Development and Evaluation of the NEPTUNE Prediction System

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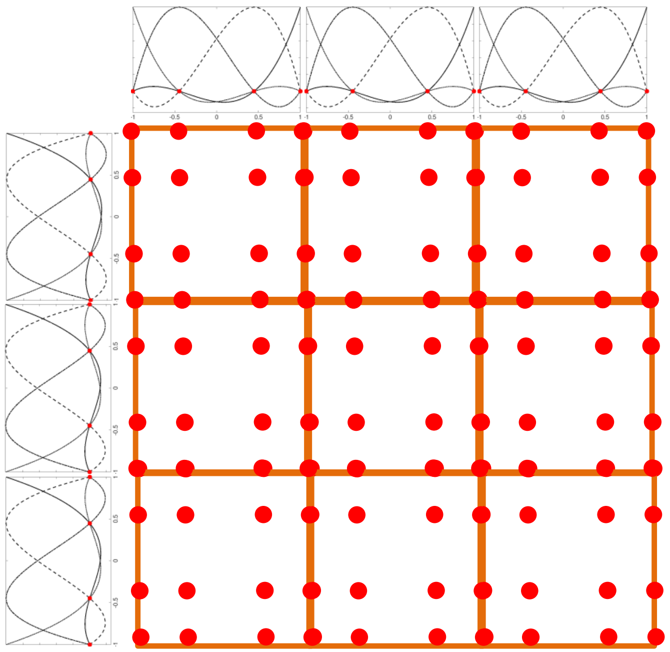
32nd Conference on Weather Analysis and Forecasting (WAF); 28th Conference on Numerical Weather Prediction (NWP); 20th Conference on Mesoscale Processes

NEPTUNE Overview

- NEPTUNE Navy Next-Generation System
  - Goal is to modernize and unify Navy NWP systems and address future exascale computational challenges
- Numerics and Time Integration:
  - Numerical solution is represented by a local polynomial expansion with **excellent computational scaling**
  - Three-dimensional **spectral element spatial discretization** on a cubed sphere
  - User determined order of accuracy (4^{th}-order default, experimenting with 6^{th}-order).
  - **H**orizontally **E**xplicit-**V**ertically **I**mplicit (HEVI) Runge-Kutta time integration scheme
  - Implicit vertical acoustic, gravitational, and advective modes. Continuous or discontinuous Galerkin tracer transport
- NEPTUNE Dynamics:
  - Fully compressible, **deep atmosphere**, **nonhydrostatic** equation set
  - **Global**, **limited area**, and **high altitude** configurations
  - Two options for the thermodynamic variable:
    - Potential Temperature for tropospheric applications
    - Internal Kinetic Energy for high-altitude applications
- NEPTUNE Physics:
  - **Common Community Physics Package** (CCPPv6)
- Coupling:
  - ESMF/NUOPC enabled component for coupling and asynchronous I/O
- NEPTUNE Data Assimilation:
  - **JEDI Infrastructure** – 3Dvar transition target with follow on Hybrid 4D-Var
  - Spectral Element Tangent Linear and Adjoint models



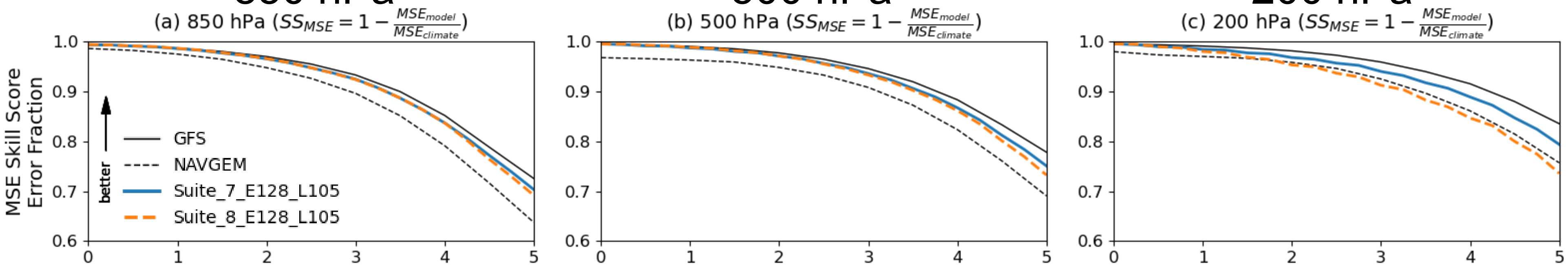
Forecast Statistics

Geopotential Height Skill Scores

Suite 7	Suite 8
Thompson	Thompson
MYNN-EDMF	MYNN-EDMF
MYNN	MYNN
Tiedtke	SAS
Tiedtke	SAS
RRTMG	RRTMG
CIRES uGWPv0	CIRES uGWPv0
Noah MP	Noah MP
GFS NSST	GFS NSST

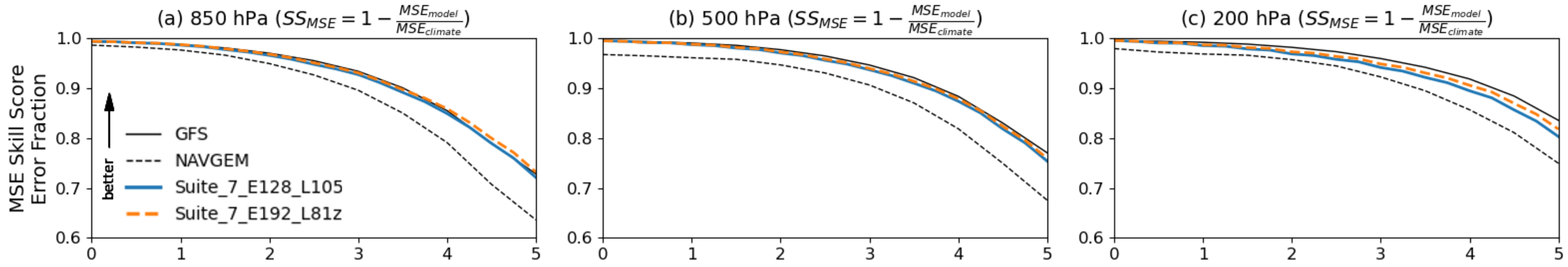
Suite 7 vs. Suite 8 (13 km)

850 hPa 500 hPa 200 hPa



Suite 7: 9 km vs. 13 km

850 hPa 500 hPa 200 hPa



- NEPTUNE 5-day forecast skill using the Suite 7 Physics is overall on par with the GFS operational forecasts
- NEPTUNE 9-km (E192L81) forecasts have slightly improved skill relative to the 13-km resolution (E128L105)

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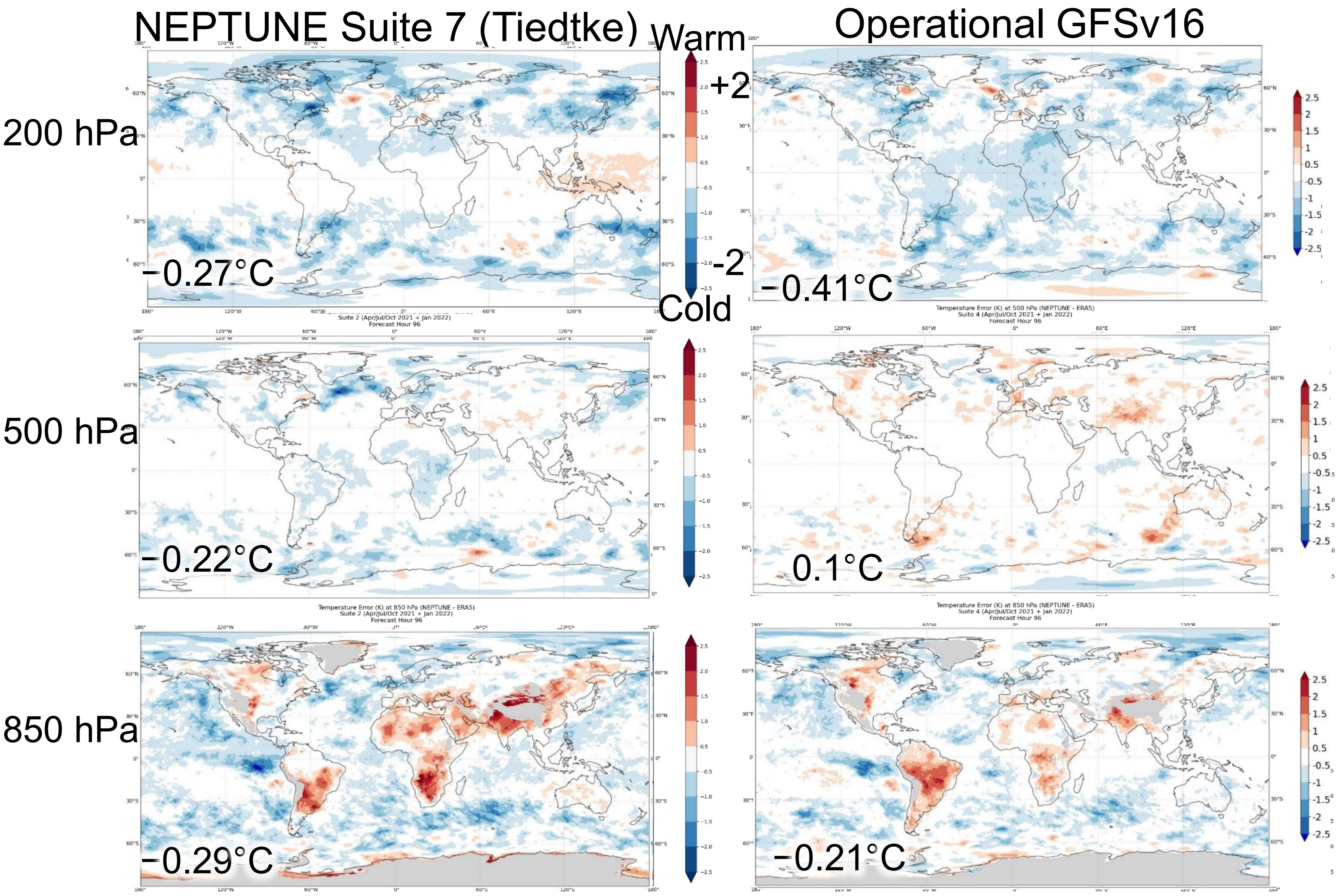
Forecast Temperature Bias

Temperature Bias (96-h Forecast Verified with ERA5 Reanalysis)

- 96-h temperature bias for Apr/Jul/Oct/Jan 2021-22 (GFS cold starts, verified with ERA5)
- E128 (dx~13 km), 105 levels,

- Suite 7 has lowest temperature biases (200 hPa and 500 hPa)
- 850 hPa bias colder over the water in Suite 7 than Suite 8
- Warm bias: SA, Africa, Asia
- Bias grows rapidly in 0-24-h and little growth beyond (24-120h)



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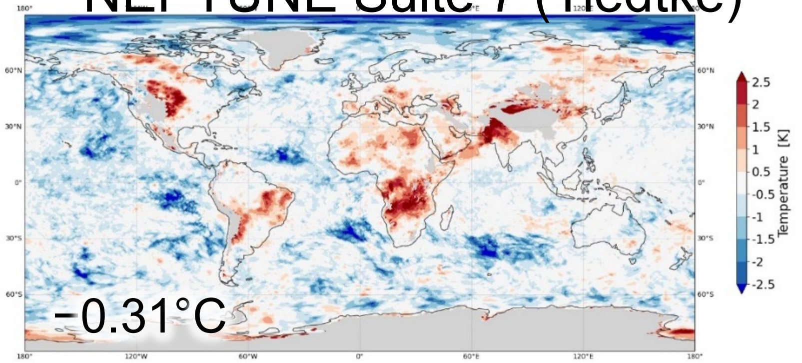
Forecast Temperature Bias

850-hPa Temperature Bias (24-h Forecast Verified with ERA5 Reanalysis)

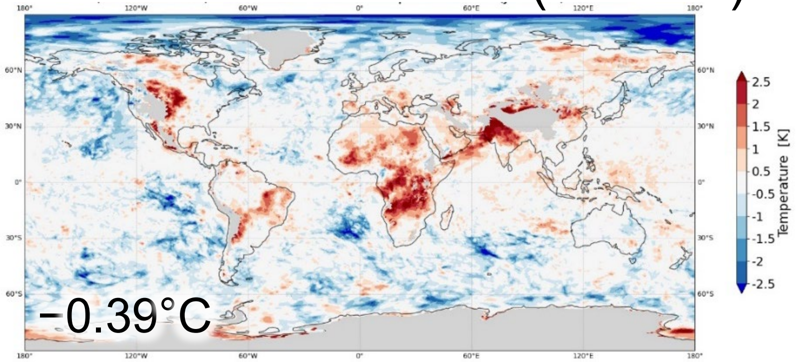
- 24-h temperature bias for 6 July 2021 cases (GFS cold starts, verified using ERA5)
- E128 (dx~13 km), 105 levels
- Similar low-level cold biases over maritime regions and warm continental biases
- NEPTUNE has no implicit numerical diffusion and uses light background diffusion. Stability issues with Suite p8.

	Suite 7 Control	Suite 8	Suite p8 GFS_v17_p8
Microphysics	Thompson	Thompson	Thompson
PBL and Turbulence	MYNN-EDMF	MYNN-EDMF	TKE EDMF
Surface Layer	MYNN	MYNN	GFS
Deep Convection	Tiedtke	sa-SAS	sa-SAS
Shallow Convection	Tiedtke	sa-SAS	sa-SAS
Radiation	RRTMG	RRTMG	RRTMG
Gravity Wave Drag	CIRES uGWPv0	CIRES uGWPv0	GFS uGWP
Land Surface Model	Noah MP	Noah MP	Noah MP
Ocean	GFS NSST	GFS NSST	GFS NSST

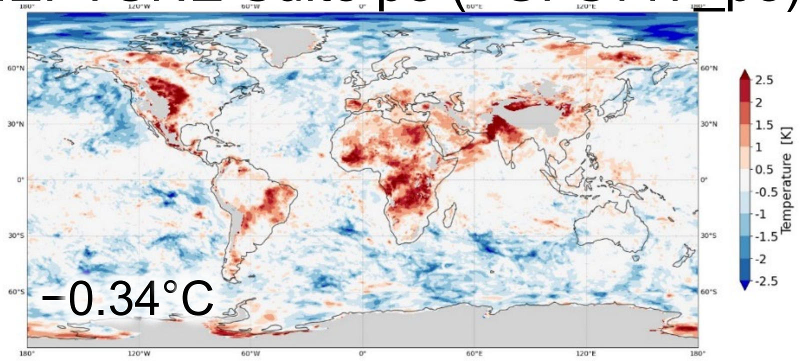
NEPTUNE Suite 7 (Tiedtke)



NEPTUNE Suite 8 (sa-SAS)

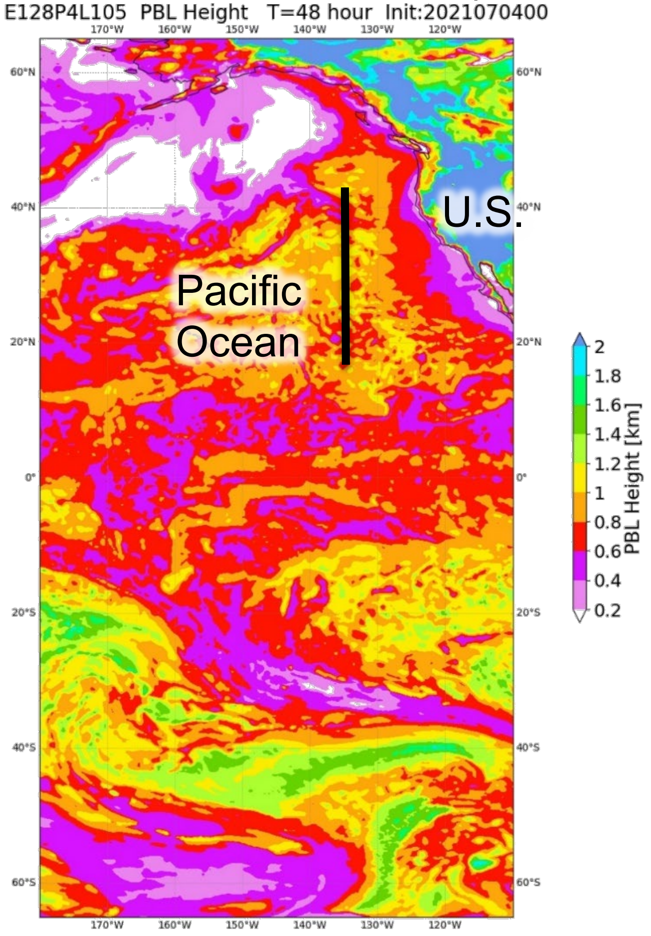


NEPTUNE Suite p8 (~GFSv17_p8)

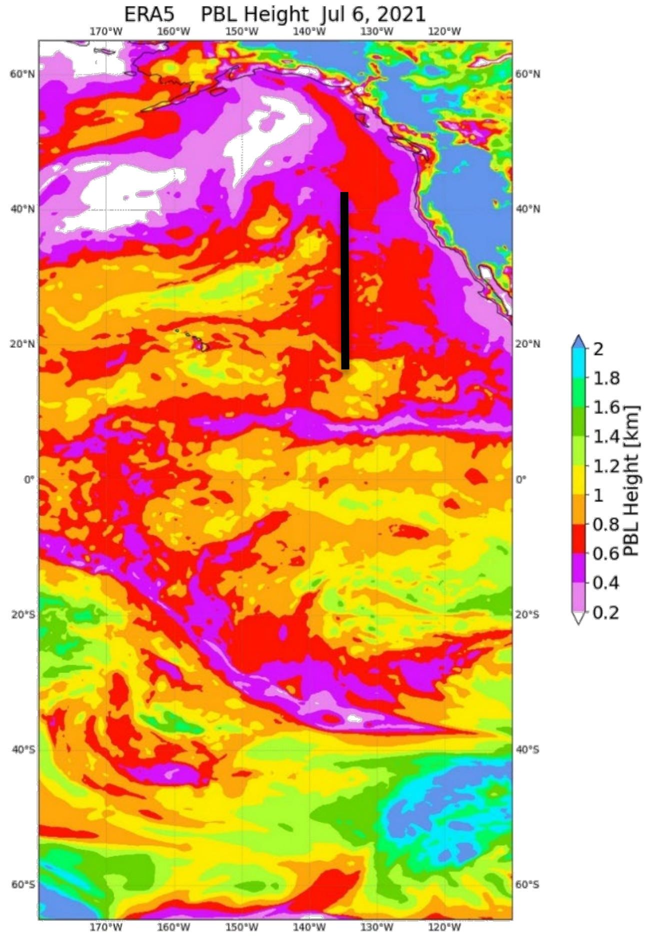


Boundary Layer Prediction

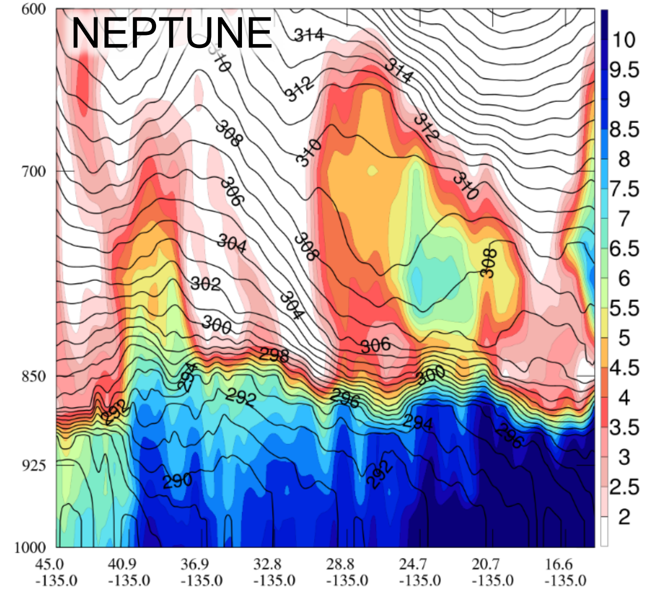
48-h NEPTUNE E128 (13.5 km)

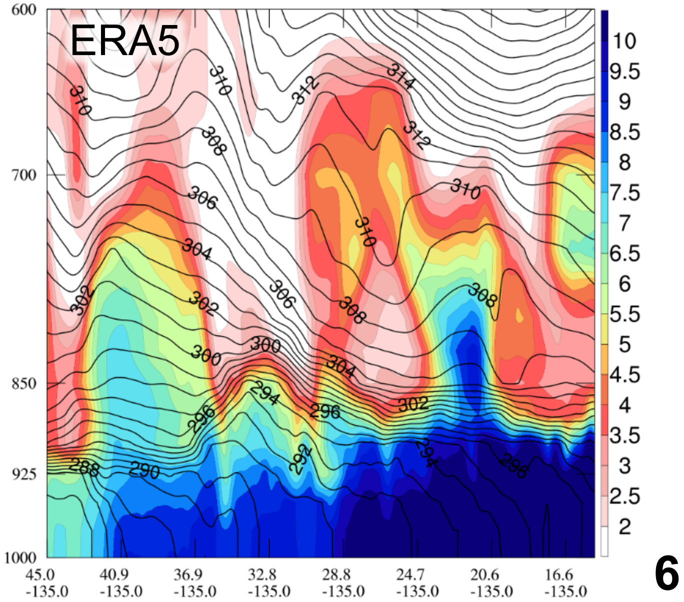


ERA5 (31 km)



Potential Temperature, Water Vapor





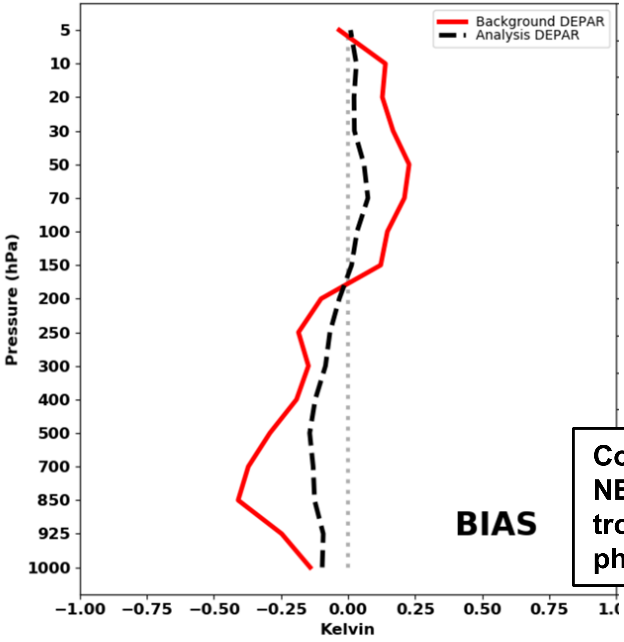
- Preliminary analysis of NEPTUNE boundary layer characteristics using Suite 7 compare favorably with reanalyses (ERA5)
- Next steps: analyze more forecasts and compare with reanalysis and obs

Data Assimilation

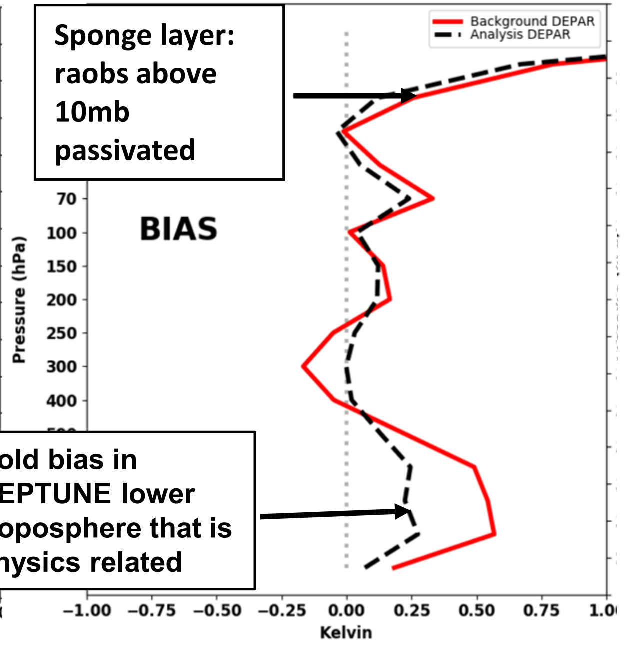
JCSDA JEDI DA Cycling Tests

Development: DA and Model improvement

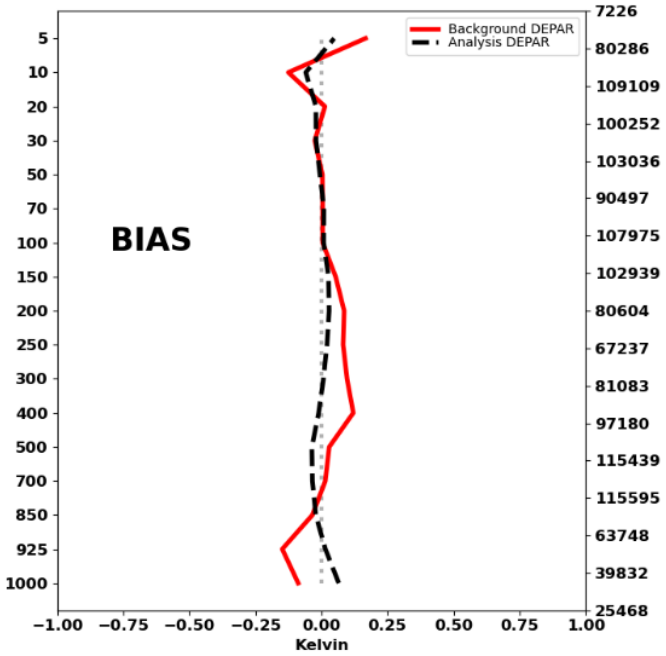
NAVGEM: 30 day average raob global temperature bias (ending on 2021011512)



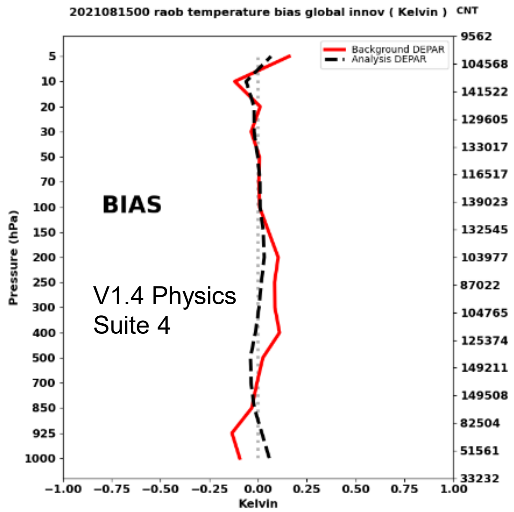
NEPTUNE v1.2: 30 day average raob global temperature bias (ending on 2021011512)

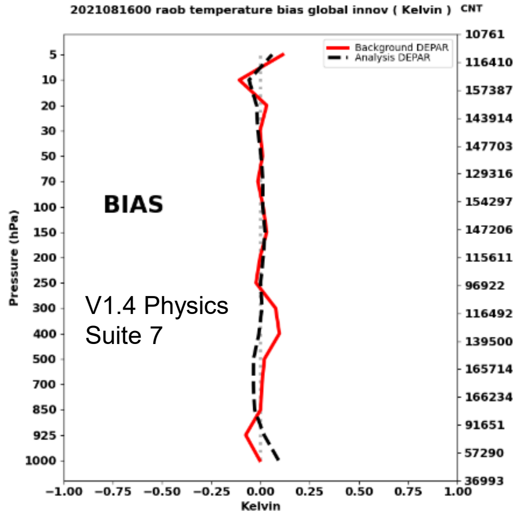


NEPTUNE v1.3.2: 14 day average raob global temperature bias (ending on 2021082000)



NEPTUNE v1.4 initial testing:
10 day average raob global temperature bias
(ending on 2021081600)





— Observation minus forecast
---- Observation minus analysis

Radiosonde bias and standard deviation are comparable magnitude to NAVDAS-AR

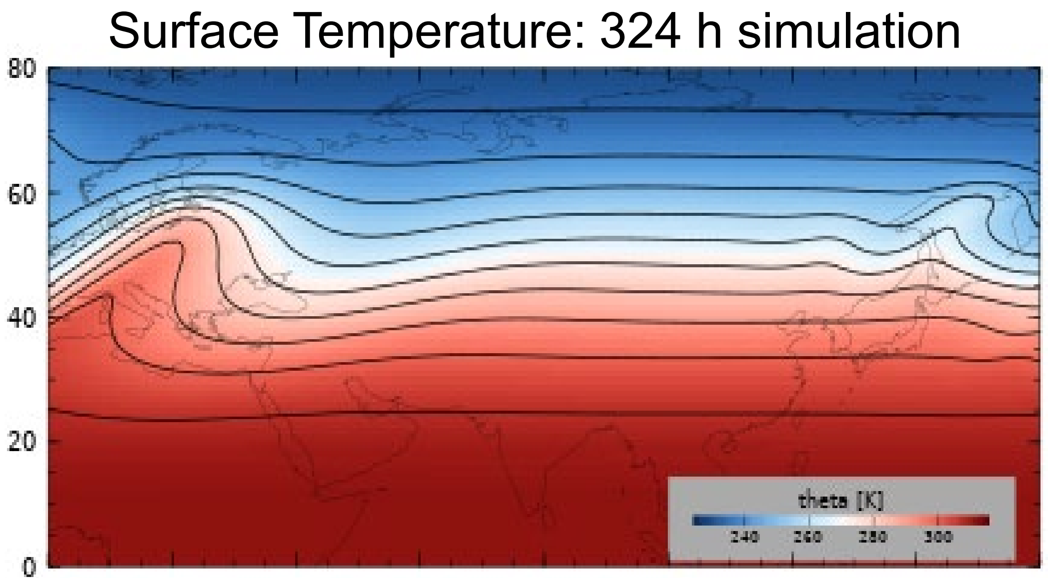
NEPTUNE Adjoint Development

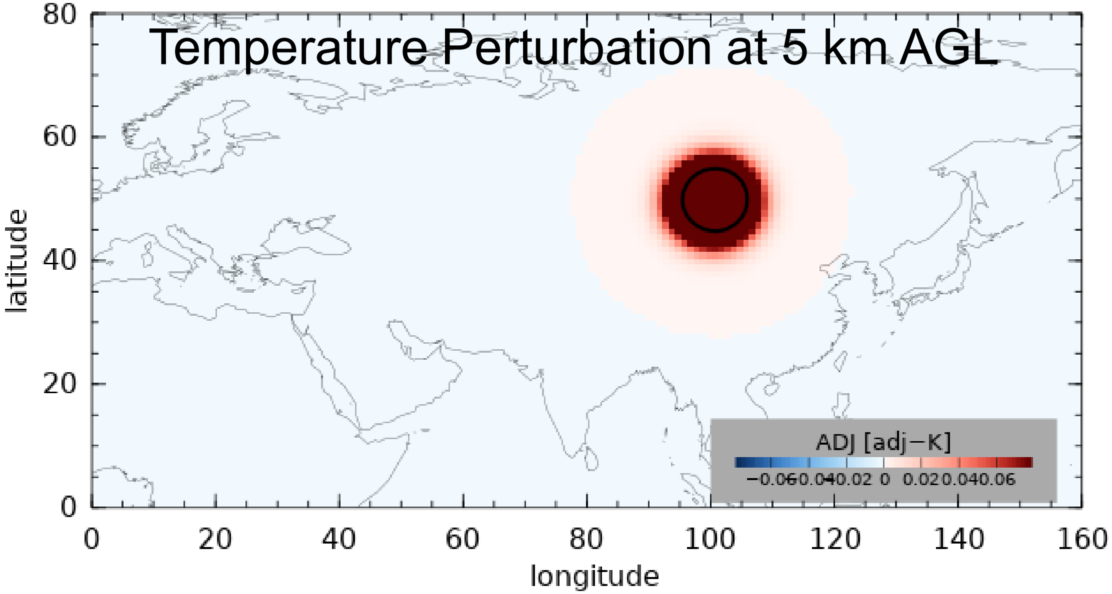
Development of the NEPTUNE TLM and Adjoint
- Hybrid 4DVar DA
- Sensitivity studies
- NEPTUNE TLM and adjoint for dry dynamics complete, developing simplified physics TLM/ADJ

TLM testing:
- Compare TLM to a perturbed run of the non-linear model
- Use unstable baroclinic wave test case, perturb model after day 10, evolve perturbation in TLM

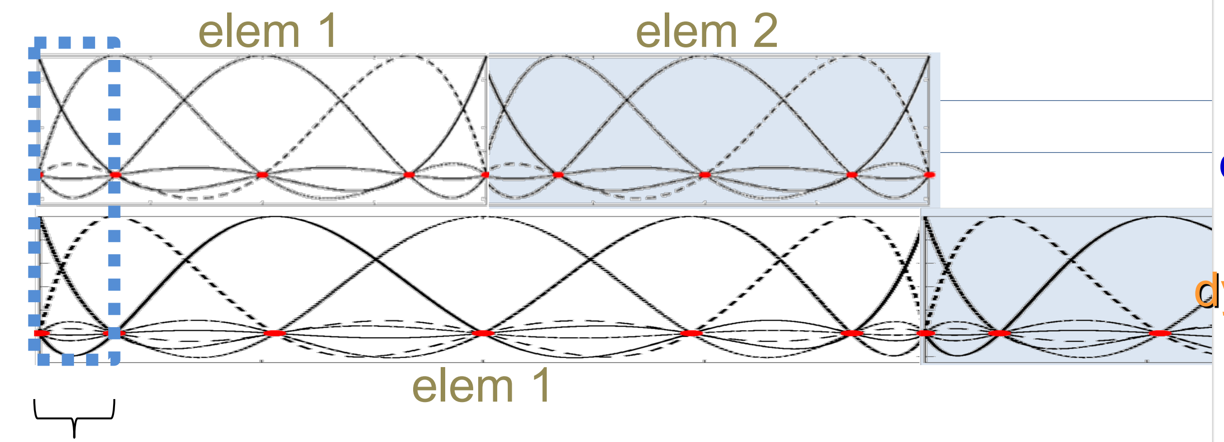
Adjoint testing:
- Currently validating adjoint of DG transport

Zaron et al. 2022 (Tellus)



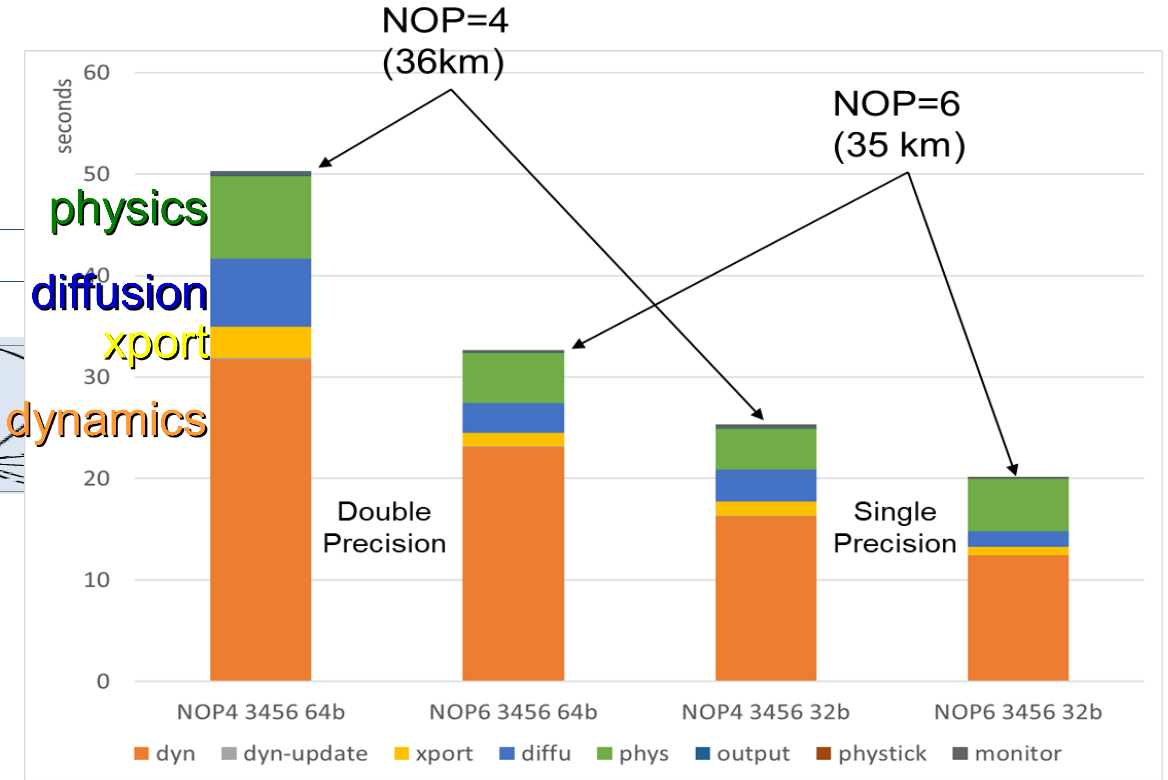


NEPTUNE Higher-Order Numerics



nominal dx = minimum node spacing on an element

P4 →4th order , P6 → 6th order polynomial



Can higher-order basis functions provide same accuracy at lower cost?

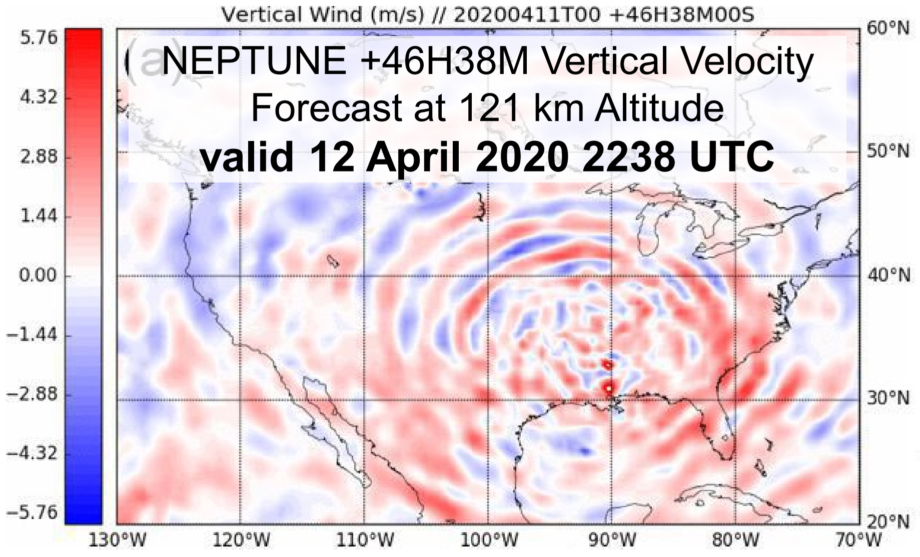
- \+ P=6 element covers ~2x the distance as P=4 with the same dx and dt
- \+ Speed improvement: **1.50x** for double precision, **1.25x** for single precision

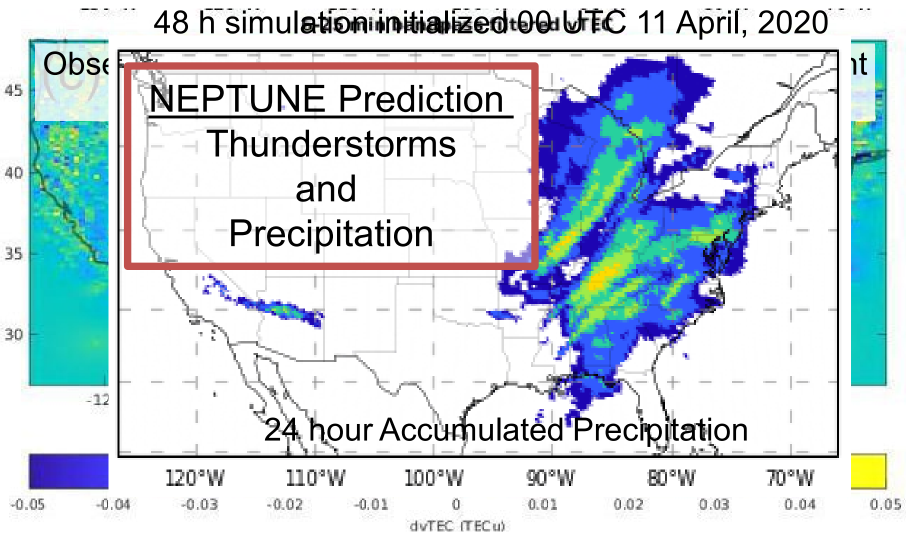
Using *minimum dx* over Gauss-Lobatto node distributions gives the same effective resolution for different polynomial orders

Alex Reinecke and John Michalakes

NEPTUNE High-Top

- Extends NEPTUNE to >450 km Altitude:
  - Thermodynamic energy equation based on $c_v T$
  - Molecular Viscosity, variable gravity, and variable composition
  - CCPP based tropospheric/stratospheric physics
  - Suite of thermosphere physics (non-CCPP)
  - High-altitude initial conditions provided by separate 0-200 km data assimilation system
  - Inputs: forecast space weather drivers (e.g., varying solar UV irradiances and geomagnetic activity)
  - Coupling to ionosphere forecast model through NUOPC (currently one-way, developing two-way)
- Forecasts for April 2020 (~36 km grid/177 levels):
  - Midwest thunderstorm complex launches deep propagating waves
  - Wave signal evident in observed ionosphere total electron count
  - Extensively validated against available observations
  - V&V reveals thermosphere prediction skill (see opposite)





Summary and Future Plans

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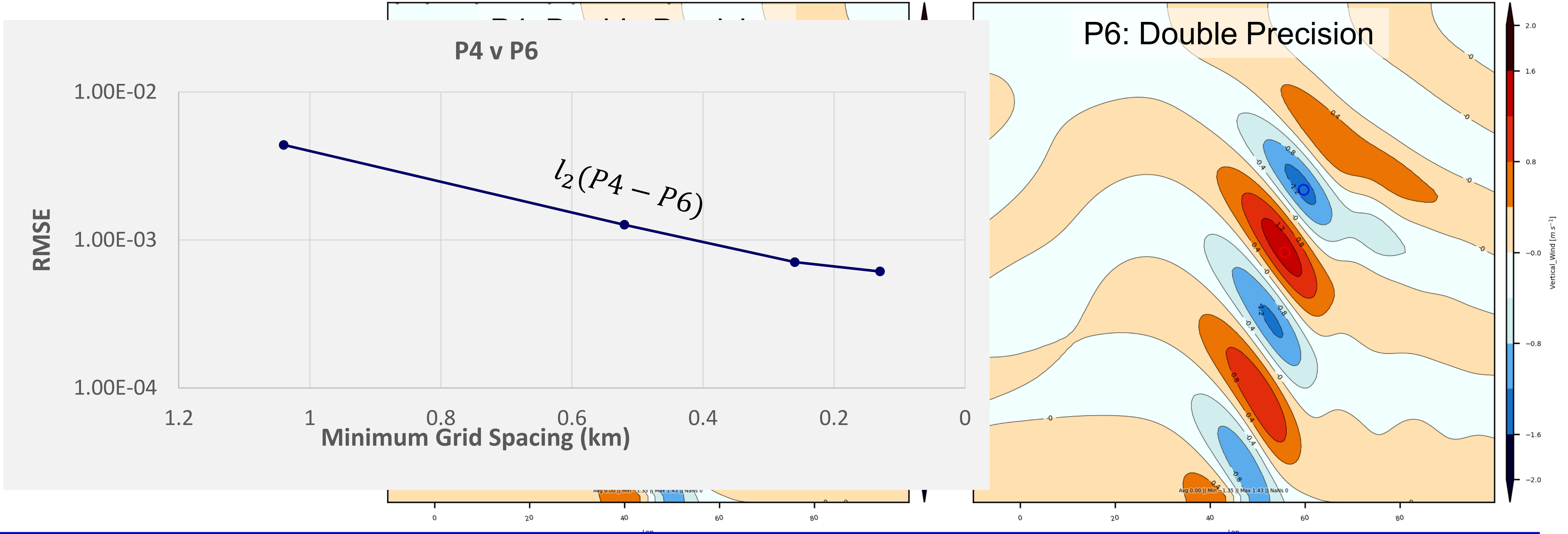
- Navy next-generation NEPTUNE prediction system using a spectral element core is under development
- NEPTUNE Suite 7 is overall competitive with GFS (v16/17) for 5-day forecasts
- Identified systematic cold (maritime) and warm (continental) biases
- Cycling DA results, using the JEDI infrastructure, are promising
- Adjoint, high-top version, and various numerical and computational advancements are being developed
- Operational transitions (to Navy FNMOC):
  - Global (2024)
  - Coupled S2S ESPC (~2026)
  - Limited Area and TC versions

Extra Slides

Polynomial Order: Idealized Validation

Vertical Velocity: Idealized Mountain Wave



- Qualitatively: Very similar P4 and P6 idealized solutions
- Quantitatively: P4 and P6 solutions converging with decreasing grid length (more elements)
  - ➢ Double precision P4 and P6 solutions are converging
  - ➢ Single precision solutions converging, but at a slower rate (not shown)

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Diagnosing a Regional Warm Bias

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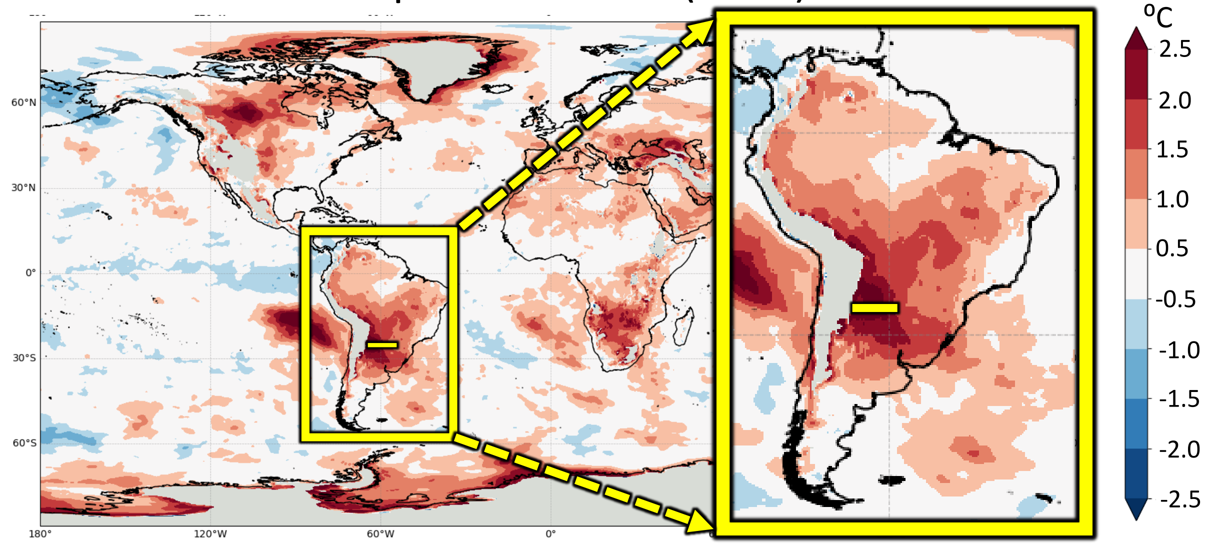
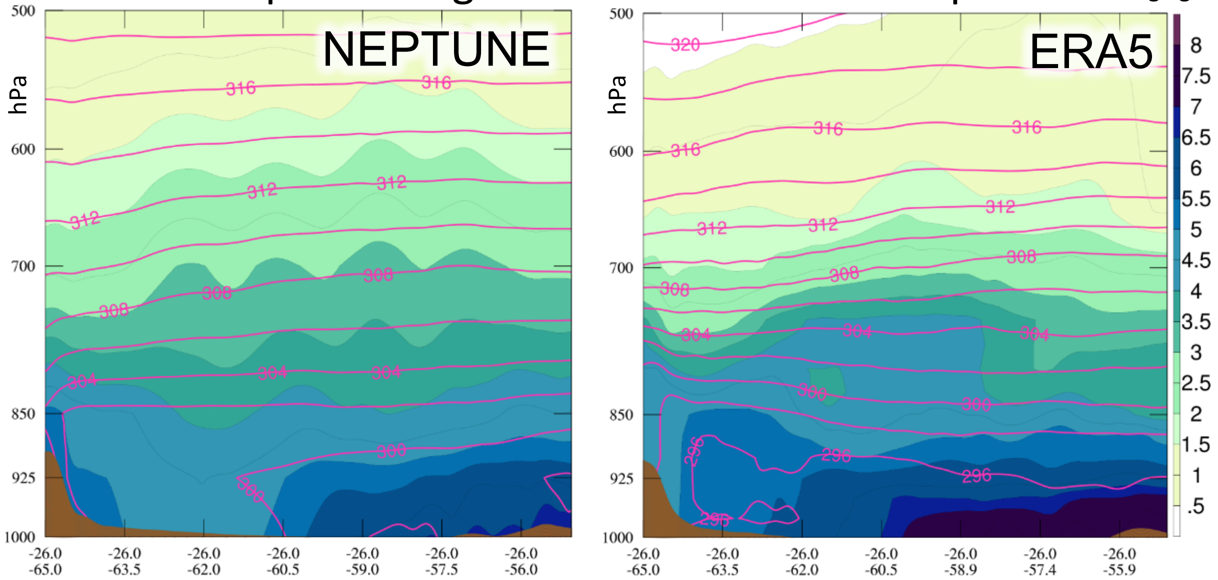
South America Temperature Bias in July

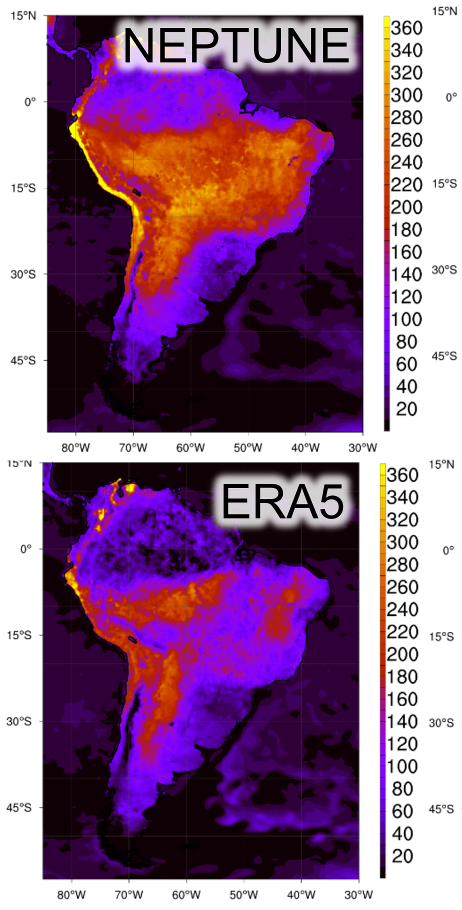
NEPTUNE Temperature Error (120h) at 850 hPa



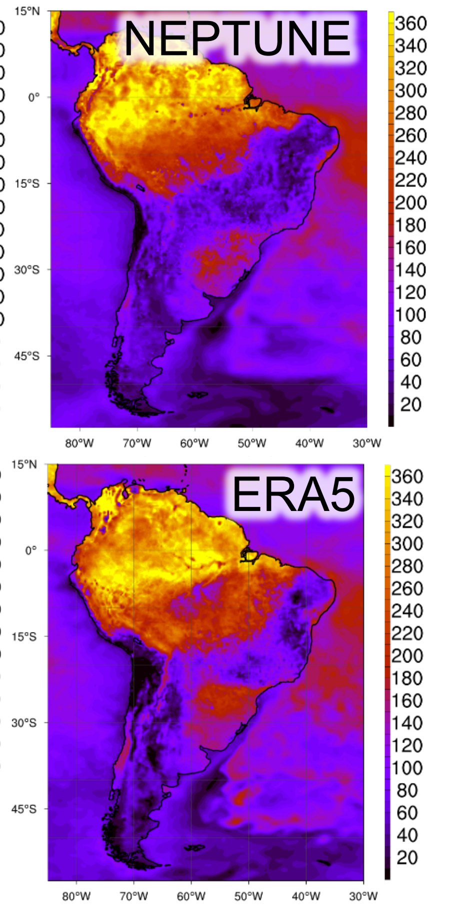
Water Vapor Mixing Ratio and Potential Temperature g kg-1



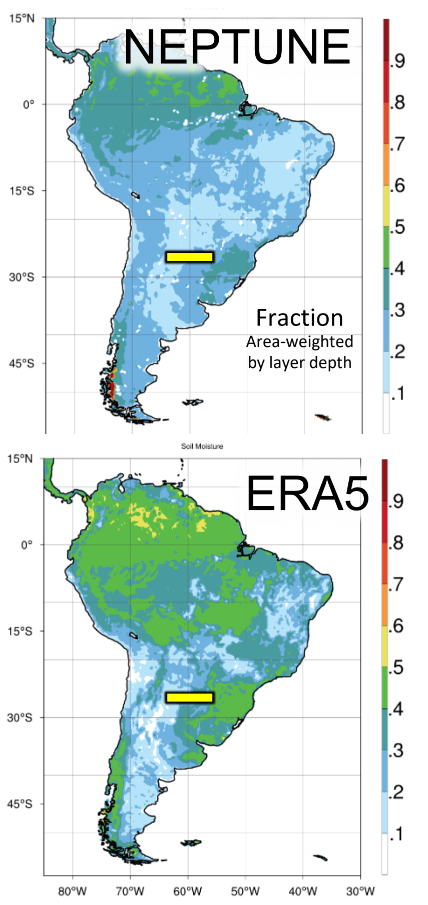
Sensible Heat Flux W m-2



Latent Heat Flux W m-2



Integrated Soil Moisture

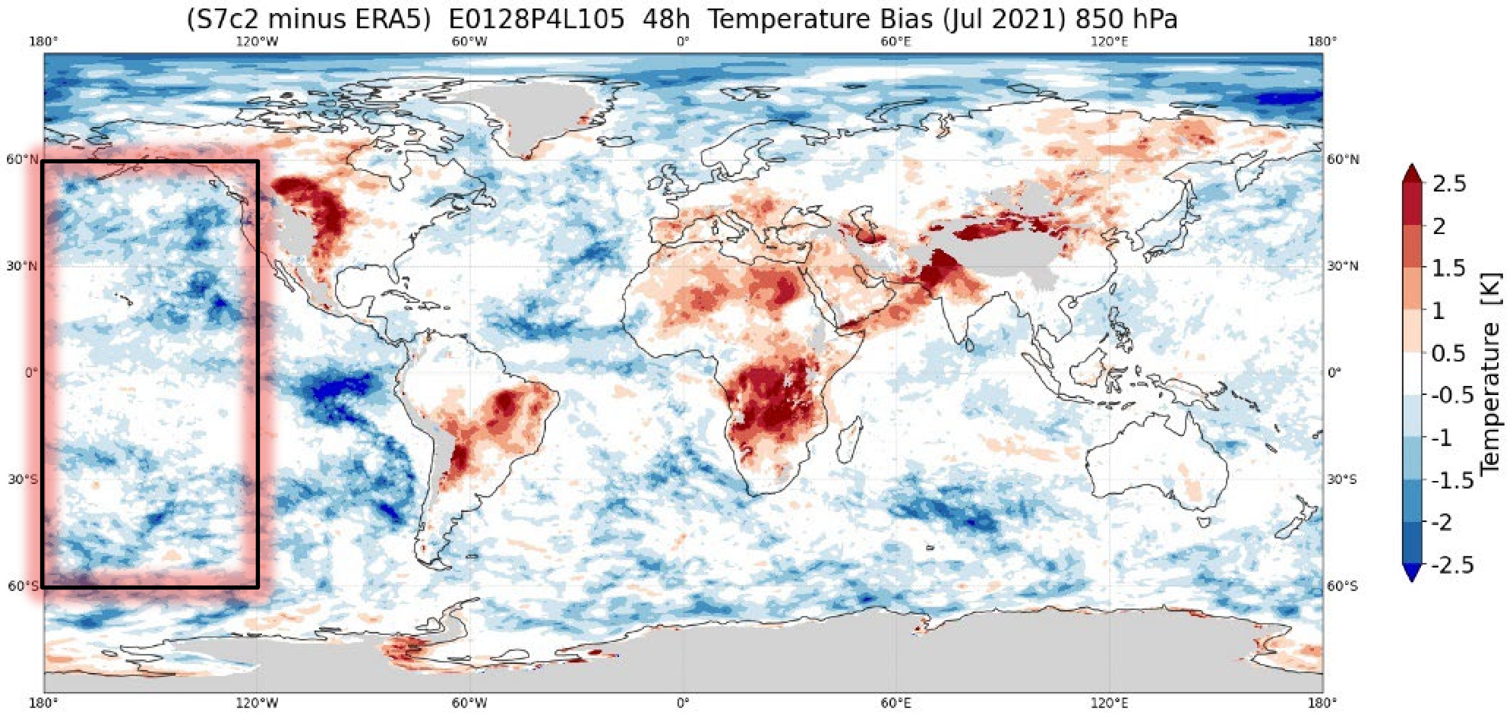


- NEPTUNE shows a warmer, drier, deeper PBL than in ERA5
- Stronger sfc heat fluxes in NEPTUNE, consistent with warm bias
- NEPTUNE shows a drier soil moisture profile than in ERA5 in many locations (often co-incident with areas of warm bias)

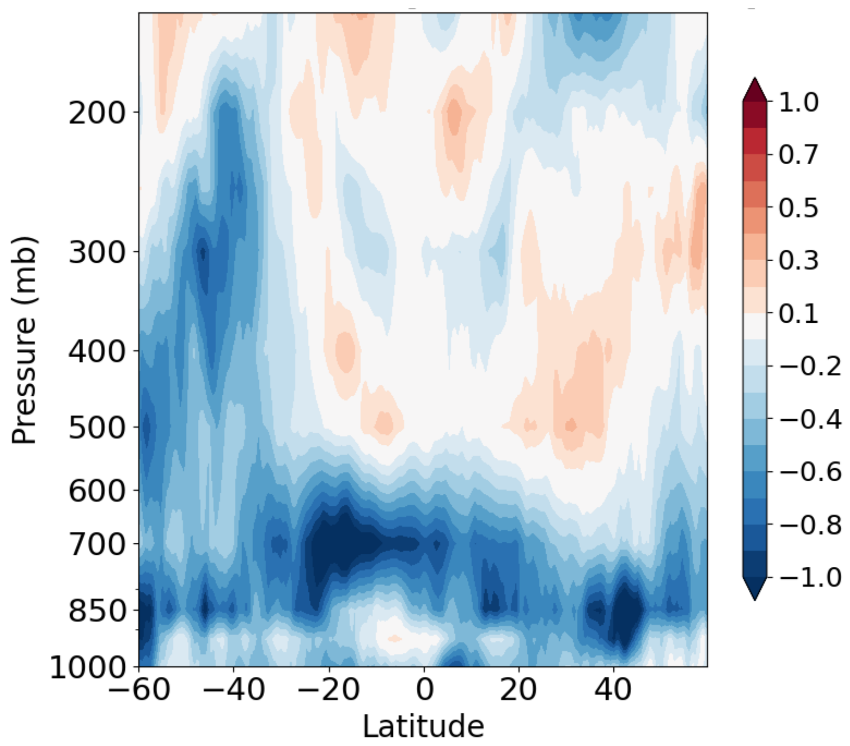
Forecast Temperature Bias

- Average 48-h temperature bias for 11 cases in July 2021 (GFS cold starts)
- E128 (dx~13 km), 105 levels, top at 70km
- Evaluation of Suite 7 (Tiedtke)
- Verified using ECMWF ERA-5

48-h Temperature Error (NEPTUNE minus ERA5)
Suite 7 (July 2021)



48-h Temperature Error Suite 7 (July 2021)
180-120W Longitudinal Average

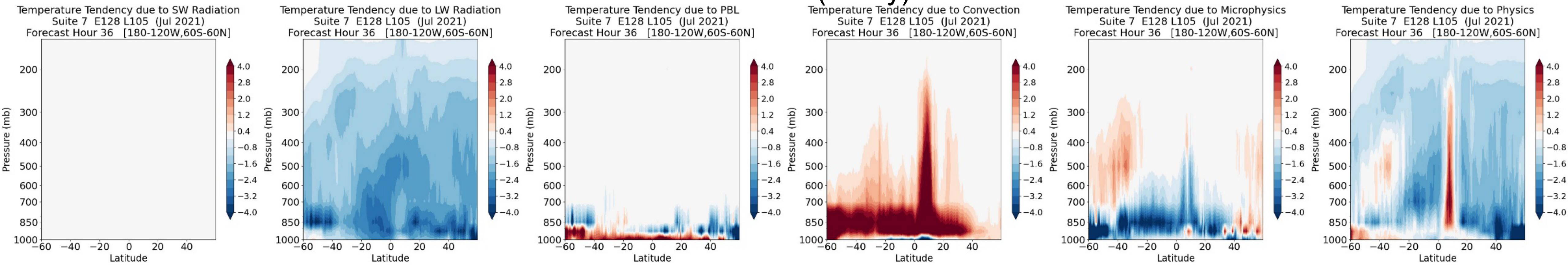


- Maritime Pacific cold bias at 850-700 hPa associated with stratocumulus
- Deeper cold bias in the extratropics

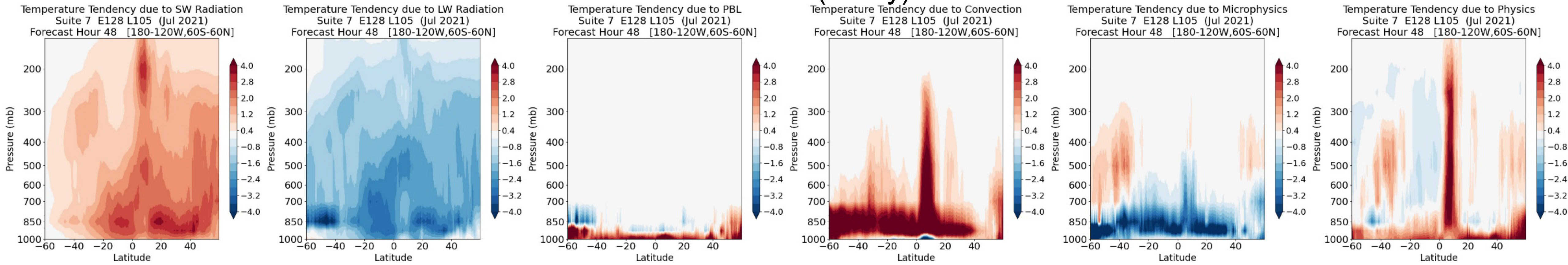
Temperature Tendencies

SW Radiation | LW Radiation | PBL | Convection | Microphysics | Total Physics

36-h Tendencies (K/day)



48-h Tendencies (K/day)



- 36-h and 48-h temperature tendencies accumulated over the previous 6h
- Main contribution to the maritime Pacific cold bias in the 700-850hPa layer are microphysics and LW radiation associated with low-level stratocumulus clouds
- Deeper extratropical cold bias may be related to convection and microphysics interactions

Precipitation Forecasts

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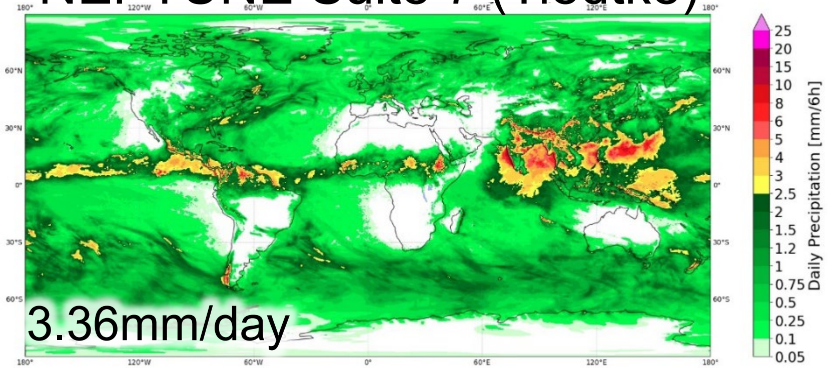
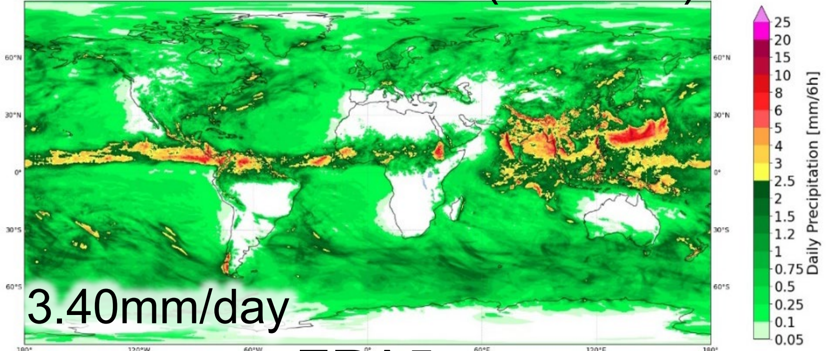
Daily Total Precipitation (mm/6h)

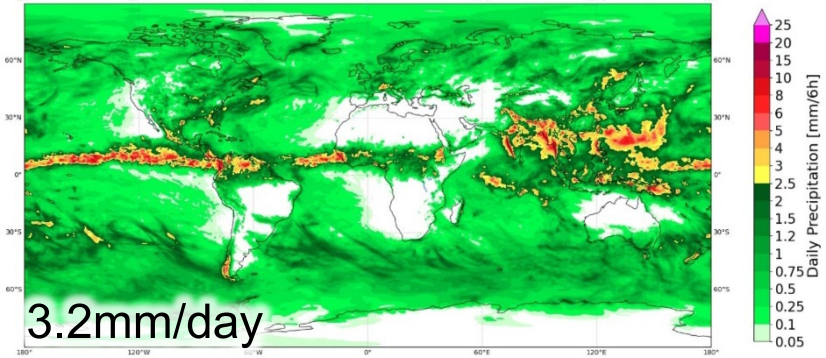
NEPTUNE Suite 7 (Tiedtke)



NEPTUNE Suite 8 (sa-SAS)

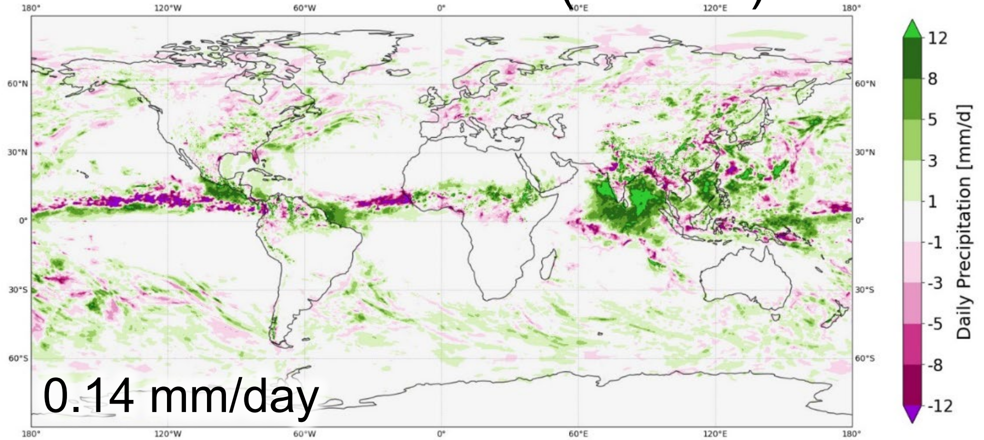


ERA5

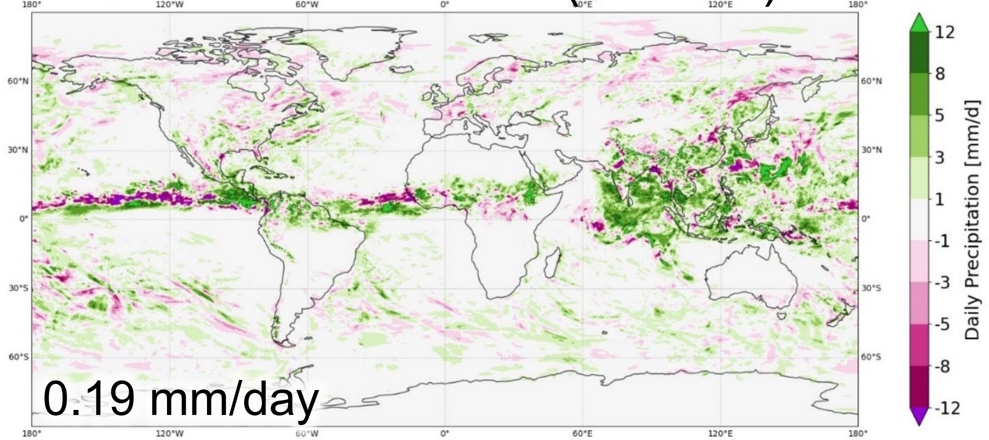


Precipitation Difference with ERA5

NEPTUNE Suite 7 (Tiedtke)



NEPTUNE Suite 8 (sa-SAS)



- Average of 10 July Cases (96h) with E128L105 (~13km)
- Both suites in good agreement with ERA5 (except ITCZ, NIO, WPAC)

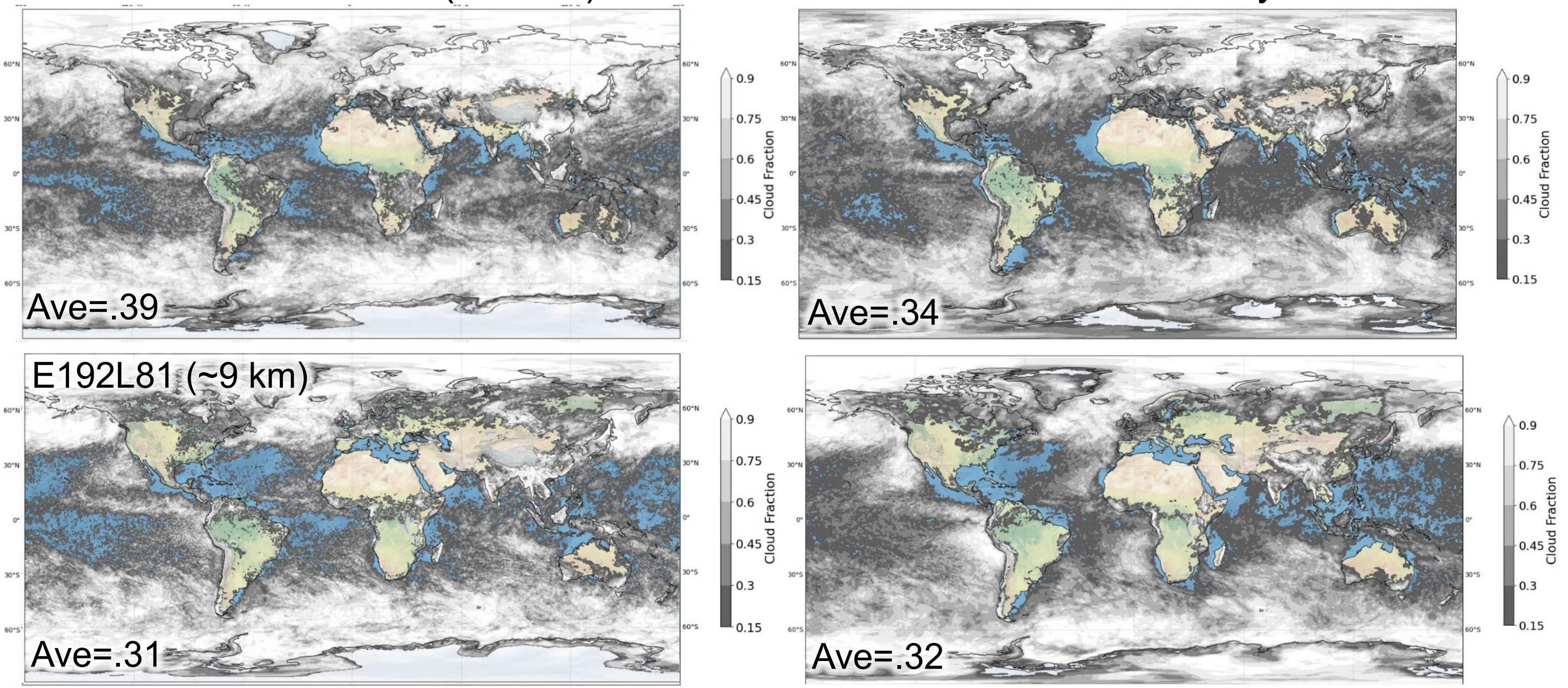
Low-Level Cloud Fraction

NEPTUNE Forecast Low-Level Cloud Fraction at 24h (E128L105 ~13 km)

NEPTUNE Suite 7 (Tiedtke) | ERA5 Cloud Analysis

January Mean

July Mean



- NEPTUNE Suite 7 low-level 24-h cloud fraction forecast mean is in good agreement with ERA5
- Over-prediction of low-level clouds over W. Pacific tropics, C. Pacific ITCZ, N. Indian Ocean
- Increasing resolution (13km to 9km) results in a reduction of low-level cloud fraction