tend to diverge after day 12

Impact of Resolution: Moist ps maxima

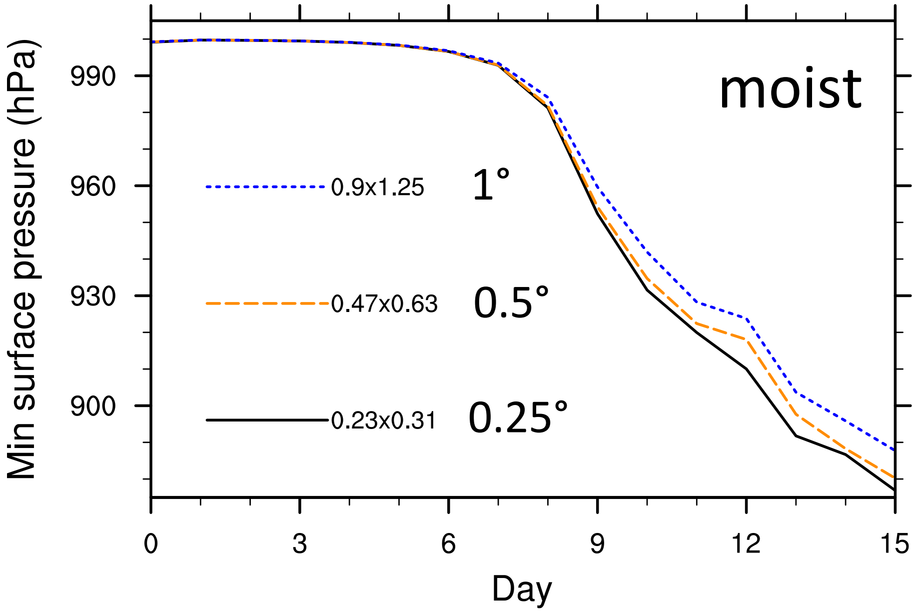

CAM FV Baroclinic wave (preciponly)


DCMIP models

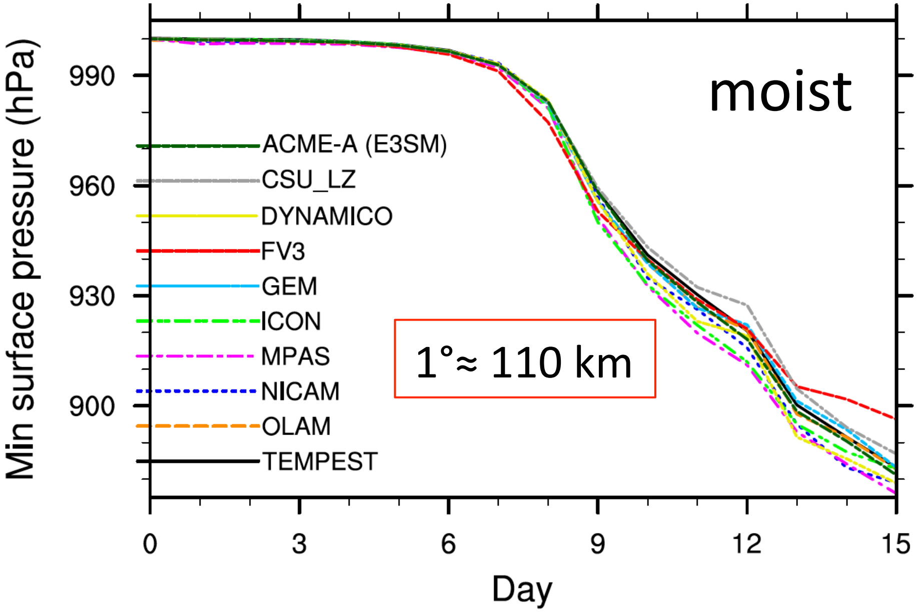
Baroclinic wave (preciponly)

- Impact of the horizontal resolution on the evolution of the surface pressure maxima is small (in moist CAM FV, similar to FV3 model)
- However, PS_{min} spread in DCMIP models increases (next slide), physics-dynamics interactions most apparent in low pressure regions with precipitation and updraft

Impact of Resolution: Moist ps minima



CAM FV Baroclinic wave (preciponly)



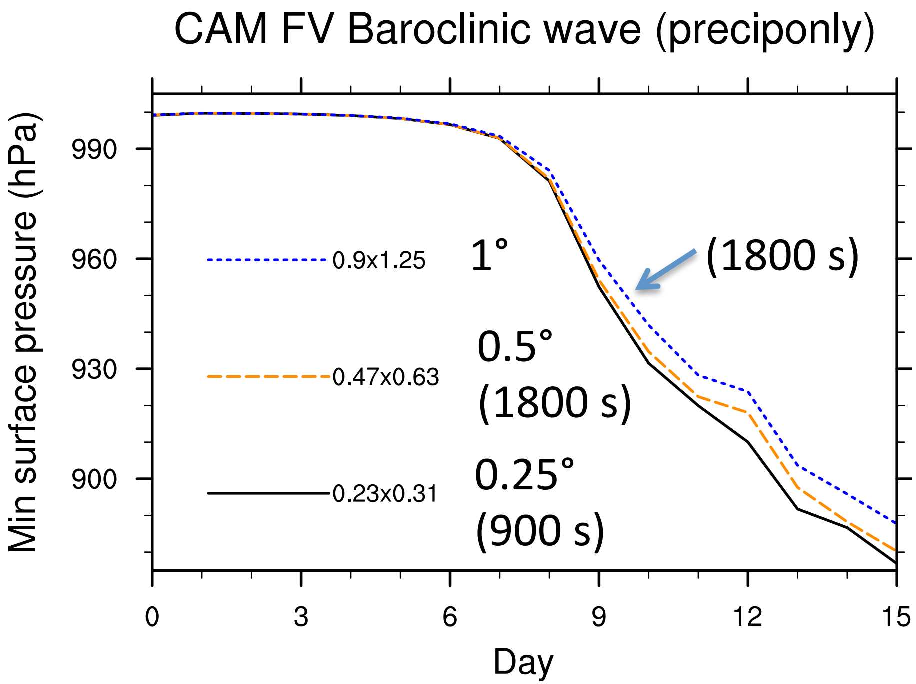
DCMIP models

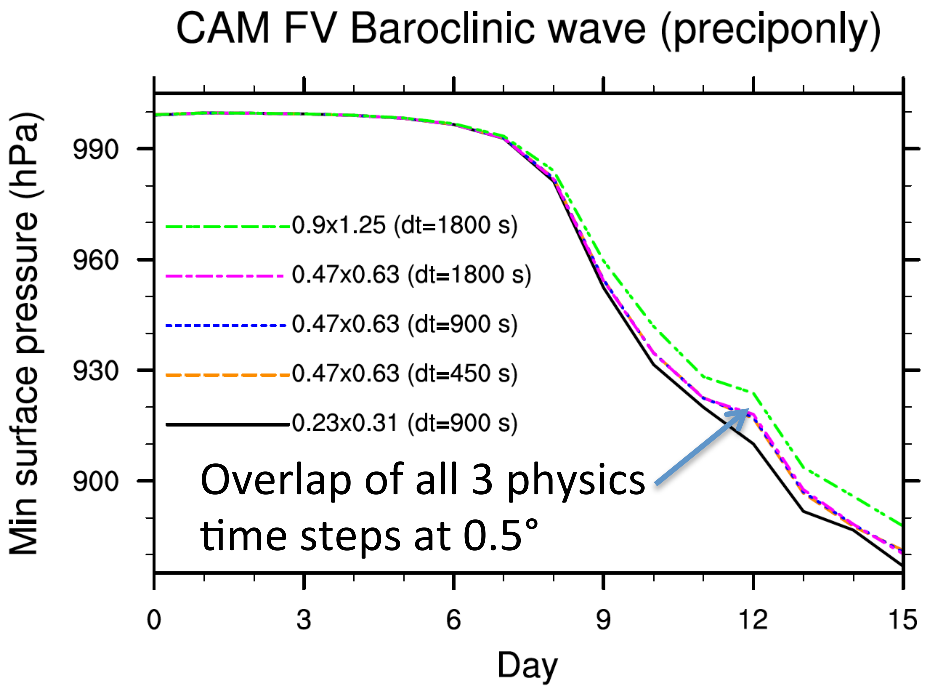
Baroclinic wave (preciponly)

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

Impact of Physics time step: Moist ps minima

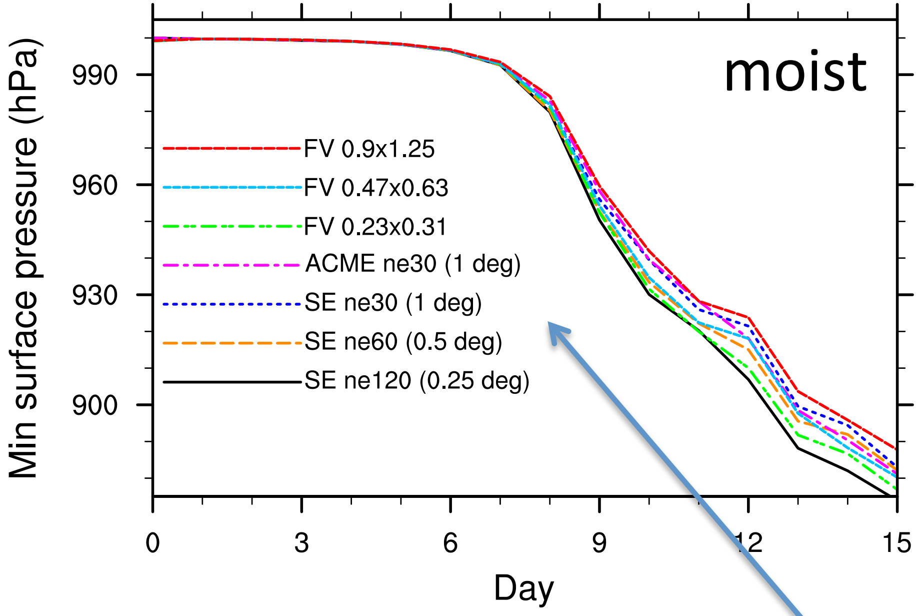
Increased resolutions often come with decreased physics time steps

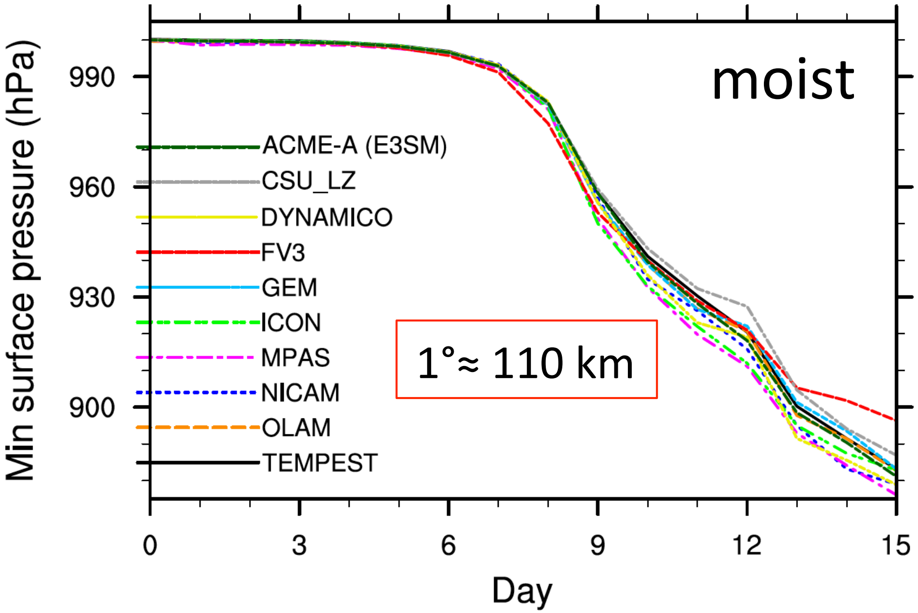




- **Varying the physics time step** from 1800 s, 900 s to 450 s has **very little impact** on the minimum surface pressure evolution in CAM FV(0.5°)
- Suggests that physics time step is not the main driver for the model differences among DCMIP models

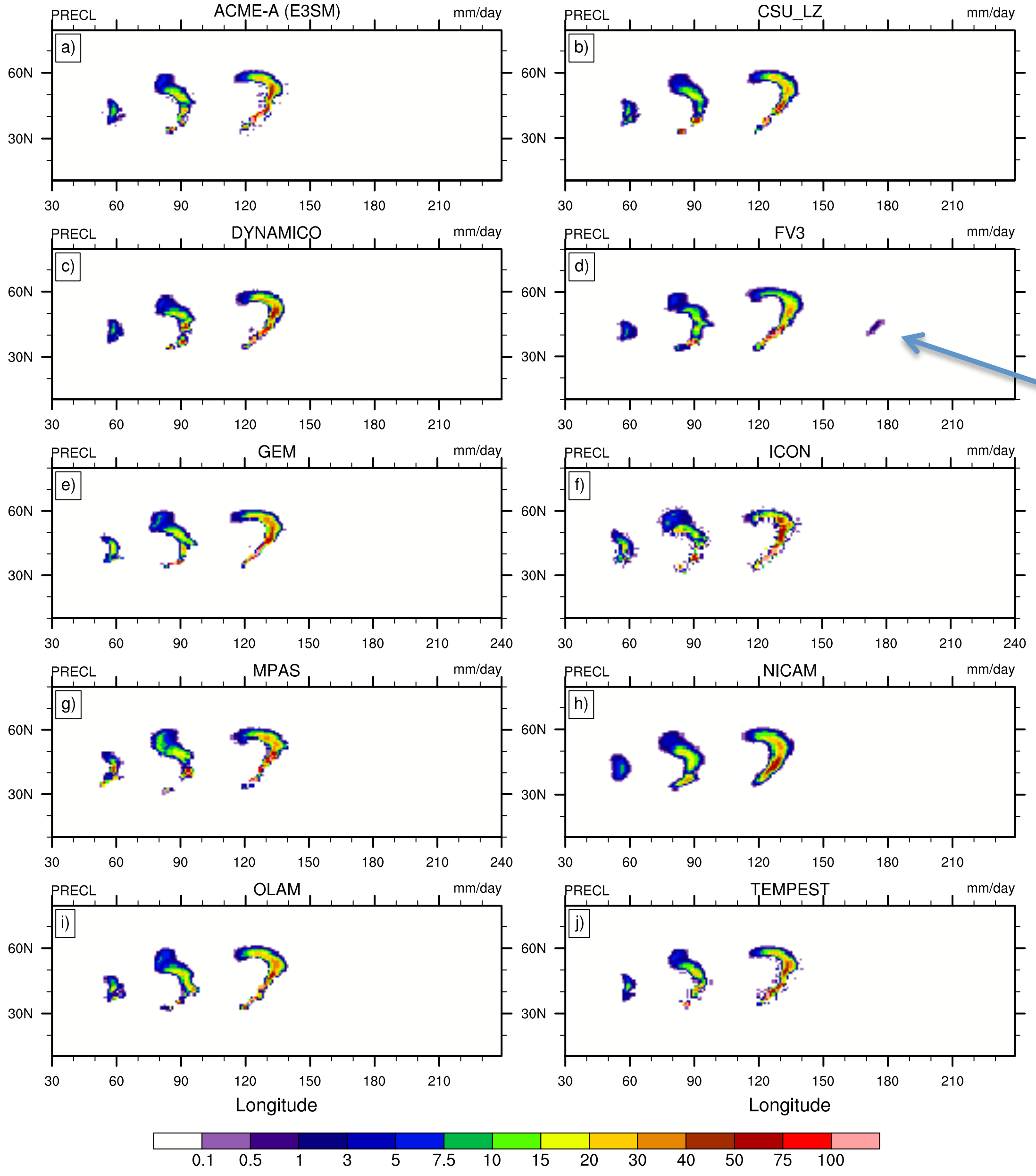
Impact of Model Design & Resolution: Moist ps$_{min}$


CAM FV/SE Baroclinic wave (preciponly)


DCMIP models
Baroclinic wave (preciponly)

- **Increasing the horizontal resolutions** from 1° (110 km) to 0.5°/0.25° (55/28 km) **strengthens the surface pressure minima** in CAM FV and CAM SE
- PS$_{min}$ spread in DCMIP models includes the effects of the effective resolutions and coupling uncertainties

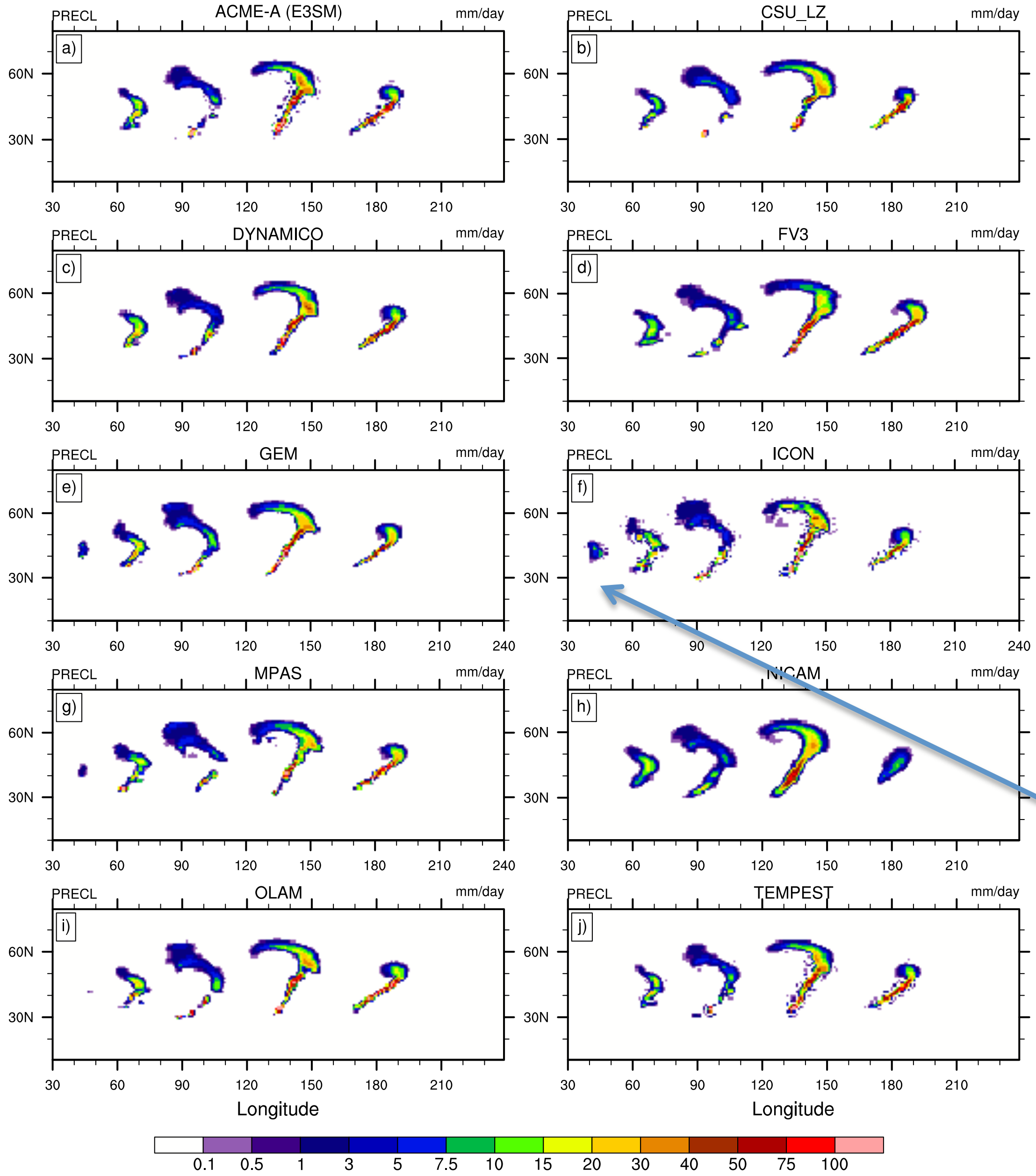
Precipitation rates in the moist baroclinic wave



Precipitation rates at day 9 (Δx=110 km): overall patterns similar, details differ

- FV3 strengthens the fastest, already shows 4th precipitation band
- Differing levels of ‘noise’ (broken contours) and diffusion in the precipitation bands are apparent

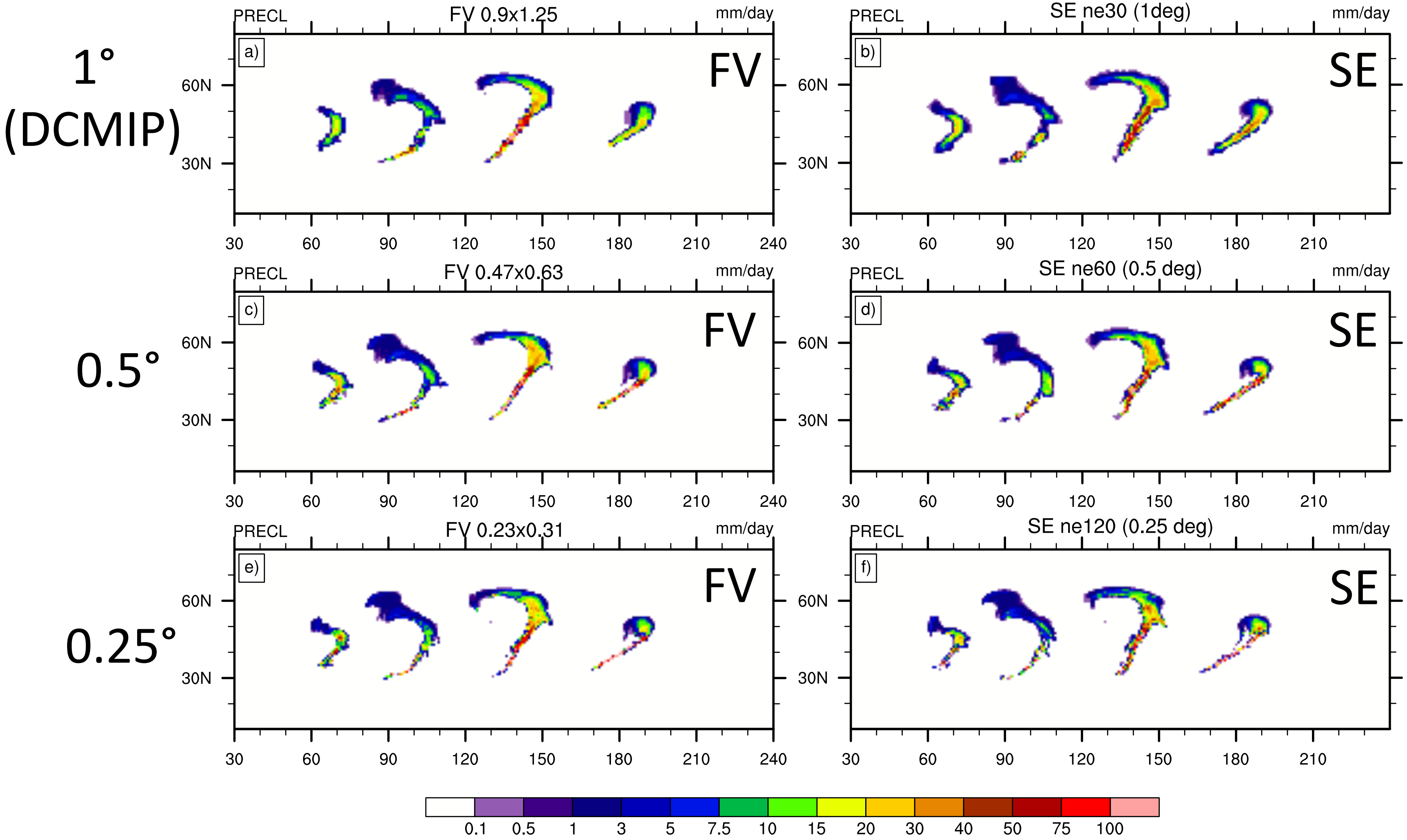
Precipitation rates in the moist baroclinic wave



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

- At day 10 precipitation bands become very narrow, tend to break up in some models (with very strong grid-point scale precipitation)
- 3 models already develop 5th precipitation band

Precipitation rates: Impact of Resolution

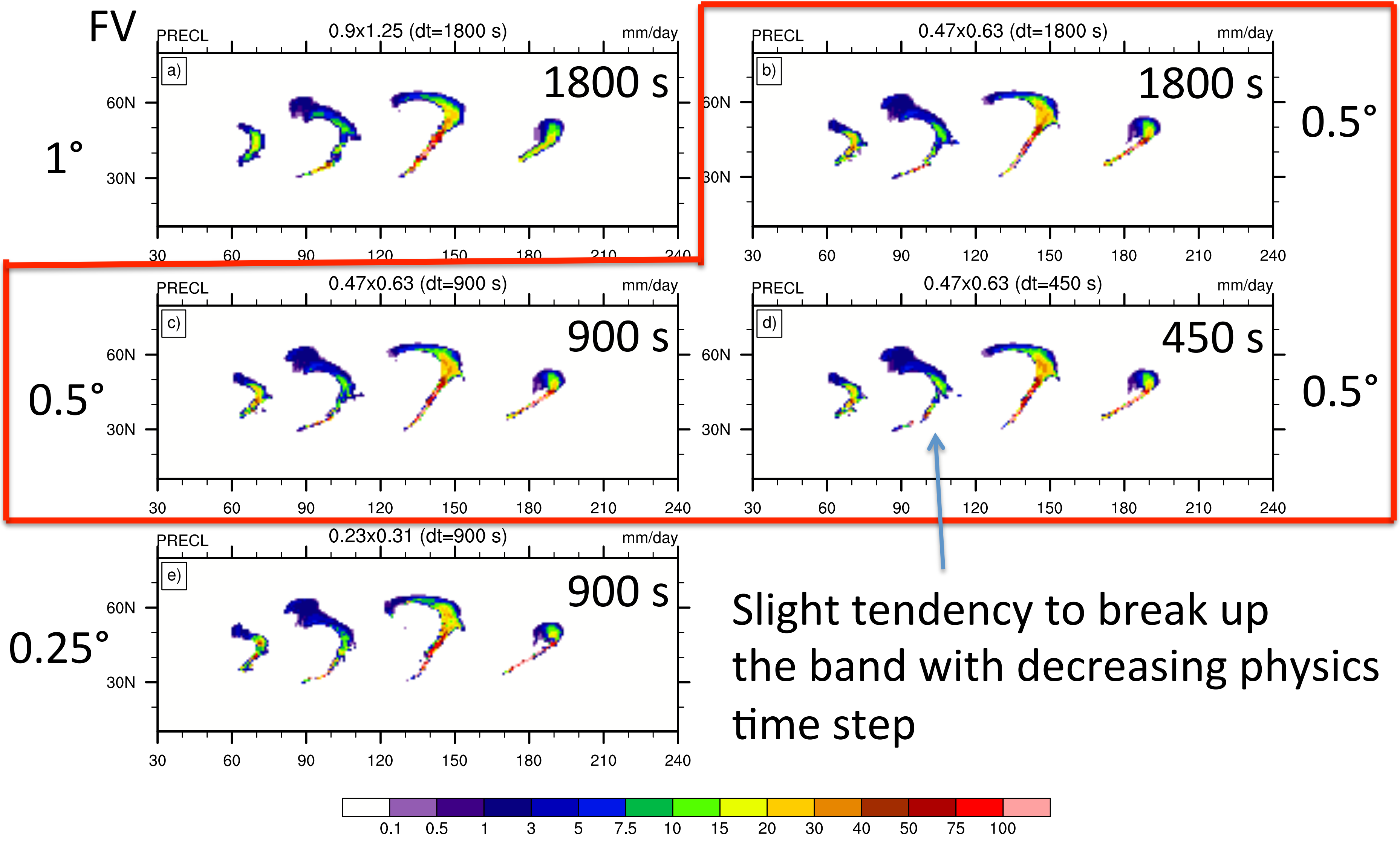


Moist CAM FV/SE baroclinic wave, preciponly, Day 10

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

Precipitation rates: Impact of Physics Time Step

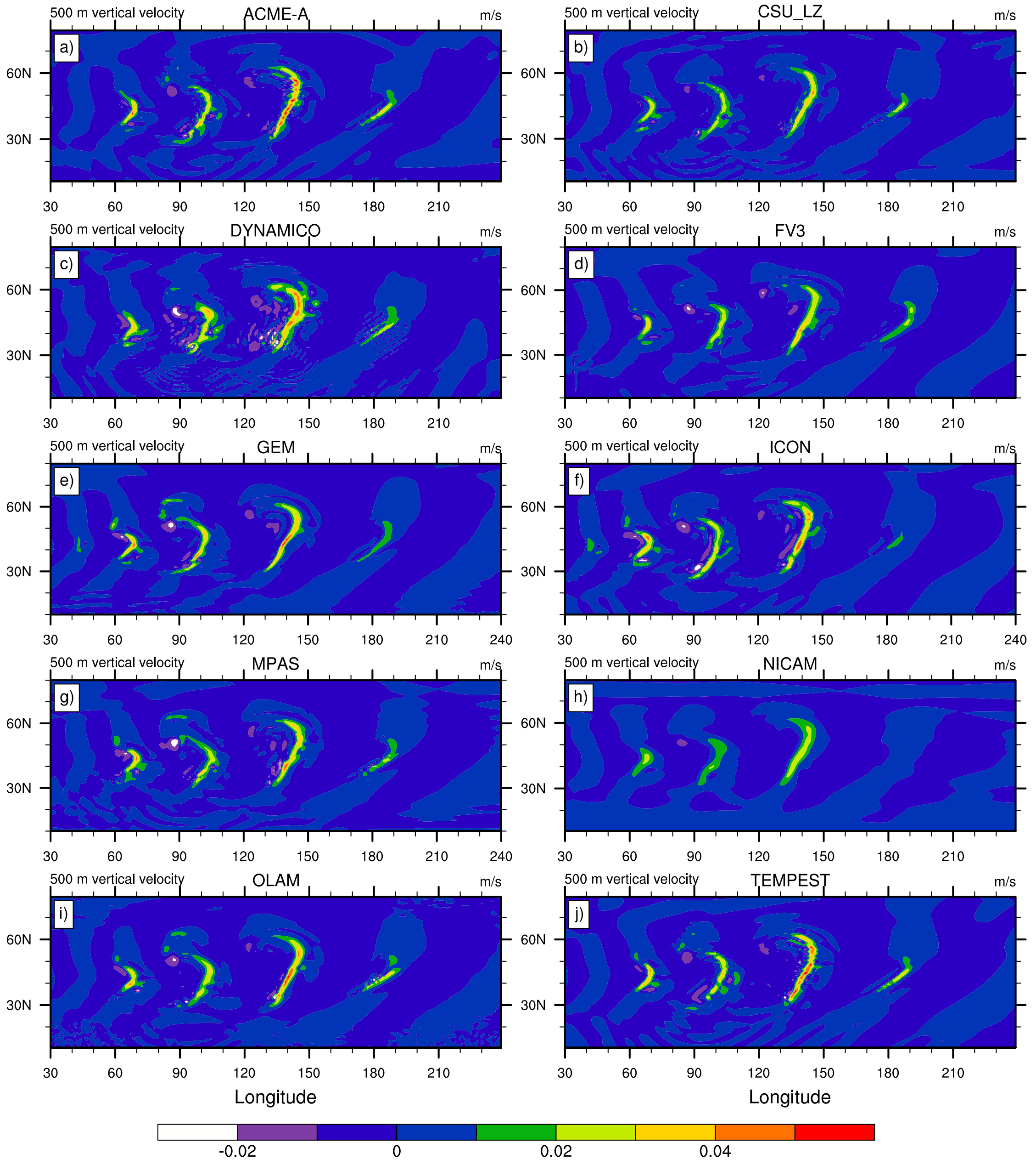
Moist CAM FV baroclinic wave, preciponly, Day 10



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

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

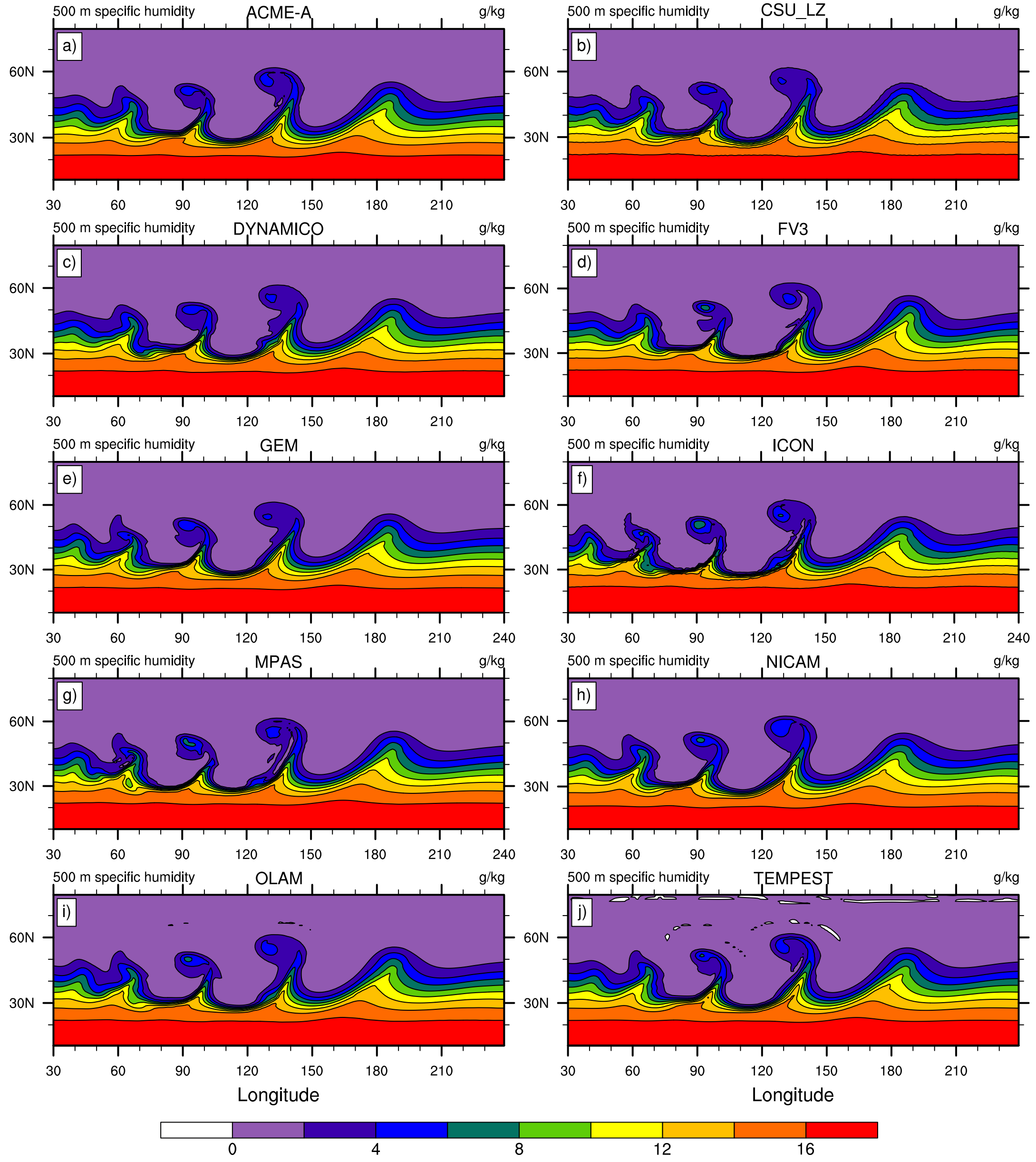
Vertical velocity in the moist baroclinic wave



500 m vertical velocity at day 10 (Δx=110 km): overall patterns similar, details differ

- Precipitation bands tightly connected to the narrow updraft areas
- Reduced updrafts translate into reduced precipitation rates
- Noisy updraft areas lead to noise in precipitation rates

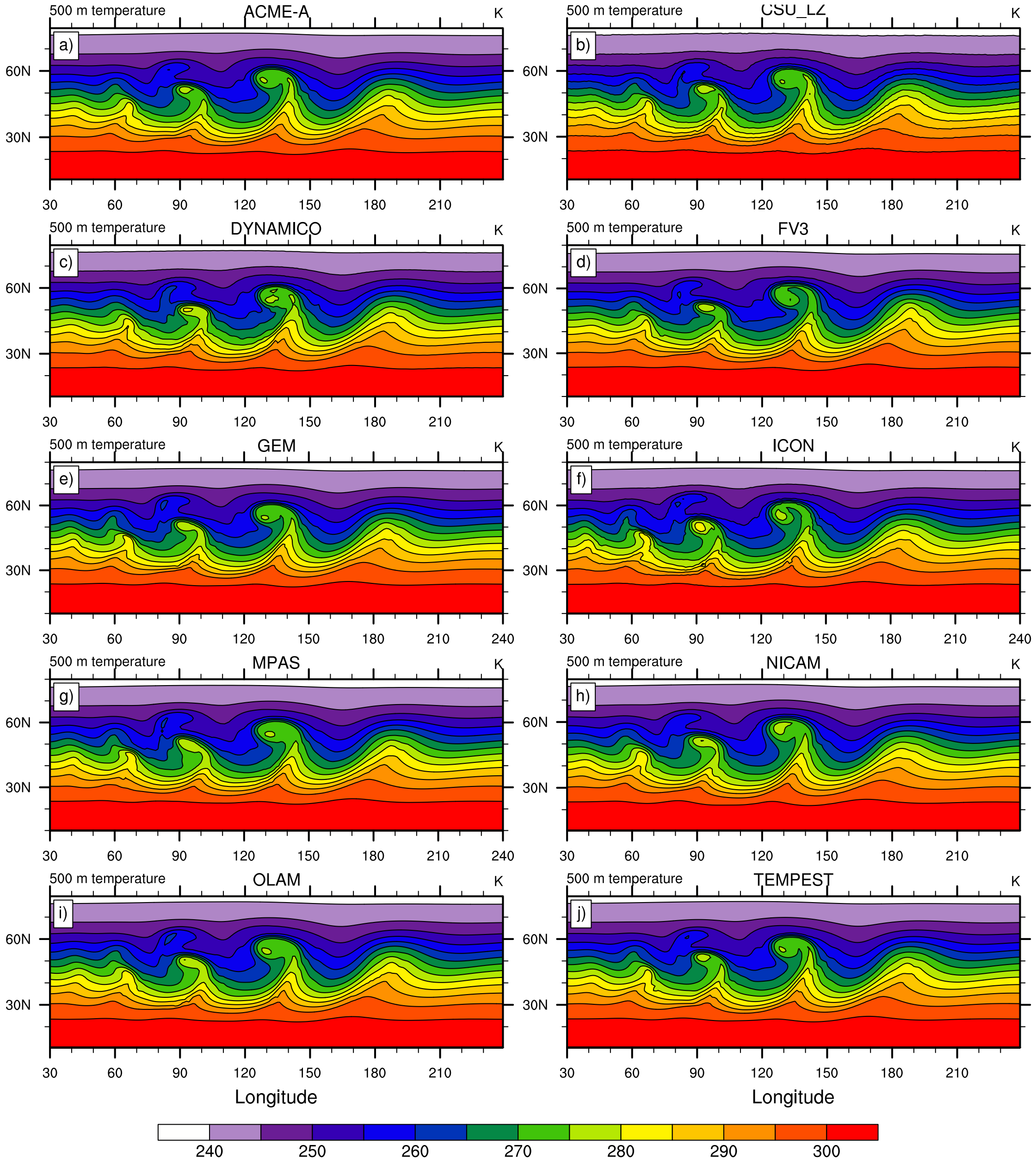
Specific humidity in the moist baroclinic wave



500 m specific humidity at day 10 (Δx=110 km): overall patterns similar, details differ

- High levels of specific humidity are advected from the moist tropical areas into the midlatitudes (ahead of the low pressure systems)
- Specific humidity provides moisture source for the Kessler precipitation scheme

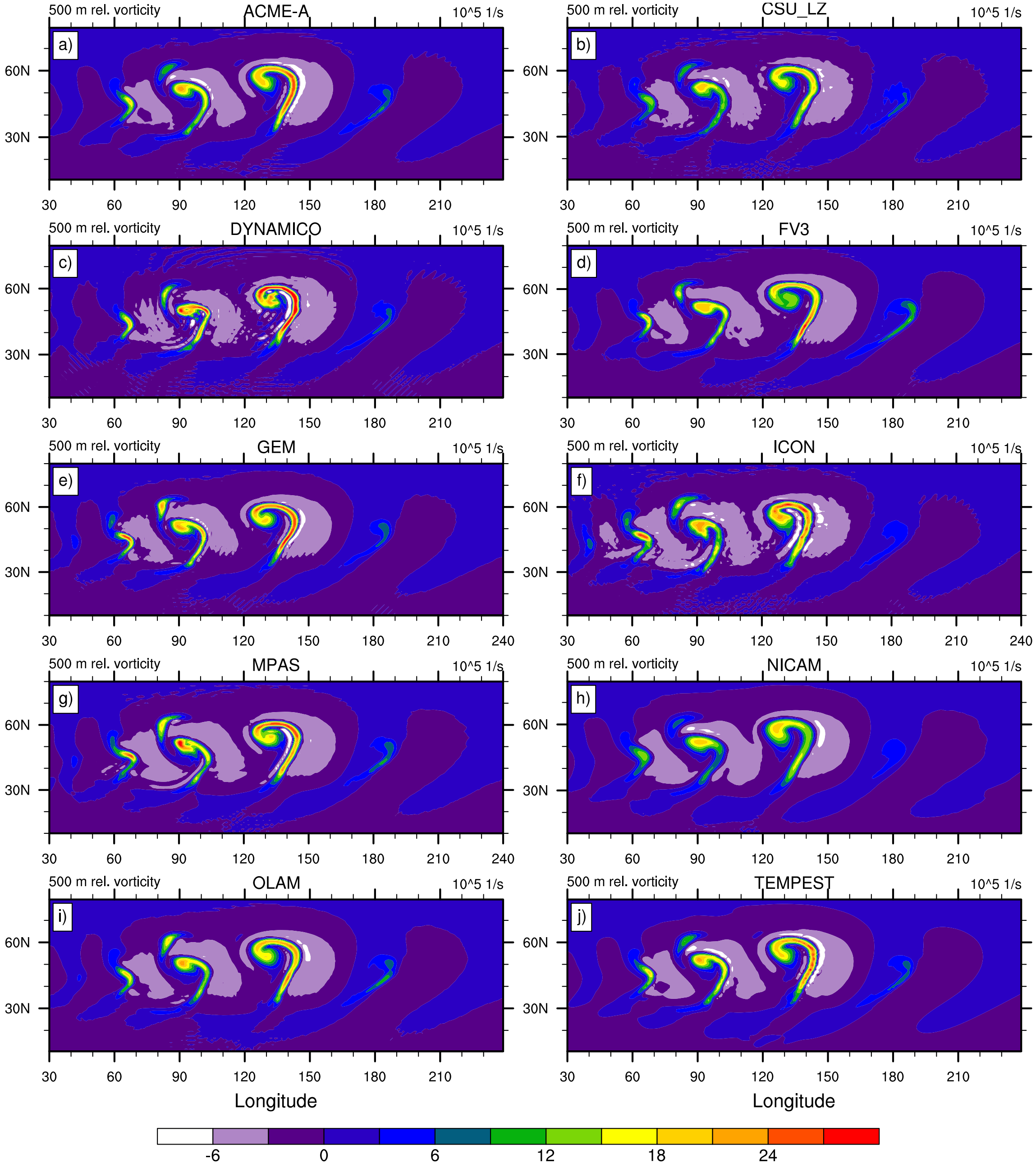
Temperature in the moist baroclinic wave



500 m temperature at day 10 (Δx=110 km): overall patterns similar, details differ

- Breaking waves at day 10 (also visible in the specific humidity field)
- Updrafts are connected to the strong temperature fronts

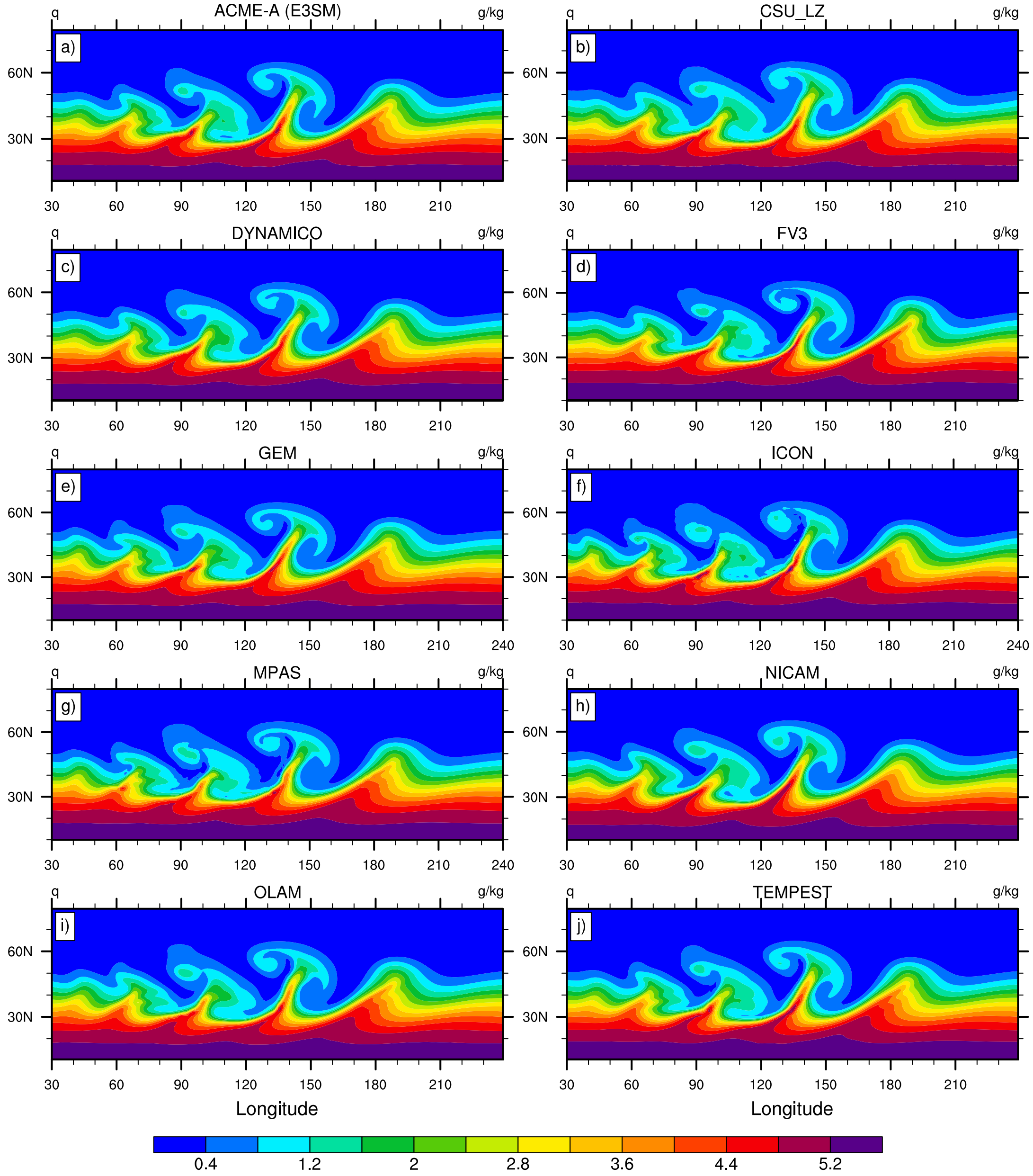
Relative vorticity in the moist baroclinic wave



500 m relative vorticity at day 10 (Δx=110 km): overall patterns similar, details differ

- Maxima and minima differ (by about 30%) and are found in very narrow strips (challenges the 110 km grid spacing)
- Vorticity highlights noise and the diffusive properties of the model

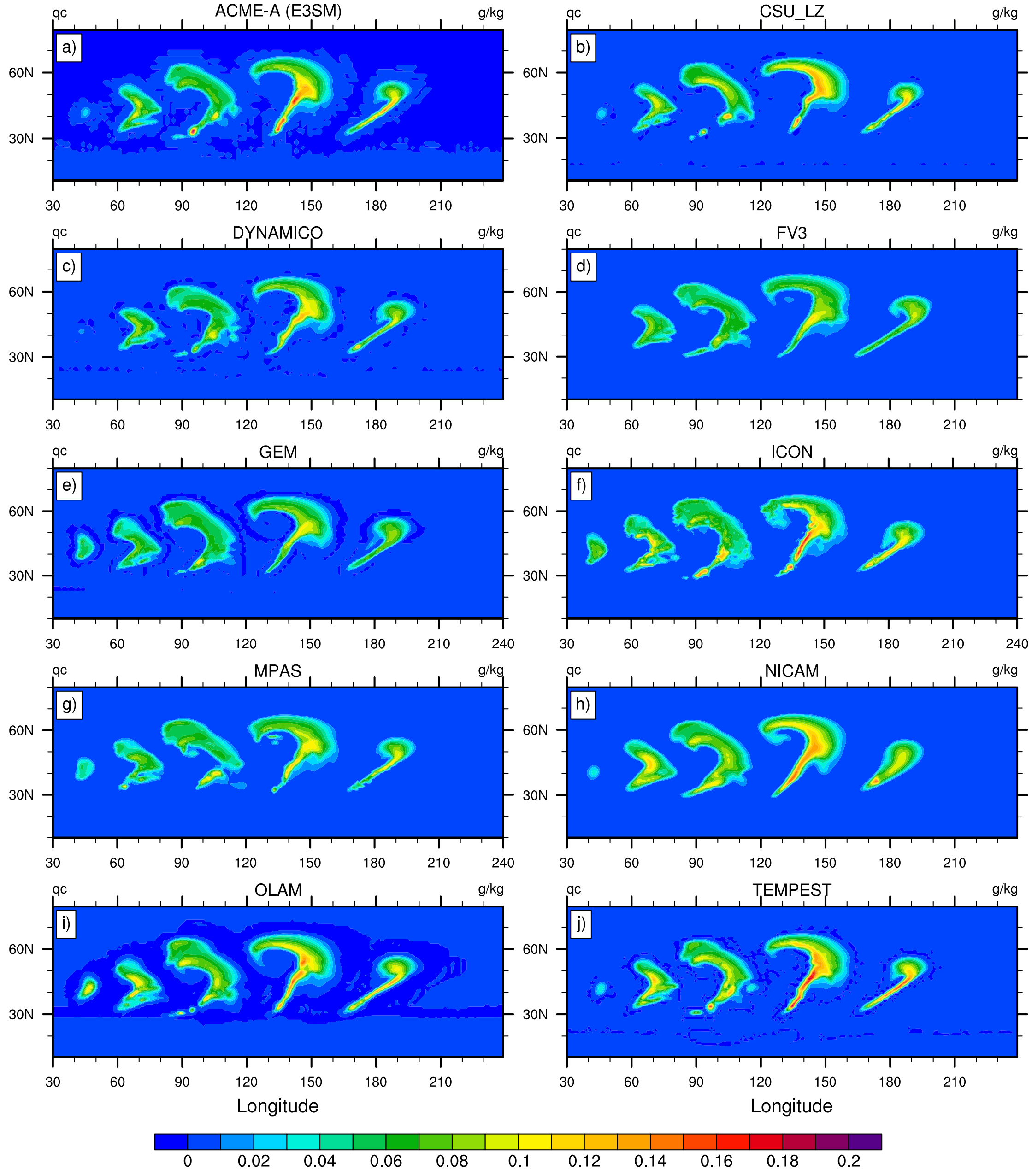
Integrated water vapor: moist baroclinic wave



Vertically integrated water vapor at day 10 (Δx=110 km): overall patterns similar, only details differ

- Seems to be predicted rather well, field is dominated by large-scale resolved advection

Integrated cloud water: moist baroclinic wave

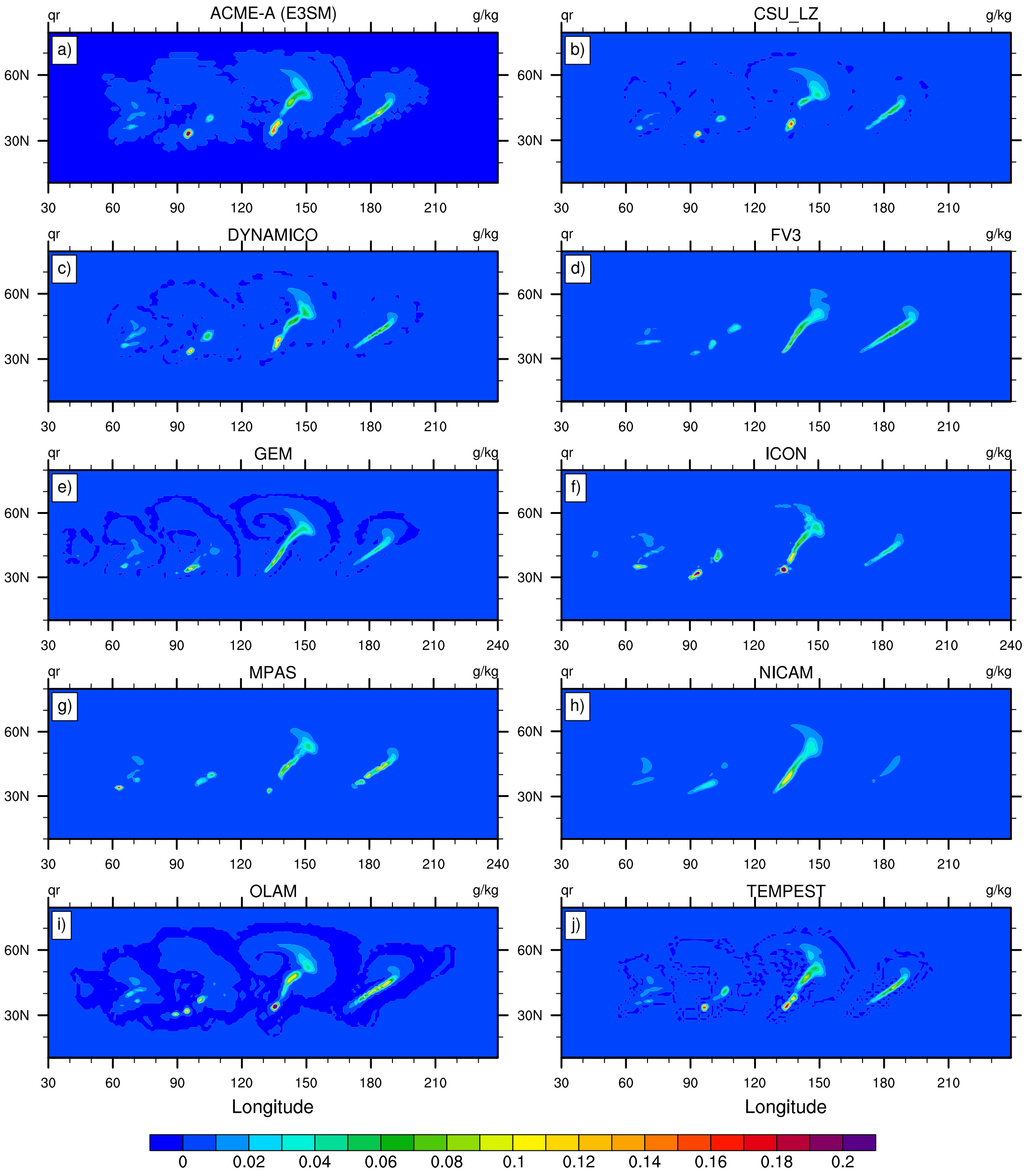


Vertically integrated cloud water at day 10

(Δx=110 km)

- Cloud water highlights the physics-dynamics interactions
- Generation of cloud water is not resolved, parameterized in the Kessler warm rain scheme
- Model differences become more apparent

Integrated rain water: moist baroclinic wave

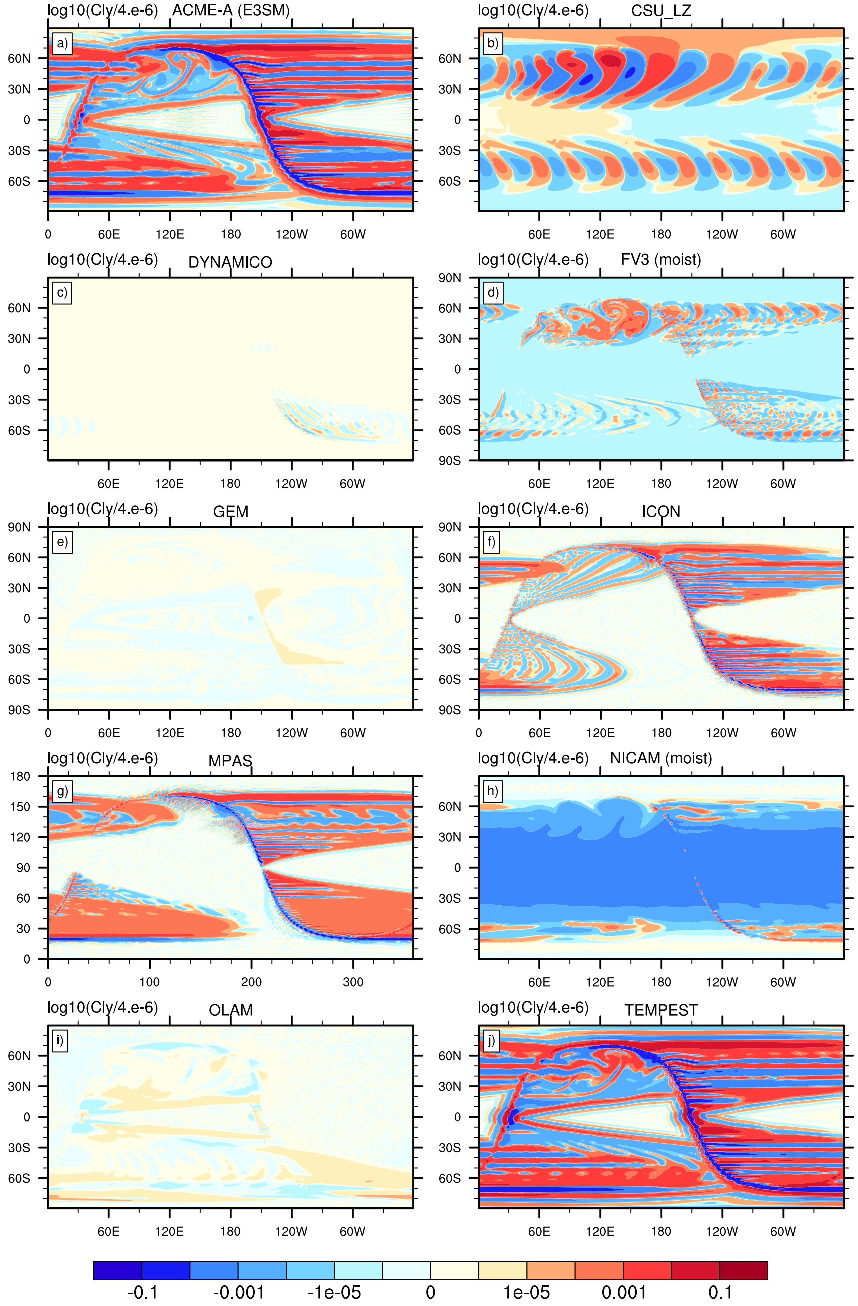


Vertically integrated rain water at day 10

(Δx=110 km)

- Rain water further highlights the physics-dynamics interactions
- Rain water comes from cloud water pool, parameterized in the Kessler scheme
- Differences become even more apparent
- Coherent patterns break up for this metric

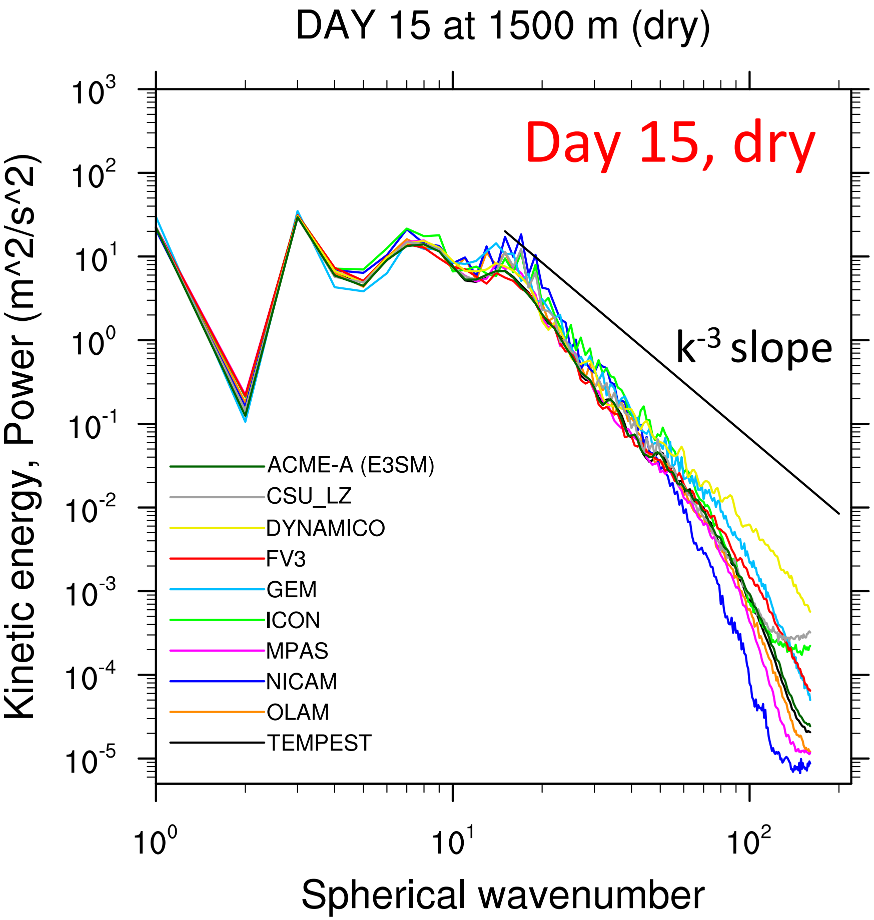
Tracer consistency in the dry baroclinic wave

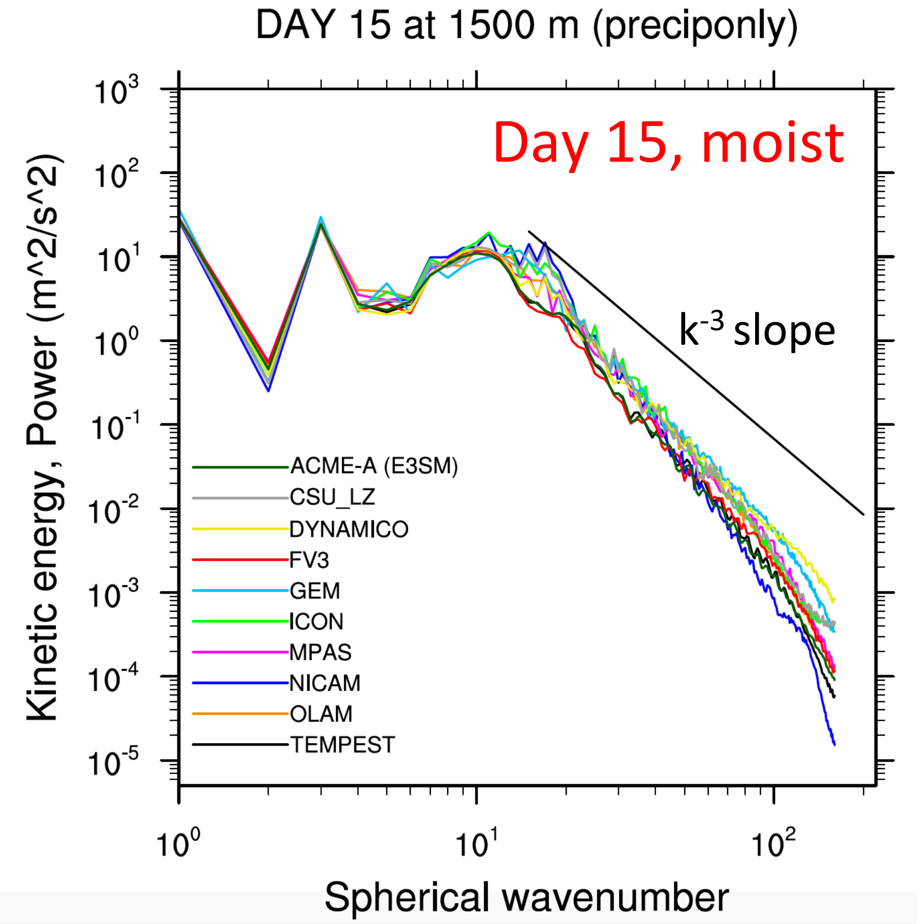


Vertically integrated tracers (weighted sum) at day 10 (Δx=110 km)

- 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

1500 m Kinetic Energy Spectra: dry and moist

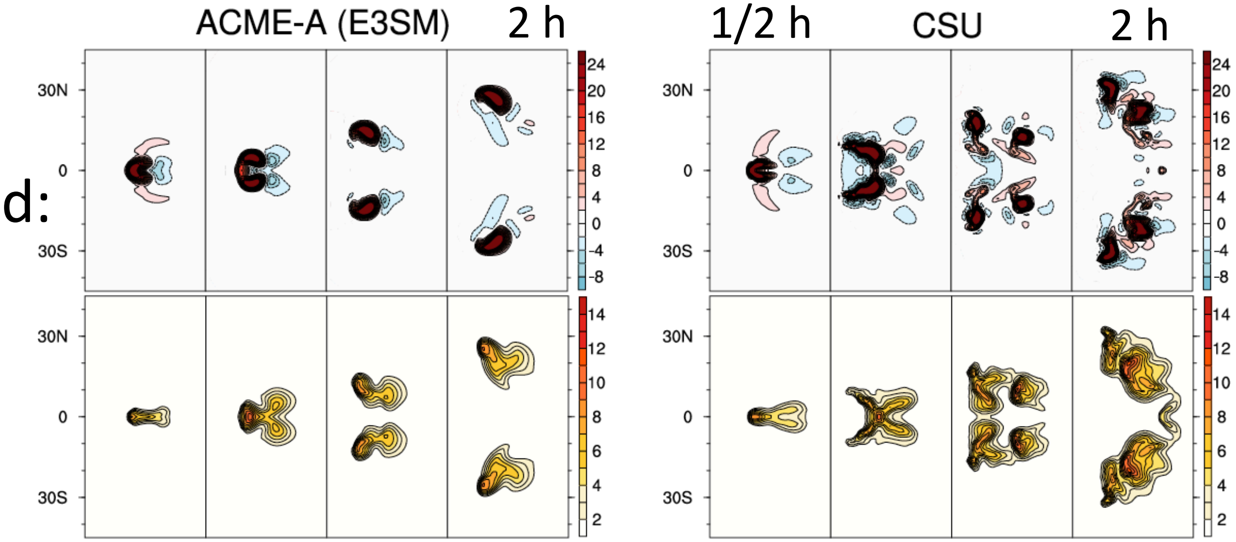




- KE spectra provide information about the diffusion properties
- Some dry dynamical cores flatten their KE spectra
- Despite nominal 1° resolutions, resolved scales vary widely as indicated by the wide spread at high wavenumbers, spread narrows in moist runs

Snapshots: Supercell Simulations (dx=1 km)

Very wide model spread: diffusion processes differ

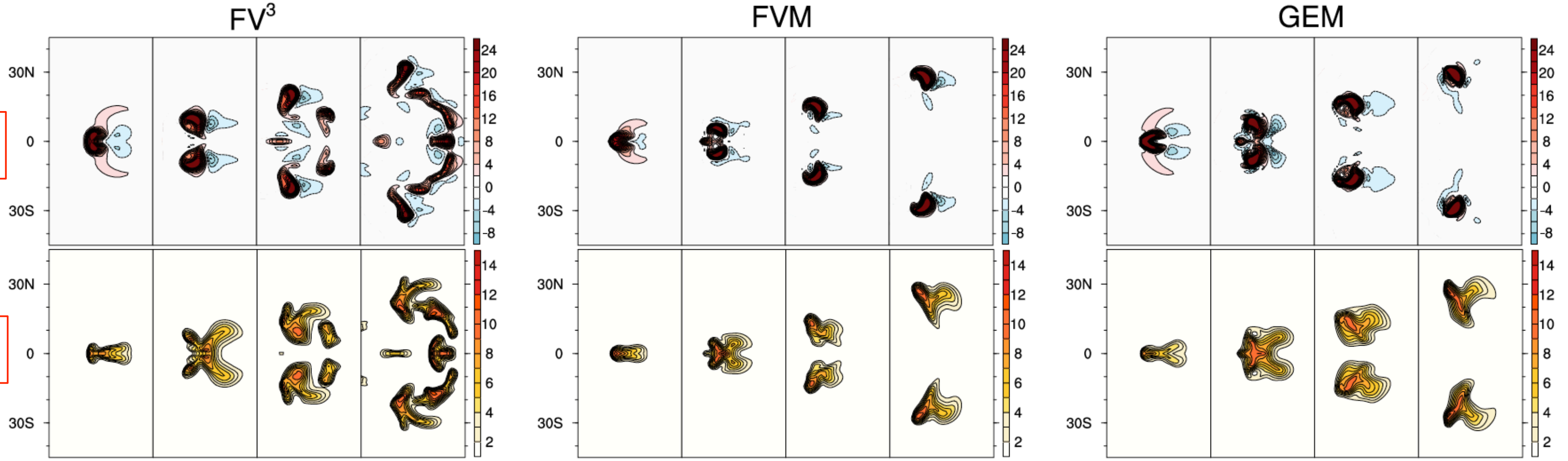


w vertical velocity

q_r rain water

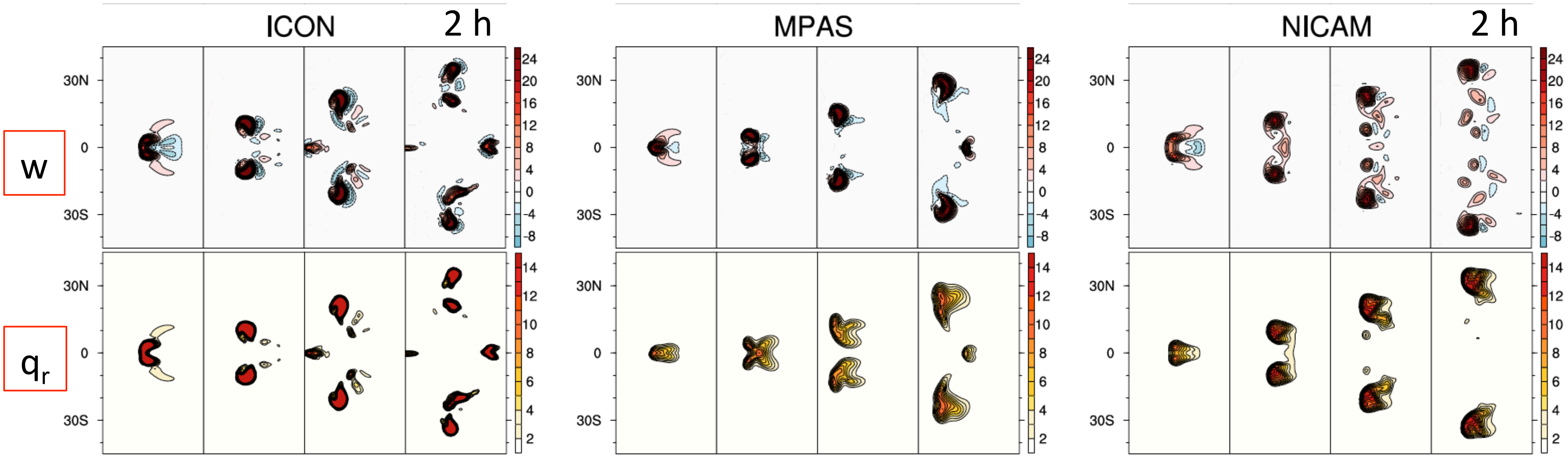
w

q_r

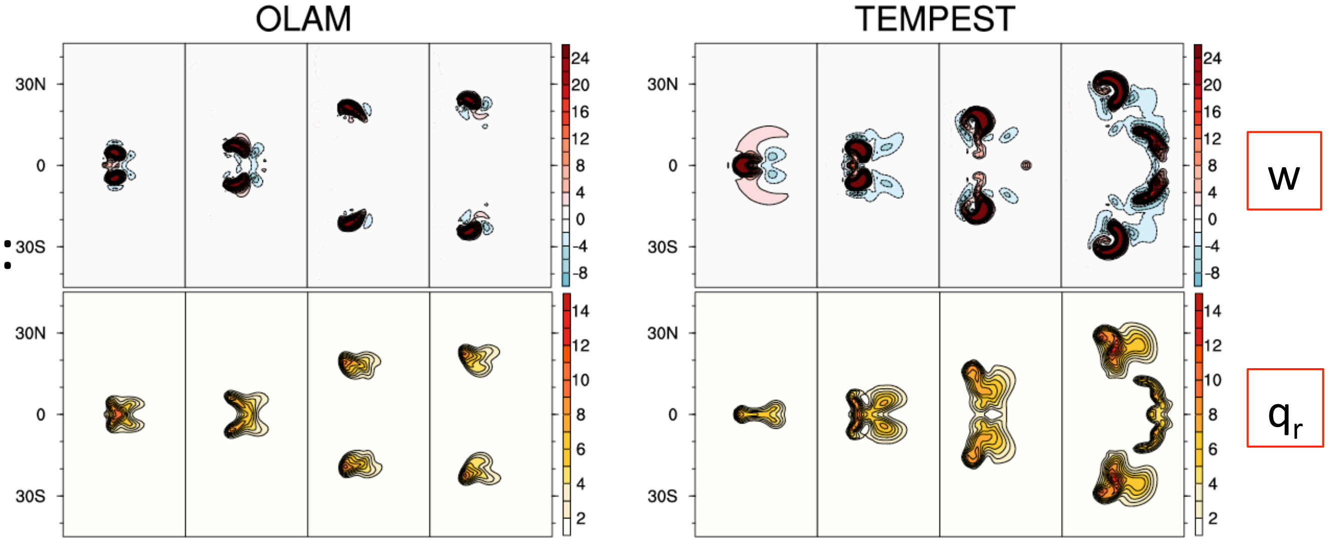


- Time series of vertical velocity (top row) and rain water (bottom row) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Snapshots: Supercell Simulations (dx=1 km)



Very wide model spread: hard to disentangle



- Time series of vertical velocity (top rows) and rain water (bottom rows) at 5 km after 30, 60, 90 and 120 minutes (horizontal resolution is 1 km)

Conclusions

- The interactions between a dynamical core and moisture processes can already be simulated with very simple model configurations, like the Kessler warm-rain scheme
- Rich data base: moist dynamical core configurations reveal aspects of the physics-dynamics coupling, related to different dynamical cores, resolutions and physics time steps
- Idealized test cases are a useful tool (with quick turn around times) to test/understand the moisture aspects
- Causes and effects can be analyzed more easily, but are still difficult to disentangle
- We currently further analyze the impact of various numerical & diffusion choices and physics-dynamics coupling decisions (e.g. Δt)

References

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DCMIP-2016 project page:
https://www.earthsystemcog.org/projects/dcmip-2016/