Extending the Dynamical Core Test Case Hierarchy: Moist Baroclinic Waves with Topography

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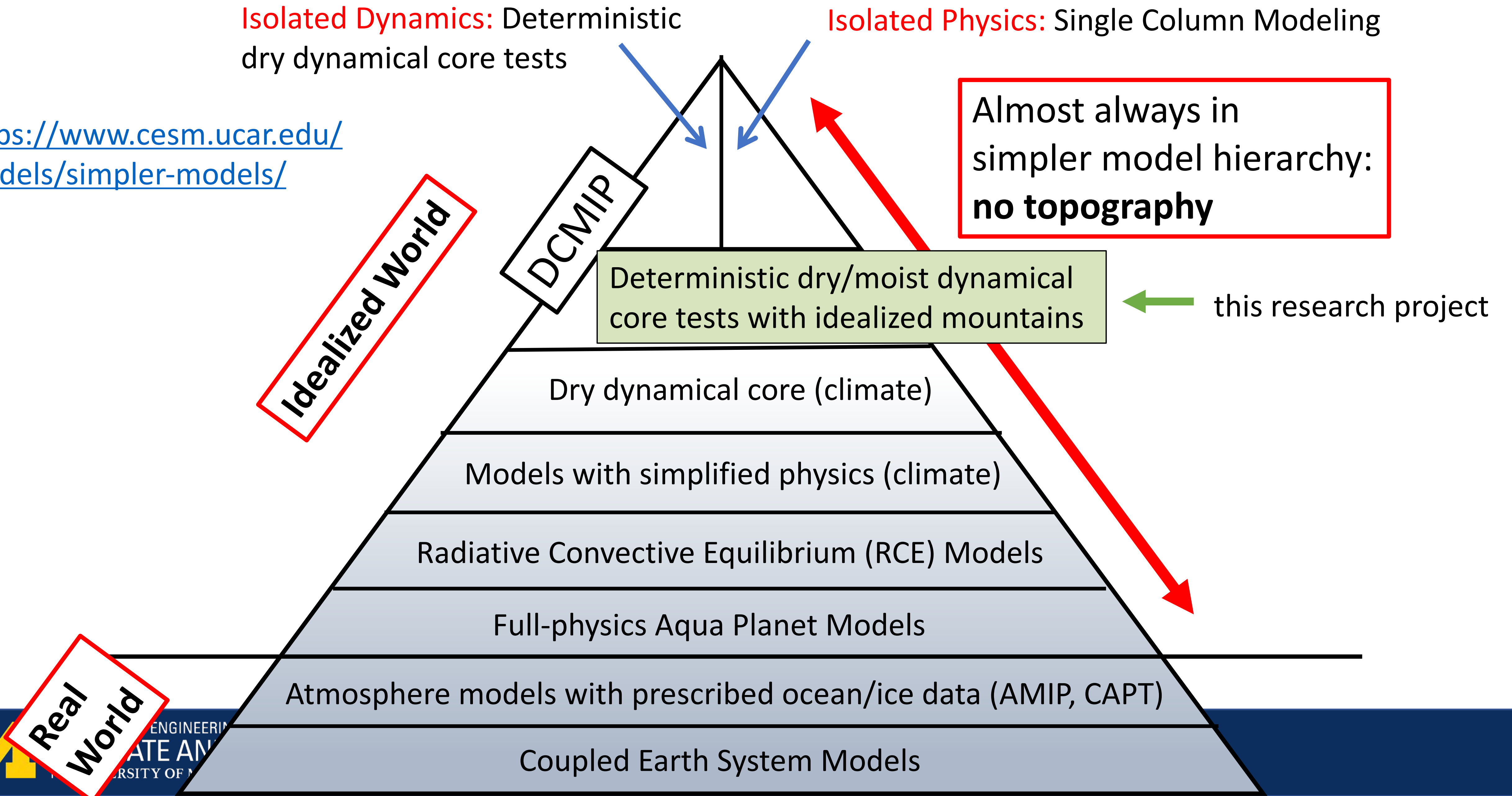
Overarching Questions

- How well is topographic forcing simulated in dynamical cores?
- What is the impact of moisture on the topographically-triggered waves?
- How does the shape and peak height of the topography impact the flow field?
- Does the impact of the topography differ in different dynamical cores?
- What can we learn about the choice of the (topography-following) vertical coordinate and the physics-dynamics coupling strategy?

➡ Answer some of these questions with the help of a GCM model hierarchy

CESM Simpler-Models Hierarchy

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



Isolated Dynamics: Deterministic dry dynamical core tests

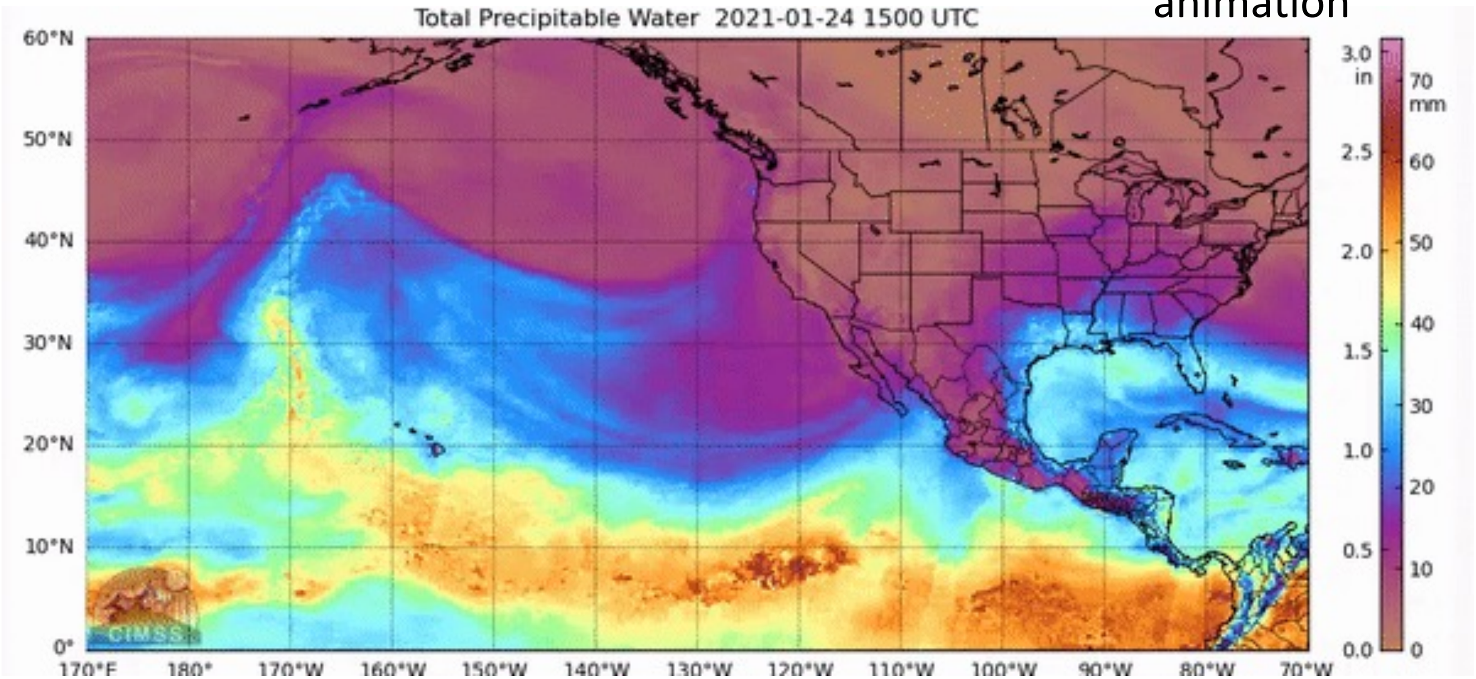
Isolated Physics: Single Column Modeling

Almost always in simpler model hierarchy: **no topography**

this research project

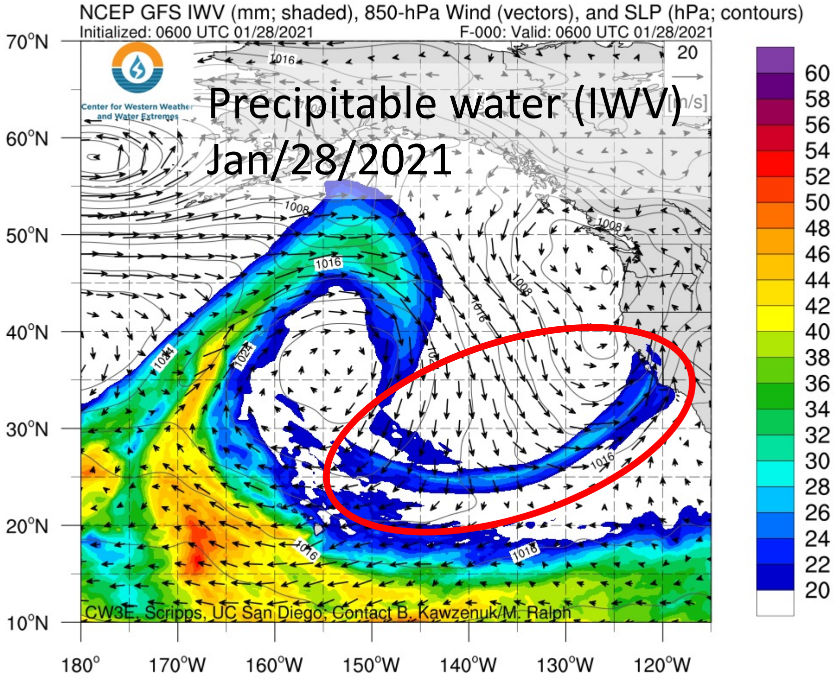
Design of the Test Case: Inspired by Atmospheric Rivers

- Land-falling atmospheric river in California on Jan/28/2021
- (Tropical) moisture gets squeezed out by mountain range upon landfall of baroclinic wave, long & narrow moisture band, presence of low-level jet



Total Precipitable Water 2021-01-24 1500 UTC

animation



NCEP GFS IWV (mm; shaded), 850-hPa Wind (vectors), and SLP (hPa; contours)

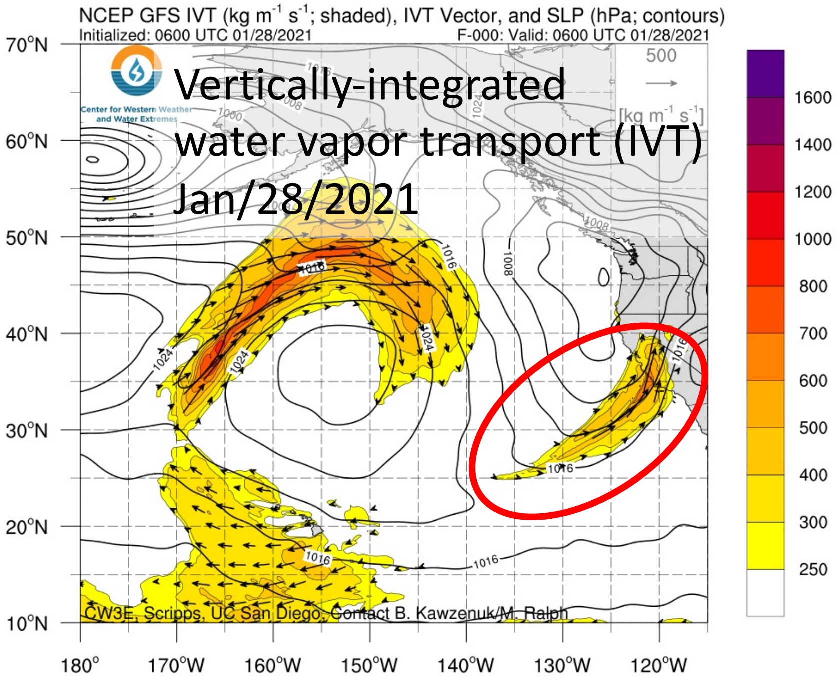
Initialized: 0600 UTC 01/28/2021

F-000: Valid: 0600 UTC 01/28/2021

Precipitable water (IWV)

Jan/28/2021

CW3E, Scripps, UC San Diego, Contact B. Kawzenuk/M. Ralph



NCEP GFS IVT (kg m^{-1} s^{-1}; shaded), IVT Vector, and SLP (hPa; contours)

Initialized: 0600 UTC 01/28/2021

F-000: Valid: 0600 UTC 01/28/2021

Vertically-integrated water vapor transport (IVT)

Jan/28/2021

CW3E, Scripps, UC San Diego, Contact B. Kawzenuk/M. Ralph

Dynamical Cores and Configuration

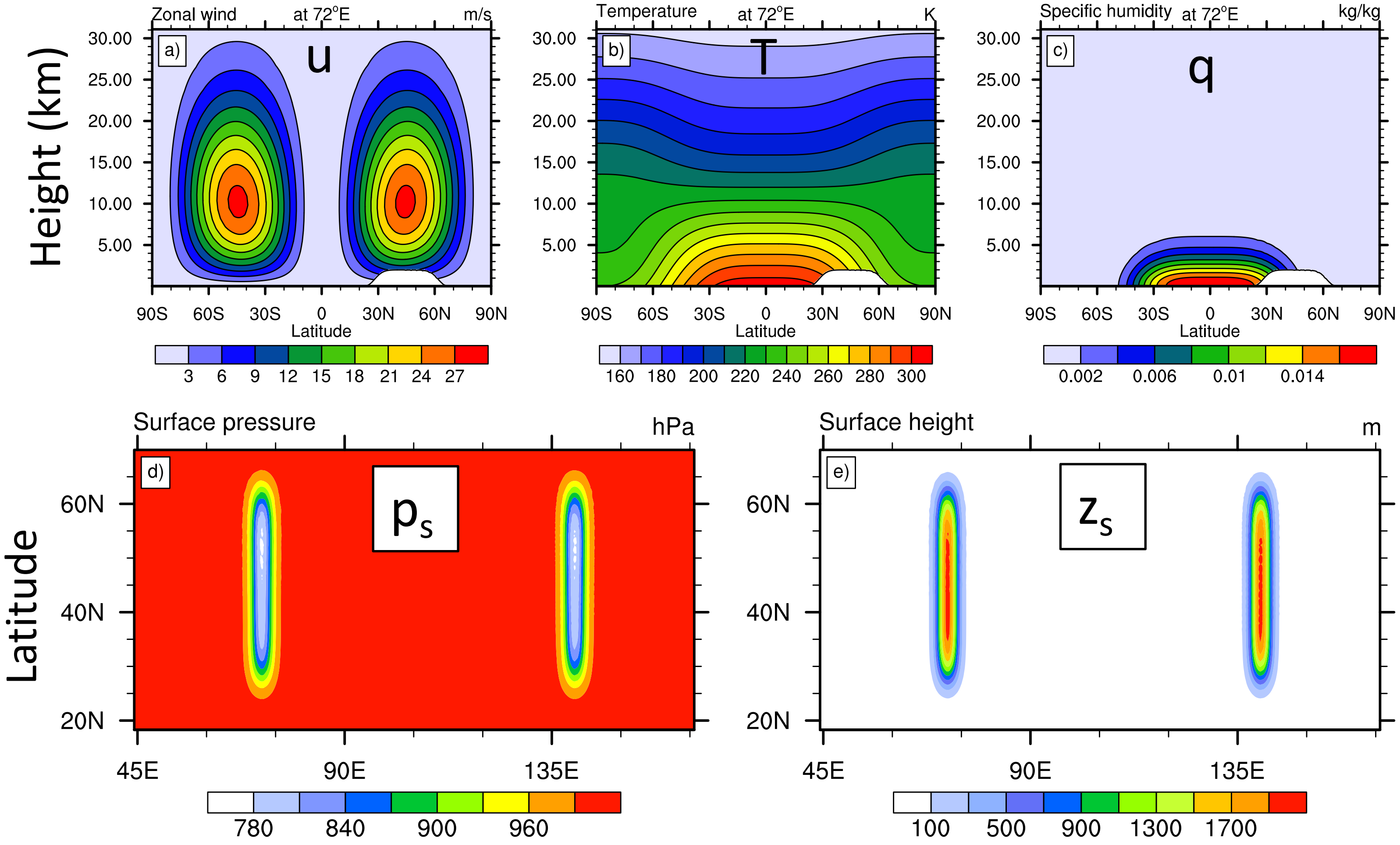
Models

- CESM 2.1.3 / CESM 2.2:
  - Spectral Element SEne60L30 (≈ 50 km)
  - Finite Volume FV05L30 (0.47˚ x 0.63˚ grid, ≈ 50 km x 65 km)
  - Finite Volume Cubed Sphere FV3C192L30 (≈ 50 km), new in CESM 2.2
- Standalone repository:
  - Model for Prediction Across Scales MPAS (60 km L30)

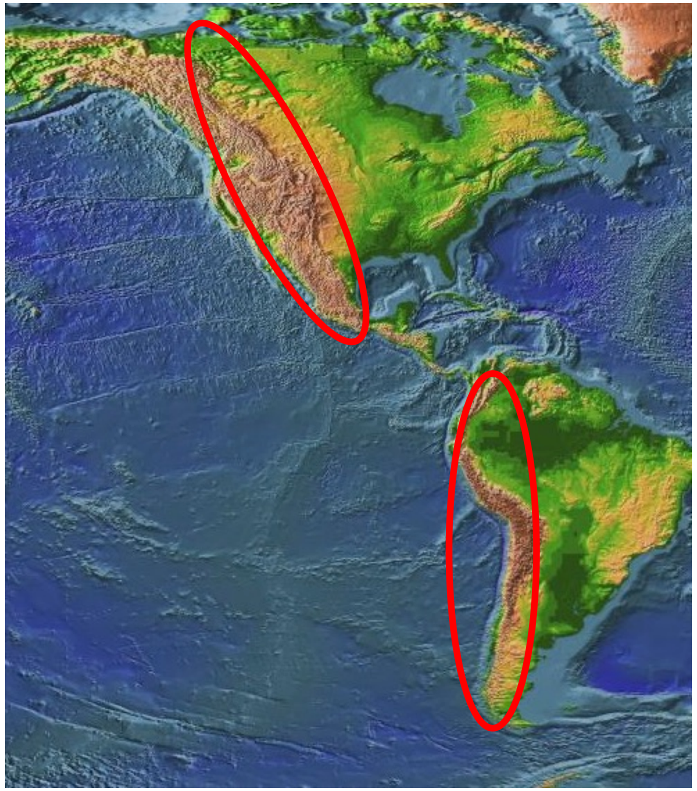
Configuration

- FKESSLER compset: Kessler warm-rain physics (precipitation only) in CESM
- Analytic moist baroclinic wave initial condition (DCMIP-2016, dry test described in Ullrich et al., 2014), added topography, initial zonal wind perturbation removed

Test Case: Initial Conditions



- Well-balanced moist initial conditions (baroclinic wave)
- Ridge mountains, 2 km peaks

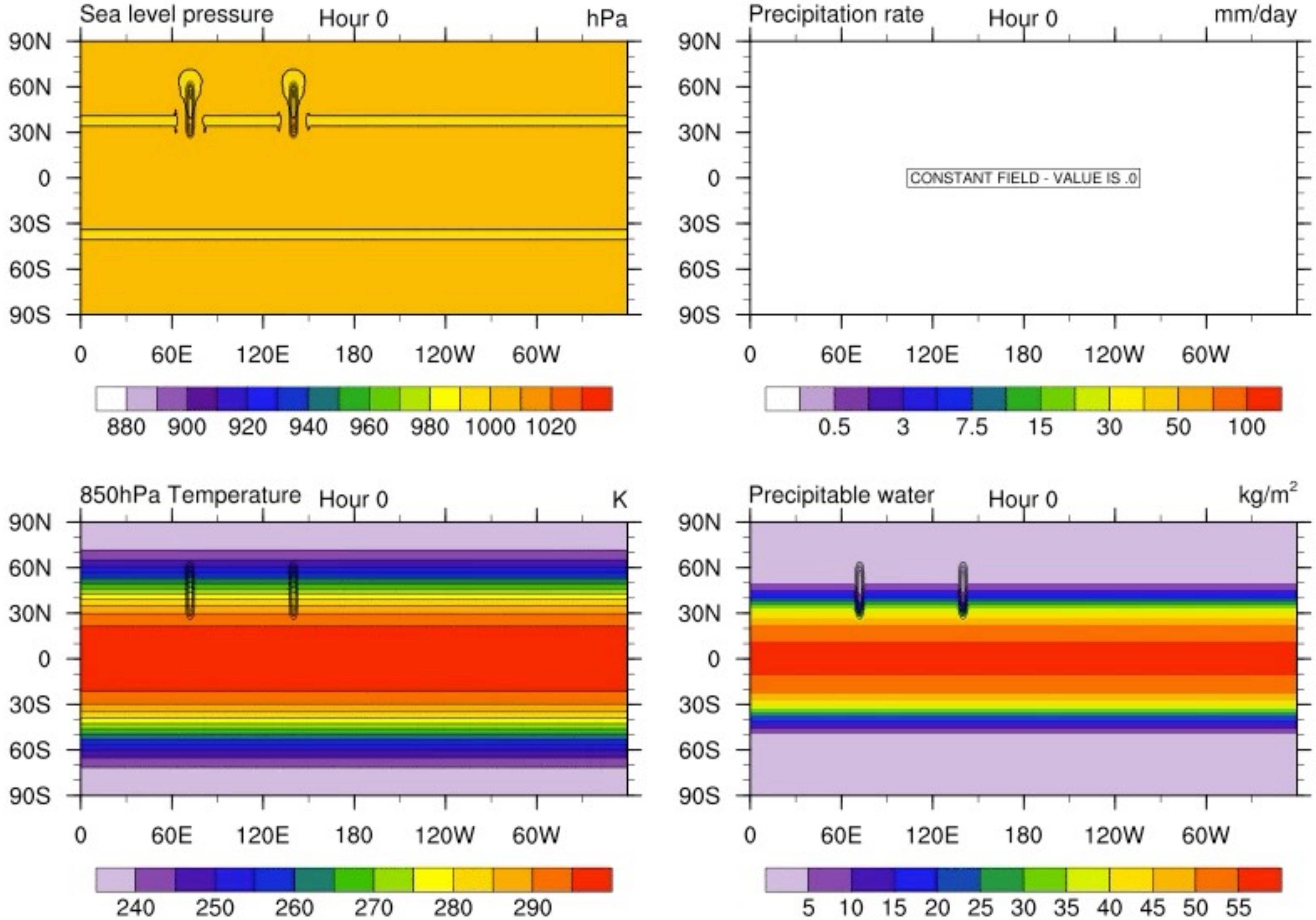


- Inspired by Staniforth and White (ASL, 2011) & DCMIP-2016 (Ullrich, Melvin, Jablonowski, Staniforth (QJ, 2014))

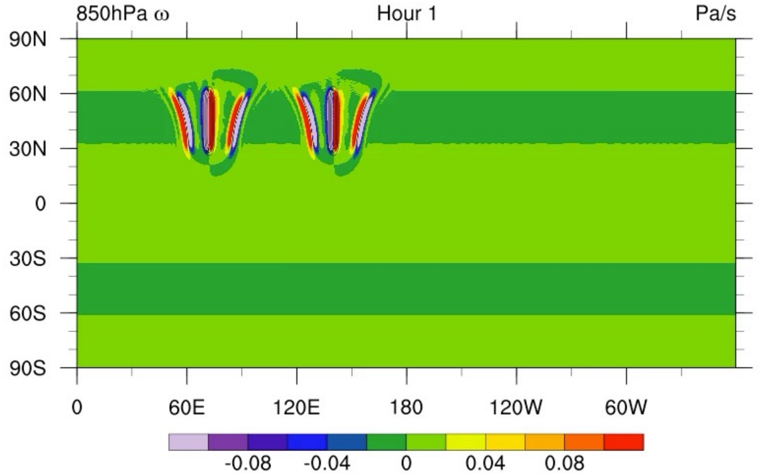
Characteristics of the Test Case

- Well-balanced moist initial conditions (baroclinic wave), analytically prescribed
- 10-day simulation reveals flow pattern
- Mountains serve as initial perturbations and provide continuous forcing

10-day animation

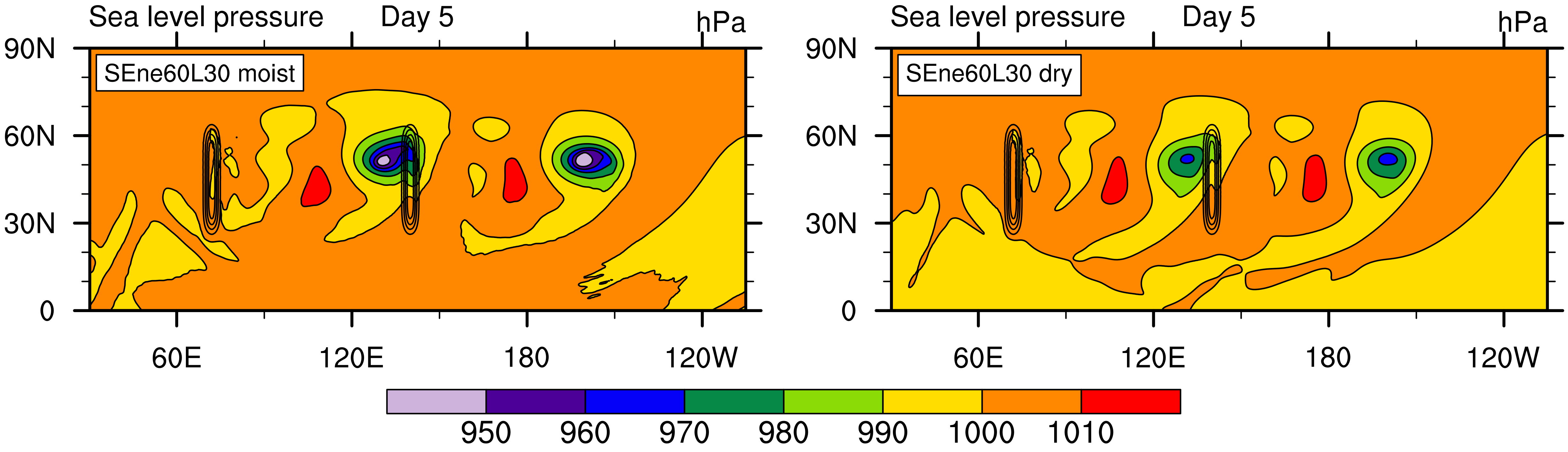


Snapshots of the CESM2.2 SE ne60L30 (50 km) dynamical core with Δt_{phys} = 900 s, rsplit = 3, nsplit = 2, qsplit = 1, ftype = 2 (hybrid)



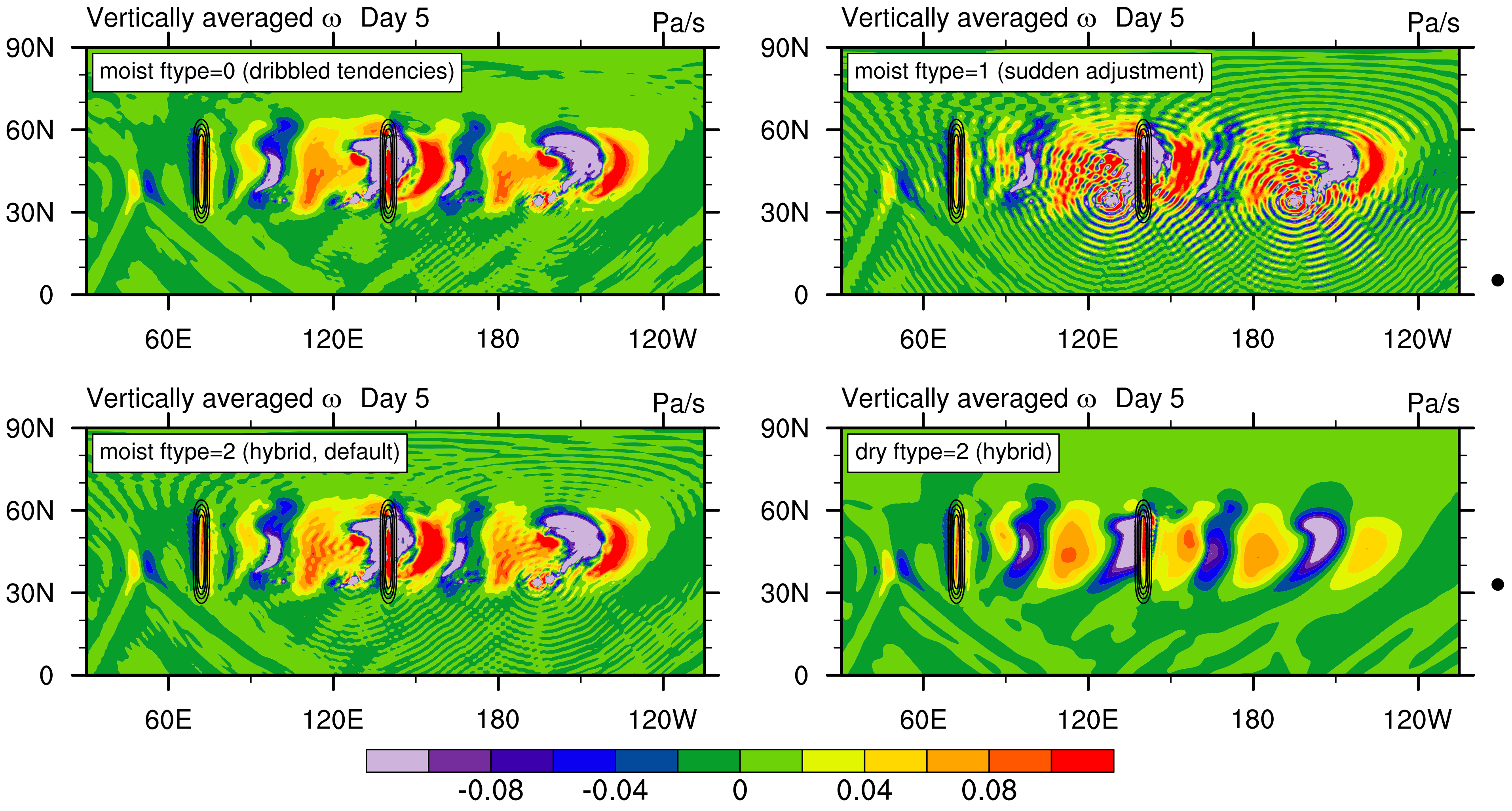
10-day animation

Application Examples: Moist versus Dry



- Moisture processes (warm-rain Kessler physics) **intensify** the evolution of the baroclinic wave
- At day 5, the minimum sea level pressures are **941 hPa** (moist) and **966 hPa** (dry)

Application Examples: Physics-Dynamics Coupling



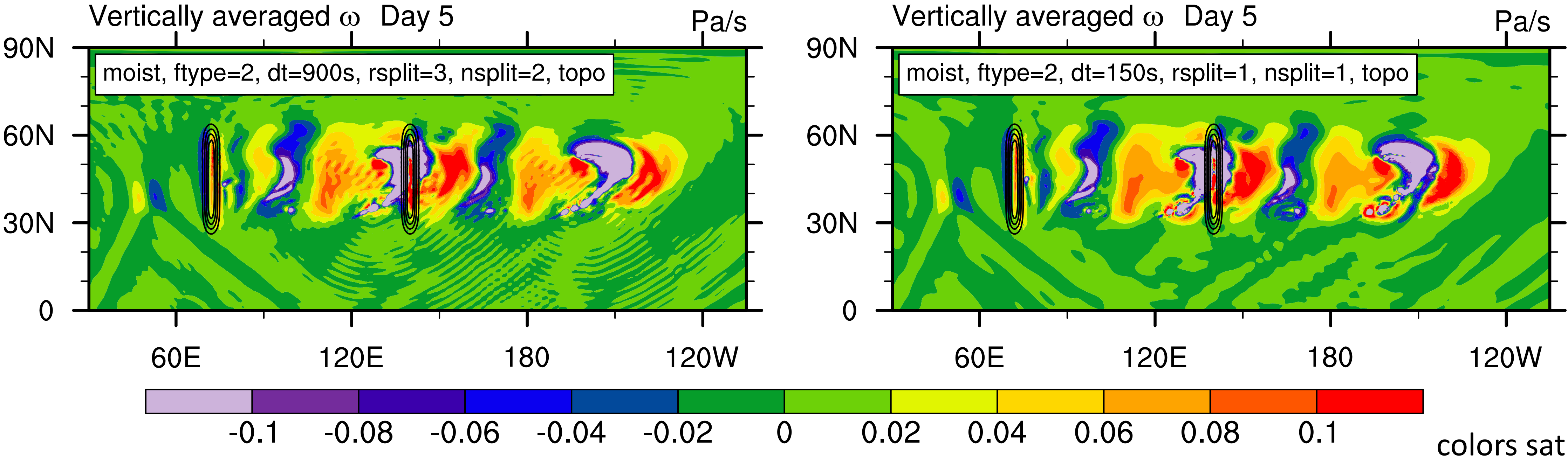
colors saturate to highlight small scales

CESM 2.1.3
SEne60L30 (50 km):
Δt_{phys} = 900 s, rsplit = 3,
nsplit = 2, qsplit = 1

- Test case reveals impact of SE’s physics-dynamics coupling strategy (ftype)
- hybrid: sudden adjustments of tracers like specific humidity, dribbled otherwise

Application Examples: Physics-Dynamics Coupling

CESM 2.2 SEne60L30

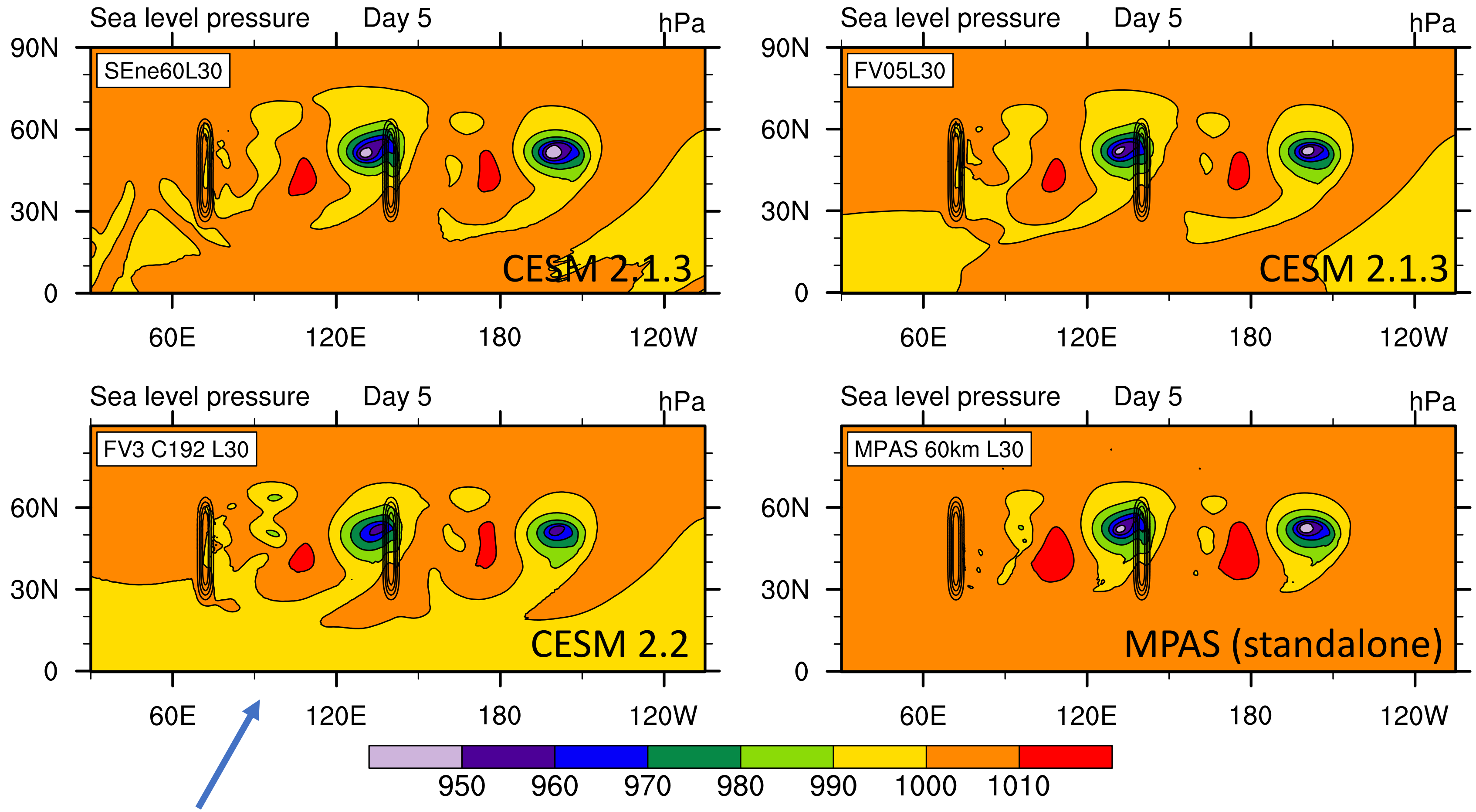


colors saturate

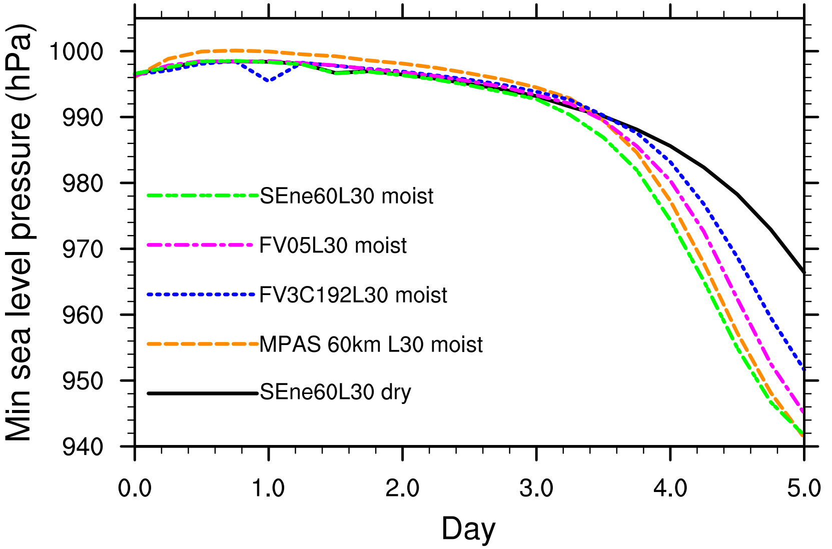
- Numerical noise in SE: Consequence of the long physics time step with subcyled dynamics (here with Δt_{phys} = 900 s, rsplit = 3, nsplit = 2, qsplit = 1, ftype=2)
- Using the same short physics and dynamics time step of $\Delta t_{phys} = \Delta t_{dyn}$ = 150 s eliminates the numerical noise in SE
- Likely: increasing the strength of the horizontal diffusion / divergence damping will also eliminate the noise (small-scale gravity wave oscillations)

Application Examples: Dycore Intercomparisons

Resolutions: ≈ 50 km L30



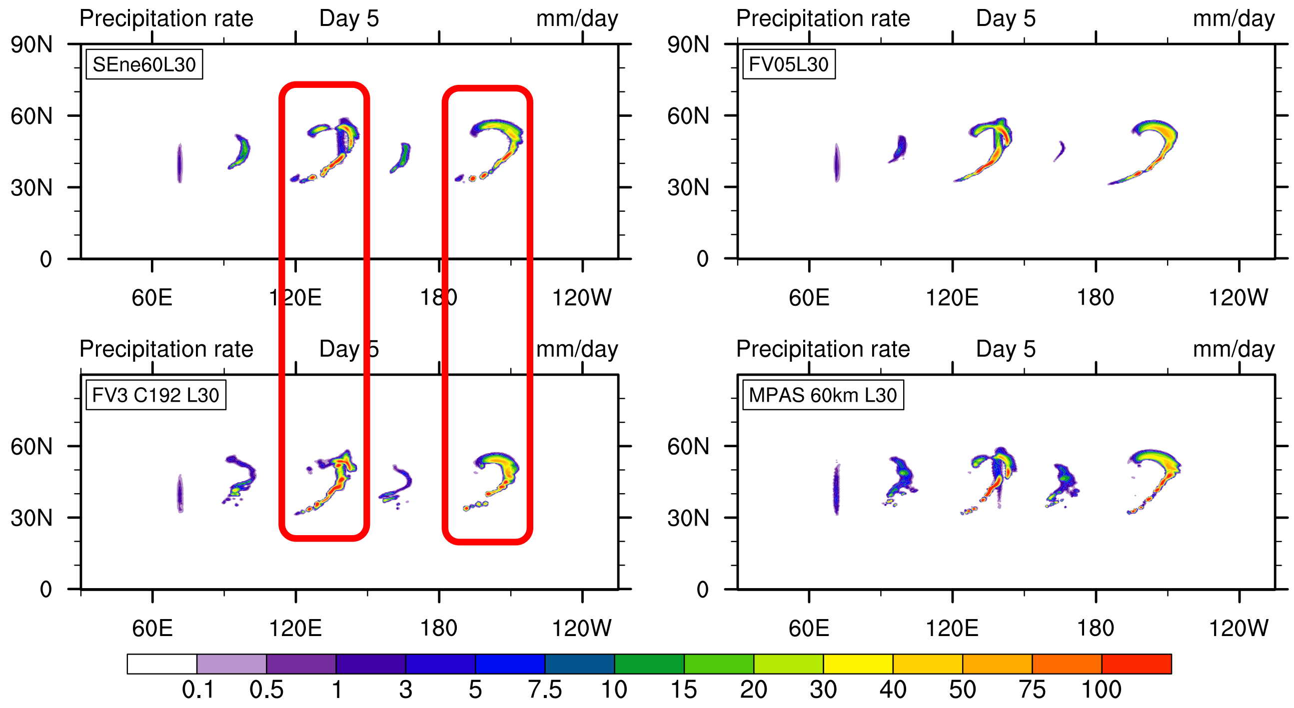
Time series: Minimum sea level pressure

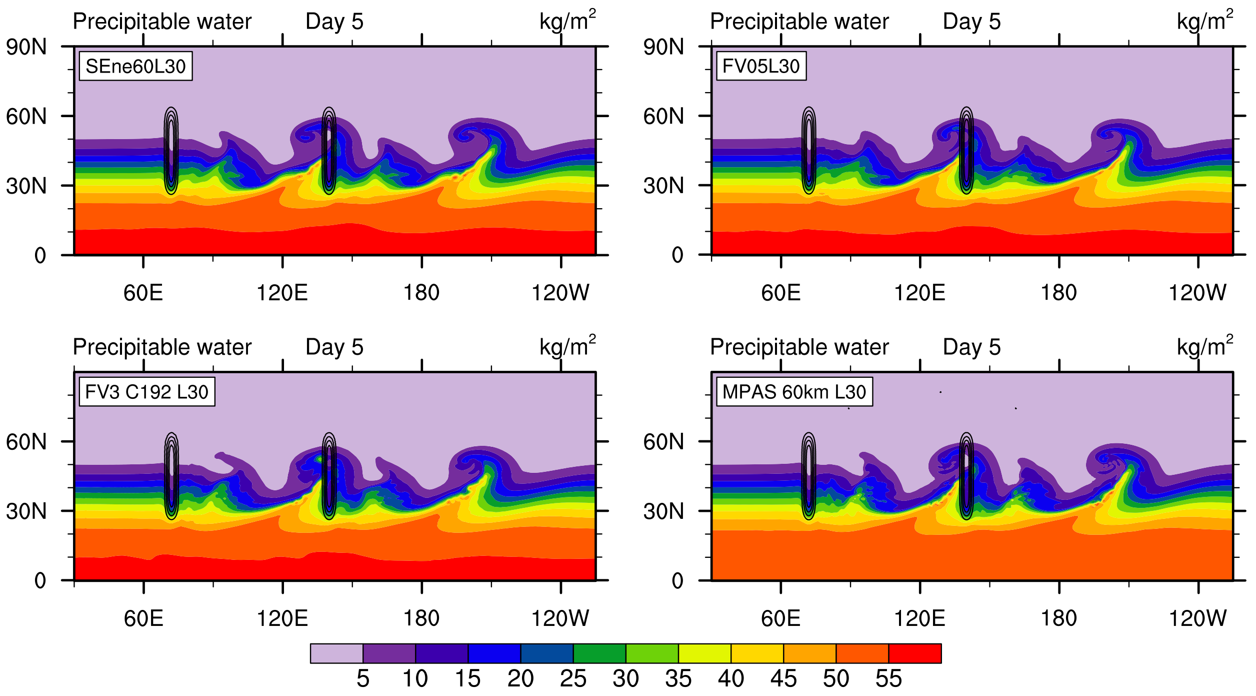


FV3 intensification strongly depends on its diffusion settings (here with hord=10).
Less diffusive FV3 hord=5 simulations closely resemble the SE and MPAS evolutions.

- Overall: sea level pressure patterns are similar
- But: considerable differences in the intensification (by day 5)

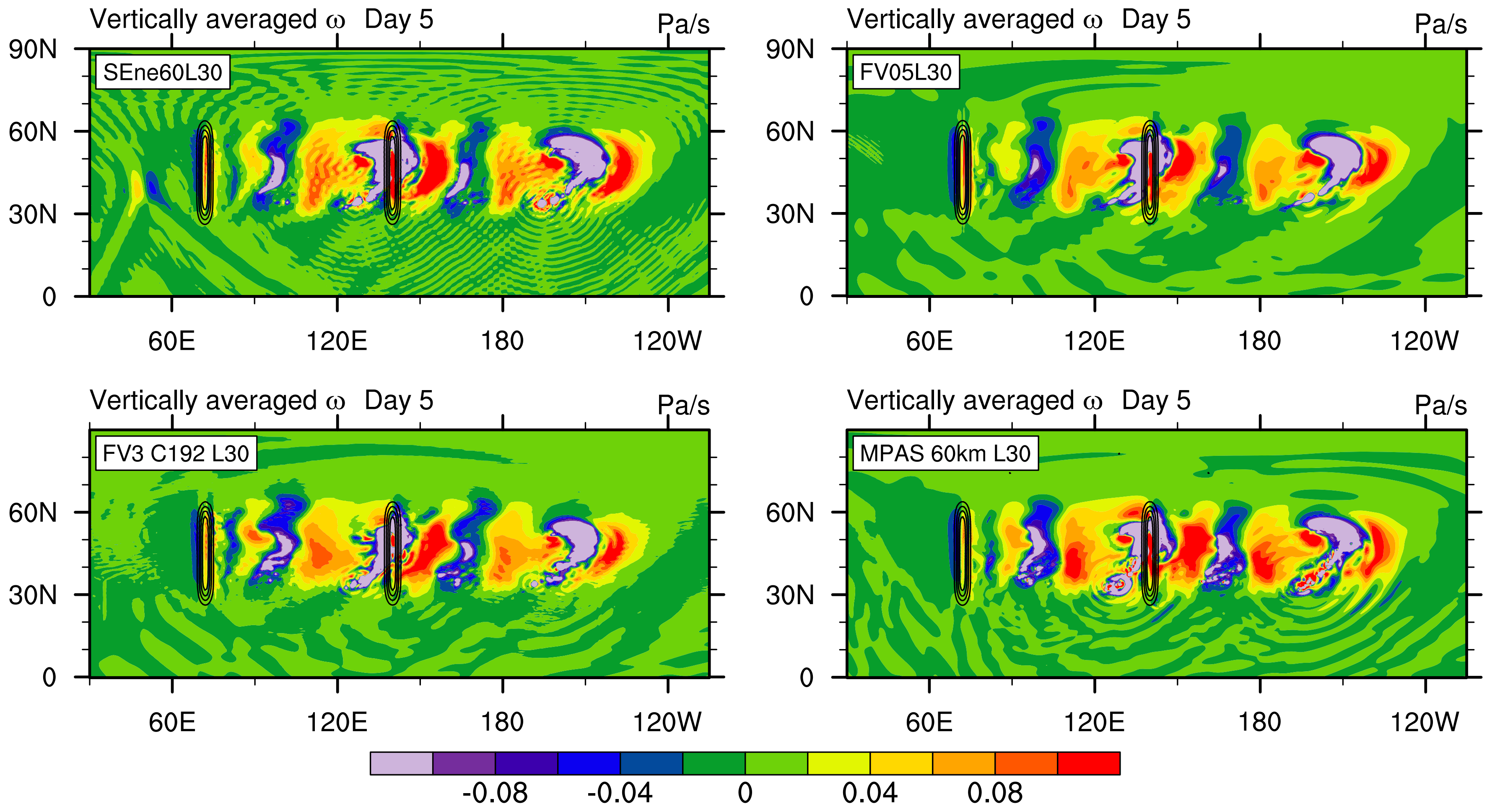
Application Examples: Dycore Intercomparisons





- Mountain test case reveals differences in the rain response in the dynamical cores
- Comparisons between leading rain band (no mountain interference) and middle rain band (hitting the mountain) are insightful
- Evolution of frontal zones with sharp (vertically integrated) precipitable water signatures that have similarities to flows in atmospheric rivers

Application Examples: Dycore Intercomparisons



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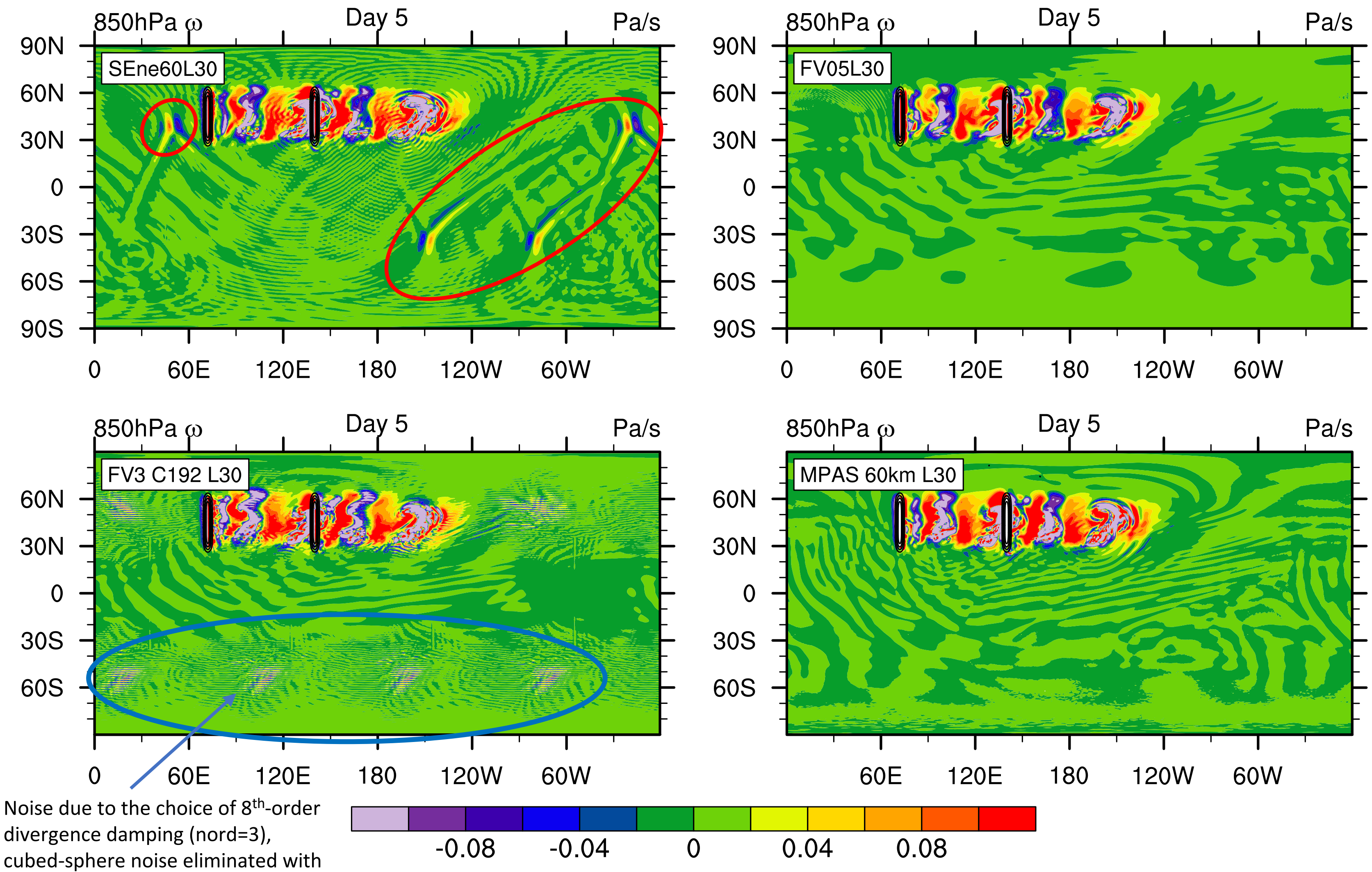
- Local spectral method in SE shows signatures of spectral ringing (numerical noise)
- Noise not obvious in other dycores

Application Examples: Dycore Intercomparisons



Noise due to the choice of 8th-order divergence damping (nord=3), cubed-sphere noise eliminated with 6th-order div-damping (nord=2)

colors saturate to highlight small scales

- Initially: all dycores have signatures of **global high-speed gravity waves** triggered by slight initial imbalance
- In **SE**: global gravity waves are **persistent** **(little damping)**, have high amplitudes and are still present by day 5-10
- FV3 shows signs of the **cubed-sphere grid**, grids not obvious in SE and MPAS

Summary & Future Work

- Test case with focus on topography: Additional element in the simpler-model hierarchy
- Helps answer many fundamental dynamics questions:
  - moist versus dry dynamics
  - impact of mountain shape, size and peak heights on clouds, rain and flow field
  - Topographic gravity wave studies
- Sheds light on numerical designs of dynamical cores and their physics interplay
  - Physics-dynamics coupling
  - Hydrostatic versus nonhydrostatic designs
  - Diffusion
  - Simulation of clouds and rain (placement, rain amount, shape of rain bands, etc.)
- Two publications in development: (1) Characteristics of the test case, (2) fundamental dynamical behavior