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

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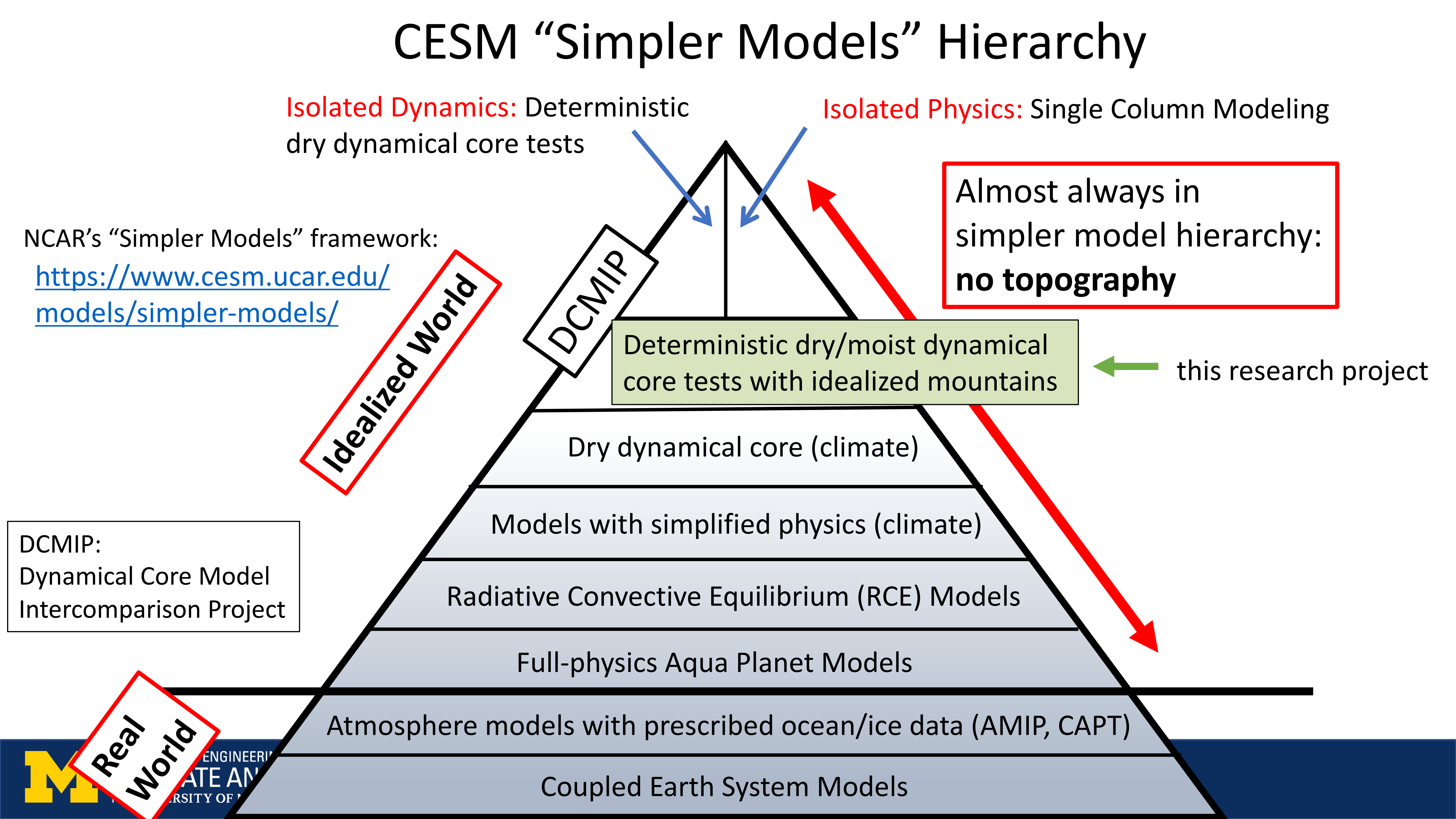
Overarching Questions

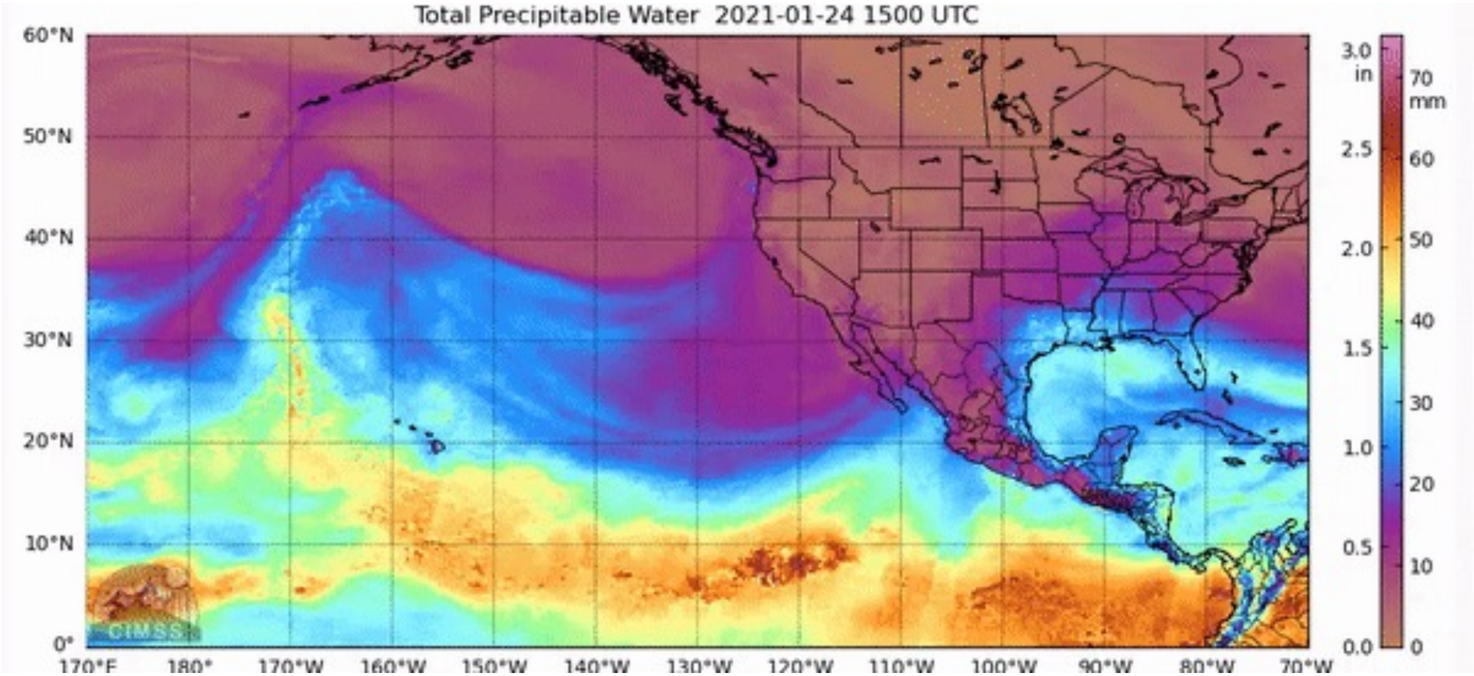
- How well is topographic forcing simulated in dynamical cores?
- What is the impact of moisture on the topographically-triggered waves?
- Does the impact of the topography differ in different dynamical cores?
- What can we learn about the choice of the (topography-following) vertical coordinate and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

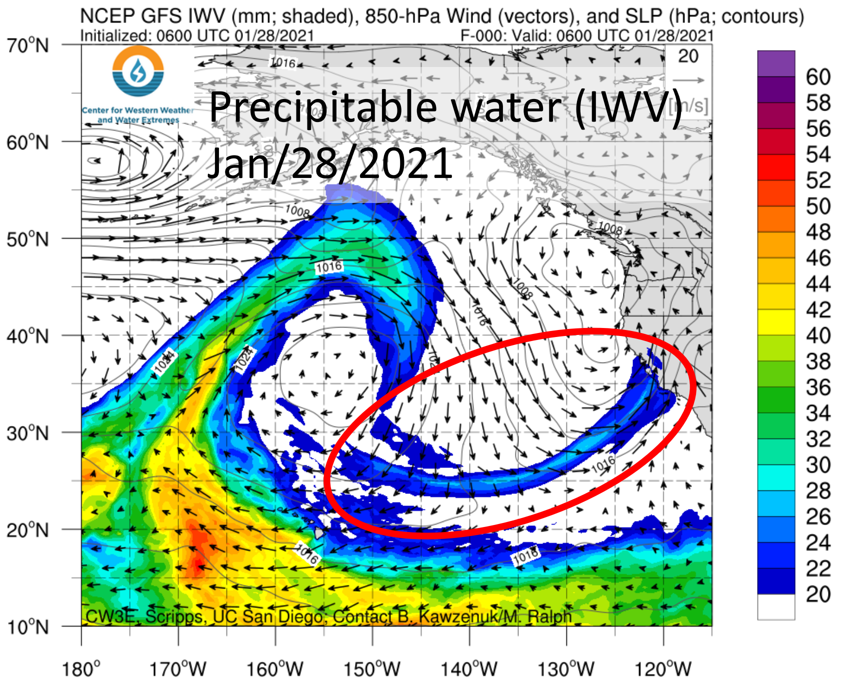
➡ Answer some of these questions with the help of a model hierarchy

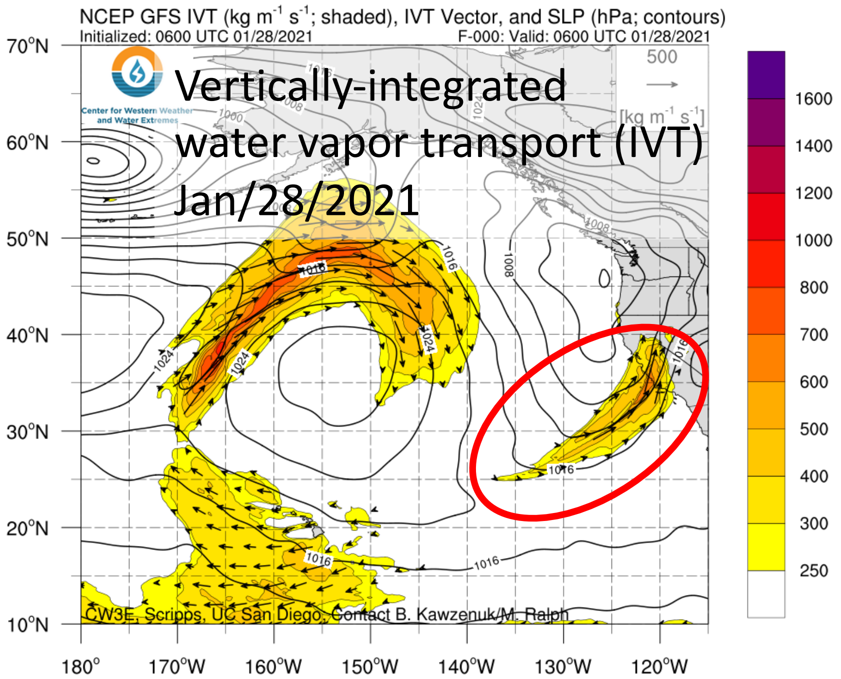

CESM "Simpler Models" Hierarchy
Isolated Dynamics: Deterministic dry dynamical core tests
Isolated Physics: Single Column Modeling
NCAR's "Simpler Models" framework:
https://www.cesm.ucar.edu/models/simpler-models/
Idealized World
DCMIP
Almost always in simpler model hierarchy: no topography
Deterministic dry/moist dynamical core tests with idealized mountains
this research project
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
DCMIP:
Dynamical Core Model Intercomparison Project
Real World

Design of the Test Case: Inspired by Atmospheric Rivers (ARs)

- 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







Dynamical Cores and Test Case Configuration

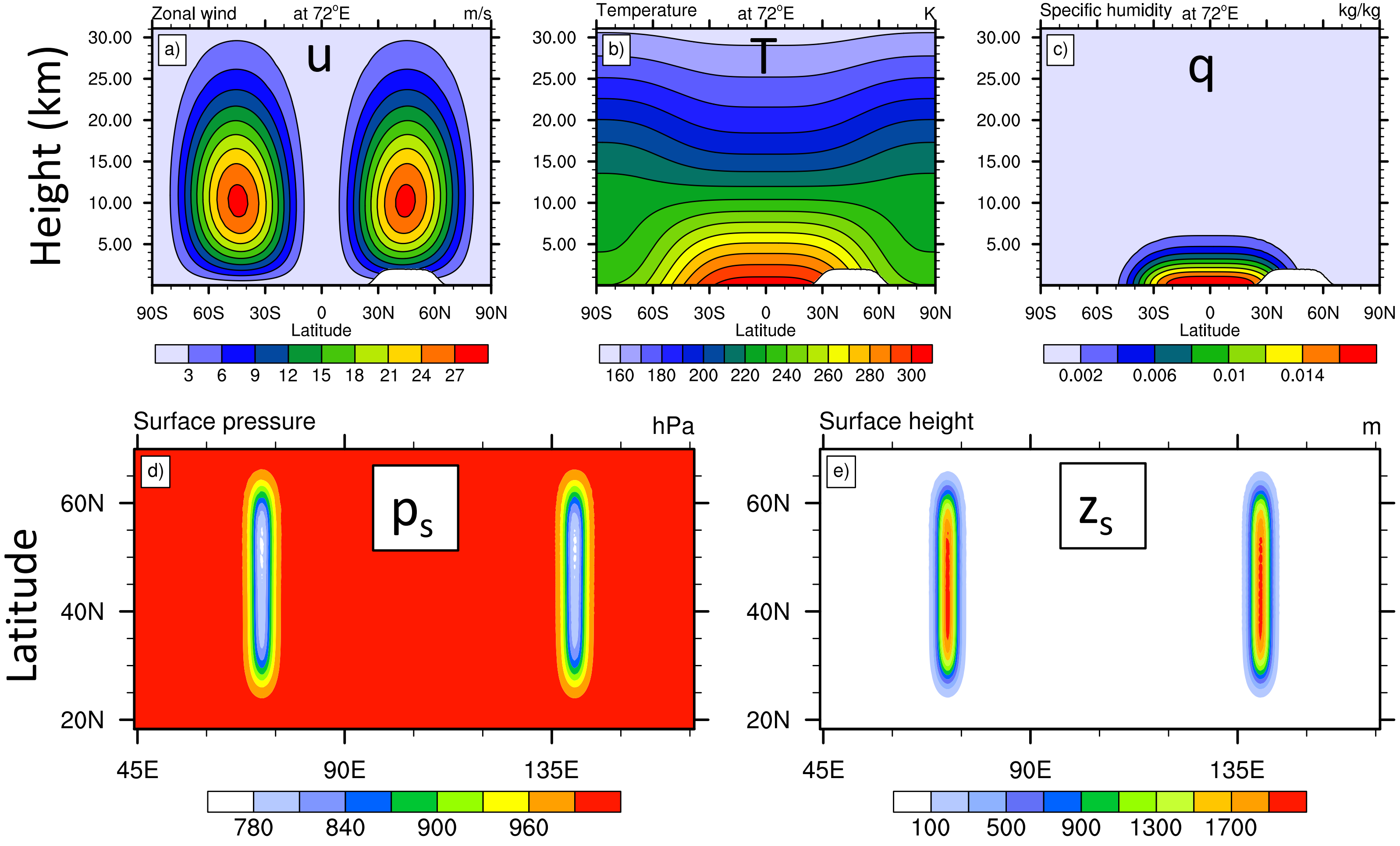
Models

- NCAR's Community Earth System Model (CESM 2.1.3 / CESM 2.2) with the dynamical cores:
  - 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) from NOAA GFDL, new in CESM 2.2
- Standalone dynamical core repository for MPAS:
  - Model for Prediction Across Scales: MPAS (60 km L30)

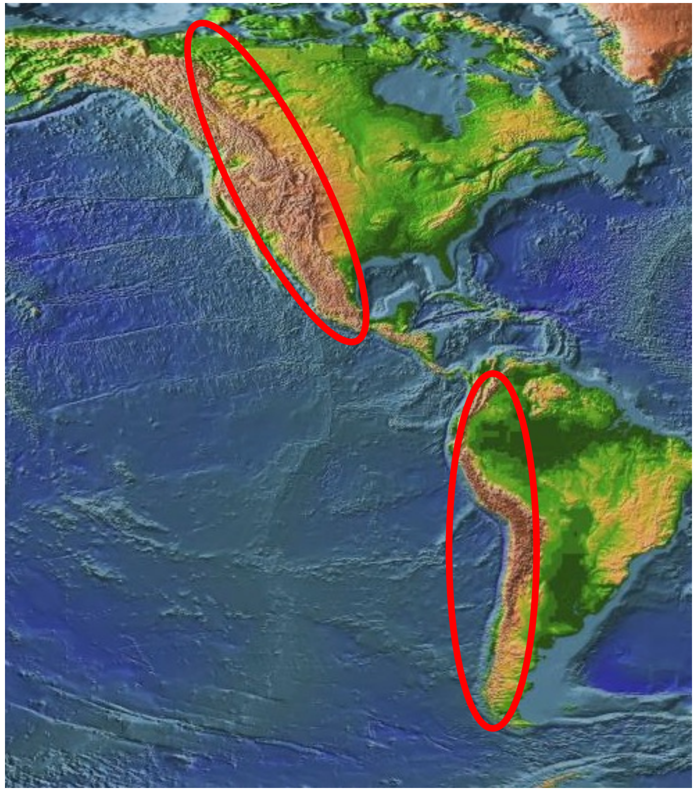
Configuration

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

Initial Conditions



- Well-balanced moist initial conditions (baroclinic wave)
- 2 ridge mountains, 2 km peaks, shape resembles Rockies & Andes

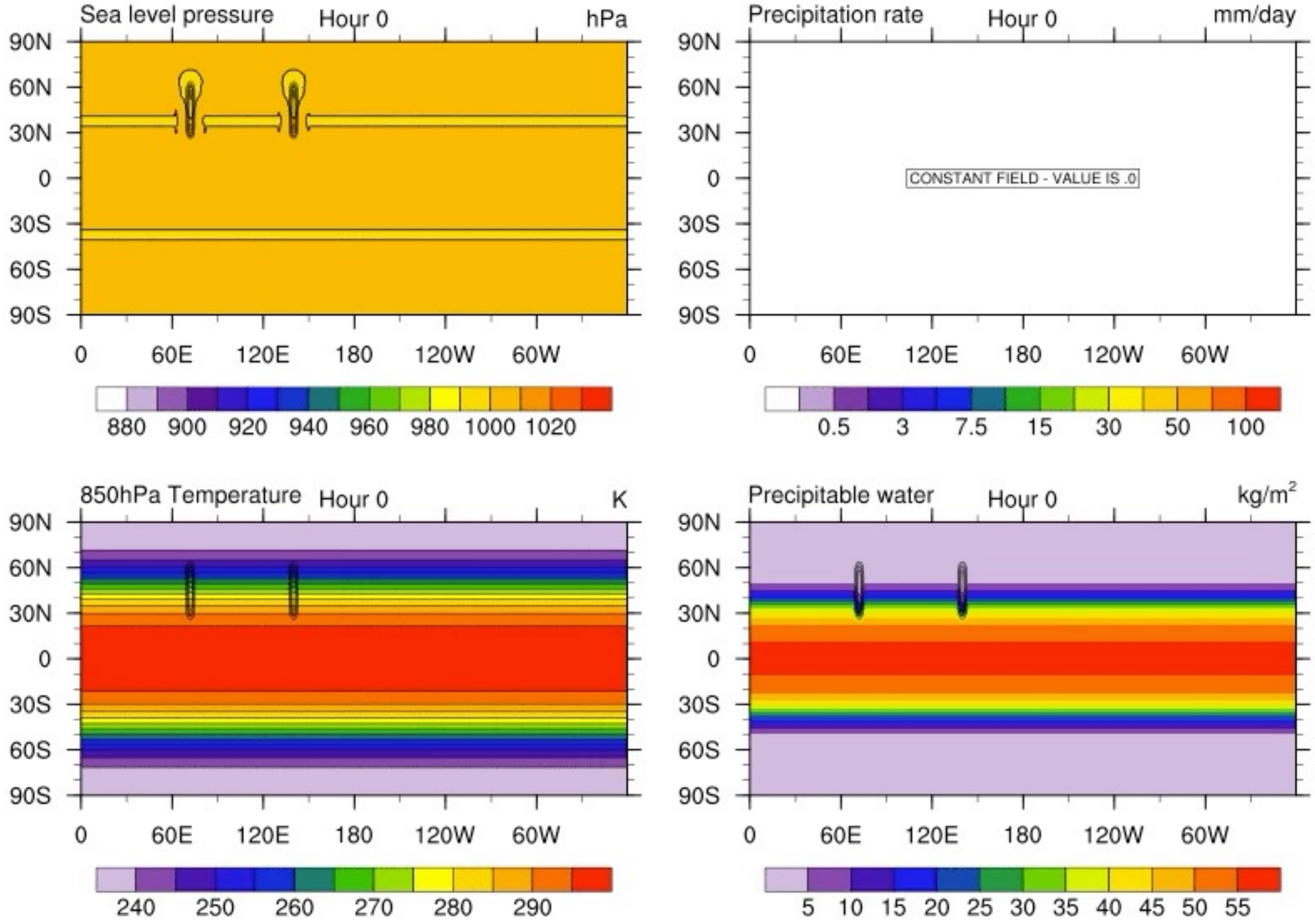


- Inspired by Staniforth and White (ASL, 2011) & DCMIP-2016 (Ullrich, Melvin, Jablonowski, Staniforth (QJ, 2014))

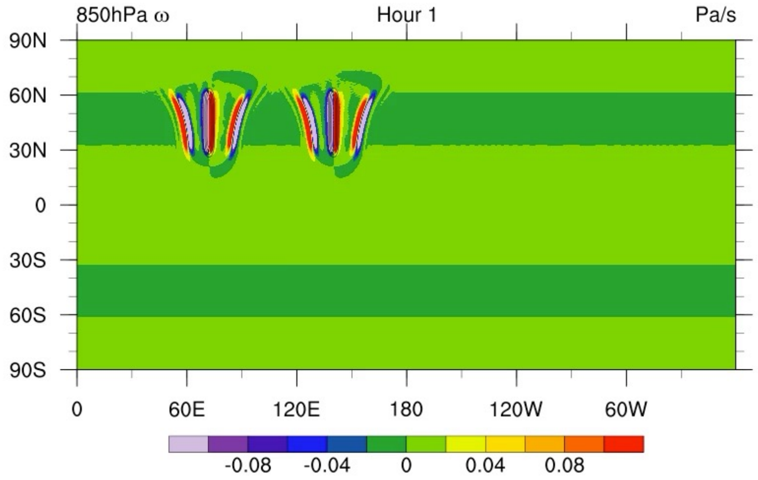
Characteristics of the Test Case

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

240-hour animations



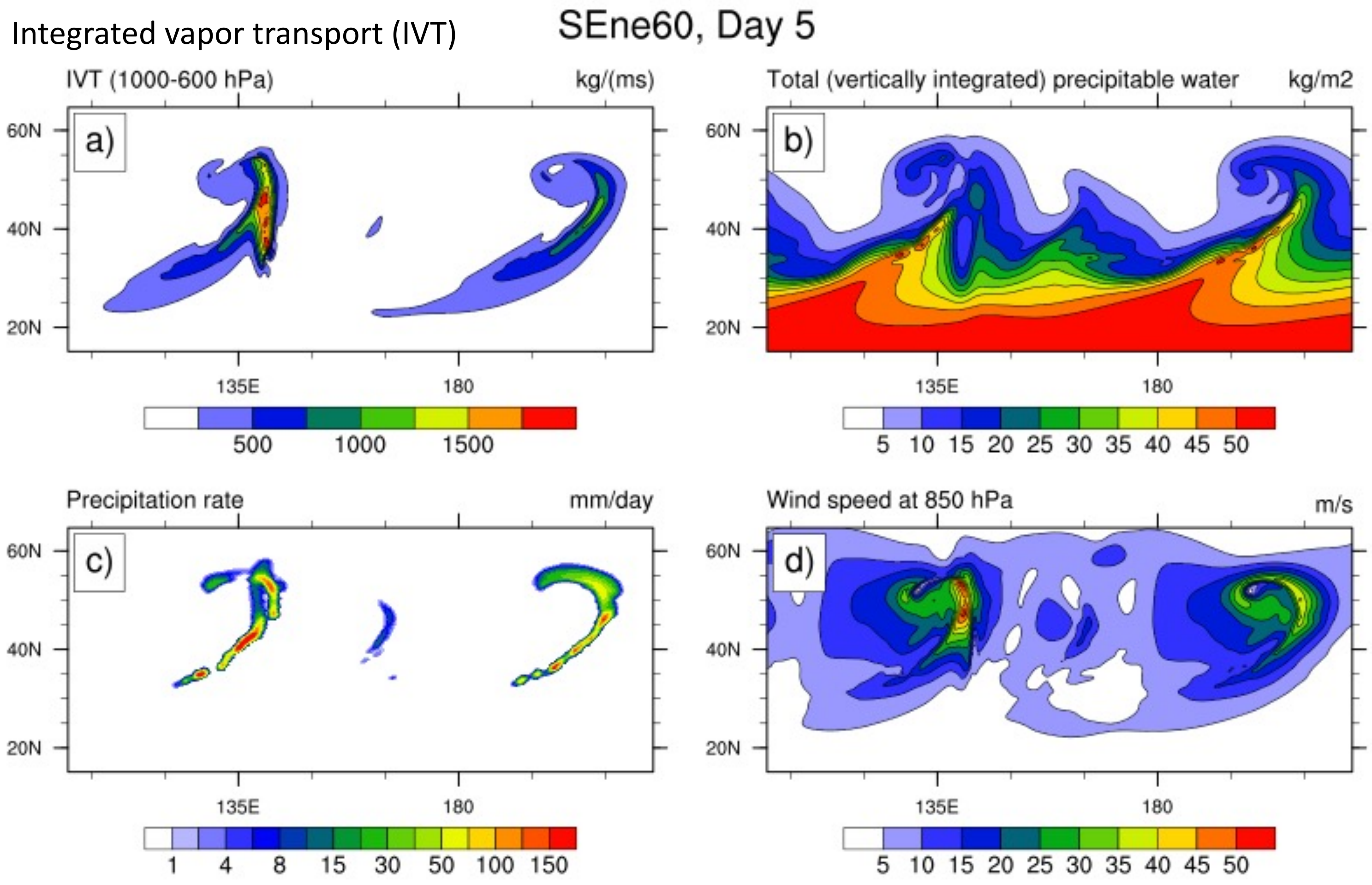
Snapshots of the CESM2.2 SE ne60L30 (50 km) dynamical core with Δt_{phys} = 900 s, rsplit = 3, nsplit = 2, qsplit = 1, ftype = 2 (hybrid)



Presence of propagating external modes in SE, under investigation

Test Case Inspired by Atmospheric Rivers (ARs):

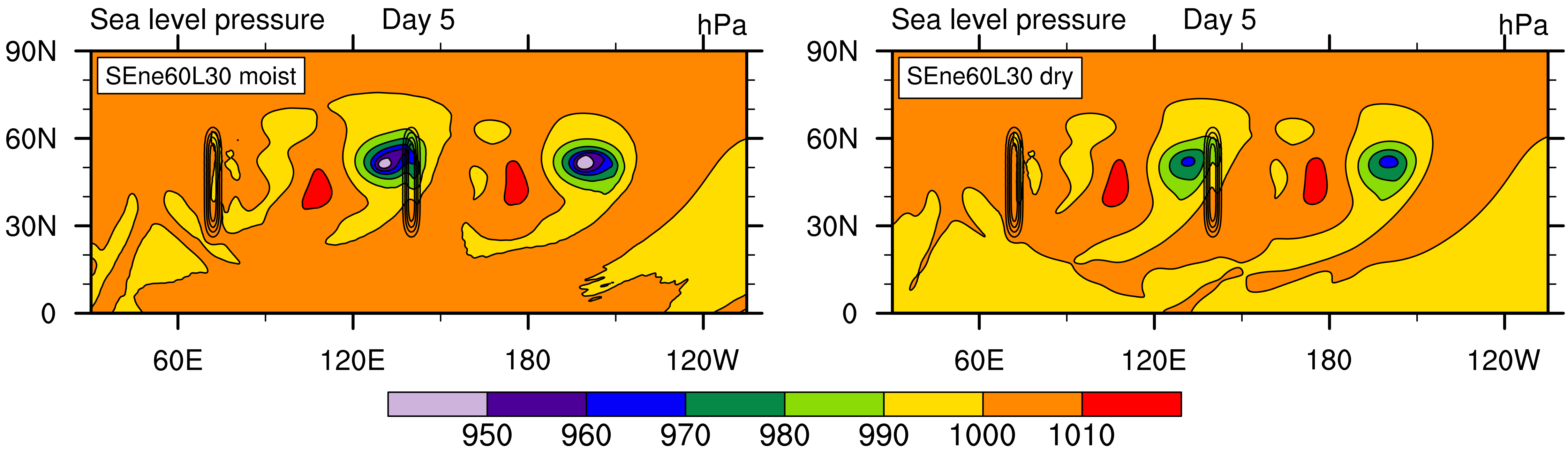
Integrated vapor transport (IVT)



CESM's SEne60L30 (50 km) with the double ridge shows characteristics of ARs by day 5:

- a, b) tropical moisture gets transported into the midlatitudes and is squeezed out by the western mountain range upon 'landfall' of baroclinic wave
- c) long & narrow precipitation bands develop (several thousand km long)
- d) presence of low-level jets

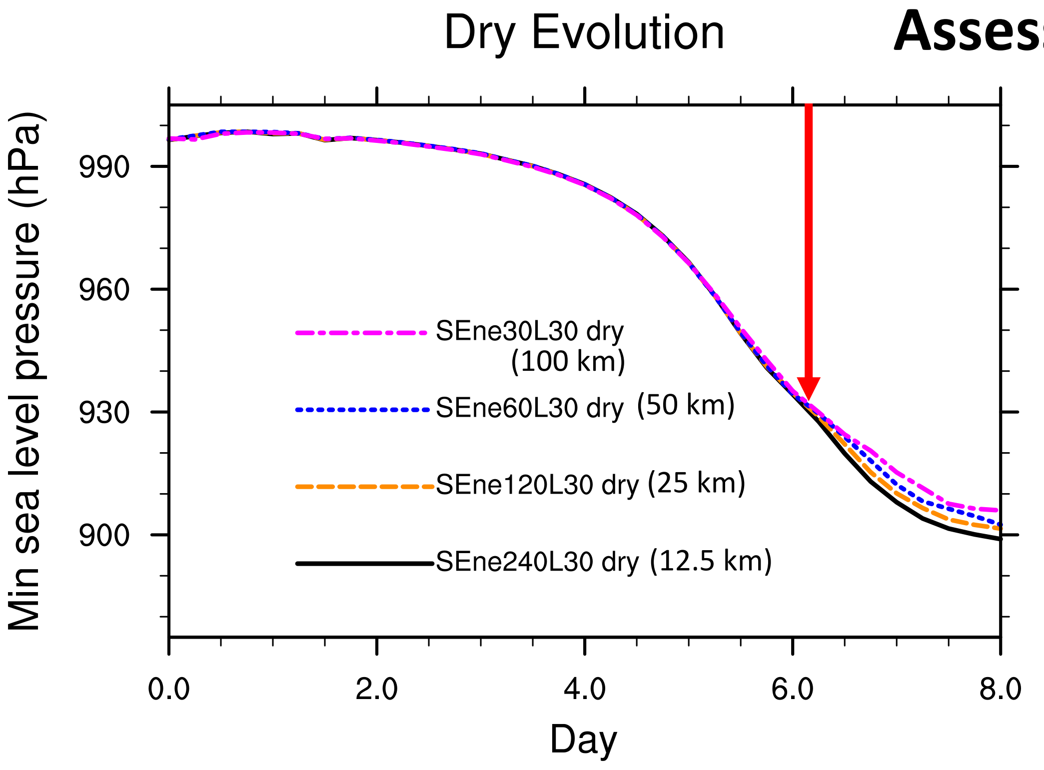
Application Examples: Moist versus Dry

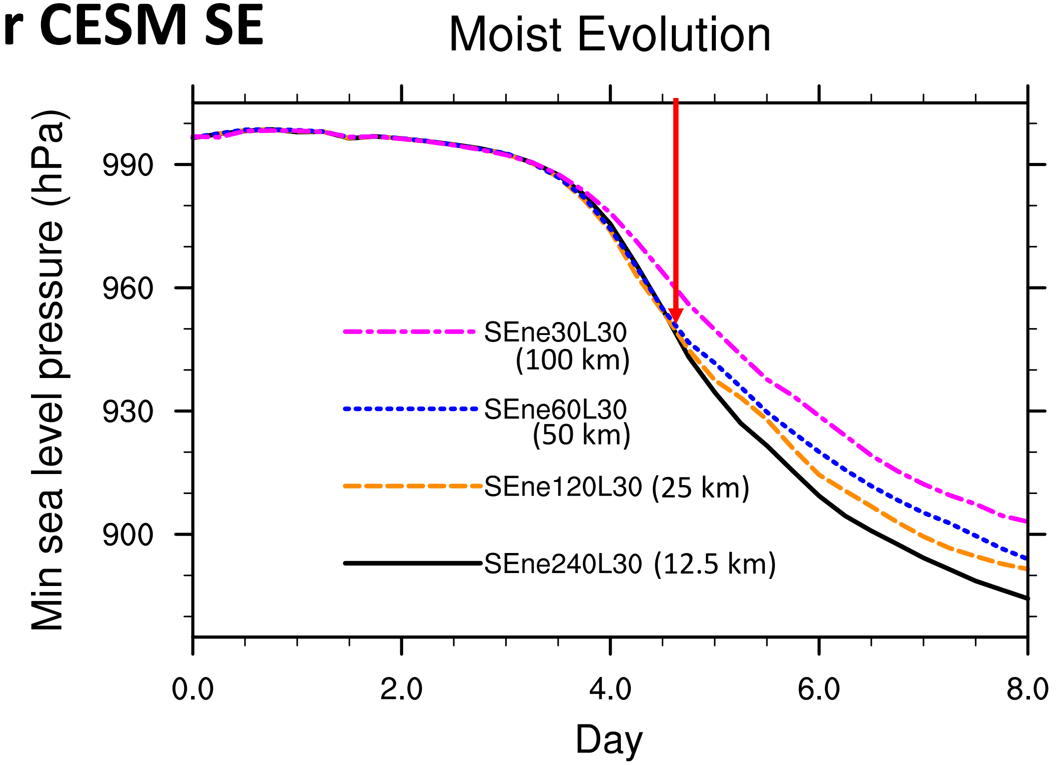


- Dry and moist flow patterns resemble each other
- Moisture processes (warm-rain Kessler physics) **intensify** the evolution of the baroclinic wave
- At day 5, the minimum sea level pressures (SLP) are **941 hPa** (moist) and **966 hPa** (dry)

Application Examples: Convergence - Moist versus Dry

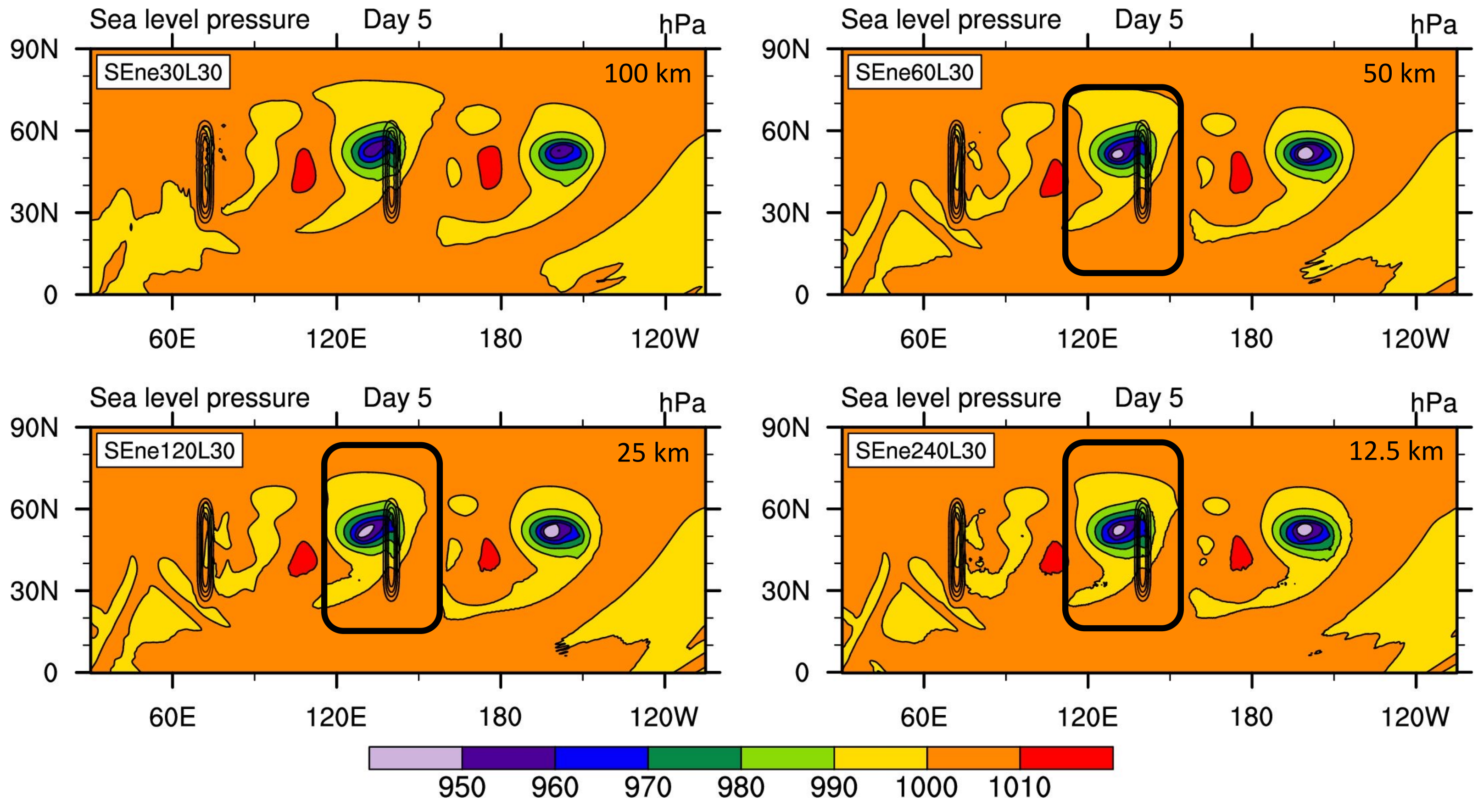
Assessed for CESM SE





- Dry: SLP evolution in SE converges with increasing horizontal resolution up to ≈ day 6
- Moist: Structure and intensity of SLP evolution in SE (for 50, 25 and 12.5 km) converged until ≈ day 4.5
- Higher resolution leads to further intensifications after day 4.5 (moist run) and lets intensities diverge (lots of moisture interactions after day 4.5)

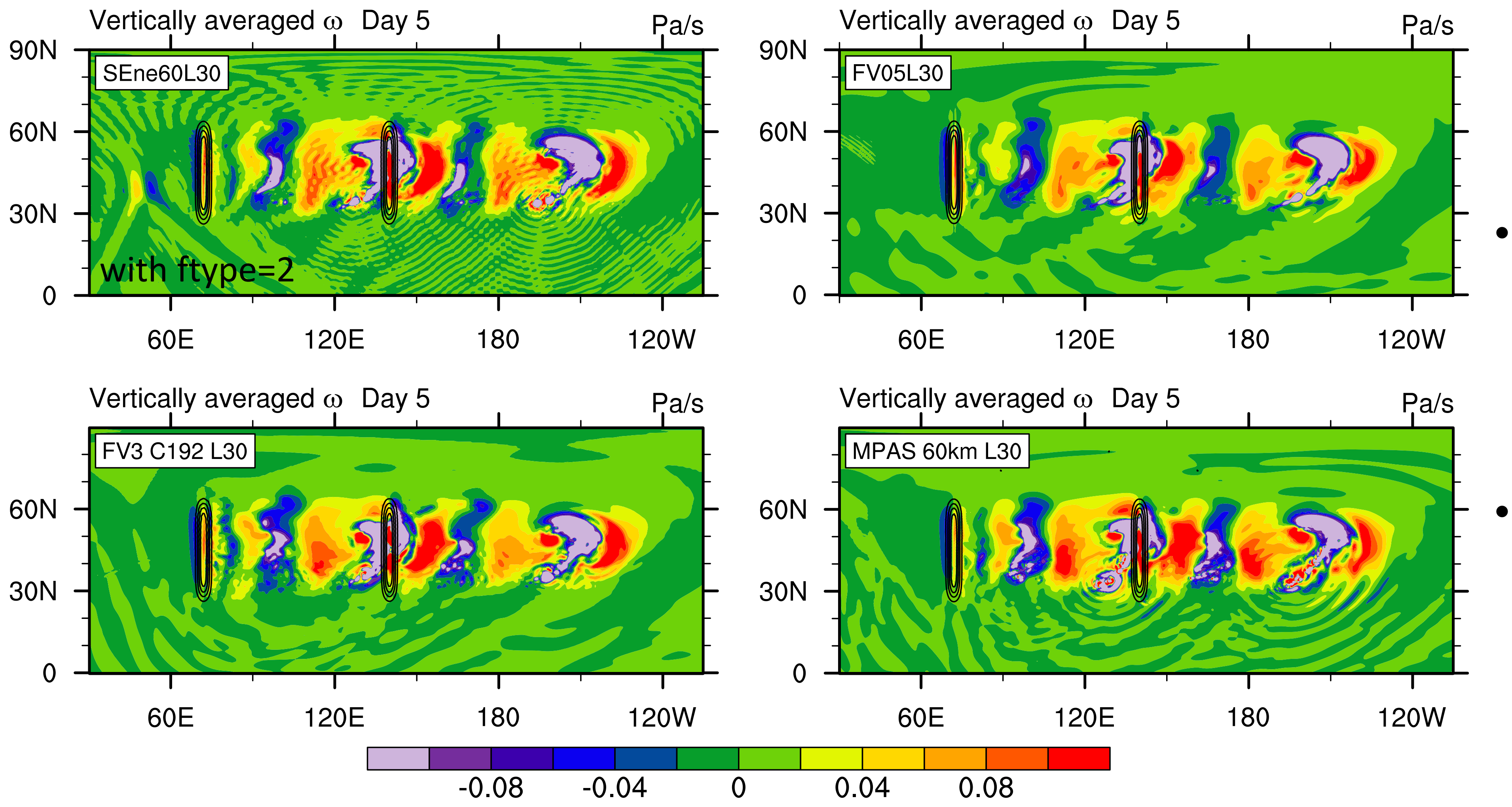
Application Examples: Convergence



Assessed for CESM SE:

- Qualitative structures of the waves generally agree across the resolutions, sign of convergence (for 100 km and finer) with respect to the shapes and locations of the highs and lows
- Increasing resolution intensifies the amplitudes, especially of the lows

Application Examples: Physics-Dynamics Coupling

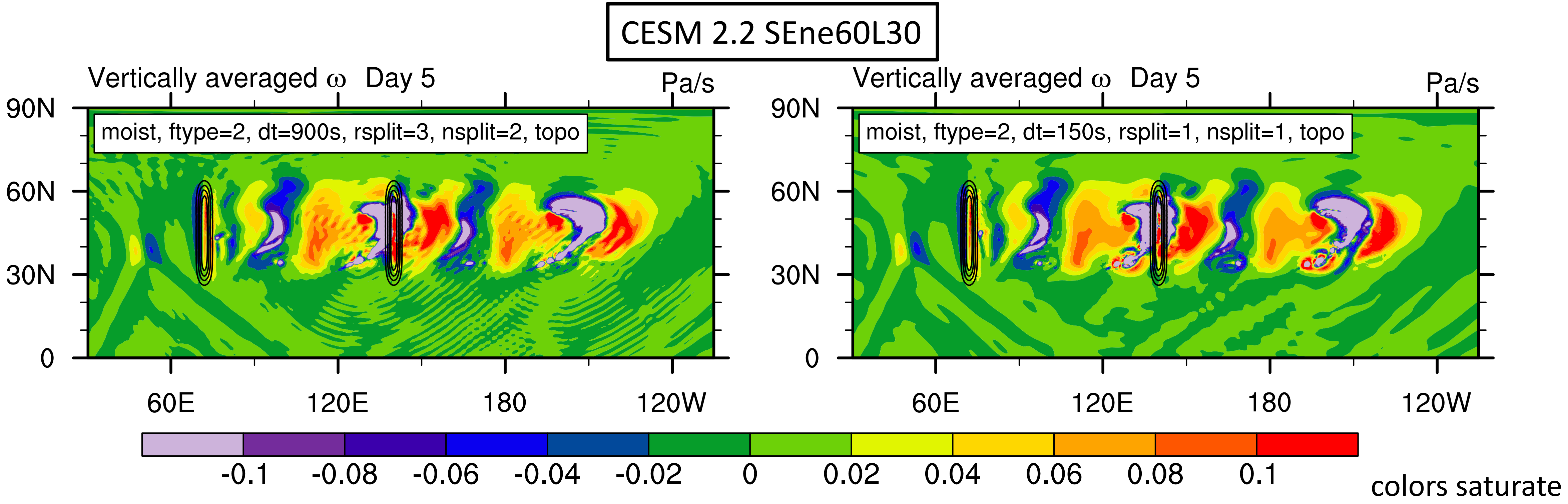


colors saturate to highlight small scales

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

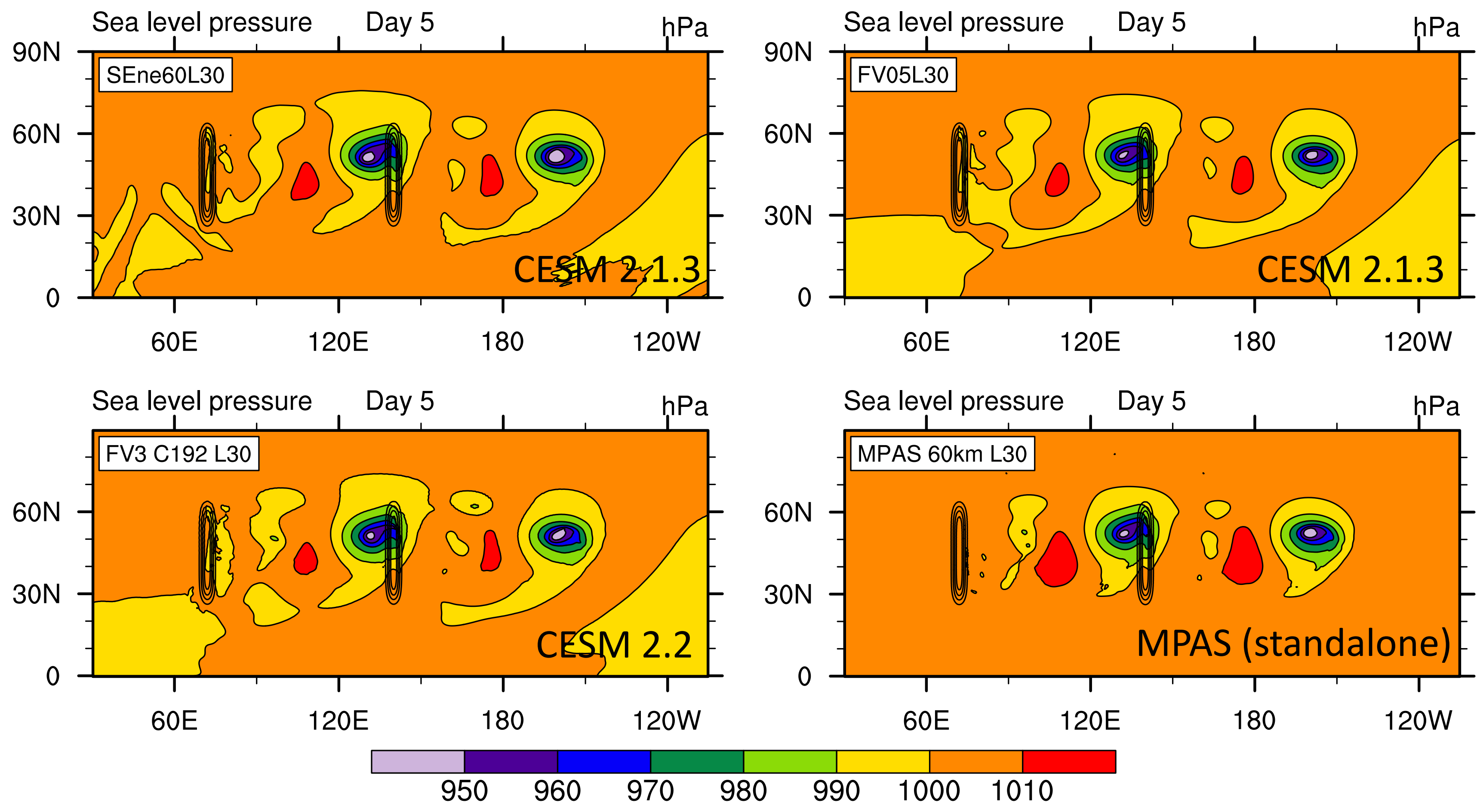
- Test case reveals impact of SE's physics-dynamics coupling strategy (denoted by *ftype*)
- Here ftype =2 (hybrid) is used in SE: denotes sudden adjustments (Δt=900 s) of specific humidity, dribbled tendencies (Δt=150 s) otherwise

Application Examples: Physics-Dynamics Coupling

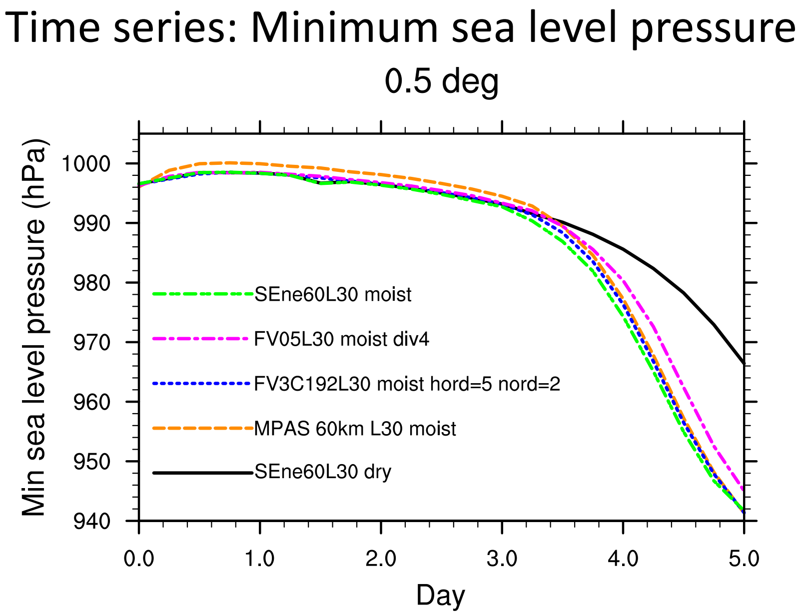


- Numerical noise in SE: Consequence of the long physics time step with subcyled dynamics (here with Δt_{phys} = 900 s, rsplit = 3, nsplit = 2, qsplit = 1, ftype=2)
- Using the same short physics and dynamics time step of $\Delta t_{phys} = \Delta t_{dyn}$ = 150 s eliminates the numerical noise in SE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

Application Examples: Dycore Intercomparisons

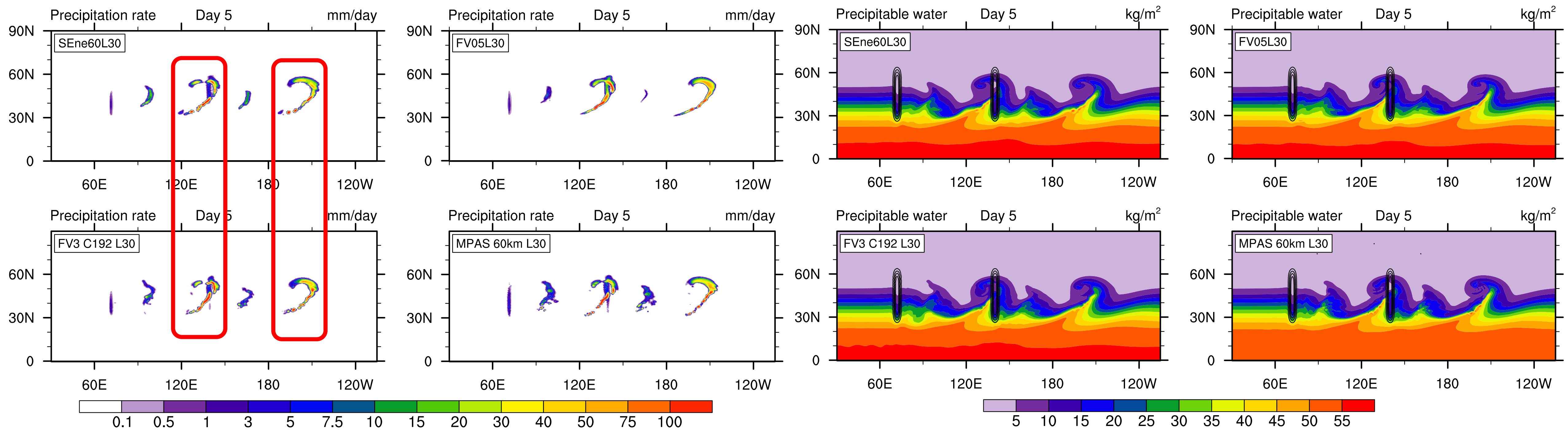


Resolutions: ≈ 50 km L30



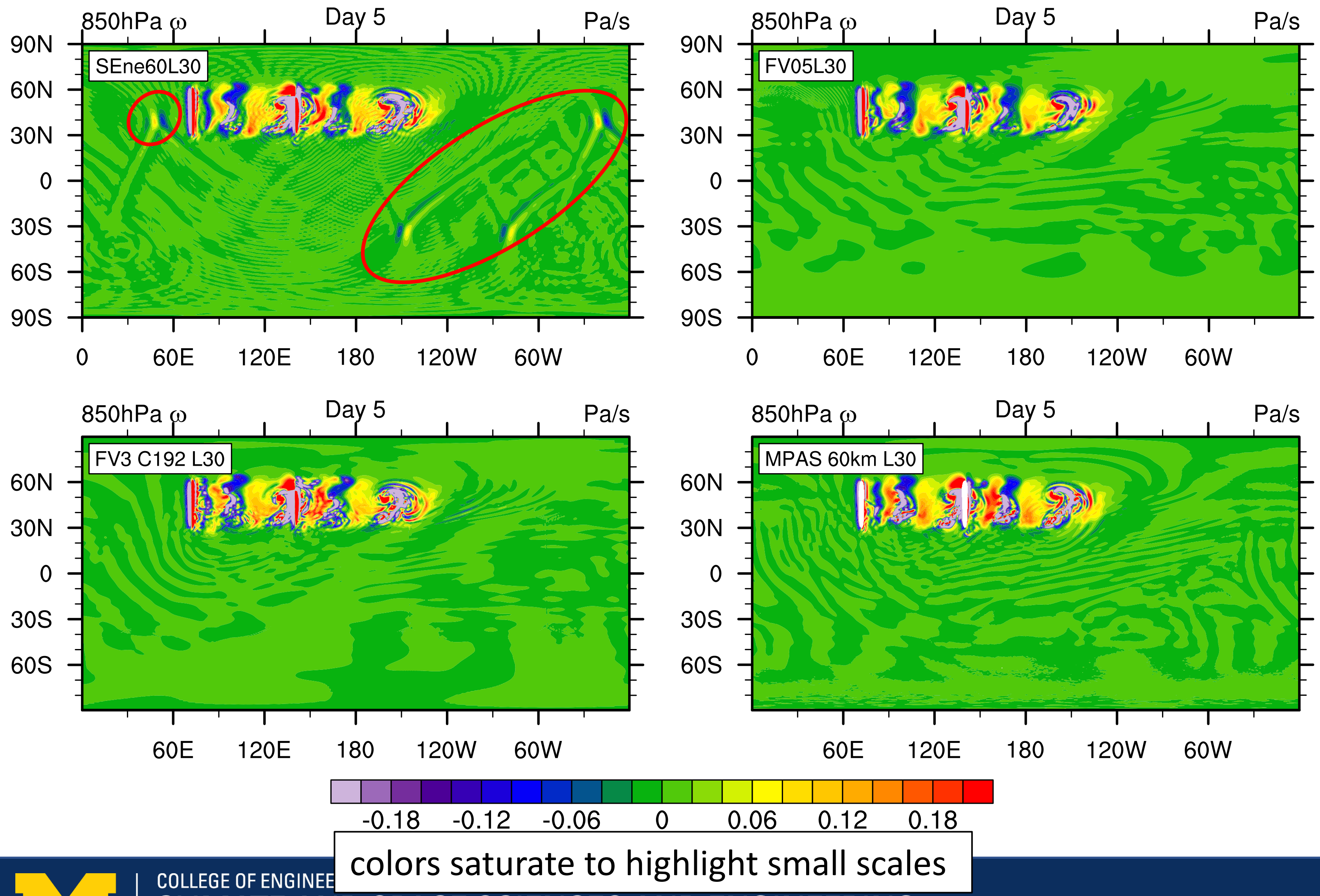
- Moist SE, FV3 and MPAS closely track at other, FV is more diffusive
- SLP minimum is highly sensitive to the diffusion settings

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



- Initially: all dycores have signatures of **global high-speed gravity waves** (external mode) triggered by slight initial imbalance
- In **SE**: globally propagating gravity waves have **high amplitudes** (in comparison to other dycores) and are **persistent** (little damping), still present by day 5 (under investigation)
- No grid imprinting is obvious in SE, FV3 and MPAS

Summary & Future Work

- Moist baroclinic wave test case with focus on topography: Additional element in the simpler-model hierarchy
- Sheds light on numerical designs of dynamical cores and their physics interplay
  - Physics-dynamics coupling
  - Diffusion
  - Simulation of clouds and rain (placement, rain amount, shape of rain bands, etc.)
  - Hydrostatic versus nonhydrostatic designs
- Two publications in development: (this talk) Characteristics of the test case, (Christiane Jablonowski's talk) fundamental dynamical behavior of mountain-induced baroclinic waves (and gravity waves)