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COUPLING PHYSICAL PARAMETERIZATIONS TO A THREE-DIMENSIONAL SEM MODEL

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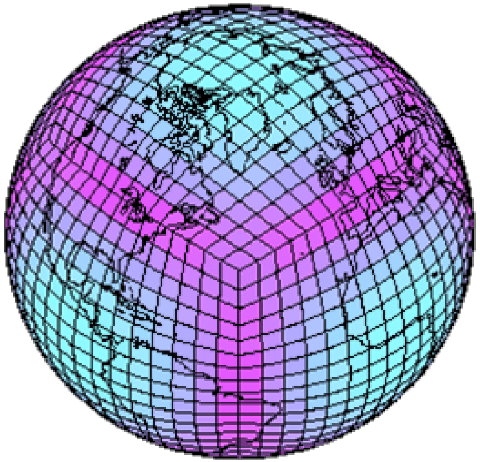
Outline

1. NEPTUNE Overview
2. Idealized physics simulation (DCMIP)
3. Real-data, full physics testing
4. Physics dynamics coupling

NEPTUNE

- [1]NEPTUNE – Future NWP for U.S. Navy
  - Non-hydrostatic, deep atmosphere formulation
  - 3D spectral element technique (high-order accurate)
  - 1D Implicit-Explicit (IMEX) 3rd-order Additive Runga Kutta (ARK3) time integration
- Flexible limited area and global grid options
  - Sphere-centered Cartesian coordinate system on the cubed sphere for global applications
  - Cartesian coordinate system for limited area applications

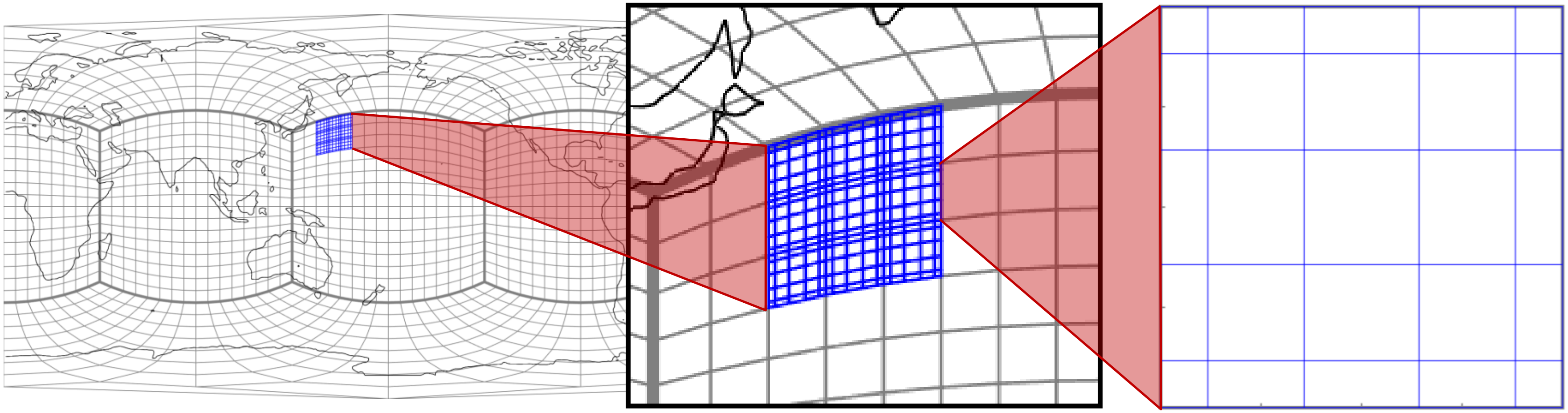


[1]***NEPTUNE:*** *__N__avy __E__nvironmental __P__rediction sys__T__em __U__tilizing the __N__UMA*[2] *__E__ngine*
[2]***NUMA****:* *__N__onhydrostatic __U__nified __M__odel of the __A__tmosphere (F. Giraldo NPS)*

NEPTUNE Dynamical Core

Spectral Element Formulation

- Solution is represented by a set of orthogonal polynomial basis functions
  - High-order accuracy with excellent computation density and scalability
  - Projects well onto next-generation computer architectures
- Orthogonality implies that solution is known at the roots of the polynomial basis functions. Irregularly spaced in the horizontal and vertical.
  - Physics implementation on irregular gird – doesn’t seem to be an issue
  - Potential to extract additional information from basis functions for physics



[1]***NEPTUNE*: *N*avy *E*nvironmental *P*rediction sys*T*em *U*tilizing the *N*UMA[2] cor*E***

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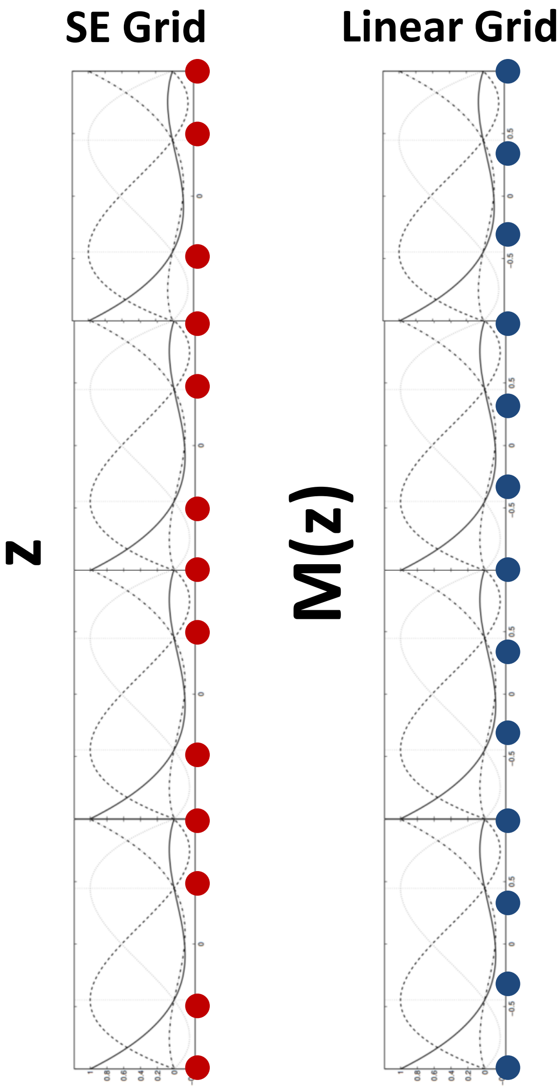
NEPTUNE AND IDEALIZED MOIST PHYSICS (DCMIP)

DCMIP Idealized Test Cases



- DCMIP*: June 2016 at NCAR
  - Evaluate NH dynamical cores with idealized moist physics test problems
- Three tests:
  - Moist Baroclinic Wave (parameterized convection)
  - Ideal Tropical Cyclone (parameterized convection, parameterized BL, simple saturation adjustment)
  - Supercell on a reduced radius sphere (Kessler MP)
- Questions for NEPTUNE:
  - What is the sensitivity of model solution to the representation of the vertical coordinate?
  - Can we map our vertical coordinate to a regularly spaced vertical grid?

*Ullrich et al, 2017. DCMIP2016: A Review of Non-hydrostatic Dynamical Core Design and Intercomparison of Participating Models. GMD, in press.

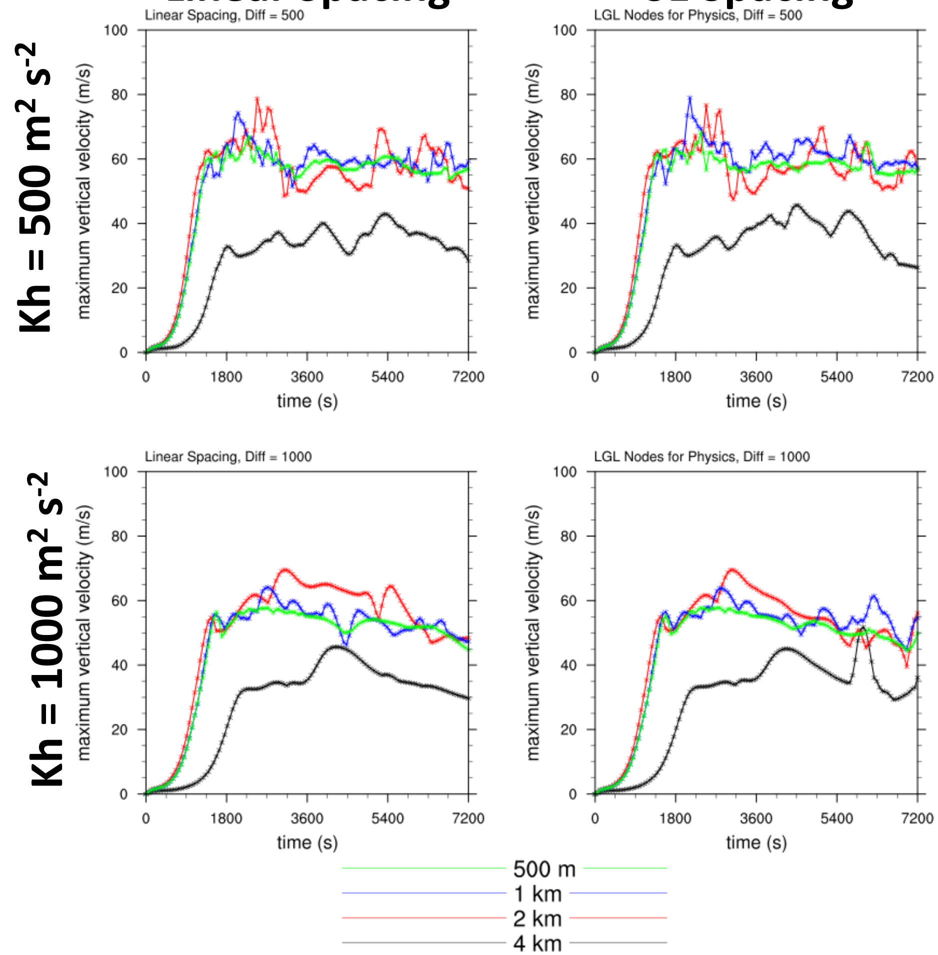
DCMIP Supercell test case

- Reduced radius sphere
- Buoyant parcel in unstable sheared environment
- Kessler microphysics, constant mixing
- Relies on explicitly resolved convection
- Run at 4, 2, 1, 0.5km horizontal spacing
- Figure shows NEPTUNE maximum vertical velocity at all resolutions for 4 potential physics grid configurations

Maximum Vertical Velocity

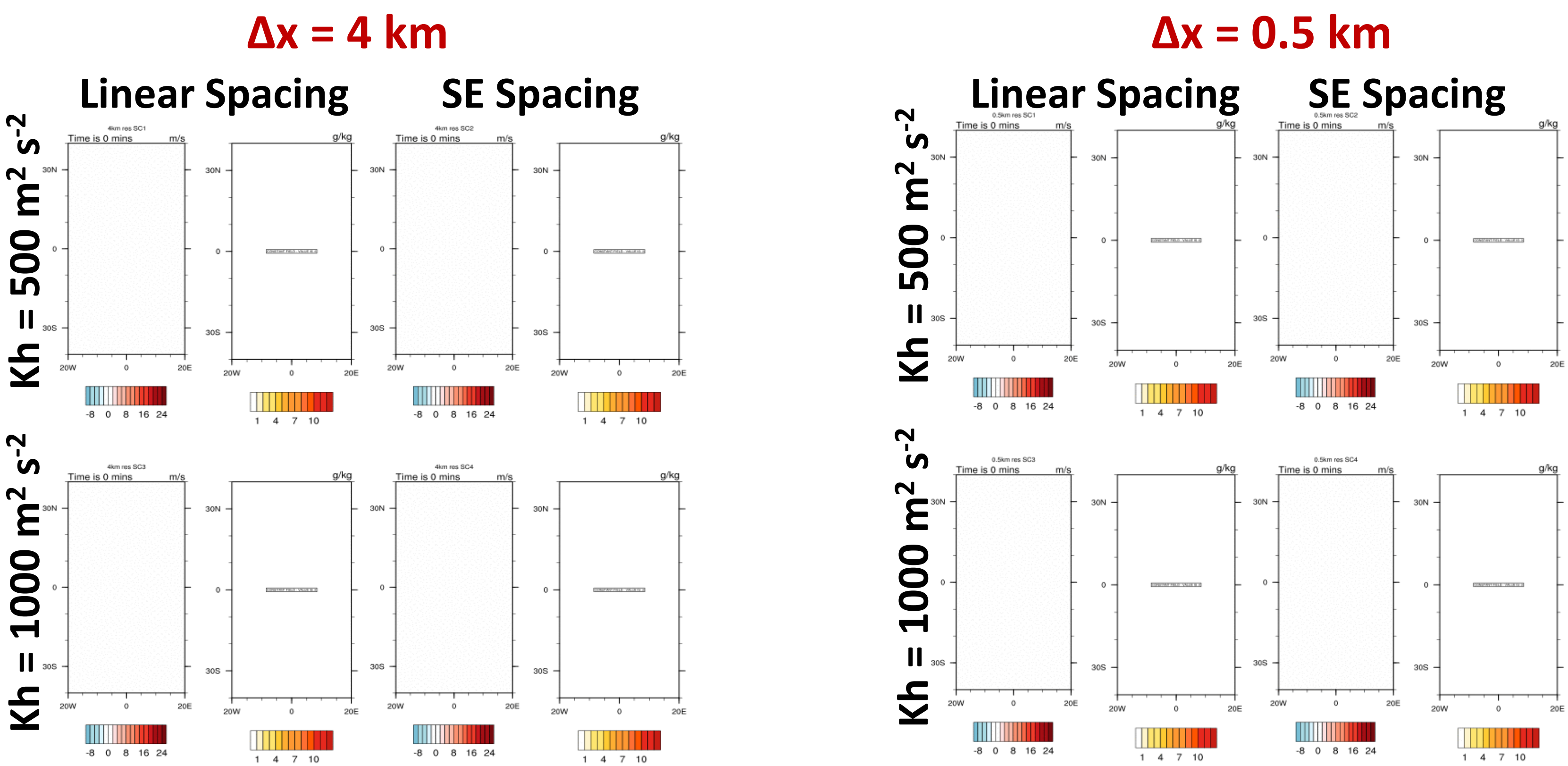
Linear Spacing

SE Spacing



DCMIP Supercell test case

- Comparison of 5km vertical velocity and cloud water mixing ratio for 4km (left) and 0.5km (right) horizontal grid spacing for 4 potential physics grid configurations
- Note significant change in structure from better resolved convection



INITIAL IMPLEMENTATION WITH GFS PHYSICS

Physics in NEPTUNE

Coupling to GFS

- To expedite NEPTUNE development, we implement physics suites using an interoperable physics driver (IPD)
  - IPD allows different centers to share common physics suites using a standardized interface
  - Standardization allows testing between dynamical cores using common physics
- Use IPD to implement GFS hydrostatic physics suite into NEPTUNE
  - Advantages: Quick access to a fully developed NWP physics suite
  - Disadvantage: IPDv4 does not allow tailoring of the suite
  - Questions remain: Is it possible to use a generic physics suite without customization to a specific dynamical core?

GFS Physics

Sequential Split/First Order Coupling

- GFS physics is run as a sequential process and split from the dynamics time step
  - Tendencies are added as N forward Euler time steps

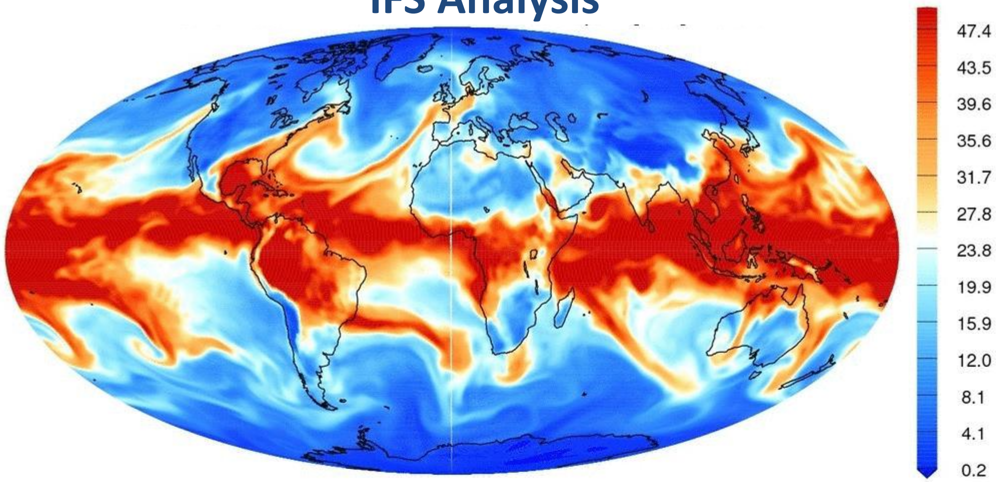
$$
\begin{aligned}
q_0 &= D(q^n) \\
q_1 &= q_0 + \Delta t \cdot P_1(q_0) \\
q_i &= q_{i-1} + \Delta t \cdot P_i(q_{i-1}) \\
&\vdots \\
q^{n+1} &= q_{N-1} + \Delta t \cdot P_N(q_{N-1})
\end{aligned}
$$

- Geopotential heights are adjusted due to heating after each forward step
  - Consistent with hydrostatic dynamics

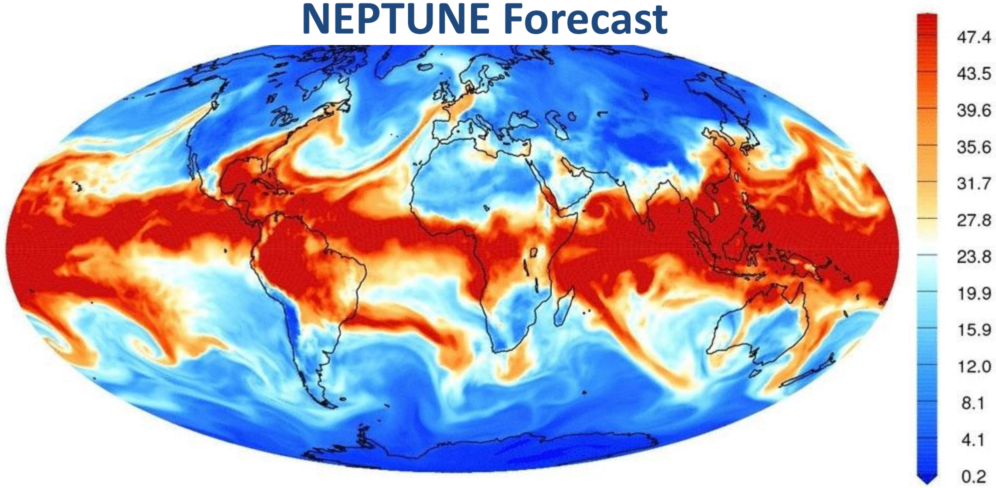
Initial Full Physics Implementation

Real data run comparison – TPW

IFS Analysis



NEPTUNE Forecast



- First step: Initialize with GFS initial conditions and evaluate forecasts against IFS analysis
- Relatively coarse resolution initial tests ~49 km
- Qualitative evaluation as a gross check on physics implementation

Initial Full Physics Implementation

Real data run comparison – Convective Precipitation

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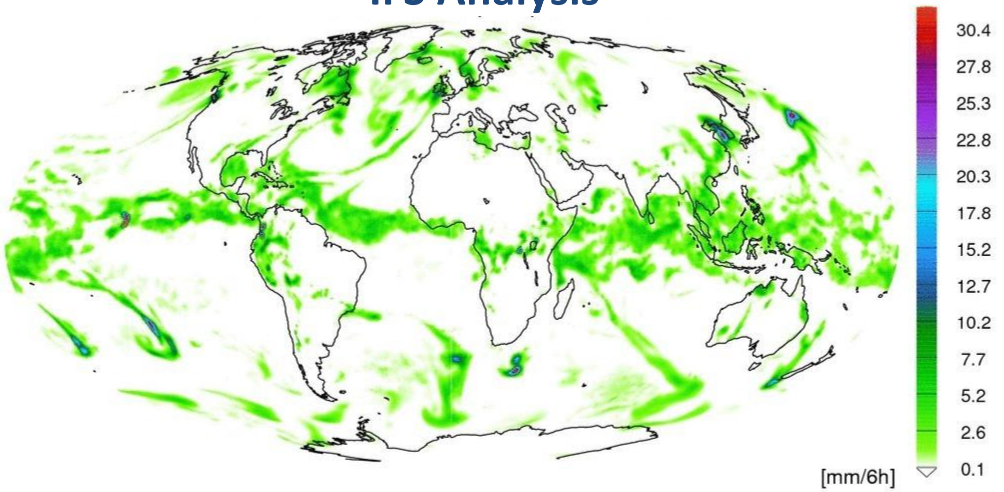
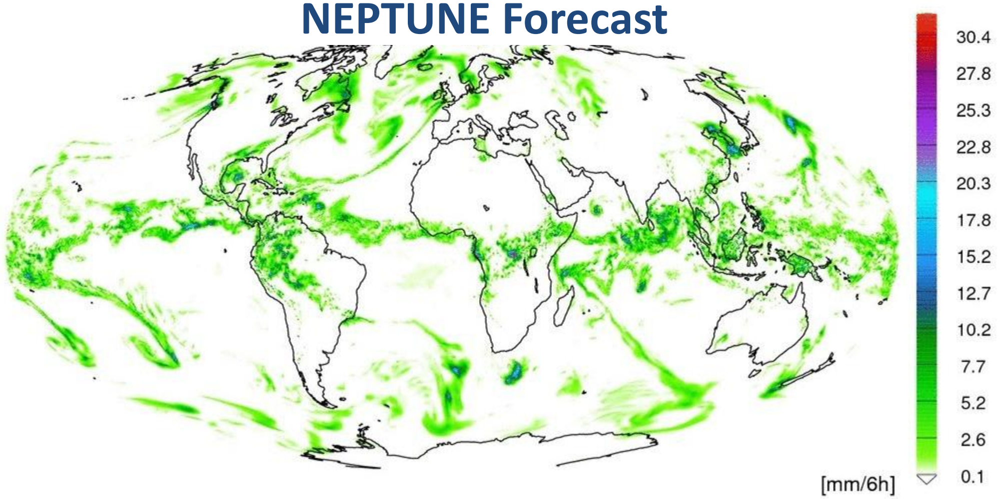
IFS Analysis



NEPTUNE Forecast

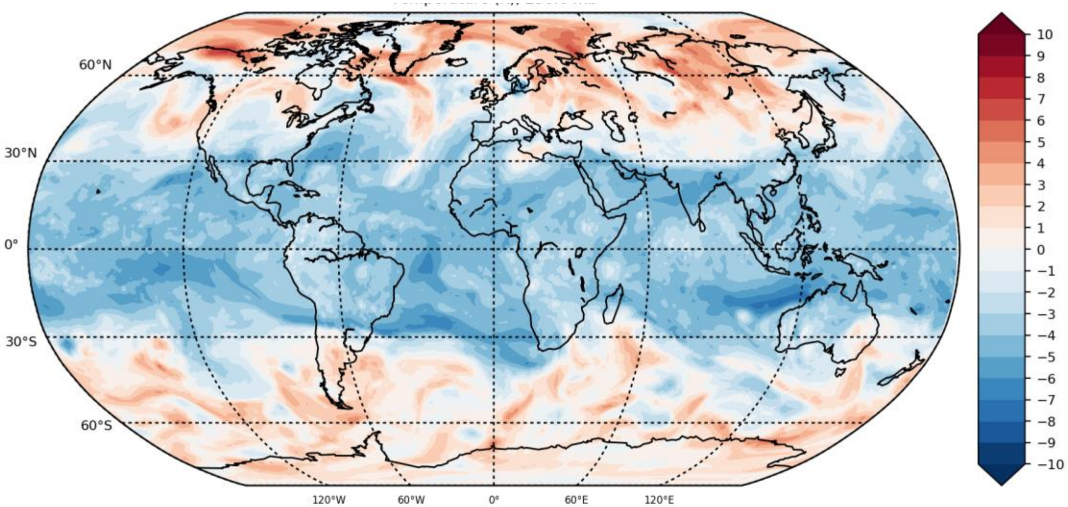


- First step: Initialize with GFS initial conditions and evaluate forecasts against IFS analysis
- Relatively coarse resolution initial tests ~49 km
- Qualitative evaluation as a gross check on physics implementation
- Parameterized convective precipitation along ITCZ and mid-latitude cyclones

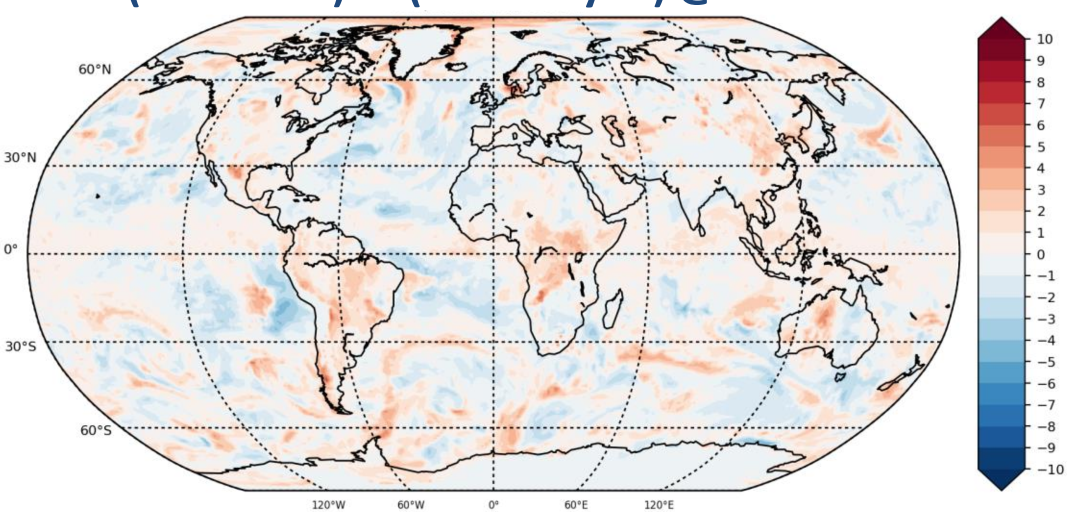
Initial Full Physics Implementation

Large Temperature Trends

T(NEPTUNE) - T(IFS Analysis) @ 250 hPa



T(NEPTUNE) - T(IFS Analysis) @ 850 hPa

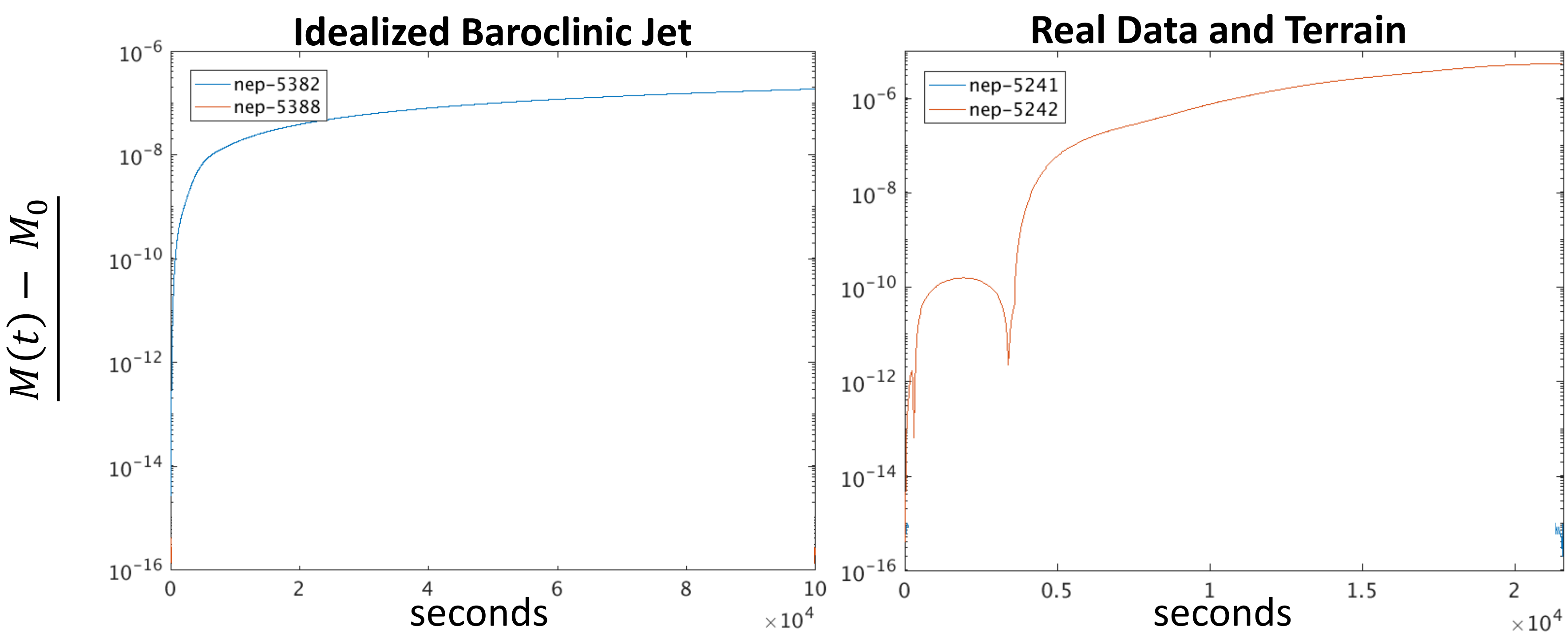


- Rapid and substantial cooling of NEPTUNE temperatures
- ΔT of 5-10 degrees in 24-48 h forecast relative to IFS
- Not clear if it was a physics, dynamics, or physics-dynamics coupling issue

Dry Mass Loss in NEPTUNE

Relative Mass Change

- NEPTUNE was not conserving dry mass loss in dynamics
- Two main issues were identified and fixed
  - Application of the lower boundary in the presence of terrain for 3D spectral elements
  - Use of Cartesian winds instead of contravariant winds in elements



PHYSICS DYNAMICS COUPLING AND THE GREYZONE

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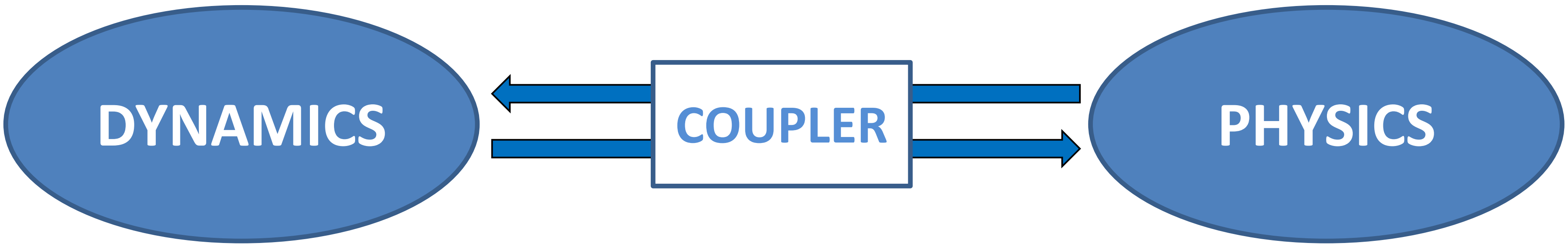
Grey Zone Physics

Hydrostatic Physics in a NH model

- NEPTUNE is non-hydrostatic with isochoric coordinate system
  - Designed for multi-scale simulation with global and limited area applications
- GFS physics package is hydrostatic with an isobaric pressure coordinate
  - Targets synoptic to sub-synoptic hydrostatic scales
- What should we think about when coupling the two?
  - Incompatibilities between hydrostatic physics and non-hydrostatic dynamical core?
  - Can the spectral elements be exploited?

Physics Dynamics Coupling

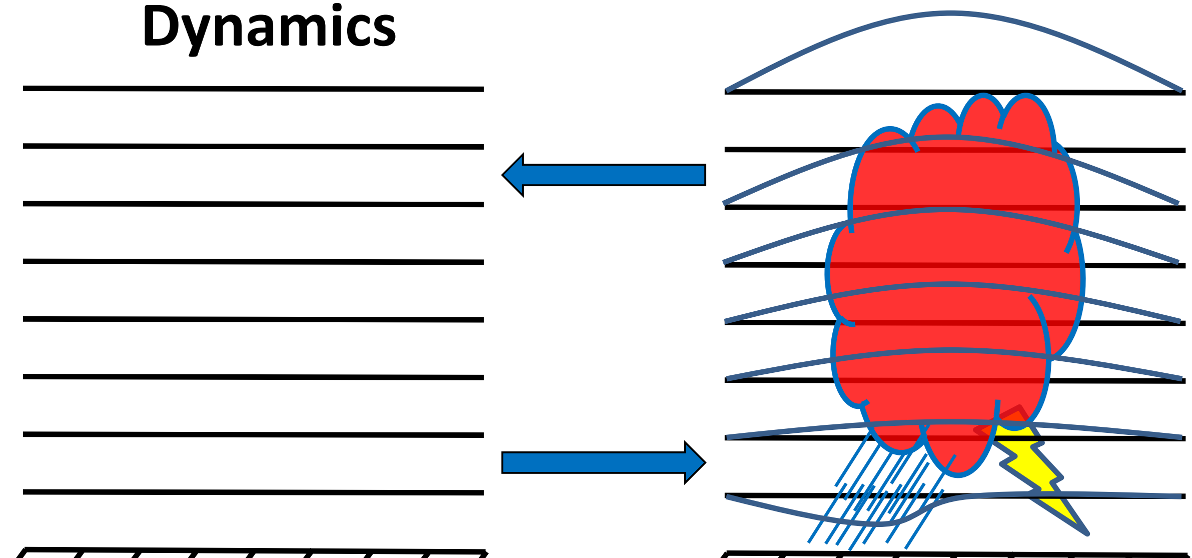
Hydrostatic Physics/Non-hydrostatic Dynamics



Consideration when coupling a non-hydrostatic model to a hydrostatic physics package

Non-hydrostatic Dynamics

Hydrostatic Physics



Isochoric Process
$\theta - \rho$

Isobaric Process
$T - \phi$

- Global physics make isobaric and hydrostatic assumptions
- Diabatic heating/cooling modifies geopotential heights through hydrostatic balance
- Physics tendencies of $T - \phi$ on isobaric surface need to map to $\theta - \rho$ increments on isochoric dynamics surfaces

*GFS/IFS/NAVGEM Physics

Physics-Dynamics Coupling

Two Experiments

C **Control**: Given isobaric physics adjustment and T increment, update θ directly back to model levels

A **Adjustment**: Given $\Delta\phi$ and T increment, compute updated θ/ρ on dynamics grid by hydrostatically adjusting pressure back to the constant height dynamics levels

B **Adjustment**: Given $\Delta\phi$ and T increment, linear interpolate all physics increments back to the constant height dynamics levels

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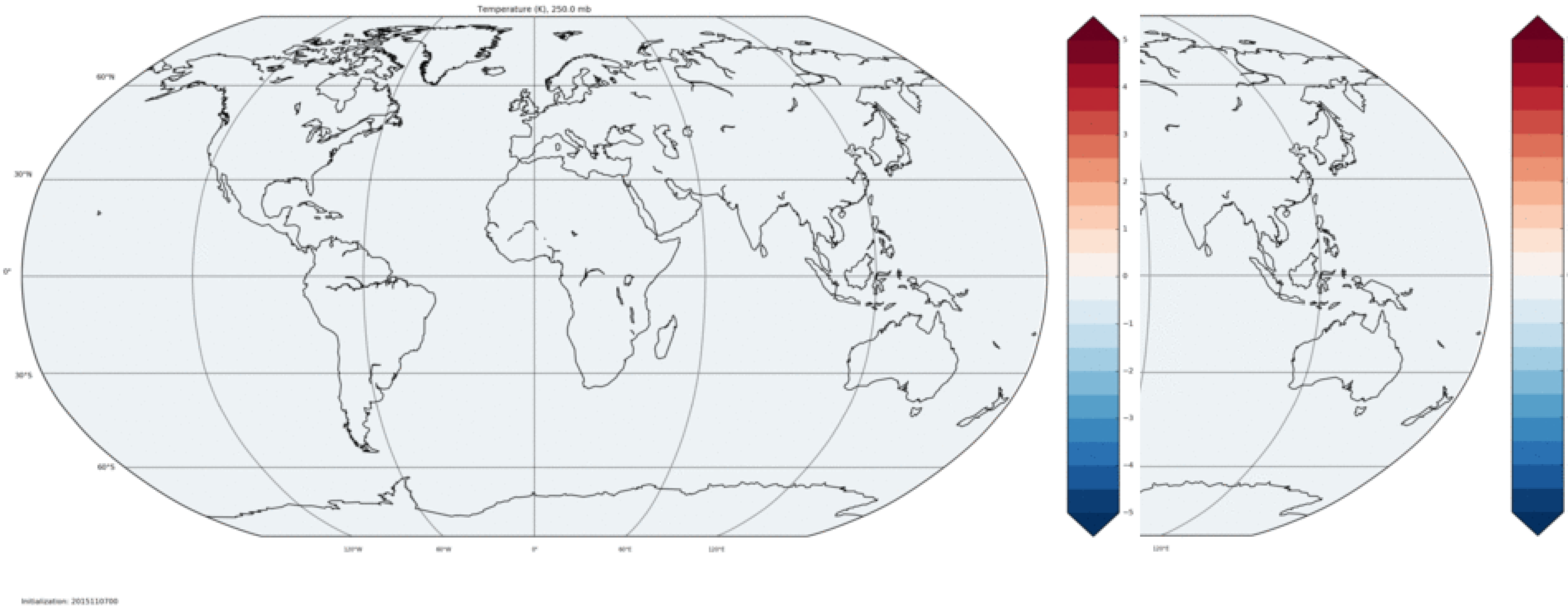
$\Delta\theta$ due Hydrostatic Adjustment

48-h NEPTUNE forecast

A – C

200 hPa　　850 hPa



- NEPTUNE E96P3L64 (~33 km average nodal spacing) forecast
- Most significant differences in tropical upper troposphere
- Large differences associated with deep convection in tropics

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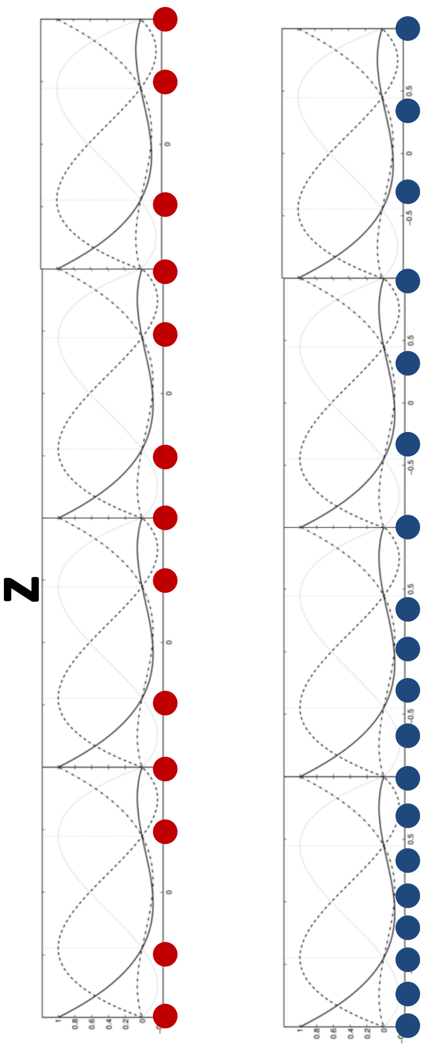
SE Coordinate

Implications for Physics



- SE vertical coordinate is unique in NEPTUNE. Can we exploit it?
- Solution represented by orthogonal polynomial basis
  - Natural to run physics at quadrature/nodal points
  - For 3rd-degree polynomials, negligible sensitivity in physics to non-uniform spacing of the quadrature points
- Physics sees the input as a piecewise linear function
  - Gauss-Legendre polynomial space is much richer than a piecewise linear function of the nodal points
  - Resolution of the GL polynomial space is higher than that suggested by the nodal spacing*
- Can we increase the vertical and horizontal grid spacing so that the linear representation is consistent with the polynomial basis?
  - How does this relate to the greyzone?

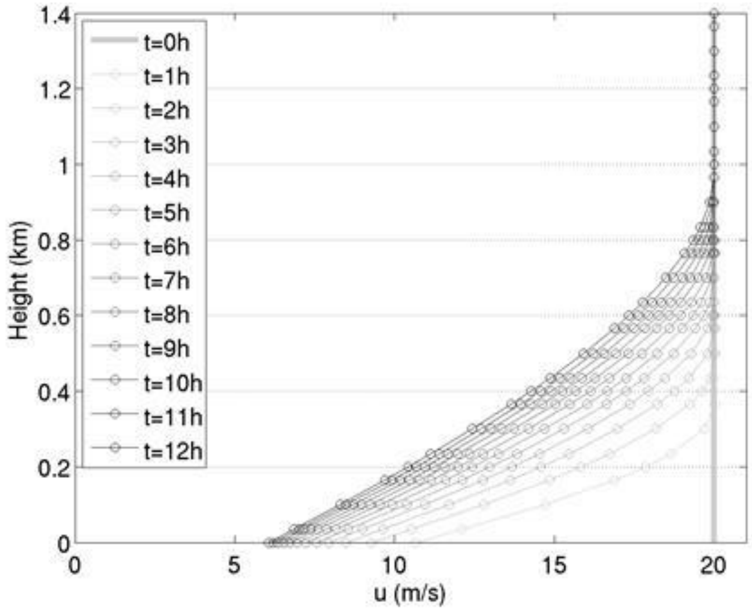
*Karamanos, G.-S., S. J. Sherwin, J. F. Morrison, 1999: Large Eddy Simulation Using Unstructured Spectral/HP elements. *Recent Advances in DNS and LES*, **54**, 245-256.

Physics-Dynamics Coupling

- How to blend existing physics packages and the spectral element numerical framework?

- Fast processes, such as mixing, should be consistent and tightly coupled with the dynamics

$$q_d = D(q^n) + P_F(q^n)$$
$$q^{n+1} = q_d + P_s(q_d)$$



- To be consistent with the dynamics, the spectral element numerics should be used to compute derivatives and inversions within the physics routines.
  - Which parameterizations, if any is this true for?

Summary

- Development of NEPTUNE continues at NRL
  - Evaluating the system with NWP physics suites
  - Unanswered questions on the best way to couple physics to a non-hydrostatic spectral element dynamical core
- SE methods offer a unique opportunity to explore the greyzone and physics-dynamics coupling issues
  - Parameterizations may need to account for and adjust to high-order numerics
  - The rich polynomial basis can potentially be used to improve the grid point representation in the parameterizations