Upcoming Innovations for CAM's Spectral Element Dynamical Core and CESM: Nonhydrostatic and Deep-Atmosphere Modeling

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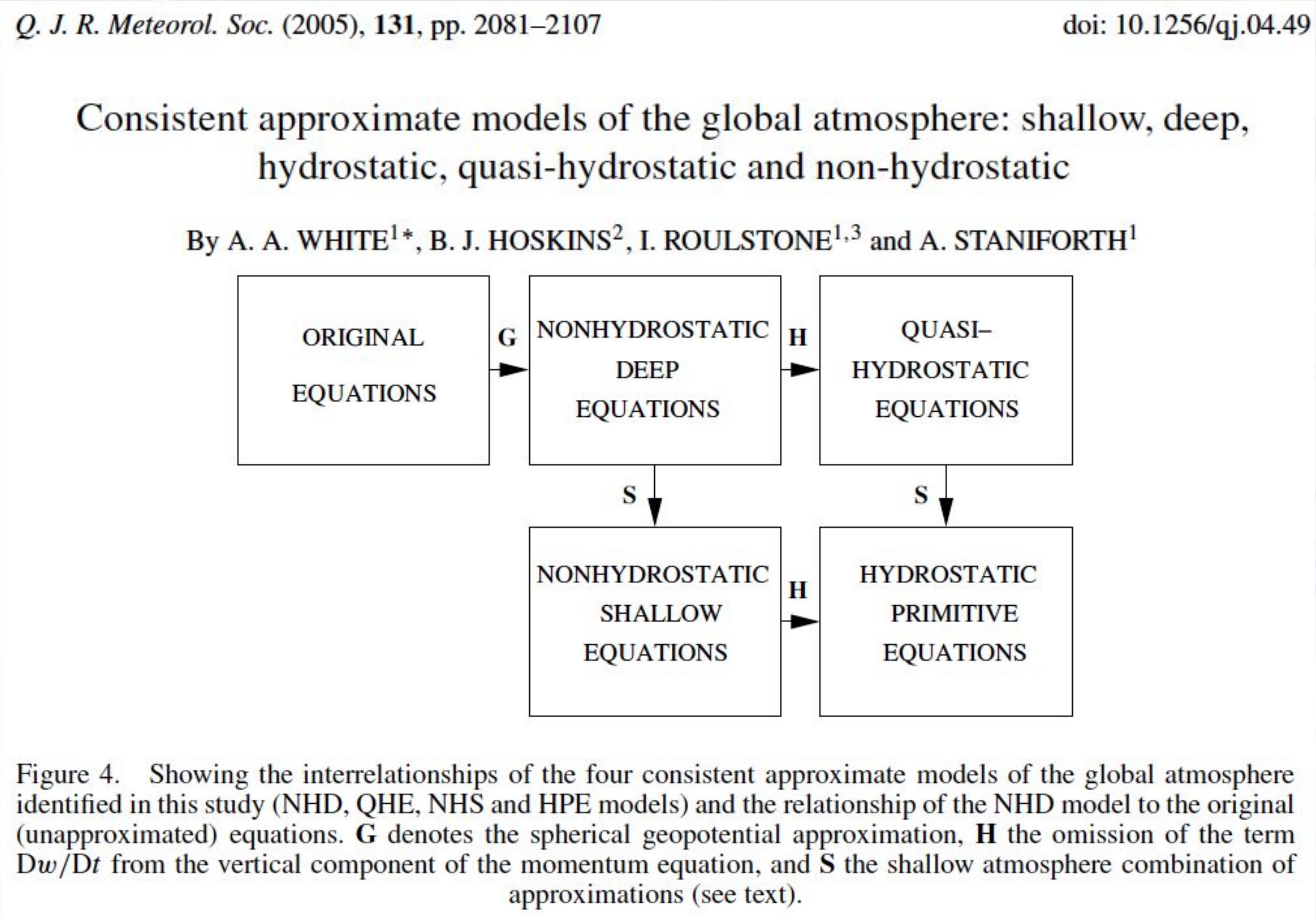
A Portfolio of Equation Sets for Dynamical Cores



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Consistent approximate models of the global atmosphere: shallow, deep, hydrostatic, quasi-hydrostatic and non-hydrostatic

By A. A. WHITE[1]*, B. J. HOSKINS[2], I. ROULSTONE[1,3] and A. STANIFORTH[1]

Figure 4. Showing the interrelationships of the four consistent approximate models of the global atmosphere identified in this study (NHD, QHE, NHS and HPE models) and the relationship of the NHD model to the original (unapproximated) equations. **G** denotes the spherical geopotential approximation, **H** the omission of the term $\mathrm{D}w/\mathrm{D}t$ from the vertical component of the momentum equation, and **S** the shallow atmosphere combination of approximations (see text).

Non-Hydrostatic Deep-Atmosphere Equations of Motion

$$\frac{Du}{Dt} - \frac{u\mathrm{v}\tan(\phi)}{r} + \frac{uw}{r} = -\frac{1}{\rho\, r\cos\phi}\frac{\partial p}{\partial \lambda} + 2\Omega \mathrm{v}\sin(\phi) - 2\Omega w\cos(\phi) + \nu\nabla^2(u)$$

$$\frac{D\mathrm{v}}{Dt} + \frac{u^2\tan(\phi)}{r} + \frac{\mathrm{v}w}{r} = -\frac{1}{\rho\, r}\frac{\partial p}{\partial \phi} - 2\Omega u\sin(\phi) + \nu\nabla^2(\mathrm{v})$$

$$\frac{Dw}{Dt} - \frac{u^2 + \mathrm{v}^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - g + 2\Omega u\cos(\phi) + \nu\nabla^2(w)$$

with variable $g = \frac{d\Phi}{dr} = G\frac{a^2}{r^2}$

$$\frac{D\rho}{Dt} + \frac{\rho}{r\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial(v\cos\phi)}{\partial \phi}\right] + \frac{\rho}{r^2}\frac{\partial(r^2 w)}{\partial r} = 0$$

$$c_v\frac{DT}{Dt} + p\frac{D}{Dt}\left(\frac{1}{\rho}\right) = J$$

$$p = \rho RT$$

$$\frac{D(\;)}{Dt} = \frac{\partial(\;)}{\partial t} + \frac{u}{r\cos\phi}\frac{\partial(\;)}{\partial \lambda} + \frac{v}{r}\frac{\partial(\;)}{\partial \phi} + w\frac{\partial(\;)}{\partial r}$$

Only approximations

- Earth is a perfect sphere
- gravity g only varies vertically

Examples: ICON (MPI/DWD), MPAS (NCAR), EndGame (UK Met Office)

Quasi-Hydrostatic Deep-Atmosphere Equations

$$\frac{Du}{Dt} - \frac{u\mathrm{v}\tan(\phi)}{r} + \frac{uw}{r} = -\frac{1}{\rho\, r\cos\phi}\frac{\partial p}{\partial \lambda} + 2\Omega \mathrm{v}\sin(\phi) - 2\Omega w\cos(\phi) + \nu\nabla^2(u)$$

$$\frac{D\mathrm{v}}{Dt} + \frac{u^2\tan(\phi)}{r} + \frac{\mathrm{v}w}{r} = -\frac{1}{\rho\, r}\frac{\partial p}{\partial \phi} - 2\Omega u\sin(\phi) + \nu\nabla^2(\mathrm{v})$$

$$\cancel{\frac{Dw}{Dt}} - \frac{u^2 + \mathrm{v}^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} - g + 2\Omega u\cos(\phi) + \cancel{\nu\nabla^2(w)}$$

with variable $g = \frac{d\Phi}{dr} = G\frac{a^2}{r^2}$

$$\frac{D\rho}{Dt} + \frac{\rho}{r\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial(\mathrm{v}\cos\phi)}{\partial \phi}\right] + \frac{\rho}{r^2}\frac{\partial(r^2 w)}{\partial r} = 0$$

$$c_v\frac{DT}{Dt} + p\frac{D}{Dt}\left(\frac{1}{\rho}\right) = J$$

$$p = \rho R T$$

$$\frac{D(\ )}{Dt} = \frac{\partial(\ )}{\partial t} + \frac{u}{r\cos\phi}\frac{\partial(\ )}{\partial \lambda} + \frac{\mathrm{v}}{r}\frac{\partial(\ )}{\partial \phi} + w\frac{\partial(\ )}{\partial r}$$

- neglect of *Dw/Dt* removes vertically propagating acoustic modes
- puts the vertical momentum balance into a diagnostic form: ‘quasi-hydrostatic’
- Equations not really in use in models

Non-Hydrostatic (NH) Shallow-Atmosphere Equations (design of almost all weather models)

$$\frac{Du}{Dt} - \frac{uv\tan(\phi)}{\overset{a}{\cancel{r}}} + \cancel{\frac{uw}{r}} = -\frac{1}{\rho \overset{a}{\cancel{r}} \cos\phi}\frac{\partial p}{\partial \lambda} + 2\Omega v\sin(\phi) - \cancel{2\Omega w\cos(\phi)} + \nu\nabla^2(u)$$

$$\frac{Dv}{Dt} + \frac{u^2\tan(\phi)}{\overset{a}{\cancel{r}}} + \cancel{\frac{vw}{r}} = -\frac{1}{\rho \overset{a}{\cancel{r}}}\frac{\partial p}{\partial \phi} - 2\Omega u\sin(\phi) + \nu\nabla^2(v)$$

$$\frac{Dw}{Dt} - \cancel{\frac{u^2+v^2}{r}} = -\frac{1}{\rho}\frac{\partial p}{\partial \overset{z}{\cancel{r}}} - g + \cancel{2\Omega u\cos(\phi)} + \cancel{\nu\nabla^2(w)}$$

with ~~variable~~ $g = \cancel{\frac{d\Phi}{dr}} = \cancel{G\frac{a^2}{r^2}}$

$$\frac{D\rho}{Dt} + \frac{\rho}{\overset{a}{\cancel{r}}\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial(v\cos\phi)}{\partial \phi}\right] + \frac{\rho}{\cancel{r^2}}\frac{\partial(\cancel{r^2}w)}{\partial \overset{z}{\cancel{r}}} = 0$$

$$c_v\frac{DT}{Dt} + p\frac{D}{Dt}\left(\frac{1}{\rho}\right) = J$$

$$p = \rho RT$$

$$\frac{D(\;)}{Dt} = \frac{\partial(\;)}{\partial t} + \frac{u}{\overset{a}{\cancel{r}}\cos\phi}\frac{\partial(\;)}{\partial \lambda} + \frac{v}{\overset{a}{\cancel{r}}}\frac{\partial(\;)}{\partial \phi} + w\frac{\partial(\;)}{\partial \overset{z}{\cancel{r}}}$$

Approximations

- Omit cos-Coriolis terms
- Omit certain metric terms
- Replace r with the radius a
- Use constant gravity g

$$\frac{Du}{Dt} - \frac{u\mathrm{v}\tan(\phi)}{a} = -\frac{1}{\rho\, a\cos\phi}\frac{\partial p}{\partial \lambda} + 2\Omega \mathrm{v}\sin(\phi) + \nu\nabla^2(u)$$

$$\frac{D\mathrm{v}}{Dt} + \frac{u^2\tan(\phi)}{a} = -\frac{1}{\rho\,\mathrm{a}}\frac{\partial p}{\partial \phi} - 2\Omega u\sin(\phi) + \nu\nabla^2(\mathrm{v})$$

$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad \text{with constant g}$$

$$\frac{D\rho}{Dt} + \frac{\rho}{a\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial(v\cos\phi)}{\partial \phi}\right] + \frac{\partial w}{\partial z} = 0$$

$$c_v\frac{DT}{Dt} + p\frac{D}{Dt}\left(\frac{1}{\rho}\right) = J$$

$$p = \rho RT$$

$$\frac{D(\;)}{Dt} = \frac{\partial(\;)}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial(\;)}{\partial \lambda} + \frac{v}{a}\frac{\partial(\;)}{\partial \phi} + w\frac{\partial(\;)}{\partial z}$$

Hydrostatic Shallow-Atmosphere Equations: Primitive Equations (all climate models, including CESM)

$$\frac{Du}{Dt} - \frac{u\mathrm{v}\tan(\phi)}{a} = -\frac{1}{\rho\, a\cos\phi}\frac{\partial p}{\partial \lambda} + 2\Omega \mathrm{v}\sin(\phi) + \nu\nabla^2(u)$$

$$\frac{D\mathrm{v}}{Dt} + \frac{u^2\tan(\phi)}{a} = -\frac{1}{\rho\,\mathrm{a}}\frac{\partial p}{\partial \phi} - 2\Omega u\sin(\phi) + \nu\nabla^2(\mathrm{v})$$

$$\cancel{\frac{Dw}{Dt}} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \qquad \text{with constant g}$$

$$\frac{D\rho}{Dt} + \frac{\rho}{a\cos\phi}\left[\frac{\partial u}{\partial \lambda} + \frac{\partial(\mathrm{v}\cos\phi)}{\partial \phi}\right] + \frac{\partial w}{\partial z} = 0$$

$$c_v\frac{DT}{Dt} + p\frac{D}{Dt}\left(\frac{1}{\rho}\right) = J$$

$$p = \rho R T$$

$$\frac{D(\;)}{Dt} = \frac{\partial(\;)}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial(\;)}{\partial \lambda} + \frac{\mathrm{v}}{a}\frac{\partial(\;)}{\partial \phi} + w\frac{\partial(\;)}{\partial z}$$

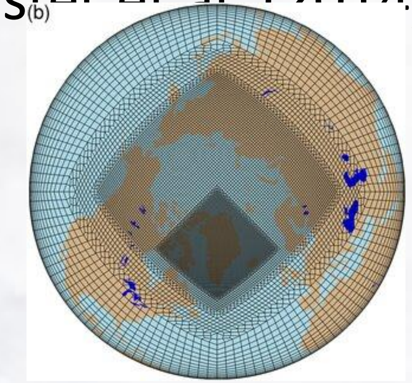
The ‘Primitive Equations’ are often abbreviated as ‘PE’.

Why Should We Expand the Dynamical Core Equation Sets that CESM offers?

- To enable new science questions
  - Explorations of the predictability of the Earth’s System
  - Modeling across the climate-weather interface, including S2S time scales
  - Cloud-system permitting high-resolution modeling at the kilometer scale
  - Whole atmosphere modeling with variable gravity (WACCM/WACCM-X)
- To further reduce the approximations / biases we make in CESM
  - Idealized studies suggest that the chronic double ITCZ problem in climate models might be related to the omissions of the cos-Coriolis terms in the PE equations
  - cos-Coriolis terms become sizable at high resolutions in the tropics
- To stay at the forefront of climate modeling at the international level
- Suggestion: integrate a nonhydrostatic (and optional deep-atmosphere) configuration of the Spectal Element (SE) dynamical core in CAM

High-Resolution Modeling Efforts

- High-Resolution Modeling with CESM so far: a 10-year journey with CAM5/CESM1
  - **Uniform-resolution CESM** SE/Finite-Volume(FV) with Δx around 11-28 km
    - 0.25˚ atmosphere with 30 vertical levels & land/river model
    - 0.1˚ ocean (POP) & ice models, or 0.25˚ AMIP configuration
    - CESM examples are Wehner et al. (2014), Small et al. (2014), Bacmeister et al. (2014, 2018), Chang et al. (2020, 2023): iHESP (HighResMIP contribution)
  - **Variable-resolution CESM SE** examples with local Δx around 7-28 km
    - AMIP mode: Zarzycki and Jablonowski (2014), Zarzycki et al. (2015)
    - Coupled mode: Herrington et al. (2022) with CESM2.2

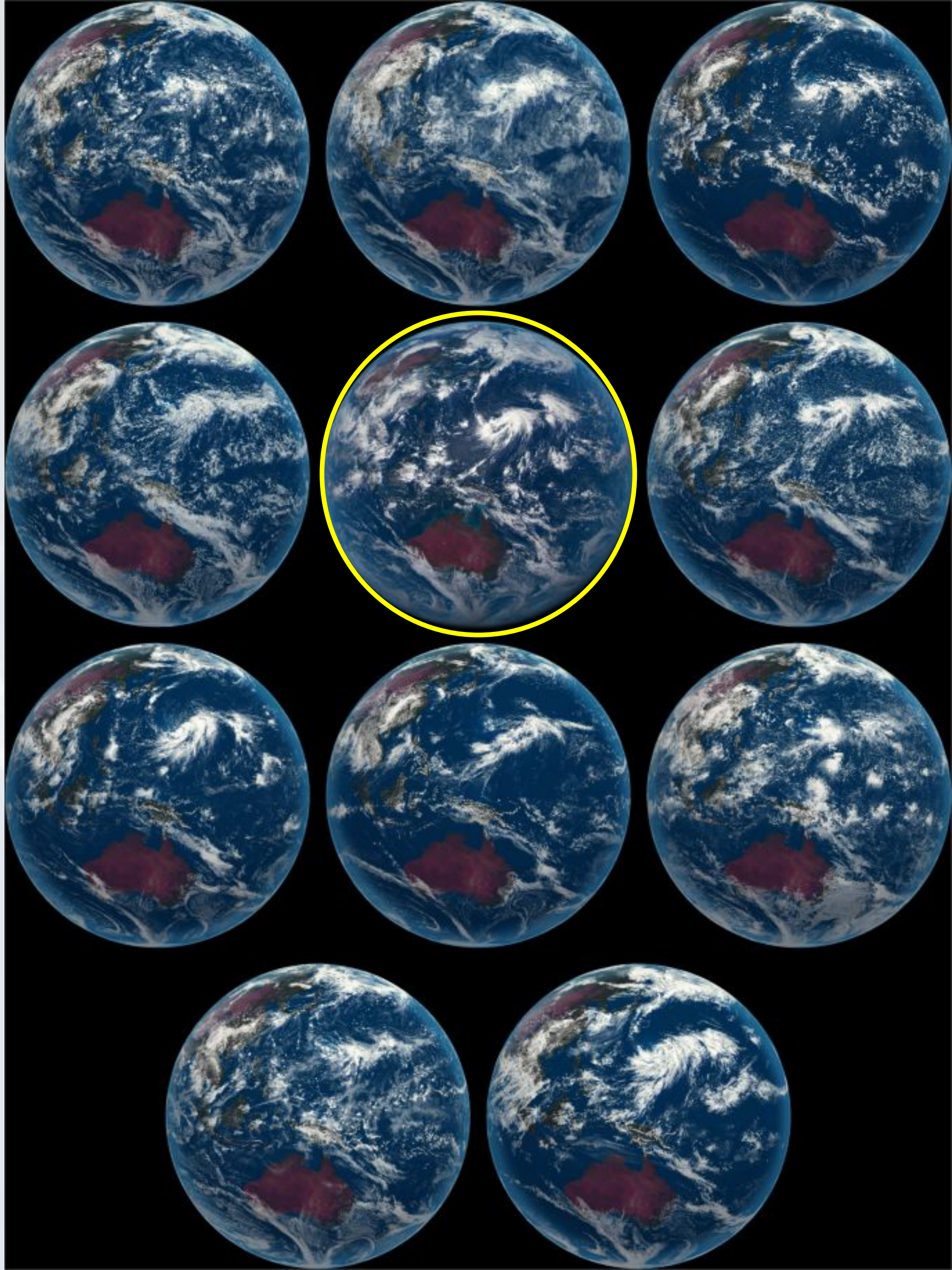


- International community
  - HighResMIP (CMIP6) / PRIMAVERA project (Europe): Δx around 28 km (Haarsma et al, 2016)
  - DYAMOND project, NASA Nature Run, Destination Earth (Europe): Δx around 3-9 km
    - 40-day initialized DYAMOND simulations (mostly AMIP): Stevens et al. (2019) https://www.esiwace.eu/the-project/past-phases/dyamond-initiative (2016-2023)

DYAMOND: International Model Intercomparison at Cloud-Permitting Scales

- Atmospheric models with 3-9 km grid spacings (40-day simulations)
- Figure: Snapshot of a cloud scene from 10 DYAMOND models and one satellite observation (day 3 is depicted)

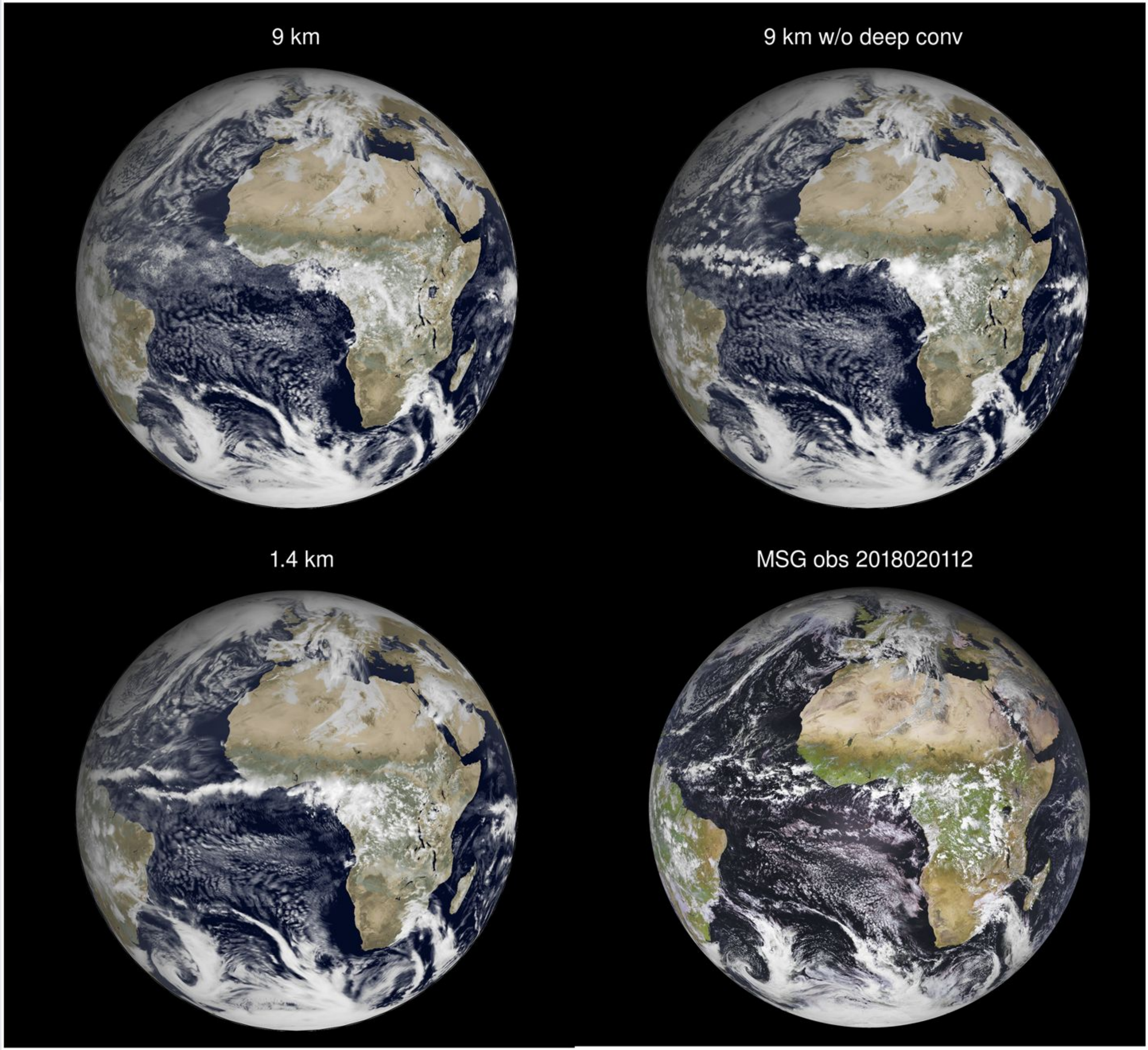
- Difficulty of distinguishing the model results from the actual satellite observation (circled): Passes the 'eyeball norm' test
- However: details can differ greatly (eyeball test does not serve as an accuracy measure)



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

- Wedi et al. (2020) conducted 4-month simulations with a 1.4 km and 9 km configuration of ECMWF’s IFS
- Deep convection was still beneficial for the IFS at 9 km (underresolved convection)
- At GFDL: L. Harris just reported on a 2-year simulation with the 3 km X-SHIELD model

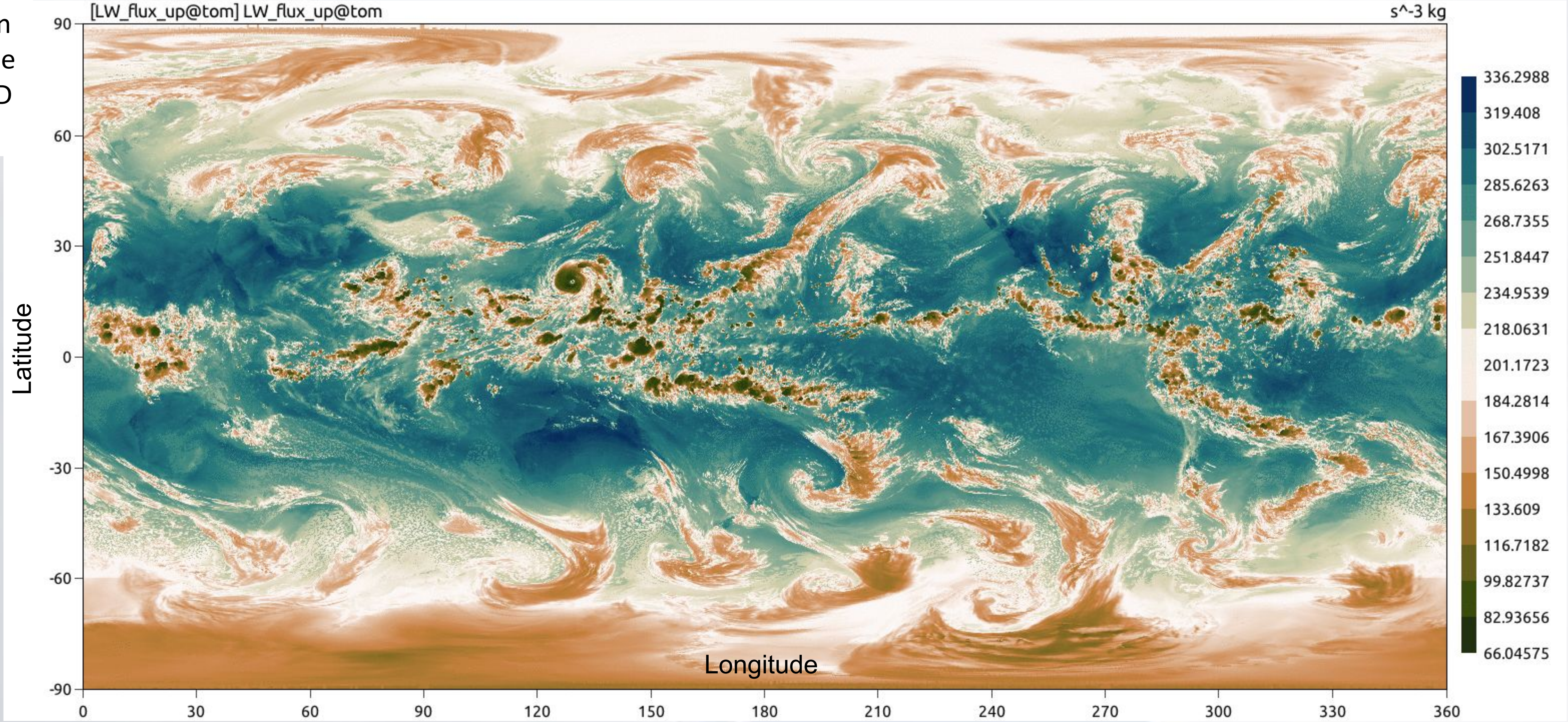


An Opportunity: DoE-NCAR SE-NH Technology Transfer

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



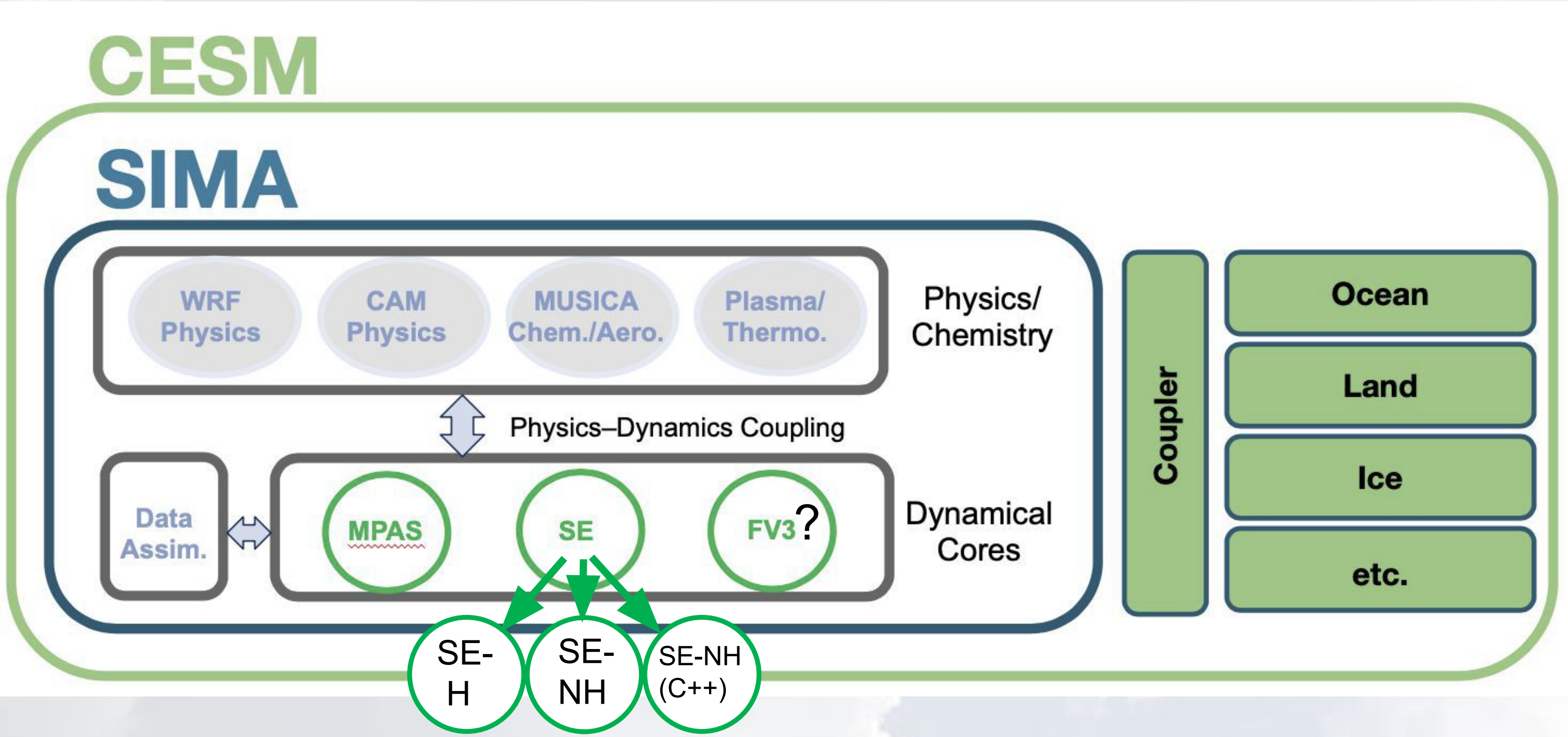
Source: https://e3sm.org/exascale-performance-of-the-simple-cloud-resolving-e3sm-atmosphere-model/

High-Res Roadmap for CESM3 (2024-2026)

- Integrate the existing DoE **nonhydrostatic** (NH) Fortran version of the Spectral Element (SE-NH) dynamical core into CESM's Community Atmosphere Model (CAM7) to enable cloud-permitting coupled climate simulations with CESM3: Workhorse model for scientific exemplars and community release
- Advance CESM's readiness for the newest HPC GPU architectures
  - include DOE's SE C++/Kokkos version of SE-NH (used in SCREAM)
  - 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)

Deeper Dive: Infrastructure Challenges

- Planned CESM / SIMA infrastructure at NCAR with various dynamical cores



- Nonhydrostatic SE (SE-NH) becomes a SE new variant
- SIMA physics-dynamics coupling interface: plans to utilize the Common Community Physics Package (CCPP) framework, enables new physics (e.g., WRF)

Deeper Dive: Dynamical Core Challenges/Opportunities

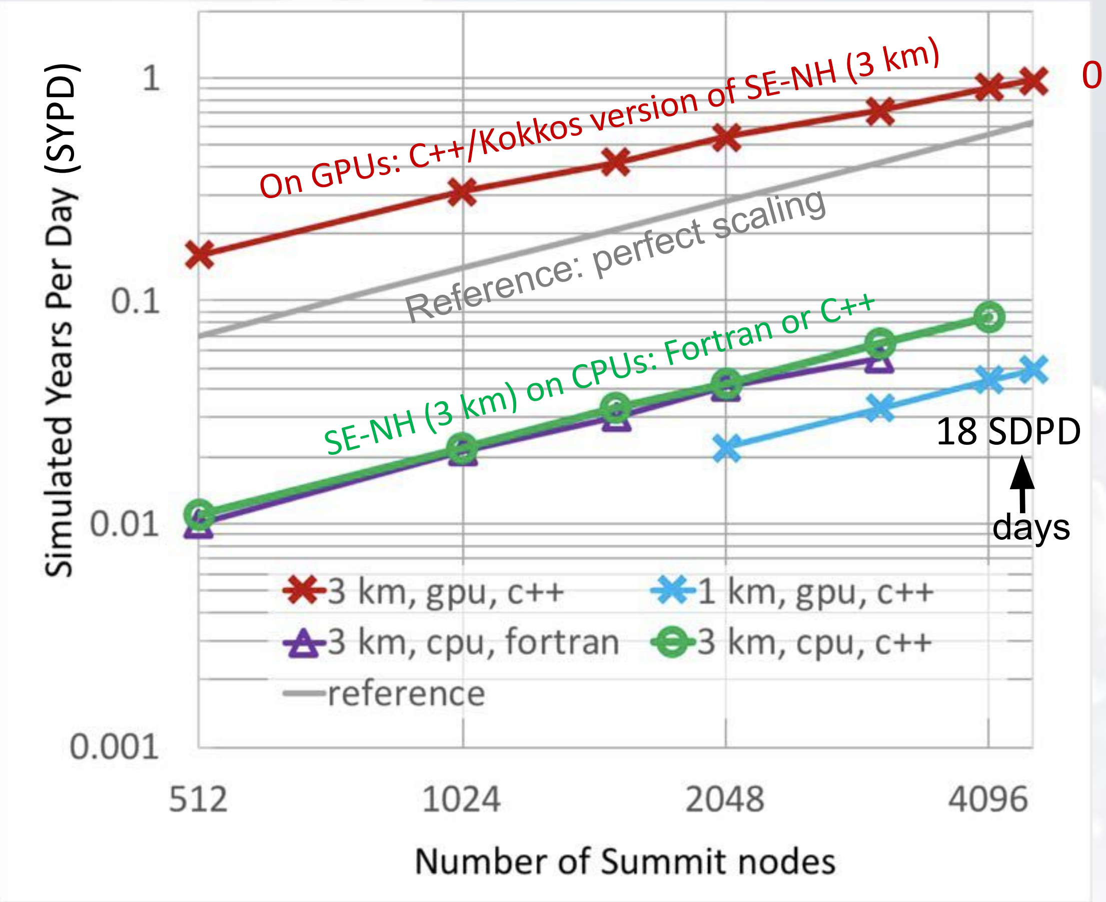
- Different SE design choices at NCAR & DOE: designs have diverged
  - SE-H: Lauritzen et al. (2018)
  - SE-NH: Taylor et al. (2020), hydrostatic switch is provided
- Hydrostatic (H) versus non-hydrostatic (NH) SE with differences in the prognostic variables
- Both H and NH SE work with vertically-Lagrangian coordinates, SE-NH can work with z-based vertical coordinate
- New semi-Lagrangian advection algorithm in SE-NH, SE-H uses the SE method or the CSLAM advection code
- Use of dry (SE-H) versus moist (SE-NH) pressure coordinate in physics
- Leverage opportunity: switch to a deep-atmosphere SE-NH configuration

Open Dynamics/Physics Questions for the KM Scale

- Debatable physics philosophies at the kilometer (km) scale:
  - switch off the **deep convection** parameterization, Freitas et al. (2020) strongly argue against this for the NASA model (DYAMOND simulations)
  - also switch off the **shallow convection** parameterization?: only the Schaer group (ETH Zuerich) does this, see Heim et al. (2023)
- Less controversial: switch off the **gravity wave drag** (GW) parameterization
- Debatable requirements for the vertical resolution: is there a need to decrease Δz with increasing horizontal Δx? If yes by how much?
  - Typical practice: vertical resolution is not scaled with Δx
- Current CAM physics choices & tuning coefficients likely fail to perform at the kilometer scale, is retuning straightforward or are alternative physics needed?

GPUs become a Must for High-Resolutions (3 or 1 km)

- Scaling: Fortran and C++ version **identical scaling/performance on CPUs**
- Performance (simulated model years / wall clock day):
  high throughput at high resolutions (3 km / 1 km) only possible on GPUs



0.97 SYPD using all of DoE's Summit HPC system

GPU software capabilities are needed for CESM to efficiently utilize Derecho and other modern HPC systems

Dynamical core E3SM (Fortran)/SCREAM (C++) performance without physics, no tracer advection, with 3 km and 1 km (blue) grid spacing

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

Parallel Research Activities at U. Michigan: Deep-Atmosphere SE-NH Configuration for E3SM

Idea:

- Develop a deep-atmosphere configuration of SE-NH
- Change the SE-NH dynamical core as little as possible indicated in red (do not change any operators)
- Deep-atmosphere (DA) terms act as corrections
- DA can be easily disabled if not needed

Symbols: $\hat{r} = \dfrac{r}{a} \quad \Pi = \left(\dfrac{p}{p_0}\right)^{R_d/c_p}$

Notation explained in Taylor et al. (2020)

$$\mathbf{u}_\tau + \left(\boxed{\frac{1}{\hat{r}}}\mathrm{HVORT}(\mathbf{u}) + f_s\right)\vec{k} \times \mathbf{u} + \boxed{\frac{1}{2\hat{r}}}\mathrm{HGRAD}(\mathbf{u}^2 + w^2)$$

$$+ \boxed{\frac{1}{\hat{r}}} w\ \mathrm{HGRAD}(w)$$

$$+ \dot{s}\frac{\partial \mathbf{u}}{\partial s} + \frac{\mathbf{u}w}{r} + f_c\begin{pmatrix} w \\ 0 \end{pmatrix} + c_p\theta_v\boxed{\frac{1}{\hat{r}}}\mathrm{HGRAD}(\Pi) + \boxed{\frac{\mu}{\hat{r}}}\mathrm{HGRAD}(\phi) = 0$$

$$w_\tau + \mathbf{u} \cdot \frac{1}{\hat{r}}\mathrm{HGRAD}(w) + \dot{s}\frac{\partial w}{\partial s} - \frac{\mathbf{u}^2}{r} - f_c u + \boxed{g} - \boxed{\mu g} = 0$$

$$\phi_\tau + \mathbf{u} \cdot \boxed{\frac{1}{\hat{r}}}\mathrm{HGRAD}(\phi) + \dot{s}\frac{\partial \phi}{\partial s} - \boxed{gw} = 0$$

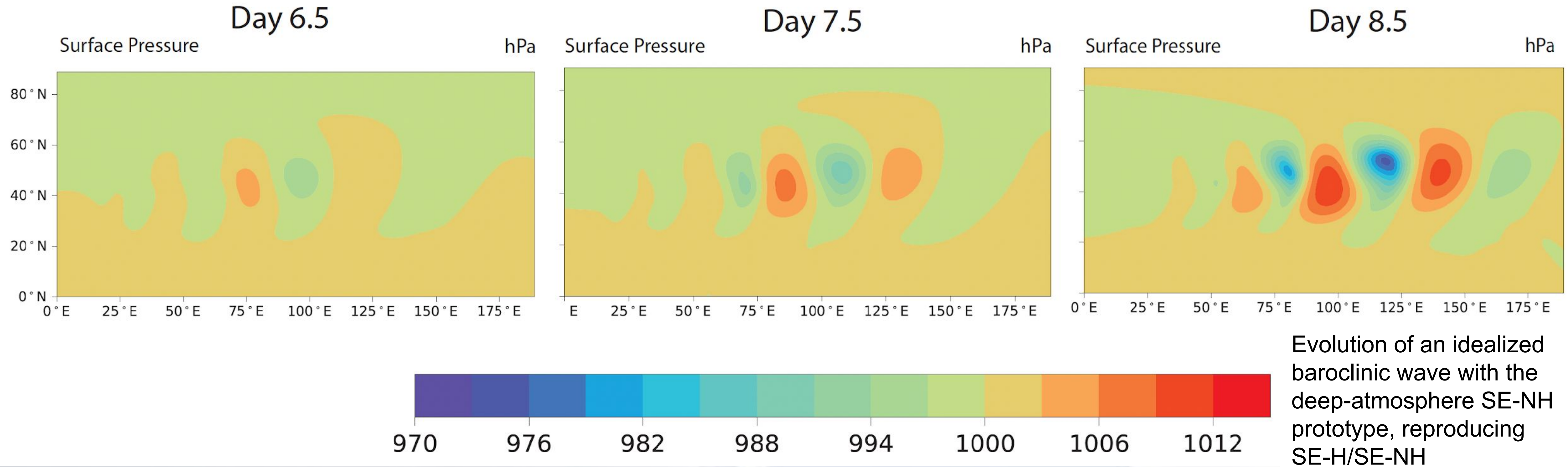
$$\Theta_\tau + \theta_v\mathrm{HDIV}\left(\boxed{\frac{1}{\hat{r}}}\frac{\partial \pi}{\partial s}\mathbf{u}\right) + \boxed{\frac{1}{\hat{r}}}\frac{\partial \pi}{\partial s}\mathbf{u} \cdot \mathrm{HGRAD}(\theta_v) + \frac{\partial}{\partial s}(\Theta\dot{s}) = 0$$

$$\frac{\partial}{\partial t}\left(\frac{\partial \pi}{\partial s}\right) + \mathrm{HDIV}\left(\boxed{\frac{1}{\hat{r}}}\frac{\partial \pi}{\partial s}\mathbf{u}\right) + \frac{\partial}{\partial s}\left(\frac{\partial \pi}{\partial s}\dot{s}\right) = 0$$

$$\frac{\partial}{\partial \tau}\left(q\frac{\partial \pi}{\partial s}\right) + \mathrm{HDIV}\left(\boxed{\frac{1}{\hat{r}}}q\frac{\partial \pi}{\partial s}\mathbf{u}\right) + \frac{\partial}{\partial s}\left(q\frac{\partial \pi}{\partial s}\dot{s}\right) = 0$$

Deep-Atmosphere SE-NH Configuration for E3SM: Transferable to CAM-SE-NH

- Status today: Deep-atmosphere SE-NH dynamical core prototype successfully tested with explicit time-stepping (slow) for an idealized baroclinic wave test case (Ullrich et al., 2014)
- Efforts are under way to update the implicit time-stepping IMEX scheme for the deep atmosphere SE-NH



Evolution of an idealized baroclinic wave with the deep-atmosphere SE-NH prototype, reproducing SE-H/SE-NH shallow-atmosphere

Summary

- Efforts are under way to
  - expand the CAM-SE equations set via non-hydrostatic and deep-atmosphere extensions
  - enable CAM’s SE-NH dynamical core to utilize GPU technology
  - benefit from the model developments conducted by the CSU/NCAR EarthWorks project (GPU readiness of the CESM physics) and DoE

- Science exemplars will be used to demonstrate CAM/CESM’s scientific capabilities at the kilometer scale (variable-resolution and 3 km global)
  - with a focus on MCSs over the CONUS domain and air-sea interactions
  - short seasonal or DYAMOND-like (40-day) initialized simulations in both AMIP and coupled mode (10 km ocean, likely POP, if possible MOM6)

- Stay tuned for actual science results (future CESM/AMWG meetings)

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