Insights from the 2025 Dynamical Core Model Intercomparison Project (DCMIP-2025)

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+ Thomas Bendall (U.K. Met Office)

CESM Workshop, Boulder, CO, June 9th, 2025

What is DCMIP-2025?

- Hands-on summer school (June 2-6, 2025) that highlighted the characteristics of the dynamical cores: **CAM-Spectral Element** and **CAM-FV3 (both non-hydrostatic/hydrostatic), CAM-MPAS,** upcoming **LFRIC-Gungho (U.K. Met Office),** plus **ML emulators for GCMs**
- DCMIP-2025 focused on the impact of topography on the flow field, physics-dynamics coupling aspects with a simple warm-rain Kessler physics scheme and idealized assessments of existing Machine Learning (ML) emulators

Group of about 60 students/postdocs & early career scientists plus model mentors, NCAR Mesa Lab

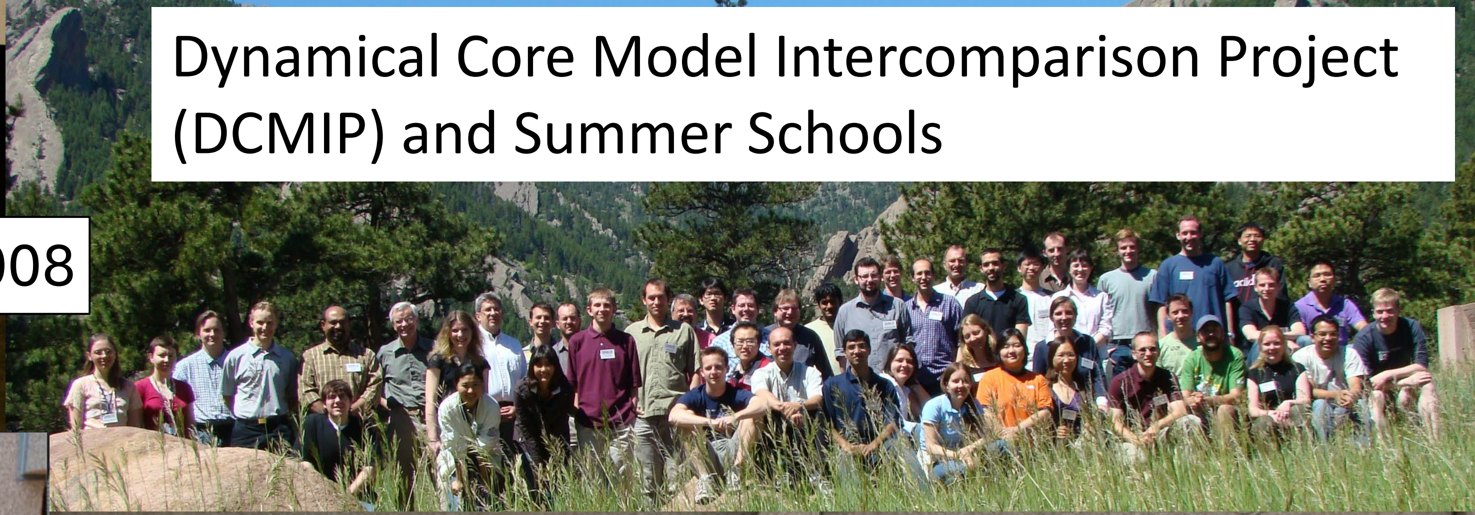
Supported by the University of Michigan via the:

- NSF StormSPEED project (main sponsor)
- NOAA UFS-R2O project

Dynamical Core Model Intercomparison Project (DCMIP) and Summer Schools

DCMIP Teams

2008



2012

2016

DCMIP

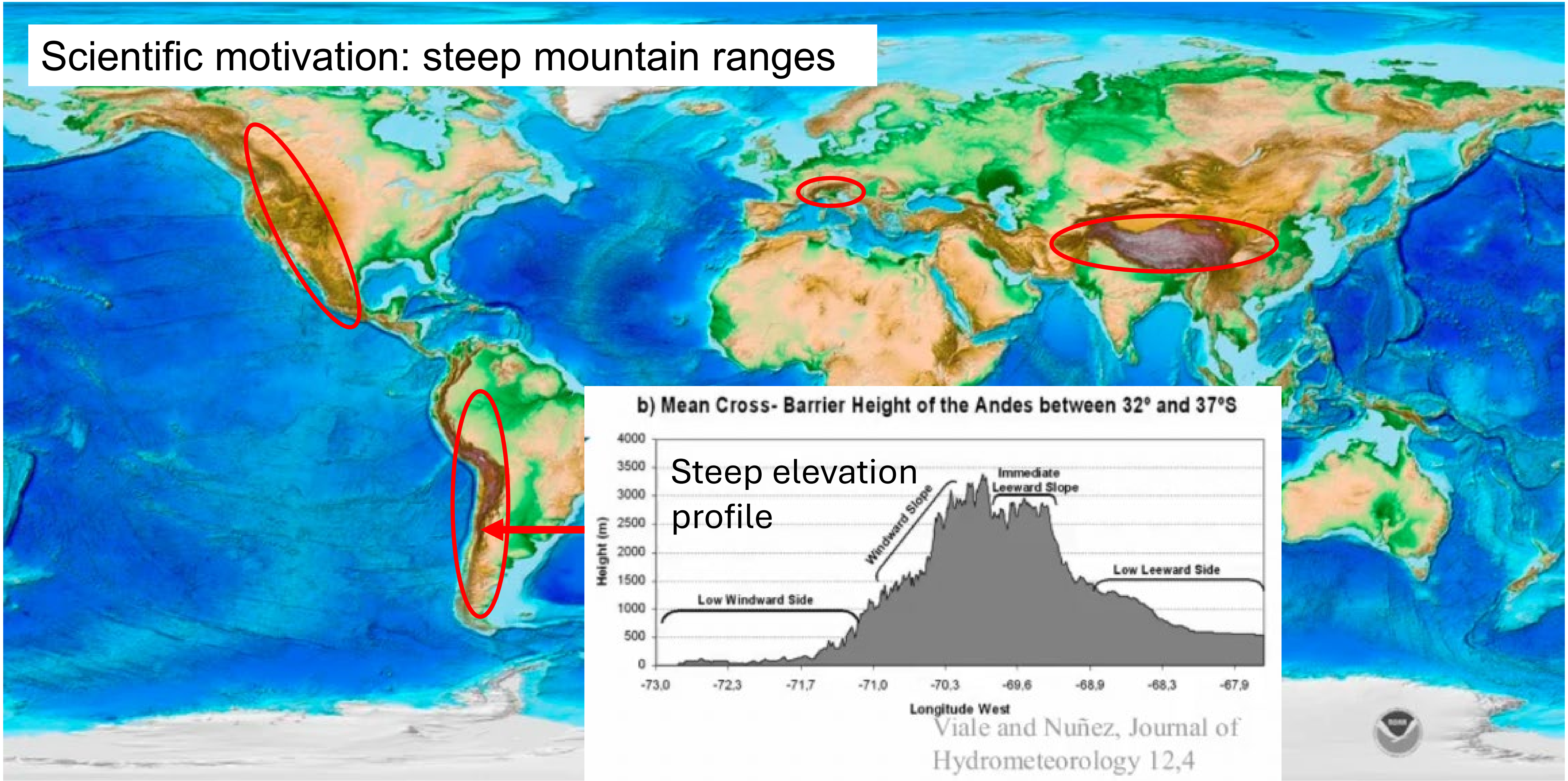
2008, 2012, 2016 & 2025

2016

Overview of the DCMIP-2025 Test Case Suite

- DCMIP-2025 webpage: https://sites.google.com/umich.edu/dcmip-2025/home
- Morning lectures on dynamical cores and GCM designs plus hands-on modeling sessions in the afternoons using idealized test cases
- Design of the idealized test cases driven by **four science themes**:
  - 1: Dry mountain-generated, breaking inertia gravity waves (hydrostatic)
  - 2: Dry mesoscale mountain-generated processes and vortices (hydrostatic)
    - 2a: Gap flow
    - 2b: Vortex shedding (von-Karman vortex streets)
  - 3: Physics-dynamics coupling: Squall line test with simple rain (nonhydro)
  - 4: Machine Learning (ML) testbed for pretrained weather emulators
    - GraphCast (Google), Spherical FourCastNet (NVIDIA), Pangu Weather

Theme 1: Breaking Mountain-Triggered Inertia Gravity Waves

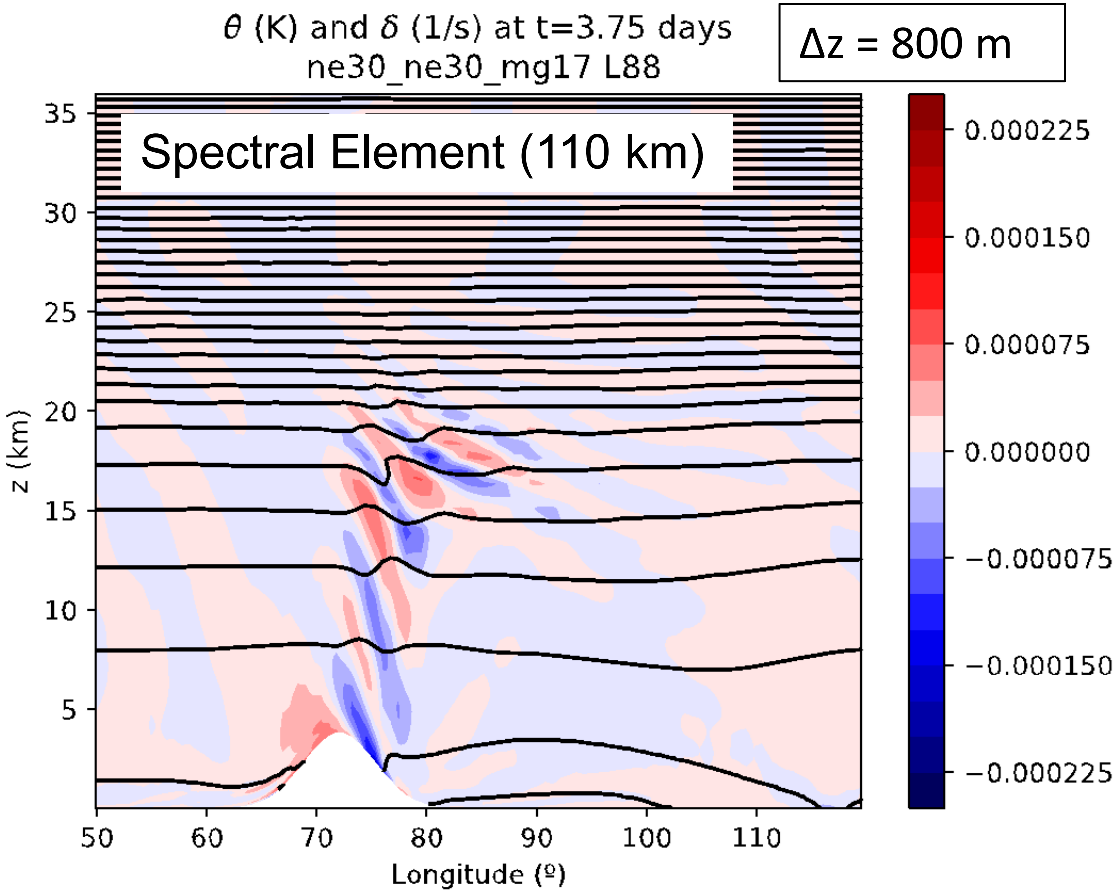


Theme 1: Example Results from CAM-SE

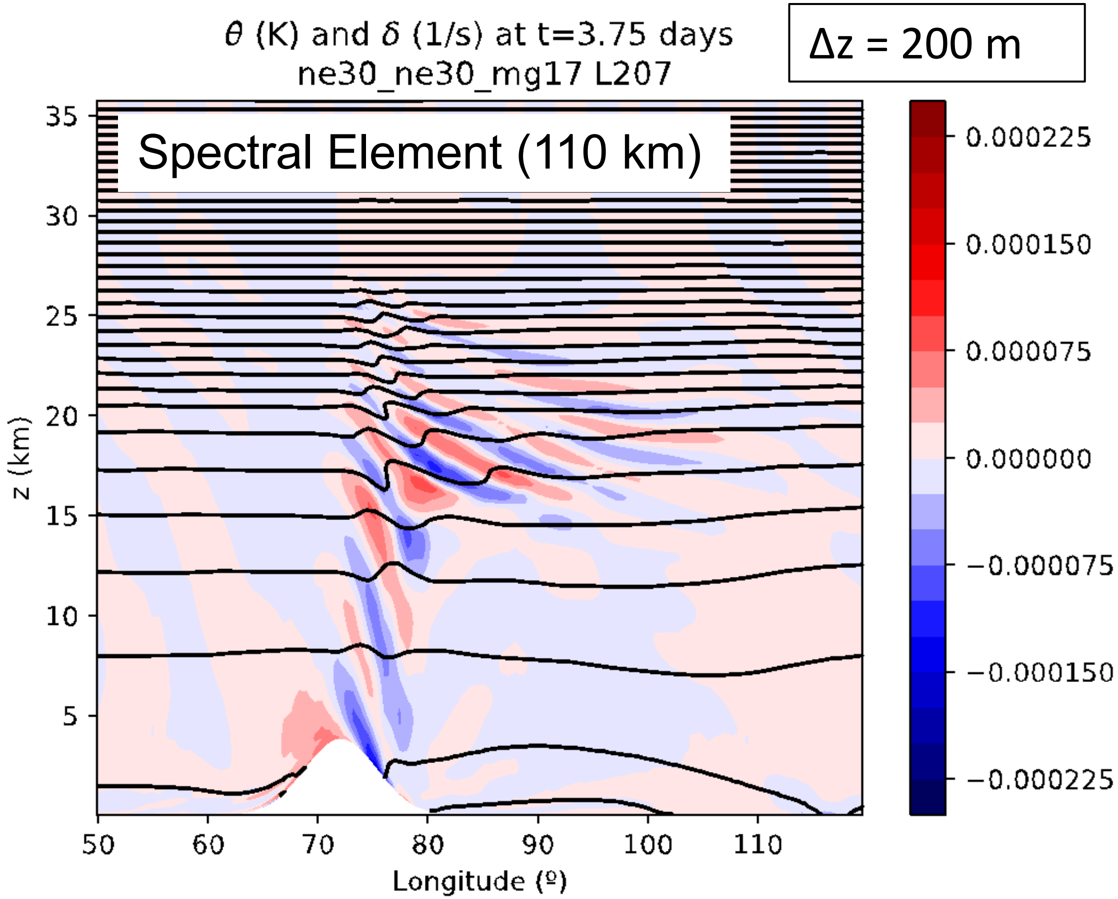
- Topographic waves are depicted by the **potential temperature** contours and horizontal divergence (colours), 4 km mountain peak
- Impact of the vertical resolution: Δz = 200 m resolves additional wave signatures, converges

Meridional cross sections of potential temperature (contours) and horizontal divergence (colors) at 35ºN at day 3.75

Δz = 800 m



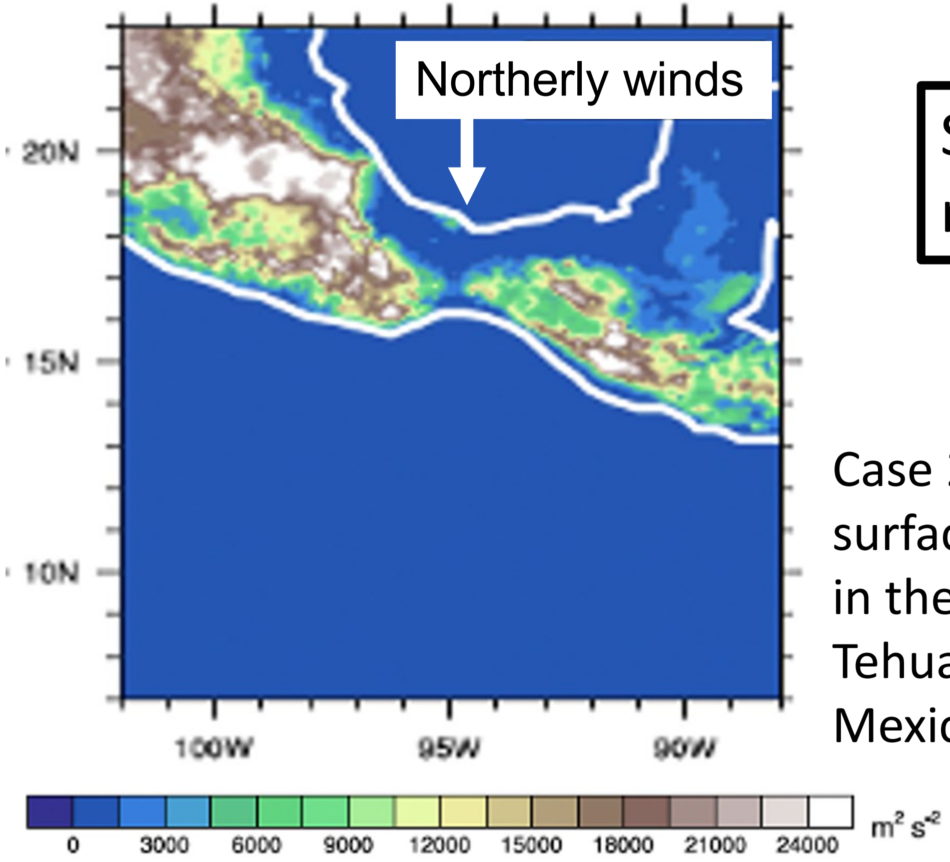
Δz = 200 m



Theme 2: Mesoscale Mountain-Generated Flows

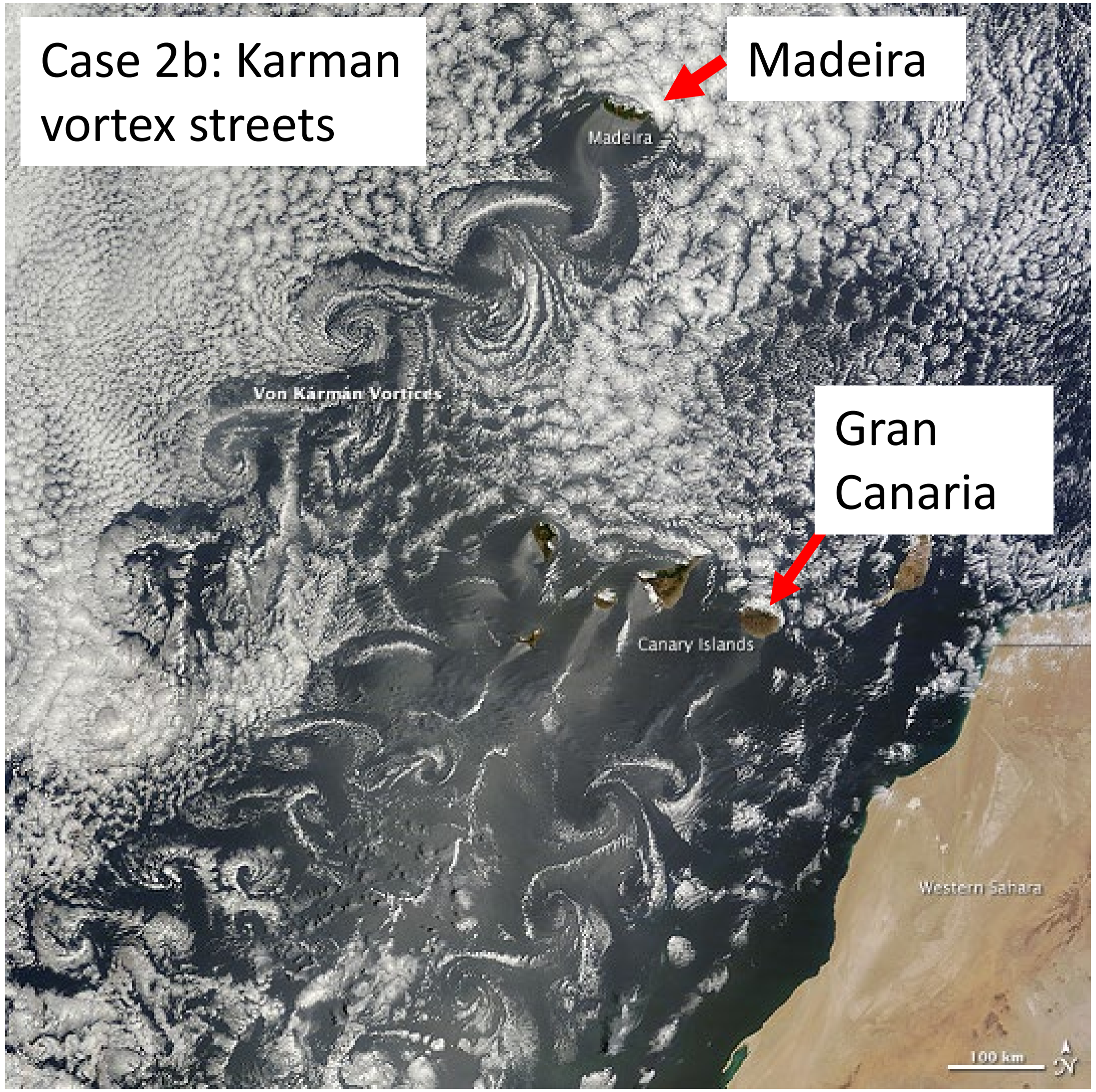
Dry hydrostatic flows: use isothermal ICs in solid body rotation with topography

- Case 2a: Gap flow
- Case 2b: Vortex shedding



Scientific motivation

Case 2a: Observed surface geopotential in the Gulf of Tehuantepec in Mexico



Theme 2a: Gap Flow Results for CAM-SE

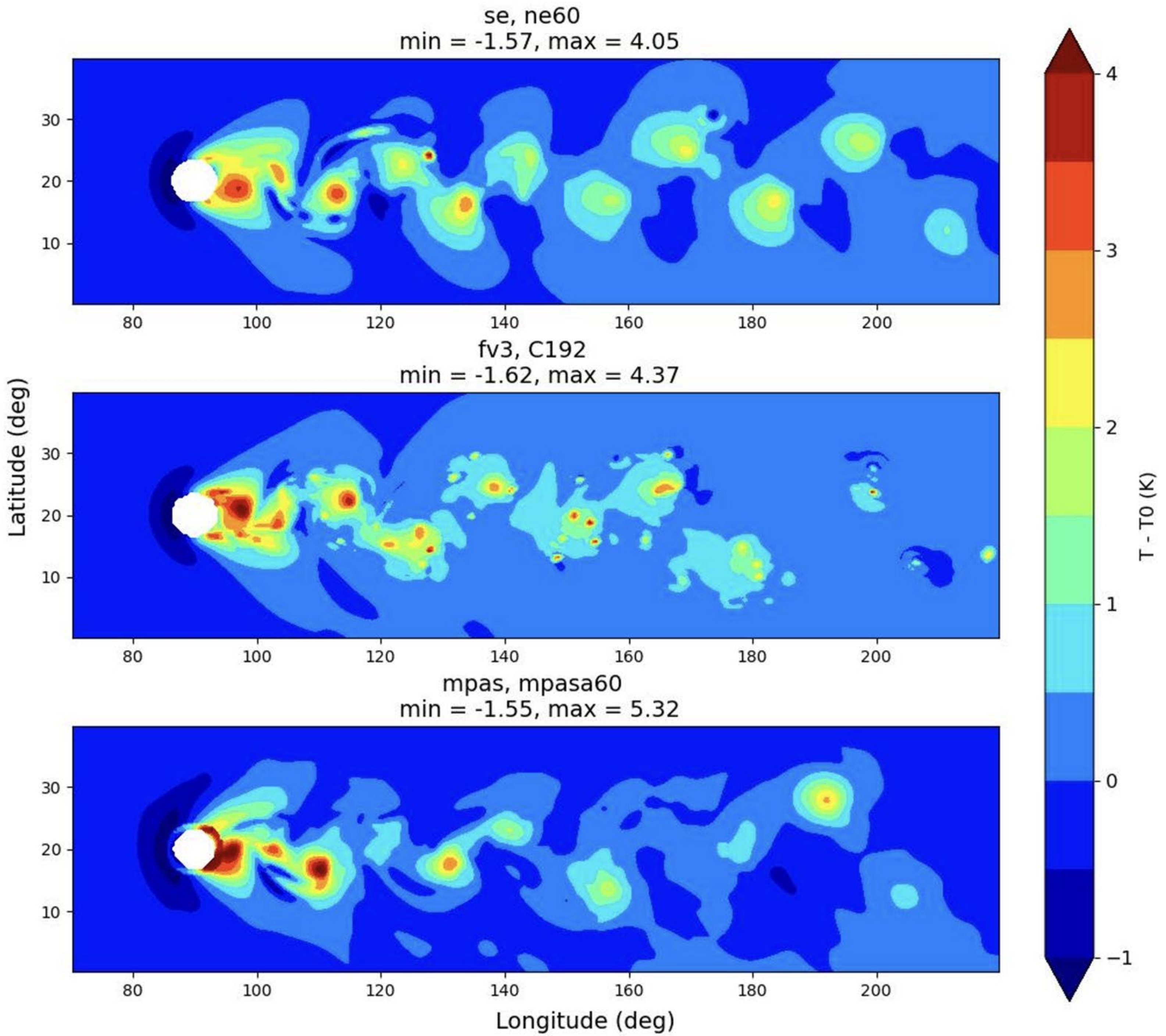
- Normalized zonal wind perturbations at z = 300 m with westerly incoming flow hitting the mountain: dry SE (1º-degree, X=20) model with Δx = 5.5 km and Δz = 300 m
- Flow accelerates through the gap, gets blocked in front of the mountain barrier (in white)

Theme 2b: Vortex Street Results from CAM-SE

- Gran Canaria: modeled as a Gaussian mountain at 20° N on a reduced-size Earth (X=20)
- Max h_0 = 1500 m, max u flow speed U = 10 m/s, isothermal T=288 K, stability N = 0.01827 s^{-1}

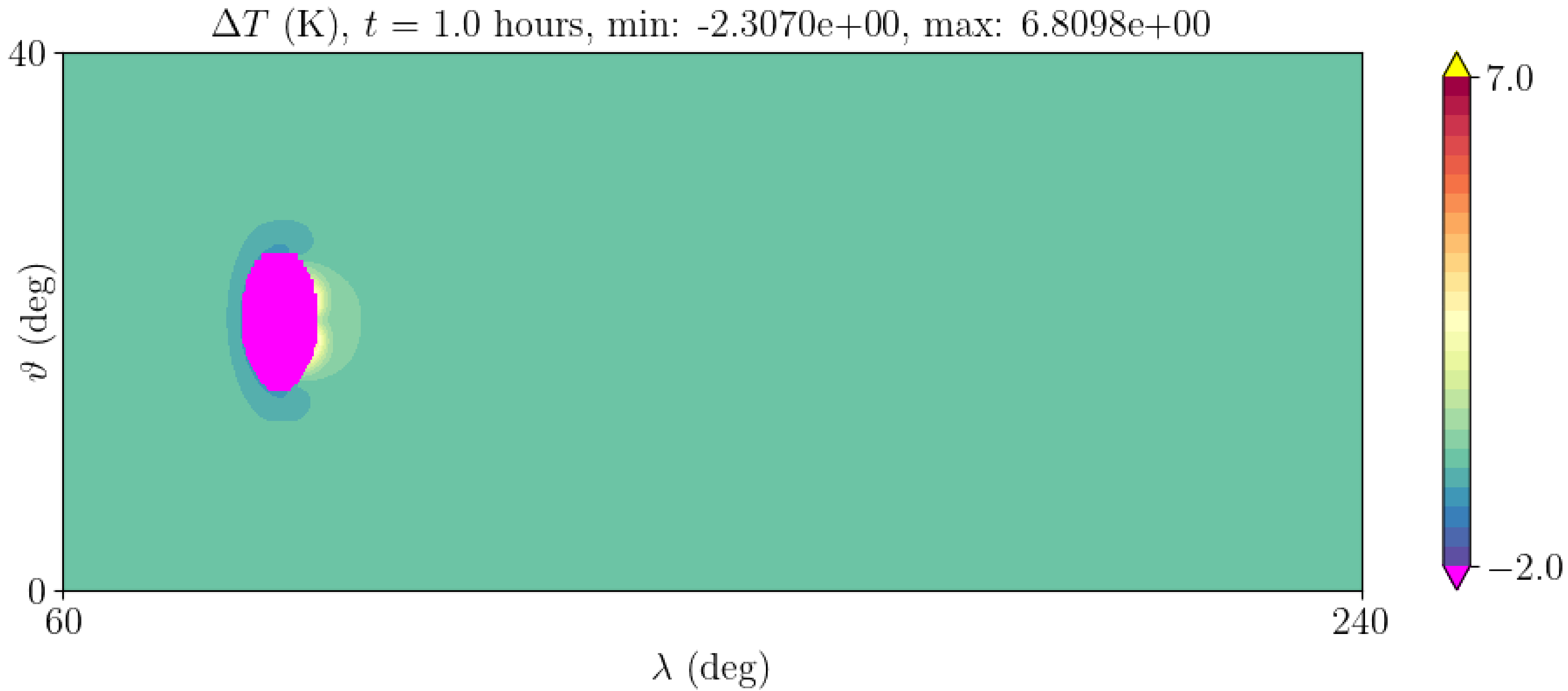
Theme 2b: Vortex Shedding Intercomparison

- No Coriolis force
- T pertubations at z = 300 m at day 1 from CAM-SE, CAM-FV3, and CAM-MPAS with Δx = 2.75 km and Δz = 300 m grid spacing in the lower domain
- Circulation patterns show sensitivities to the
  - vertical grid spacing
  - diffusion settings
  - asymmetries in the horizontal grids

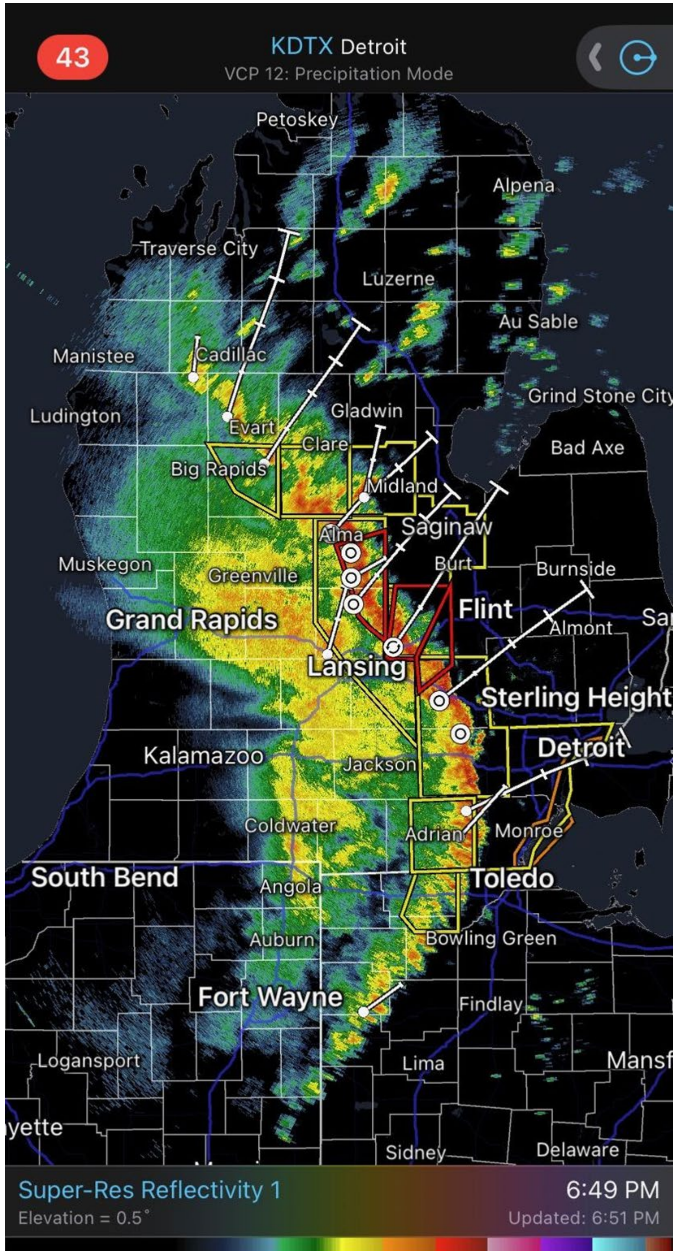


Theme 2b: Vortex Street Results from LFRIC

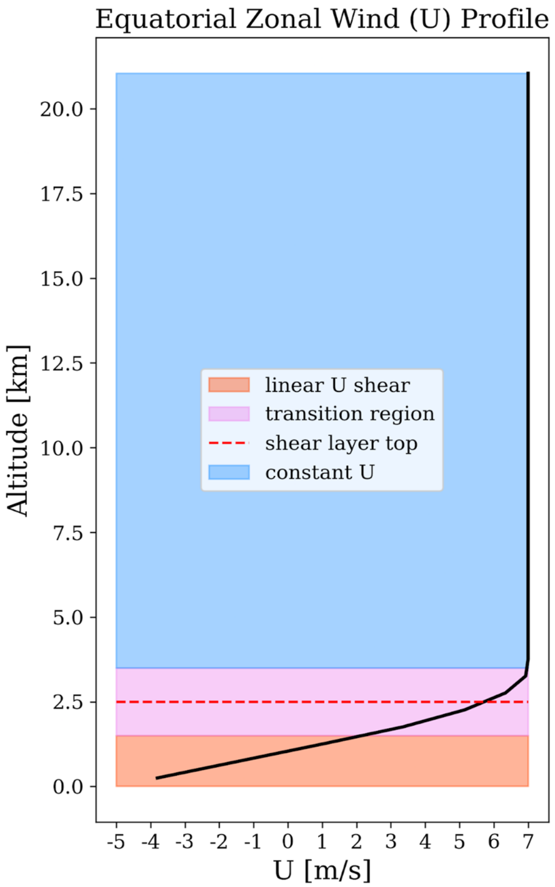
- T perturbation at 300 m, no Coriolis force, C192 resolution with X=20 (Δx = 2.75 km)
- New insights: Noise developed towards the end of the simulation

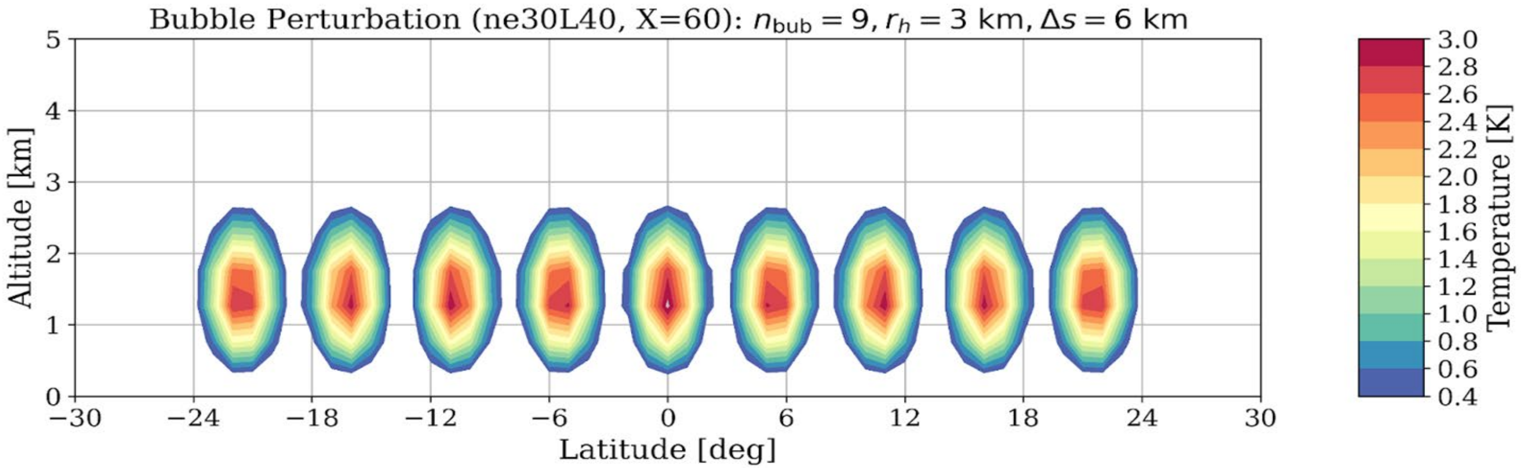


Theme 3: Squall Line Test Case



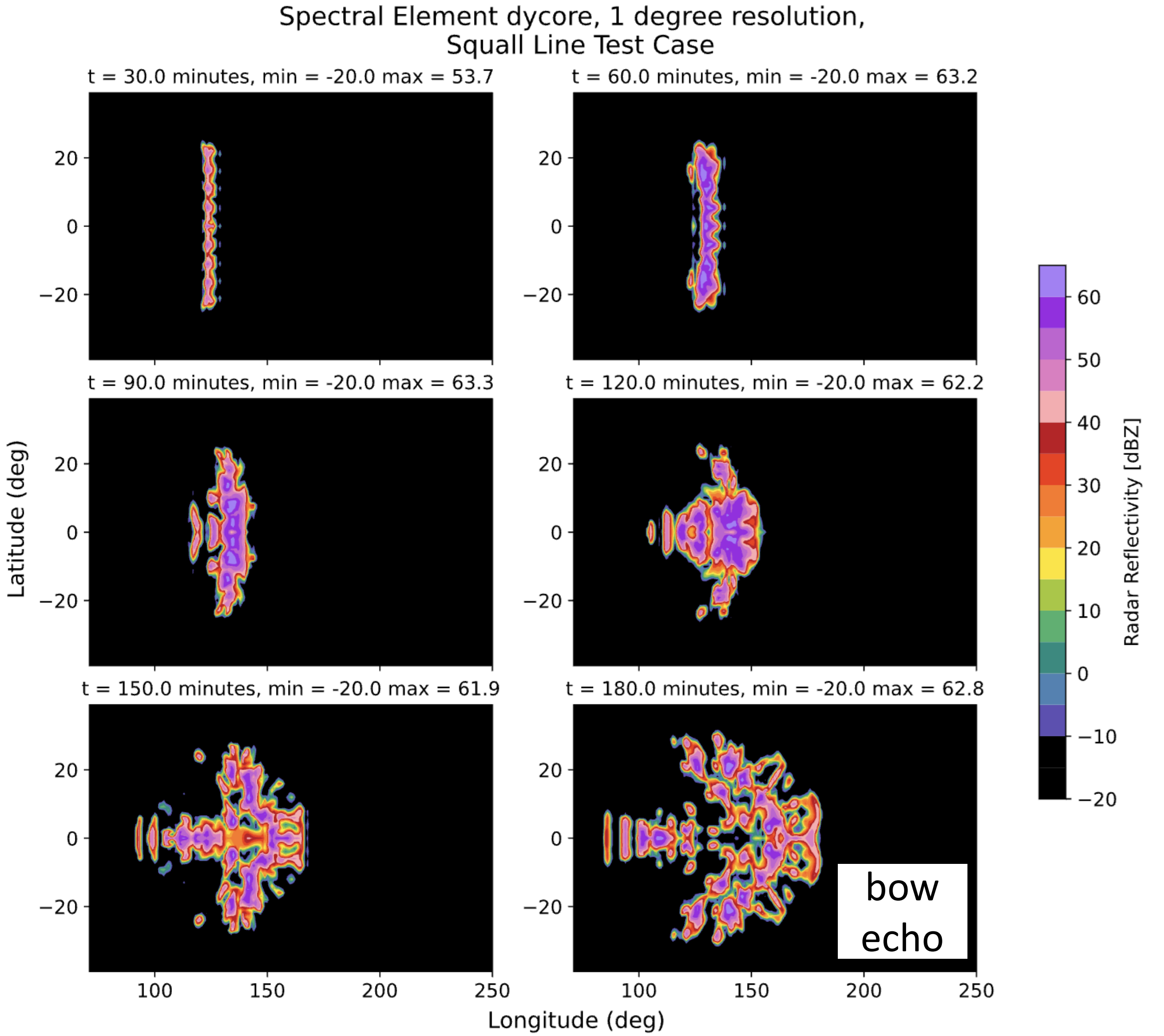
- Squall Line: A linearly-organized zone of convection with enhanced winds and precipitation
- Test of the physics-dynamics interplay
- Built upon the analytic Klemp et al. (2015) supercell initial conditions with different low-level zonal wind shear and 7-9 warm bubbles as triggers





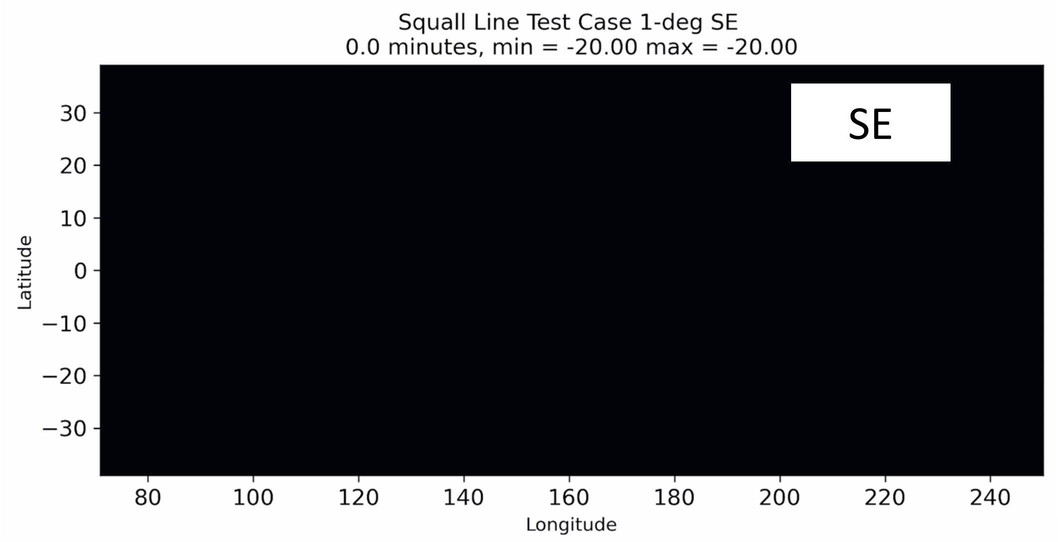
Theme 3: Kessler Microphysics with Radar Reflectivity

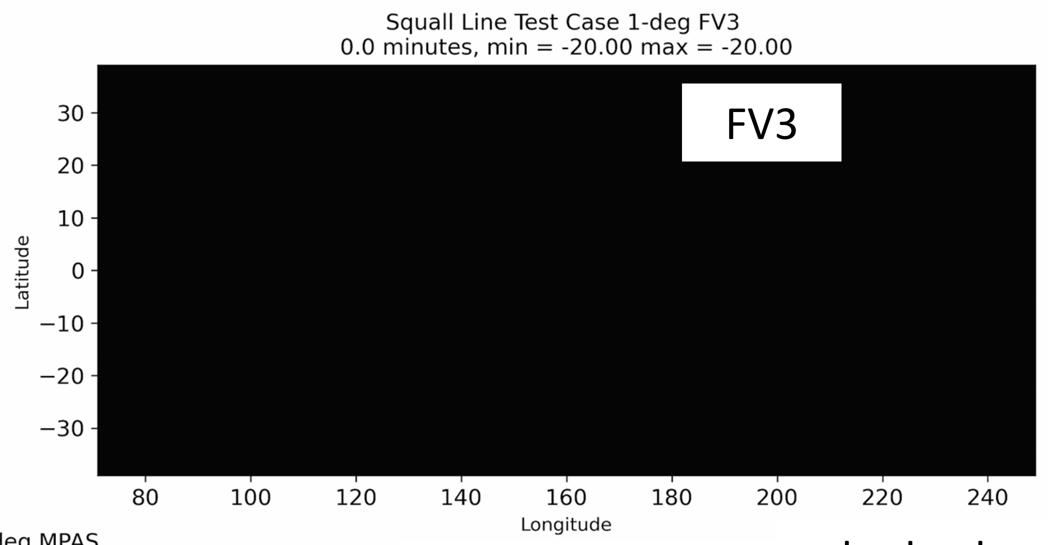
- Use Kessler physics: a simple, warm rain water microphysics scheme
- Additional radar reflectivity (Z) output variable which measures precipitation rates.
  - Often measured by weather radars to track precipitating systems like squall lines
- We use the Marshall-Palmer relationship between rain rate and Z measured in a logarithmic scale (dBZ)



Snapshots at 2.5 km with SEne30 (Δx = 1.85 km) using 40 vertical levels (L40) with Δz = 500 m, 9 warm bubbles are used as triggers

Theme 3: Squall Line Circulation Intercomparisons

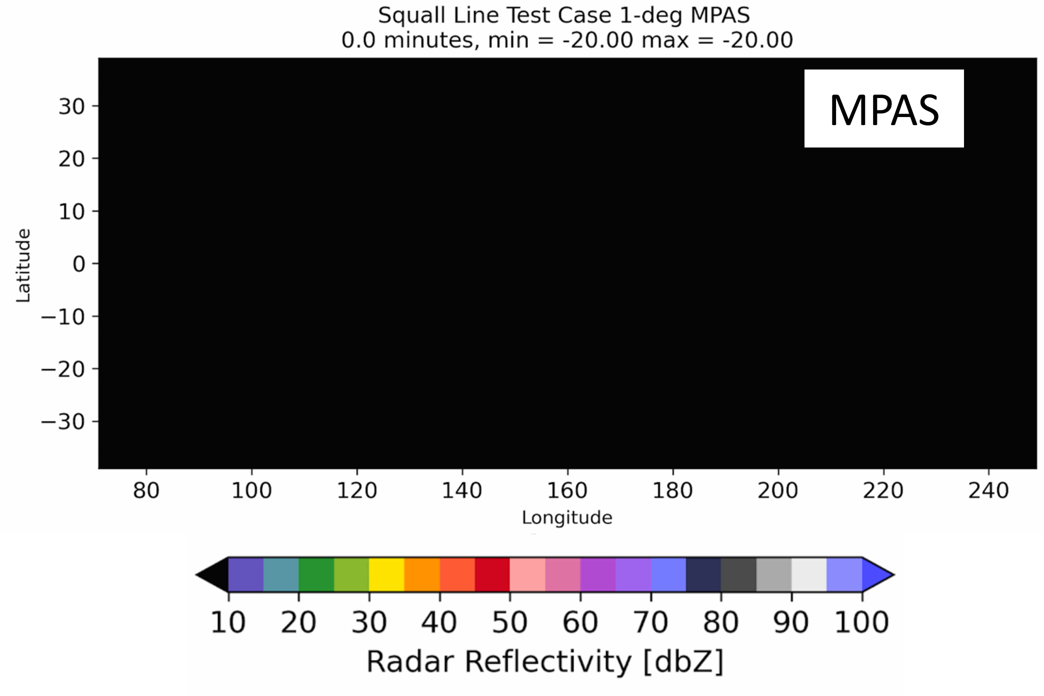




cubed-sphere grid imprinting

Radar reflectivity at 2.5 km
t = 3-hour simulations

- 1-degree horizontal resolution on a small Earth with X=60 (Δx = 1.85 km)
- Δz = 500 m vertical spacing

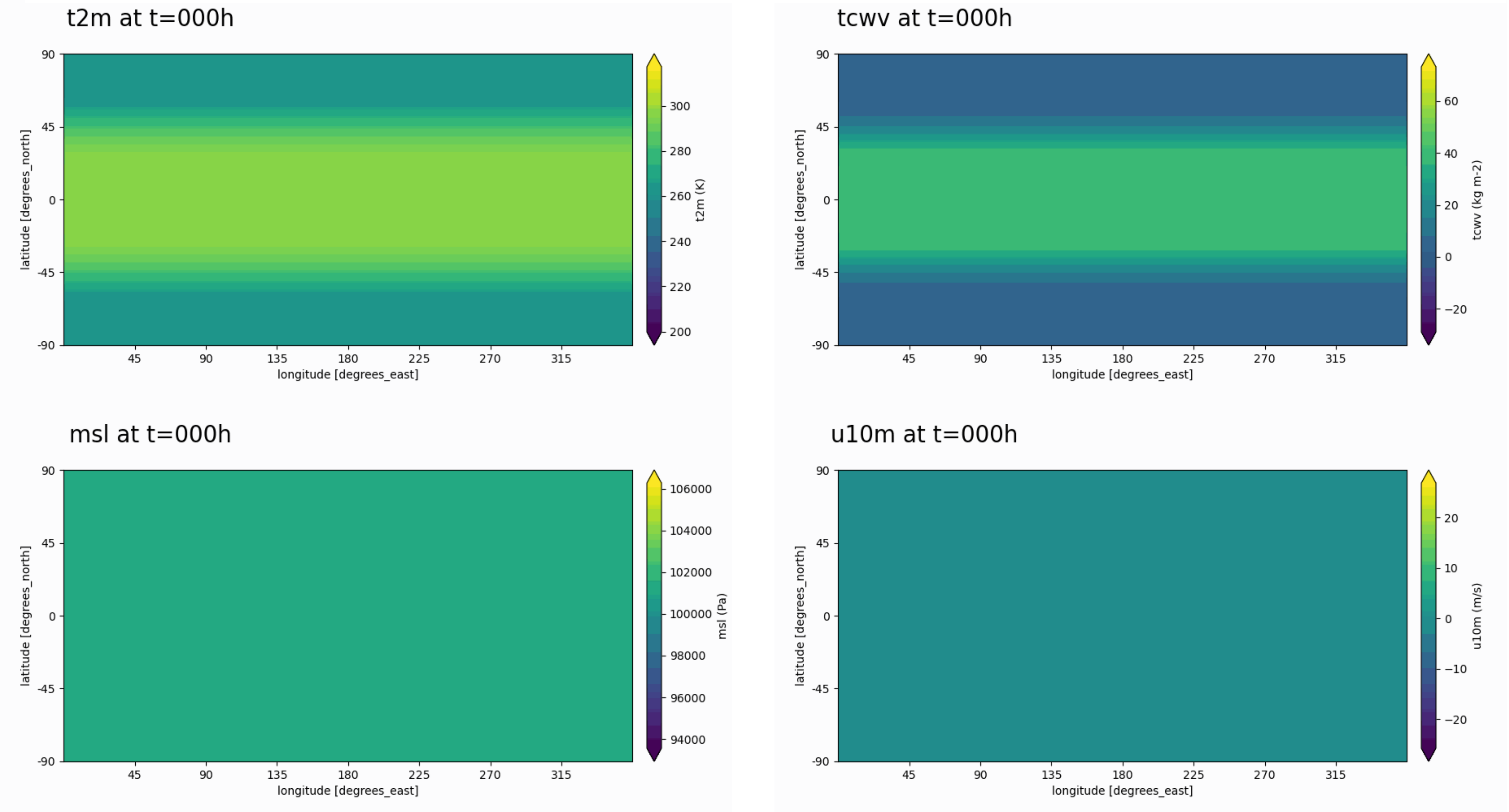


Asymmetries due to theMPAS hexagonal grid

Theme 4: Idealized Machine Learning Testbed

- Use the NVIDIA's Earth2MIP portal https://github.com/NVIDIA/earth2mip with a focus on Google's GraphCast and NVIDIA's Spherical FourCastNet emulators
- Idea: provide a pretrained neural networks (trained on ERA5 realistic data with topography, seasonal and diurnal cycles, etc.) with an out-of-sample idealized initial condition
    - Steady-state conditions (baroclinic wave initial state without a perturbation)
    - Baroclinic wave and tropical cyclone seed embedded in a smooth background flow (e.g. seasonal means derived from ERA5)
    - Steady-state conditions and baroclinic wave seed embedded using an idealized background flow (Bouvier et al., 2023)
- Questions to ask: Can the emulators develop the expected flow fields?
- What are the conservation properties?

Emulation results from Joshua Elms (Indiana University) with FourCastNet: steady-state initial condition (baroclinic wave)



Observation: Steady-state initial conditions break right away in the pretrained FourCastNet emulator, try new approach

Summary

The DCMIP-2025 summer school (June 2-6, 2025, held at the NCAR Mesa Lab)

- defined new test cases for dynamical cores and utilized the Hakim and Masaman (2024) test case ideas for ML GCM emulators
- investigated the characteristics of 3 CAM dynamical cores, LFRIC-Gungho, and 3 ML emulators (embedded in NVIDIA's Earth2MIP) via idealized test cases
- taught a group of about 50 students, postdocs, and early-career scientists how dynamical core and GCMs are built
- let the students explore variants of the test cases and the impact of resolution and dissipation on the fluid flows
- revealed some unknown instabilities in the LFRIC's Gungho dynamical core
- included an exploratory ML element to explore the physical realism of emulators
- test results will be explored further for scientific purposes
- Showcases the results on the webpage: https://sites.google.com/umich.edu/dcmip-2025