NSF StormSPEED: The 'Storm-resolving SPEctral Element Dycore' for CESM3

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Status-Quo and Motivation for NSF StormSPEED

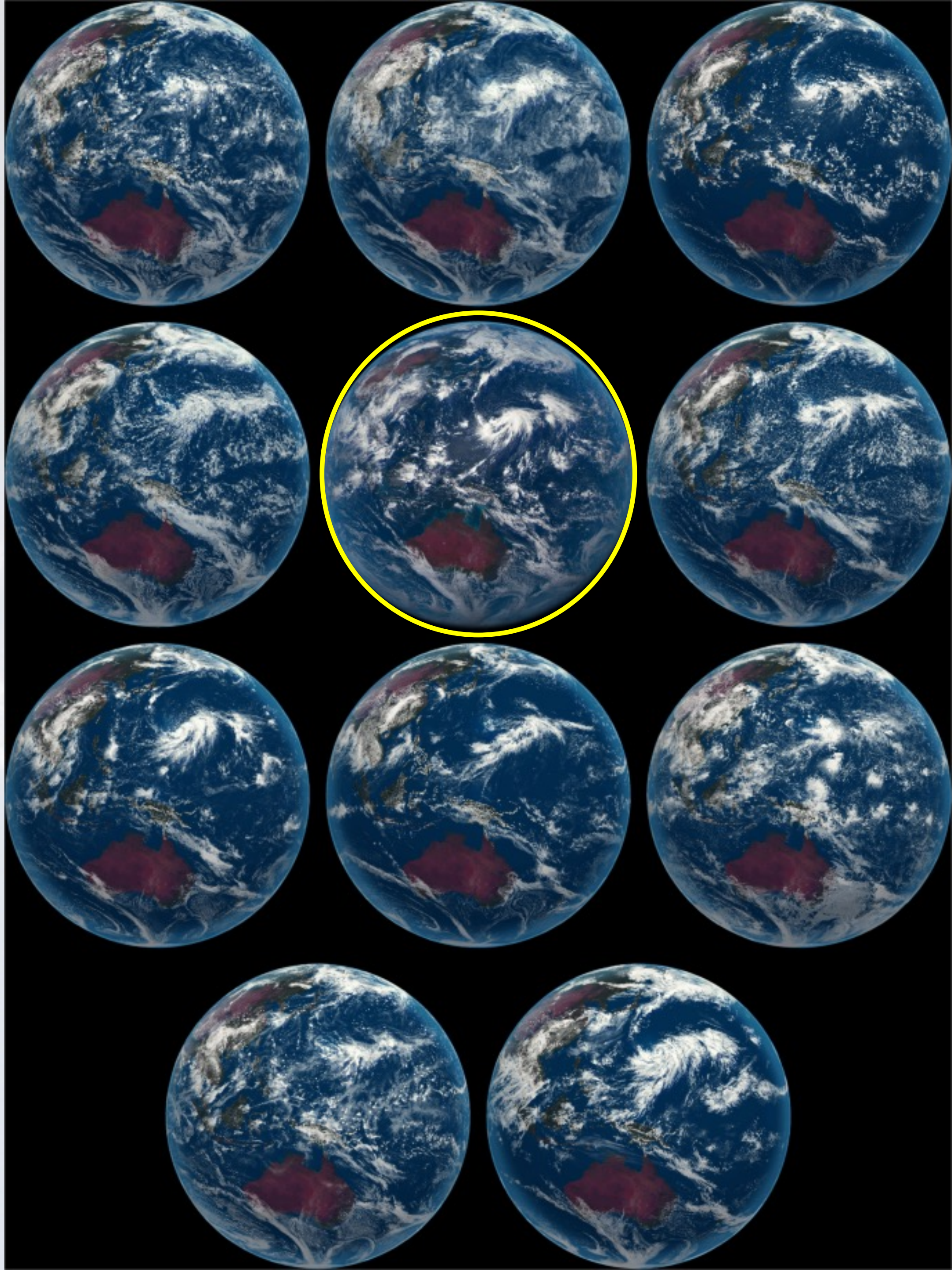
- Status-Quo: High-resolution modeling with CESM has hit a barrier:
  - CESM's uniform 25-km-scale technology is about 10+ years old, high-res CESM model development stalled (iHESP and MesaCLIP utilize CESM 1.3)
  - CESM misses emerging opportunity: many modeling centers already tackle the global kilometer-scale challenge for weather, S2S, and multi-year time scales
  - Usability of hydrostatic CESM-SE configurations: limited to 7 km or coarser
  - Ultra-high-res CESM cannot progress without a nonhydrostatic dynamical core option
  - CESM is not GPU-ready yet: needs to change to enable km-scale investigations

- Goals:
  - Turn CESM into a viable community tool for km-scale investigations
  - Contribute to the international kilometer-scale climate modeling challenge

Quick Look at the International km-Scale Modeling Landscape

DYAMOND: International Model Intercomparison at Cloud-Permitting Scales (phase 1 and 2)

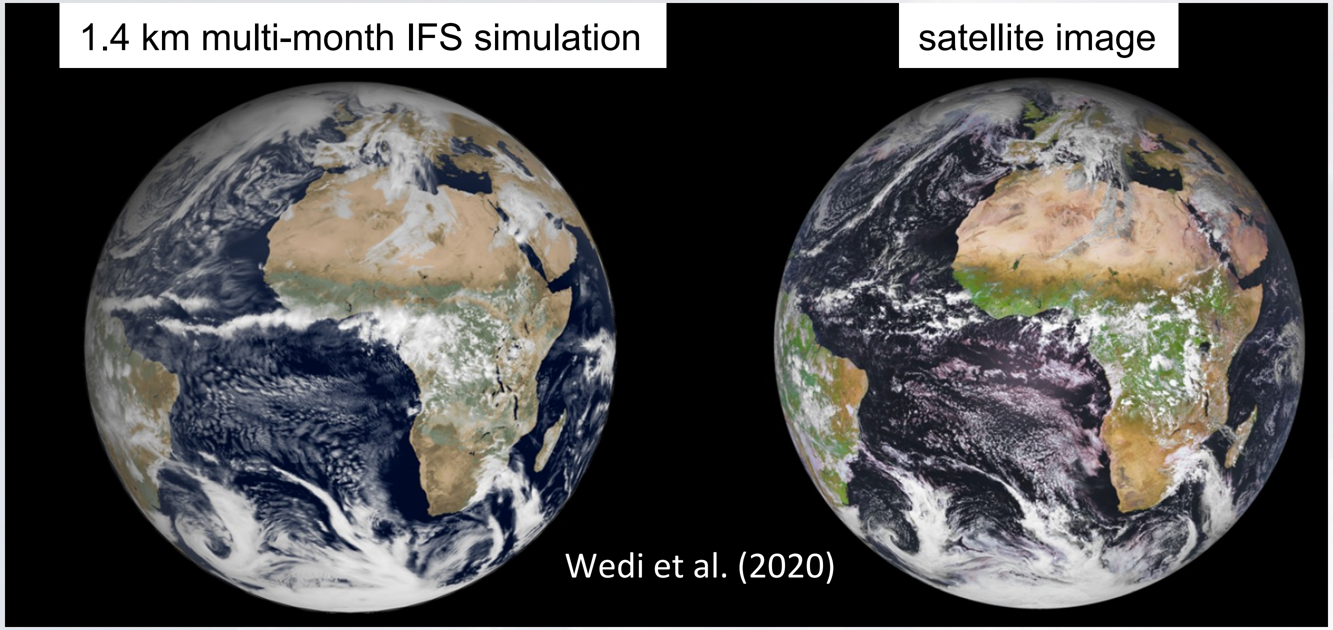
- Atmospheric models with 3-9 km grid spacings (40-day simulations in AMIP or coupled mode)
- Figure: Snapshot of a cloud scene from 10 DYAMOND-1 (summer) simulations and one satellite observation (circled, day 3 is depicted)
- DYAMOND-1 participants:
  ARPEGE-NH (Meteo France), FV3 (GFDL), GEOS (NASA), ICON (MPI), IFS (ECMWF, hydrostatic), MPAS (NCAR), NICAM (U. Tokyo), SAM (Stony Brook U., anelastic), UM (U.K. Met Office)



Source: Stevens et al. (2019)
https://progearthplanetsci.springeropen.com/articles/10.1186/s40645-019-0304-z

Beyond DYAMOND: Convection-Allowing Seasonal and Multi-Year Simulations

- 4-month simulations with a 1.4 km configuration of ECMWF's IFS (Wedi et al., 2020)
- GFDL: 2-year simulations with the 3 km X-SHIELD model
- DoE: Multi-year simulation with SCREAM (3.25 km)
- and others: NASA (GEOS), MPI (ICON) and other members of the international community



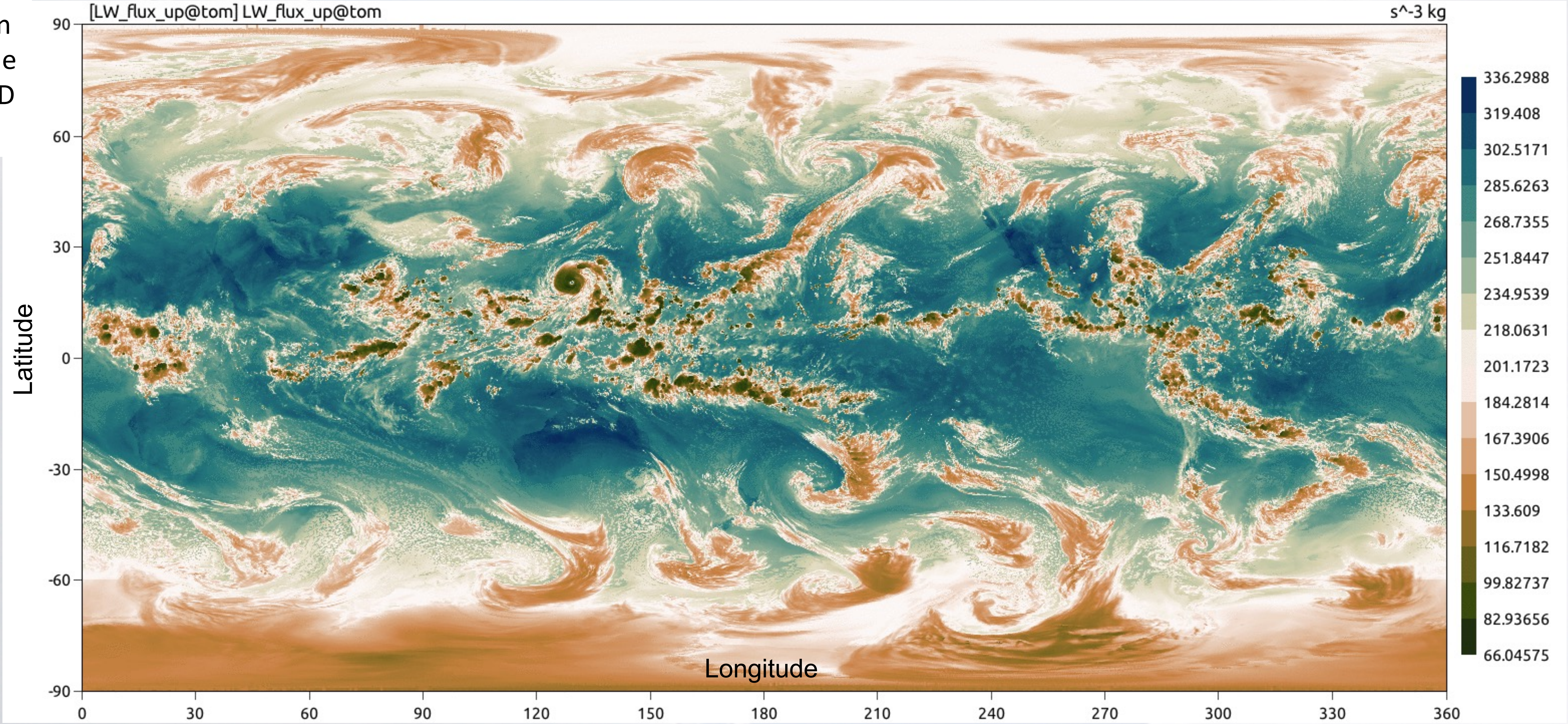
https://wmo.int/media/magazine-article/kilometre-scale-modelling-of-earth-system-new-paradigm-climate-prediction

Example from the Department of Energy (DoE)

Atmospheric model SCREAM with 3.25 km grid spacing: Realistic-looking flow features

- 1-day animation of the outgoing longwave radiation at the top of the atmosphere

Simulation follows the DYAMOND protocol



Source: https://e3sm.org/exascale-performance-of-the-simple-cloud-resolving-e3sm-atmosphere-model/

Ultra-High-Res Roadmap for CAM7/CESM3 (2024-2027)

- Integrate the existing DoE nonhydrostatic (NH) Fortran version of the Spectral Element (SE) dynamical core into CESM's Community Atmosphere Model (CAM) to enable cloud-permitting coupled climate simulations: Workhorse model for scientific exemplars and community release
- Advance CESM3's readiness for the newest HPC GPU architectures
  - include DOE's SE C++/Kokkos version (used in SCREAM) as a second step
  - leverage the GPU-ready CAM physics package (OpenACC) and the CESM infrastructure improvements & physics tunings developed by EarthWorks
- Test and demonstrate CESM's new scientific capabilities with CAM-SE-NH (Fortran) via a model hierarchy and selected scientific exemplars:
  - MCSs/precipitation over the CONUS domain (seasonal VR configuration)
  - Global storm-permitting coupled prototype: 40-day DYAMOND simulation

Advancing the GPU Readiness of CESM: Performance Boost

- Example model: DoE's Energy Exascale Earth System Model **(E3SM)** and the Simple Cloud-Resolving E3SM Atmosphere Model (**SCREAM**)

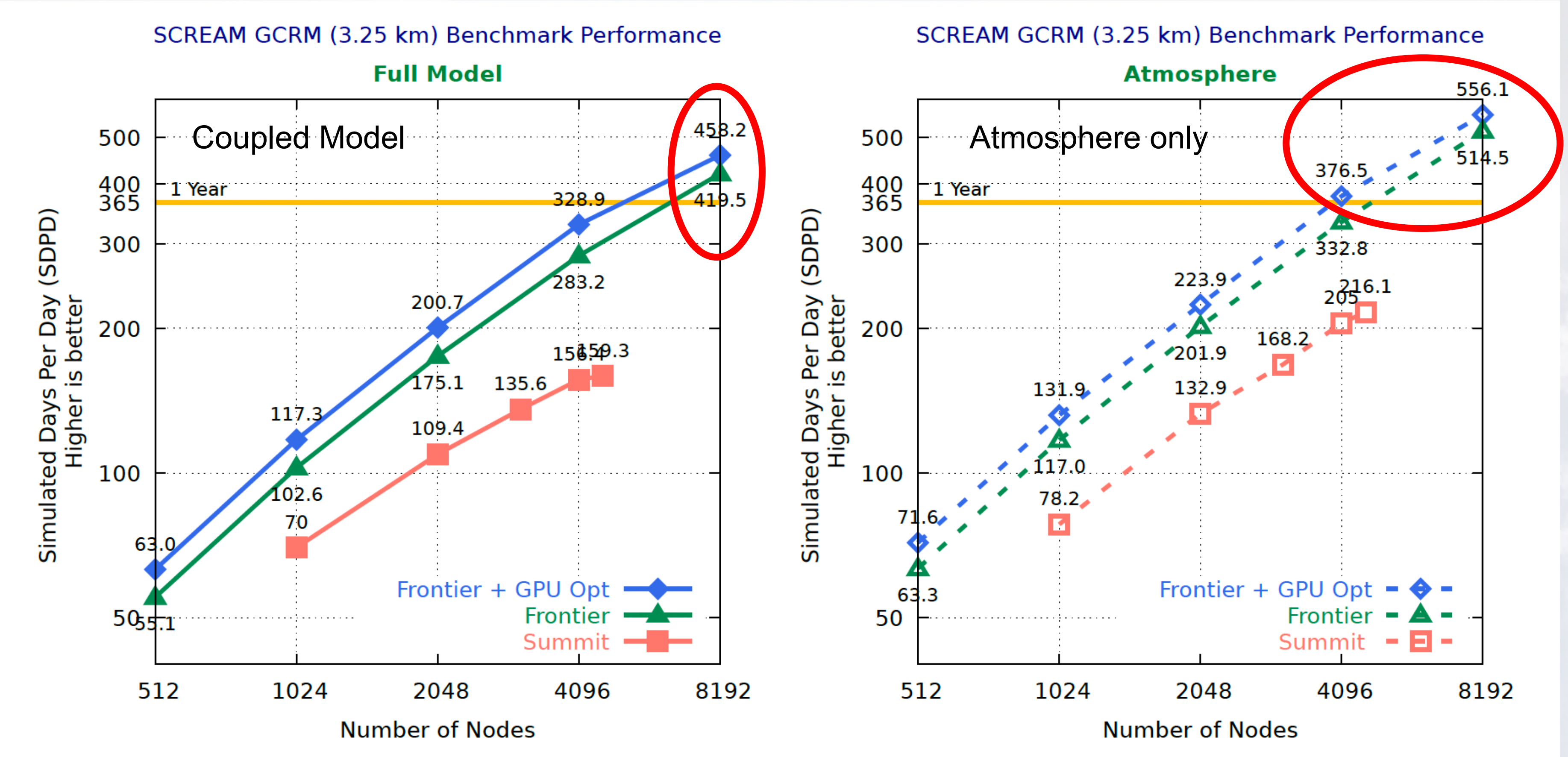
- Programming language:
  Fortran (E3SM) versus C++ (SCREAM)
- Parallel programming paradigm:
  - MPI + OpenMP (in Fortran)
  - MPI + OpenMP + OpenACC (GPU) (in Fortran)
  - MPI + Kokkos library (in C++)

- Portability to heterogeneous hardware platforms: DoE's Kokkos library can use CUDA, HIP, SYCL, HPX, OpenMP, C++ threads as backend programming model

Frontier: world's fastest HPC system with 1.206 ExaFlop/s
6/2024 Top500 list: https://www.top500.org/

GPUs become a Must for Ultra-High-Resolutions

- Experience from SCREAM: Fortran and C++ version **identical scaling/performance on CPUs**
- Performance measured in SDPD (simulated model days per wall clock day):
  high throughput at ultra-high resolutions (1-3 km) only possible on GPUs with C++/Kokkos



Breakthrough:
> 365 (1 year) SDPD

SCREAM C++/Kokkos code: 3.25 km resolution with 128 vertical layers, model top at 40 km, and 16 prognostic variables

Frontier with AMD MI250 GPUs

Summit with NVIDIA V100 GPUs

Source: Taylor et al. (2023), Gordon-Bell Prize for Climate Modelling in 2023

Scientific Drivers for NSF StormSPEED (2024-2027)

- Will the nonhydrostatic CESM-CAM-SE configuration enable the realistic evolution of extreme precipitation events, such as Mesoscale Convective Systems (MCSs) over the CONUS domain, and truthfully represent their interactions with the large-scale flow?
  - Assessed via ensembles of 4-month (spring-summer) CESM3 simulations in AMIP mode with a 3.25 km variable-resolution mesh over the CONUS domain
- How will simulations of tropical precipitation and tropical cyclones (TCs) be impacted by permitting multi-scale ocean-atmosphere interactions at cloud-permitting and ocean-eddy-permitting resolutions?
  - Assessed via 40-day AMIP and coupled 3.25 km uniform-resolution CESM3 simulations with MOM6 following the DYAMOND-1 and DYAMOND-2 protocols

Benefits for the CESM Community

- Scientific Pursuit:
  - Enable CESM-based community research at the weather-climate interface
  - Exemplars will demonstrate that the nonhydrostatic CESM-CAM-SE configuration will advance the scientific understanding of
    - mesoscale land-atmosphere interactions in the midlatitudes (MCSs)
    - air-sea interactions in tropical regions (tropical cyclones)
- Broader Impacts:
  - Ultra-high-res CESM enables the community/NCAR to push scientific frontiers
  - Aligned with the CESM and NCAR strategic plans, connects CGD, MMM, CISL
  - (Re)Builds stronger ties between NCAR/CESM and DOE, + universities
  - Leverages community activities (EarthWorks, CPTs, SE deep-atmosphere)
  - Trains future-generation scientists at universities, pushes HPC readiness

Upcoming: Dynamical Core Model Intercomparison Project (DCMIP) and Summer School: June/2-6/2025, NCAR Mesa Lab

- Stay tuned for more details
- Hands-on opportunity to learn about the non-hydrostatic capabilities of the CESM dynamical cores
- Organized by the StormSPEED team