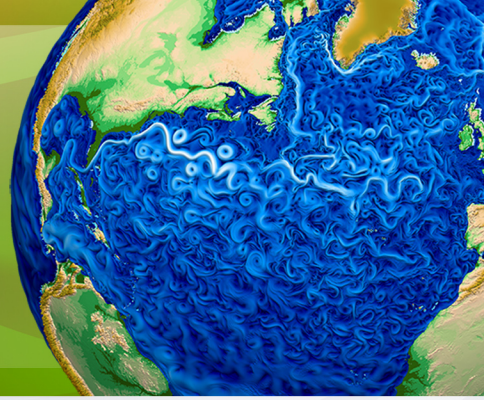
E3SM
Energy Exascale Earth System Model



# Non-hydrostatic dynamics:
## Algorithms, software, and high-resolution science

*SciDAC PI Meeting*
*July 17, 2019*


Sandia National Laboratories
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SciDAC
Scientific Discovery through Advanced Computing

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U.S. DEPARTMENT OF ENERGY

# Outline

- **Primary results & impact**
  - Performance & accuracy improvements to E3SM Atmosphere (EAM) transport
  - Fully integrated into E3SM v2
  - New diagnostic methods for high-resolution experiments
- **Methods and highlights**
  - Algorithms and software
  - High-resolution science: Non-hydrostatic dynamics
- **Ongoing & proposed work**
  - Leveraging EAM results for MPAS Ocean
  - Model fidelity improvements with minimal performance impact
  - High resolution science campaigns

# Also at this meeting

- **Poster (Tuesday):** Characterizing Non-Hydrostatic Effects in the Next-Generation E3SM Atmosphere Model
- **Poster (Thursday):** Algorithms and Software for Fast E3SM Atmosphere Tracer Transport

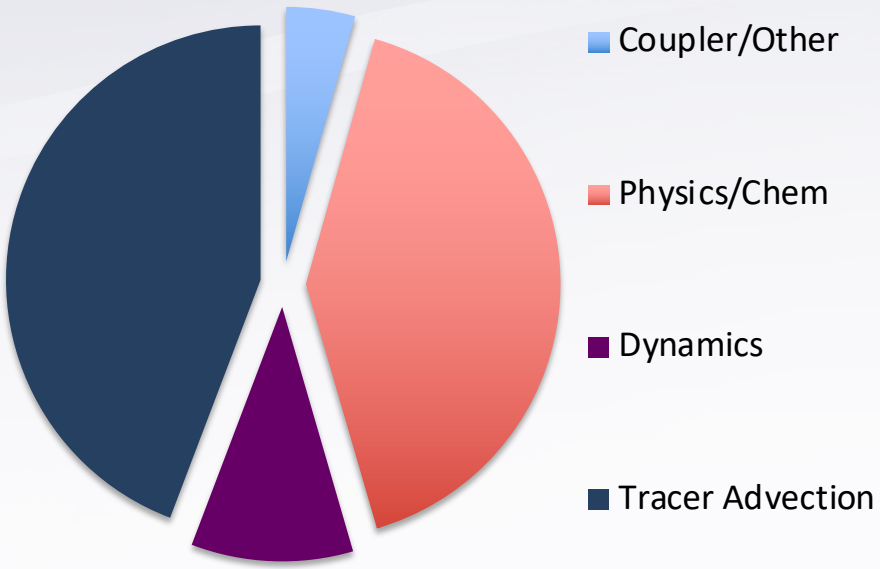
# SciDAC Pilot Phase 1: Before & after

- Transport speedup (0.25 deg, 40 tracers): ~6x
- Dynamical core (v1 dynamics + transport, no physics) speedup: ~3x
- Full atmosphere model speedup: ~2.1x

**2019: EAM/SL ready for v2**

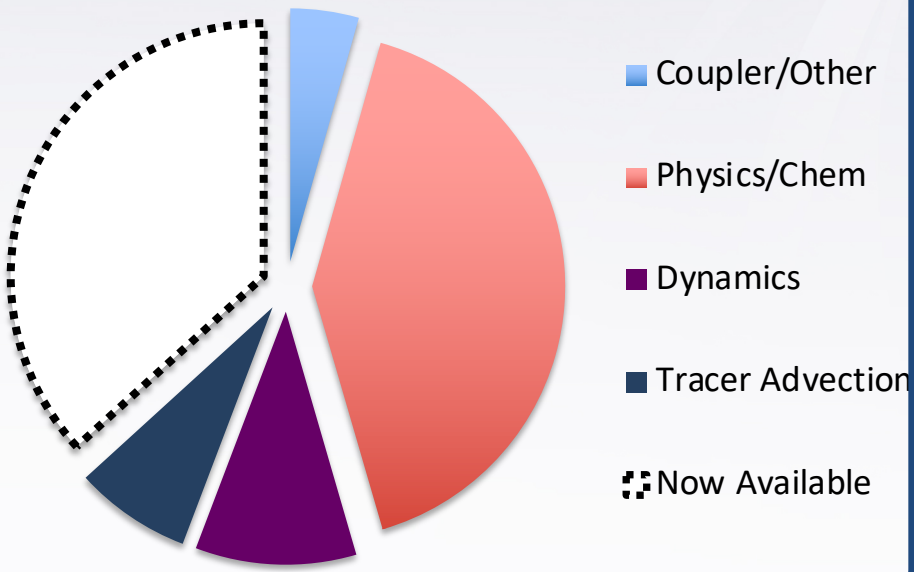
EAM v1 (2015)

Computation time by component




E3SM v1 with SL transport (now)

Computation time by component



# E3SM Atm. Dycore Performance

- SYPD (higher is better)
- Solid: Eulerian SE transport w/lim9
- Dashed: Pointwise SL + QLT
- Red: Cori (KNL)
- Green: Edison (HSW)

**6x transport speedup**

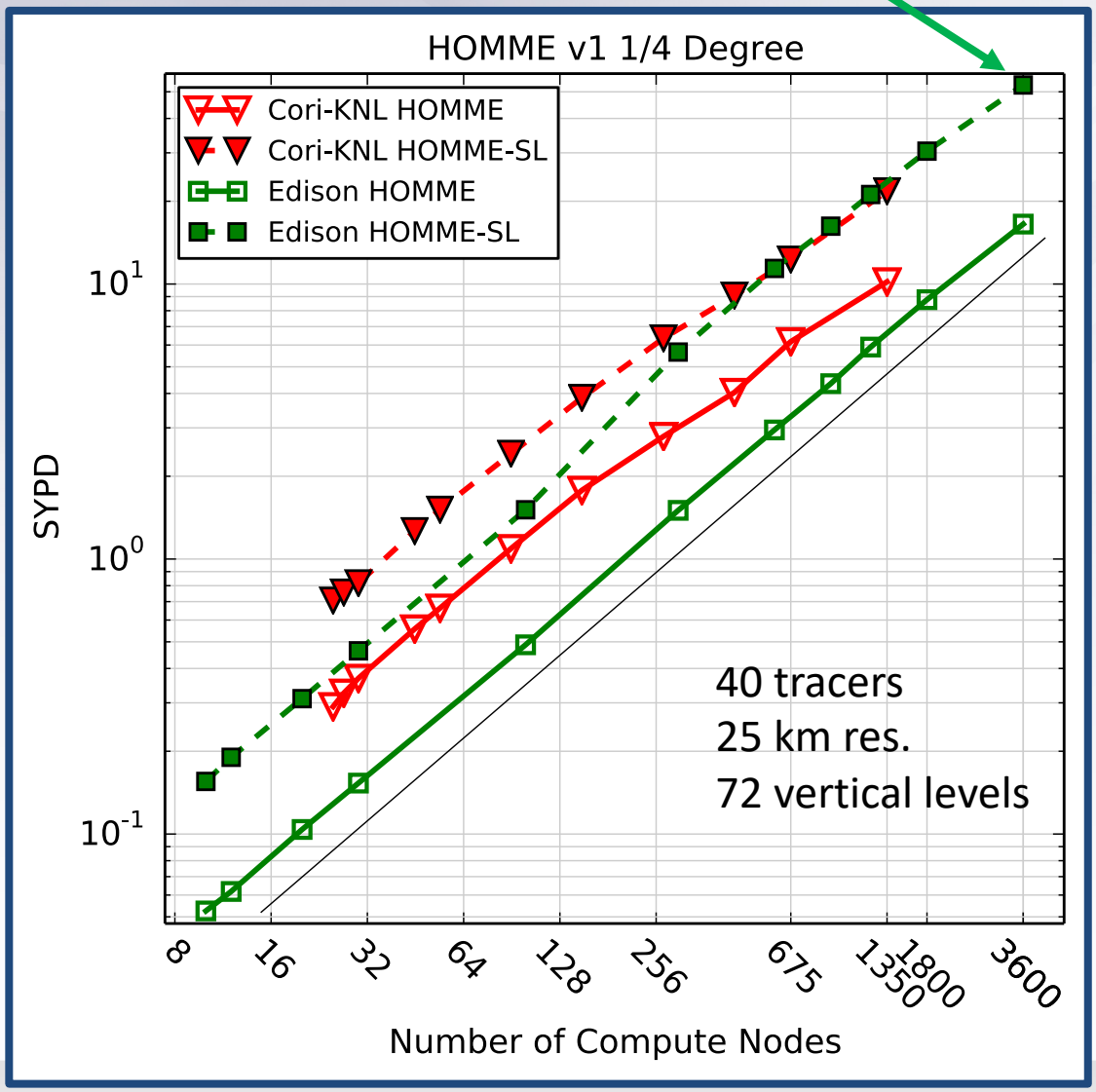
- **3x from SL:** larger time step, smaller data movement requirements
- **2x from MPI (NGD):** Reduced communication volume

**3x atm. dycore speedup**

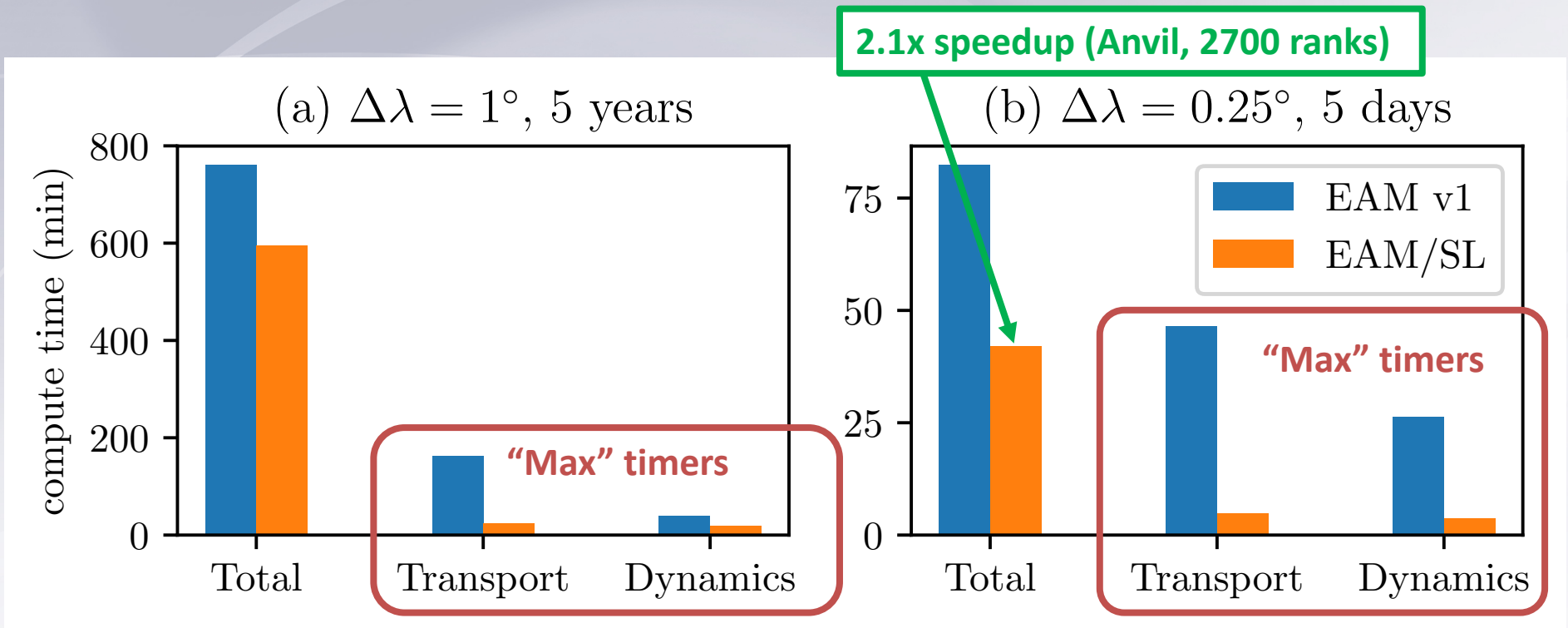
- At scale
- Appx. same for KNL

**2x full atm. Speedup**

- Physics now largest component



# Full EAM (dyn., trans., & phys.) performance




**Unexpected result:** ~10% to ~20% speedup in dynamics solver

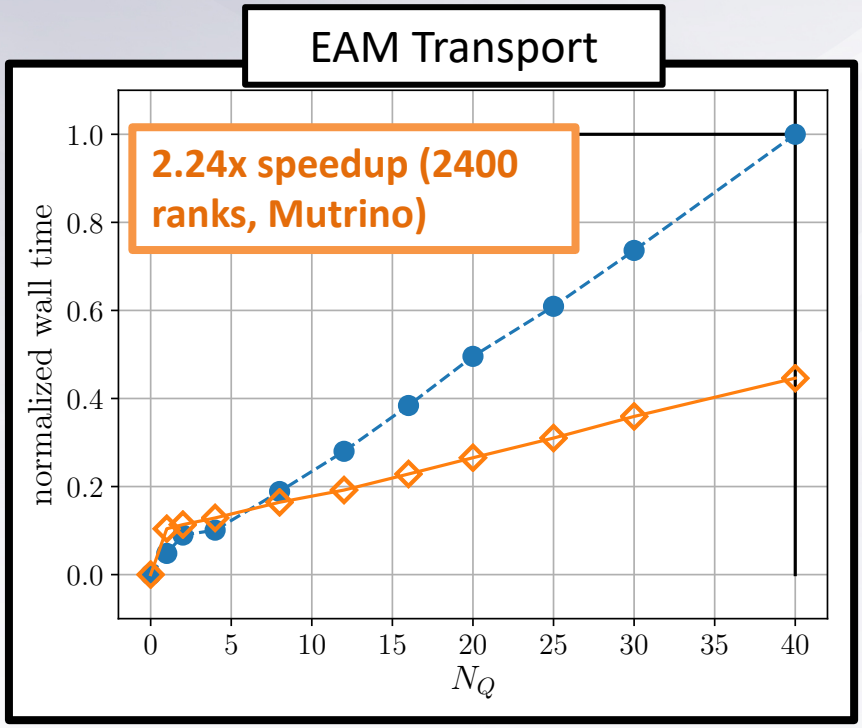
- Better use of fast memory (L3 cache)
- procs. spend less time in MPI_Wait

**More details in Thursday's poster session**

- Comparison of costs vs. resolution
- And more!

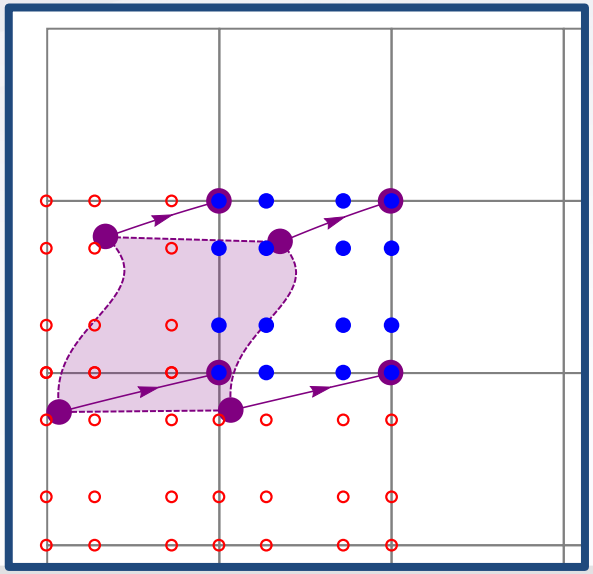
# Algorithms & software development

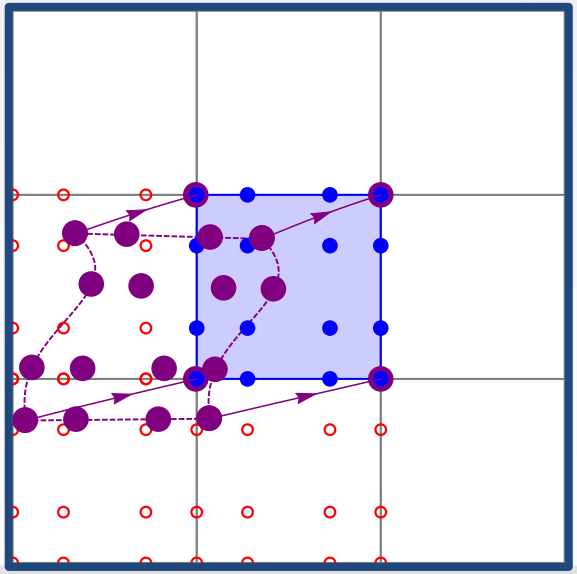
- Cell-integrated remap SL transport
- **Highlight:**
  - Conservative multi-moment transport along characteristics for discontinuous Galerkin methods, *SIAM J. Sci. Comput.*, 2019 (Accepted)
- **Insight:** High-order, remap SL …
  - Requires at least 1 global collective per timestep to achieve tracer consistency and shape preservation
  - Still lower communication volume than SL flux-form
  - Can efficiency be improved further?



# Cell-integrated SL vs. Pointwise interpolation SL

| Method: | Cell-integrated remap | Pointwise interpolation |
|---|---|---|
| Provides: | **(1) Conservation**<br>(2) Accuracy<br>(5) Efficiency (~2x) | (2) Accuracy<br>**(5) Efficiency (~3x)** |
| Needs: | **Problem A**<br>(3) Shape preservation<br>(4) Tracer consistency | **Problem B**<br>(1) Conservation<br>(3) Shape preservation<br>(4) Tracer consistency |





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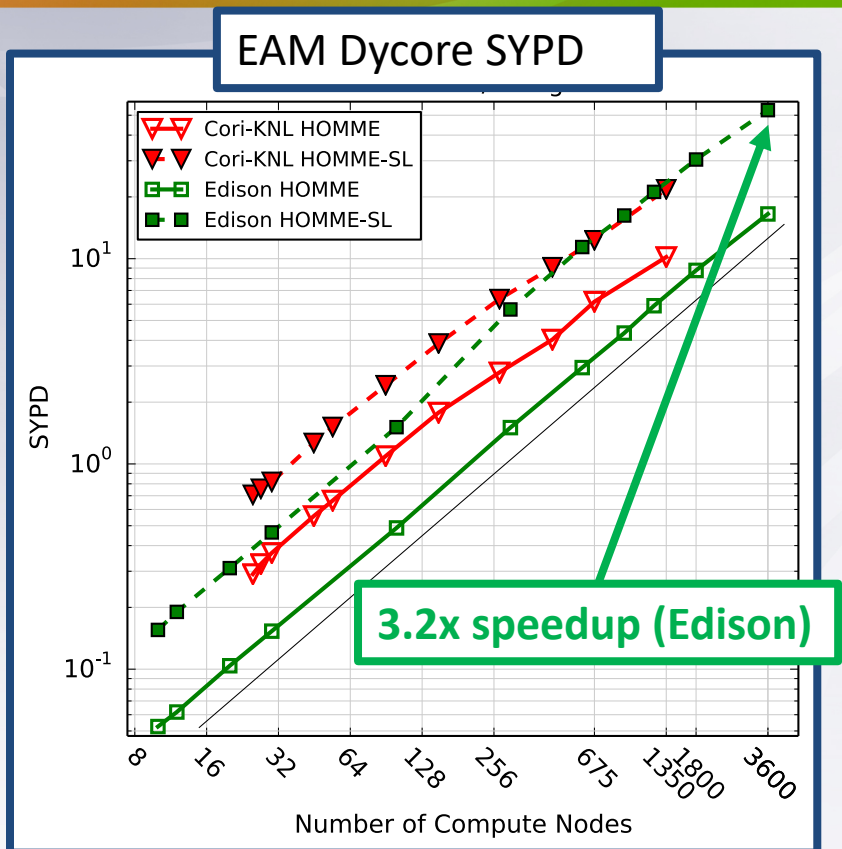
| Needs: | **Problem A**<br>(3) Shape preservation<br>(4) Tracer consistency | **Problem B**<br>(1) Conservation<br>(3) Shape preservation<br>(4) Tracer consistency |

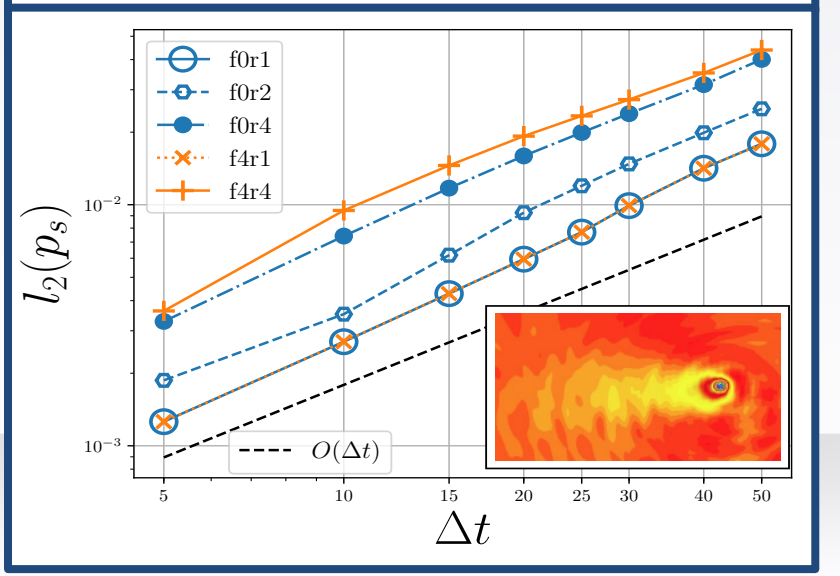
Claim 1: An algorithm that provides locally bounds-preserving shape preservation is sufficient to also provide tracer consistency.

Claim 2: Solving **Problem A** without losing conservation is equivalent to solving **Problem B**.

# Algorithms & software

- Stabilized interpolation SL transport with Communication-efficient Density Reconstruction (CDR)
- **Highlight:**
  - Communication-efficient property preservation in tracer transport, *SIAM J. Sci. Comput.* 41(3), C161—C193, 2019.
  - Mass conservation, tracer consistency, and shape preservation solved in **smallest possible number of global collectives**
  - **Verification:**
    - Improved accuracy in space
    - Convergence in time **with simplified physics**

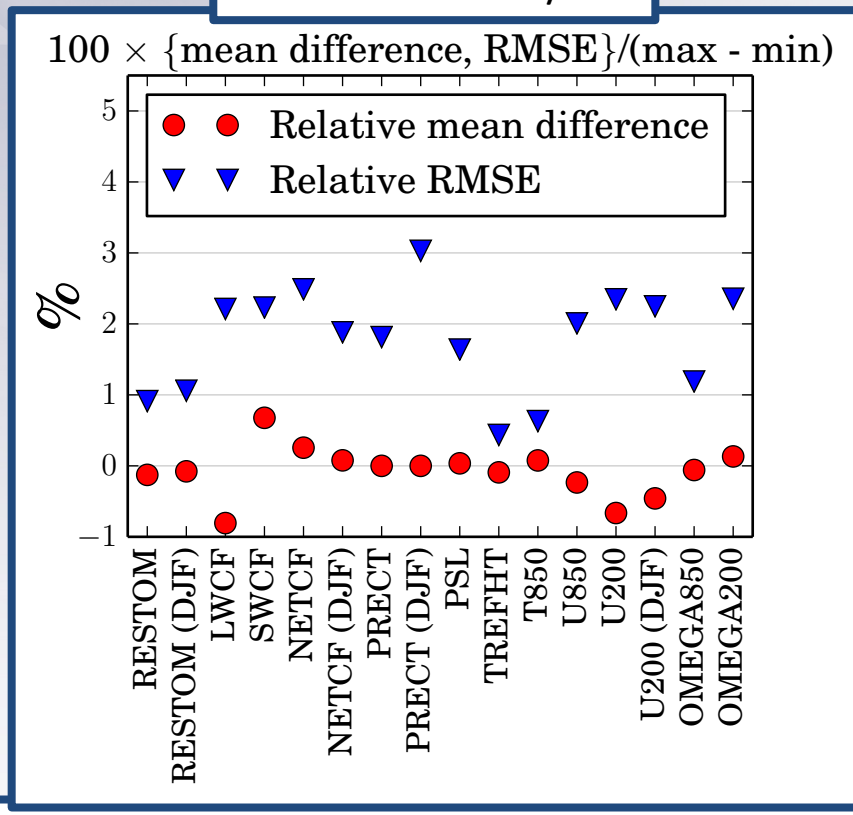


# Algorithms & software

- **Highlight:**
  - Software release
  - COMPOSE: Library for communication-efficient, property-preserving, semi-Lagrangian tracer transport
- Climate validation
- Integration for E3SM v2
  - CDR/ISL transport
  - Time step coupling
  - **Already in E3SM Master**

EAM v1 vs. EAM/SL

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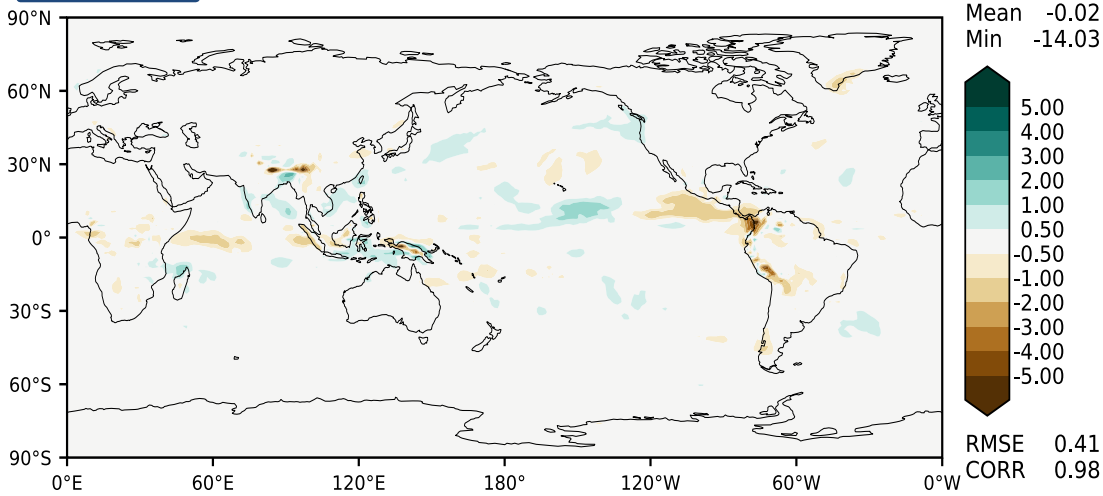
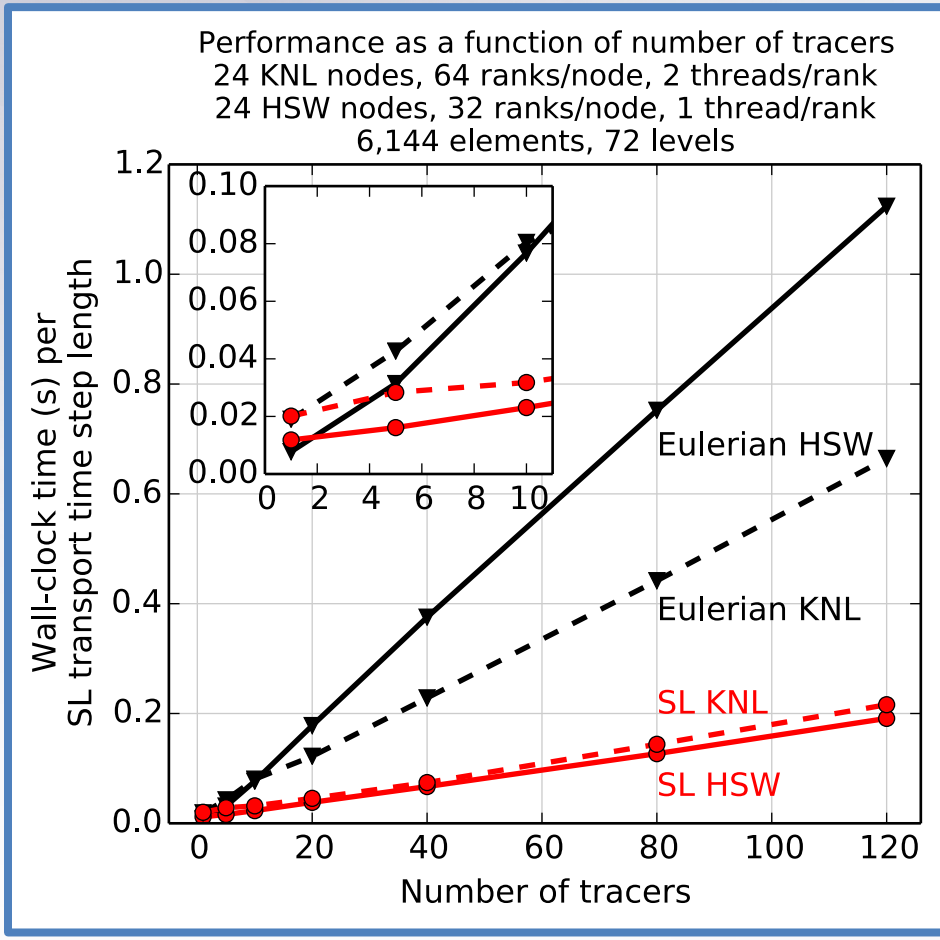



E3SM Energy Exascale Earth System Model

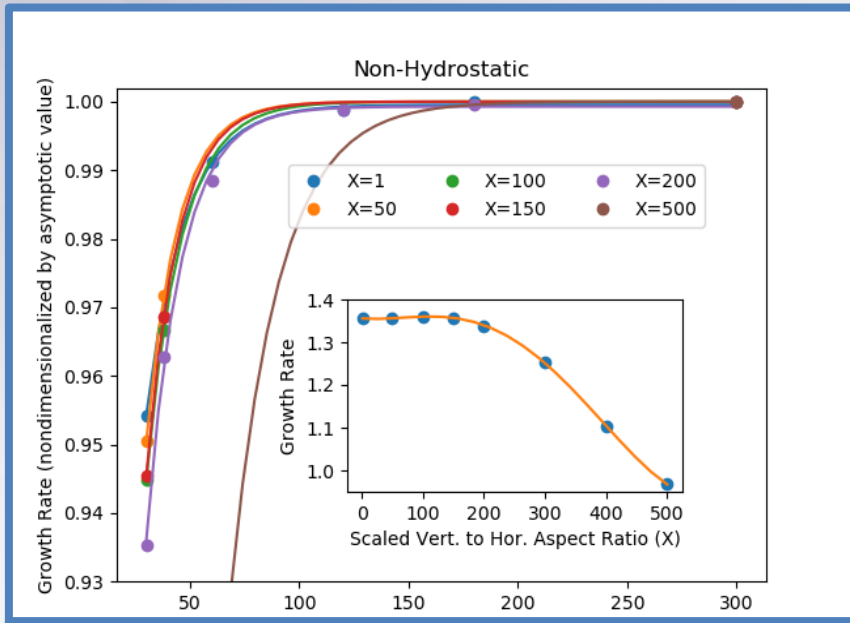
# Hi-res science: Physics for hi-res

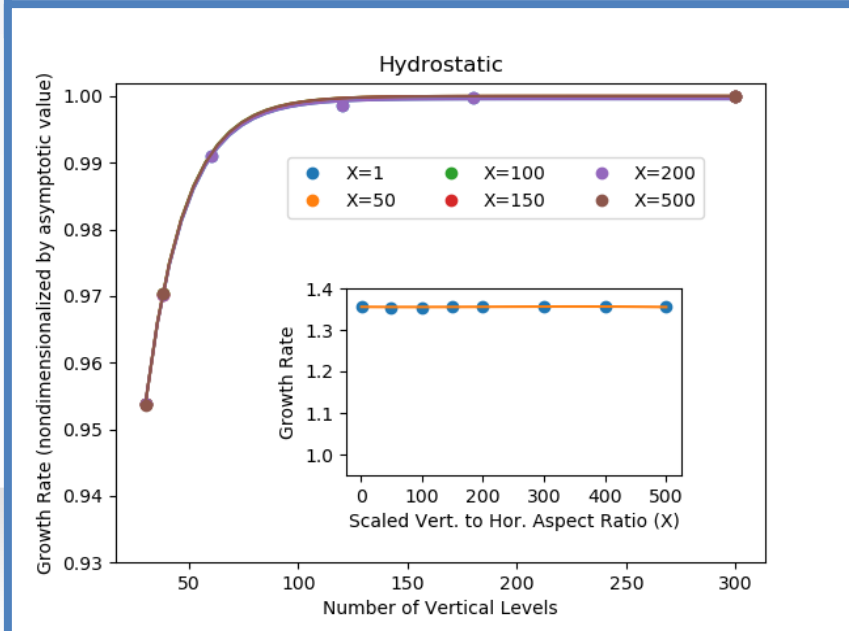
- BER Call for Proposals March 2019
  - Aerosol & aerosol-cloud interaction identified as “crucial” for E3SM v3, v4
  - Accurate representation may require additional tracer species
  - Multi-tracer efficiency of new SL methods provides significant advantages over E3SM v1



# Hi-res science: Quantifying non-hydrostatic effects

- Vertical resolution requirements in hydrostatic vs. non-hydrostatic models (right)
- Multiscale interactions
  - Physically accurate or numerical artifacts?
- **Results:** EAM v3, v4 may require increased number of levels to reduce numerically-triggered small-scale features

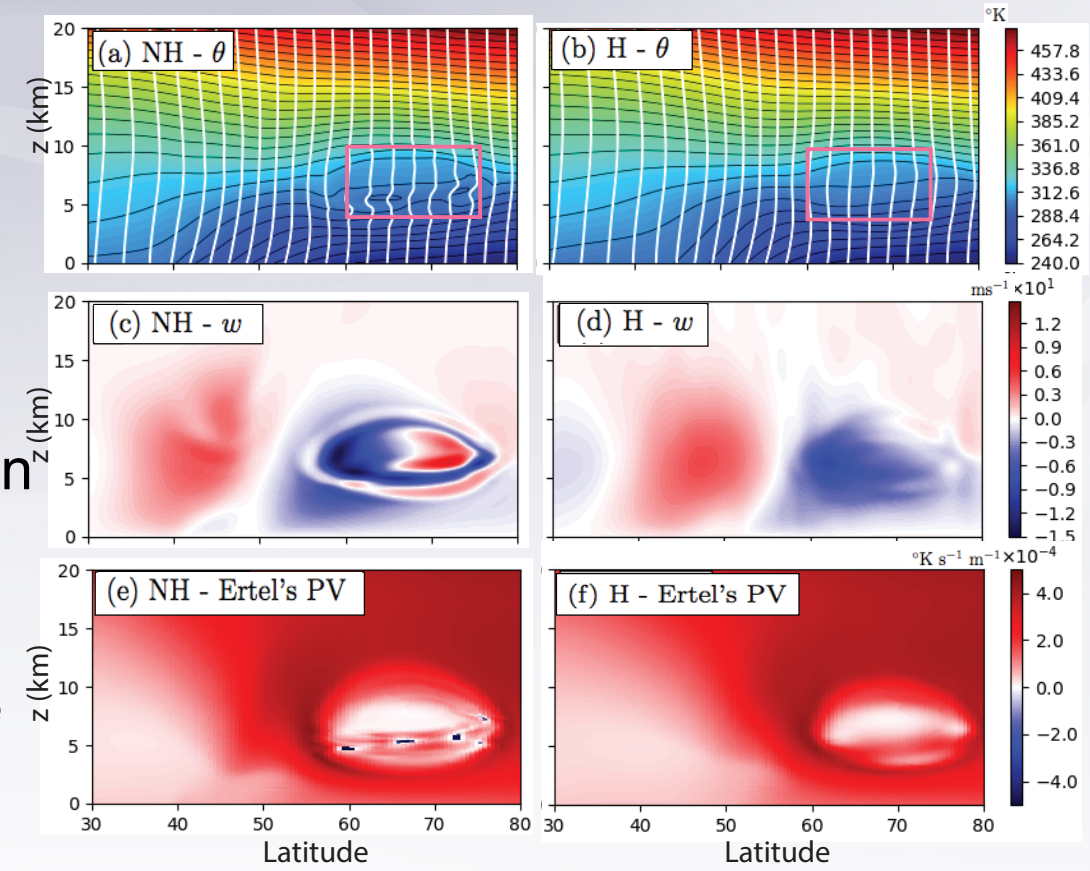



E3SM Energy Exascale Earth System Model

# Symmetric instability

- Small-scale process
- Intensifies rain bands in extratropical cyclones
  - Large effects on regional precip.
- Diagnosed by change in sign of EPV (right)
  - **EPV now in EAM**
- **Results:** EAM-NH capable of representing sym. inst., EAM-H is not



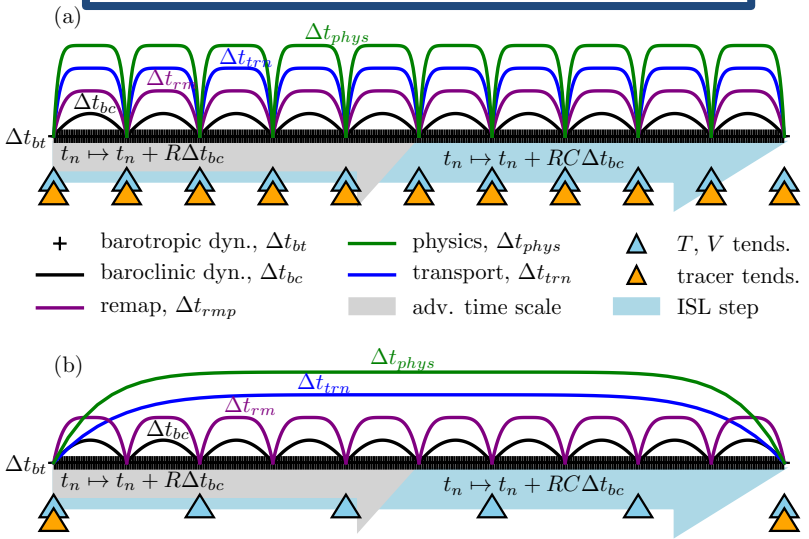

**More details in Tuesday's poster session**

- Comparison of NH to H with baroclinic instability
- And more …

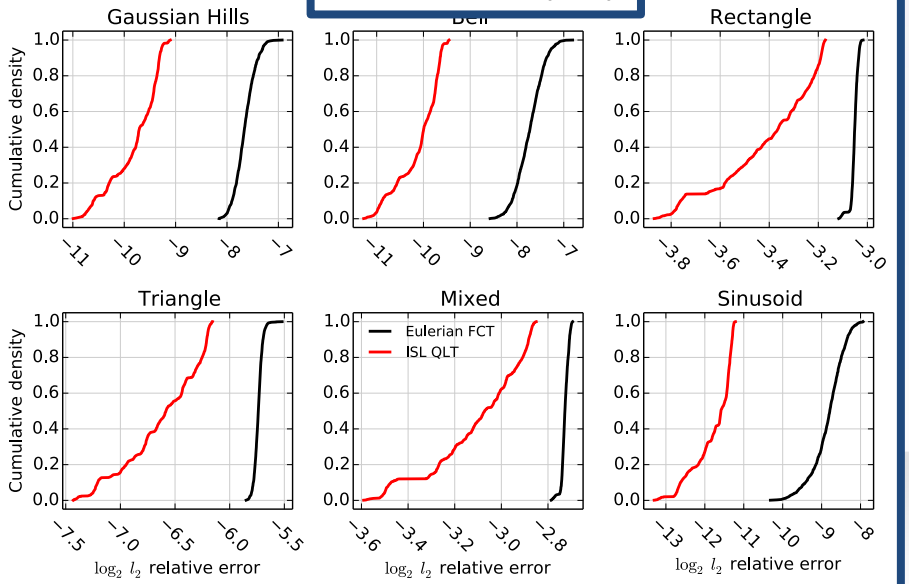
# Proposed for Phase 2

- Algorithms/Software
  - SL Trans. for MPAS Ocn (right)
    - No degradation in accuracy, conservation, consistency
    - Significant performance gains, esp. BGC
  - High-order tracer transport
    - Improved resolution of small scales
    - No timestep penalty
- NH Science
  - Radiative-Convective Eq.
    - RCEMIP contribution
  - Tropical cyclone climo.
  - Condensate loading

MPAS Ocn. Time step coupling




ISL vs. FCT (1d)




E3SM Energy Exascale Earth System Model

# Summary

- Phase 1 impacts:
  - Model speedup @ 0.25 deg: Transport up to 6x, Dycore 3x, EAM 2x
  - EAM v2 with 120 tracers now runs as fast as v1 with 40 tracers
  - Aerosol modeling no longer constrained by transport
  - Flexible time-step coupling methods
  - COMPOSE Software already employed by other projects (LDRD, SciDAC)
  - Better understanding of NH effects in EAM, how to diagnose them
- Phase 2 impacts:
  - Transfer algorithms & tailor an implementation for MPAS Ocean
  - Improve perf. of BGC campaign
  - Add resolution to tracers without time step penalty
  - RCEMIP experiments
  - Hi-res climatology