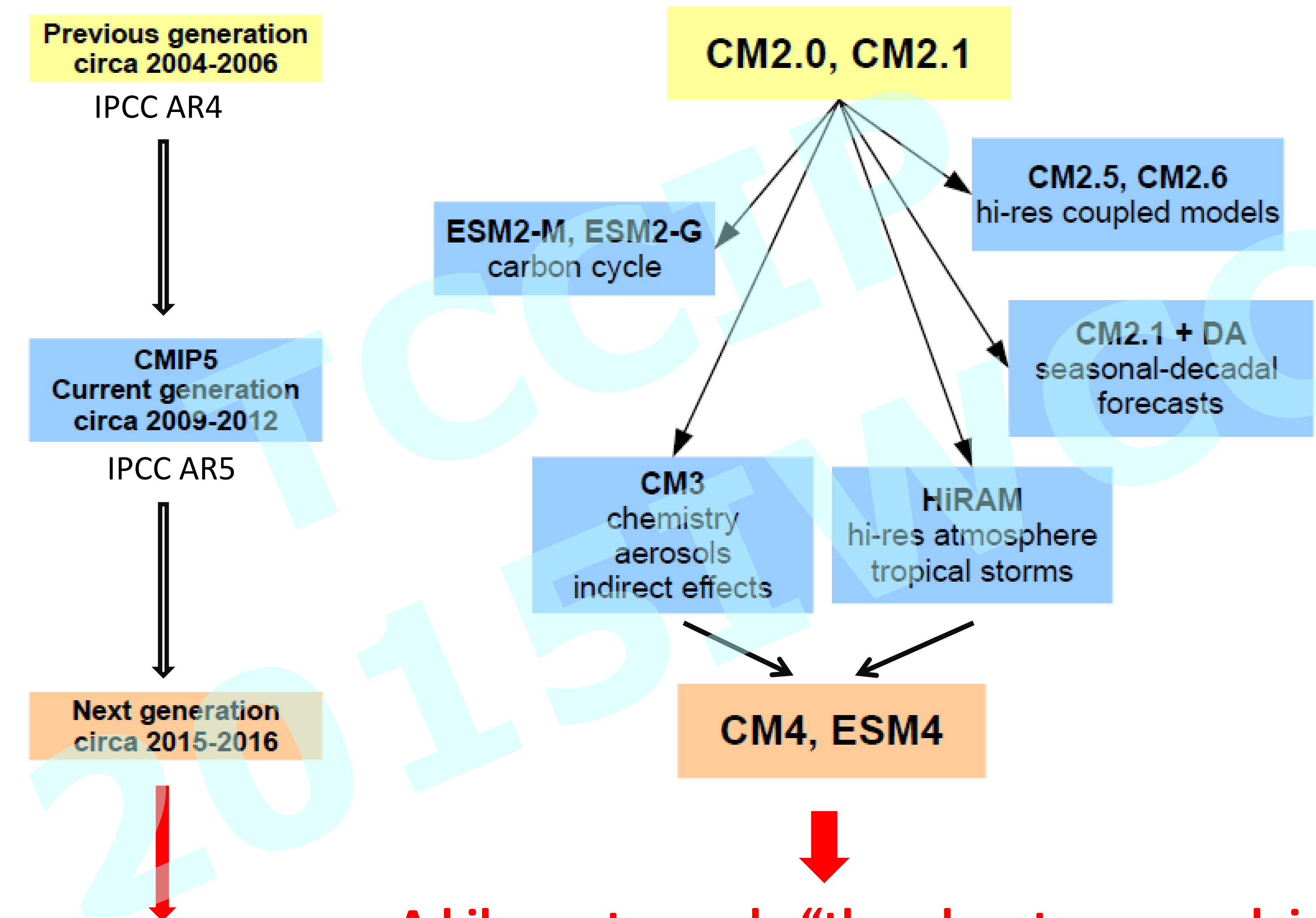
Recent advances in High-Resolution Weather-Climate modeling at GFDL

Shian-Jiann Lin

NOAA/Geophysical Fluid Dynamics Laboratory
Princeton, NJ, USA

Workshop on High-Resolution Climate Simulations, Projection, and Application
Academia Sinica, Taipei, Taiwan
Jan 19-20, 2015

Brief history of GFDL climate models

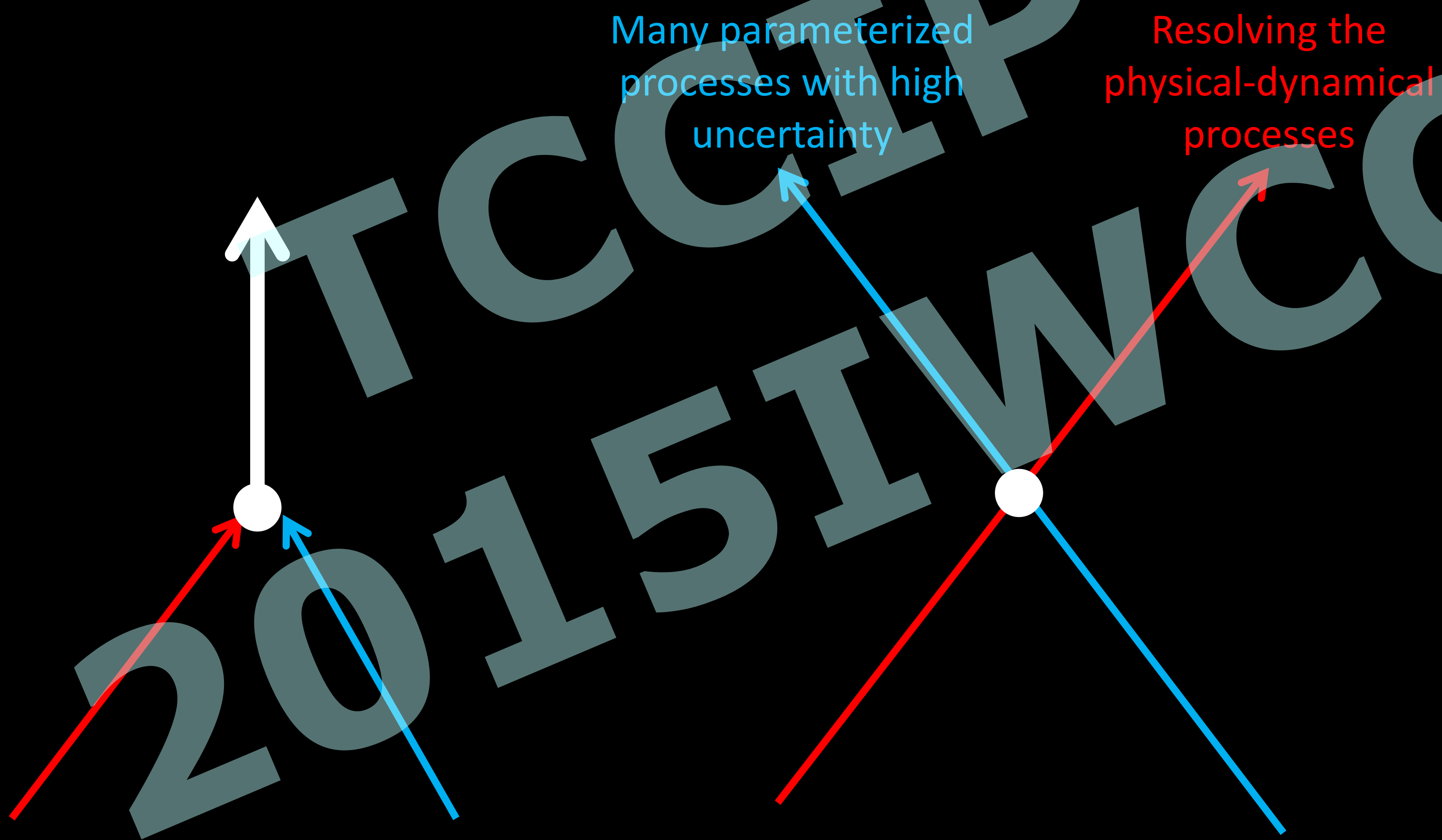


Beyond the next IPCC: 2020 – 2030?

A kilo-meter scale "thunder storm-resolving" weather-climate model?

Weather vs. climate models:

are they at a converging or crossing point?

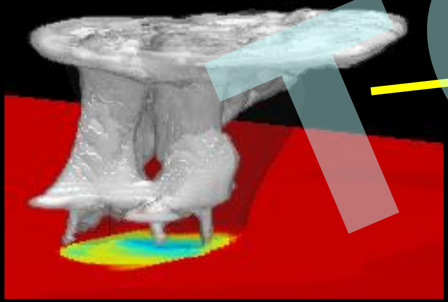


NOAA's Integrated modeling strategy?

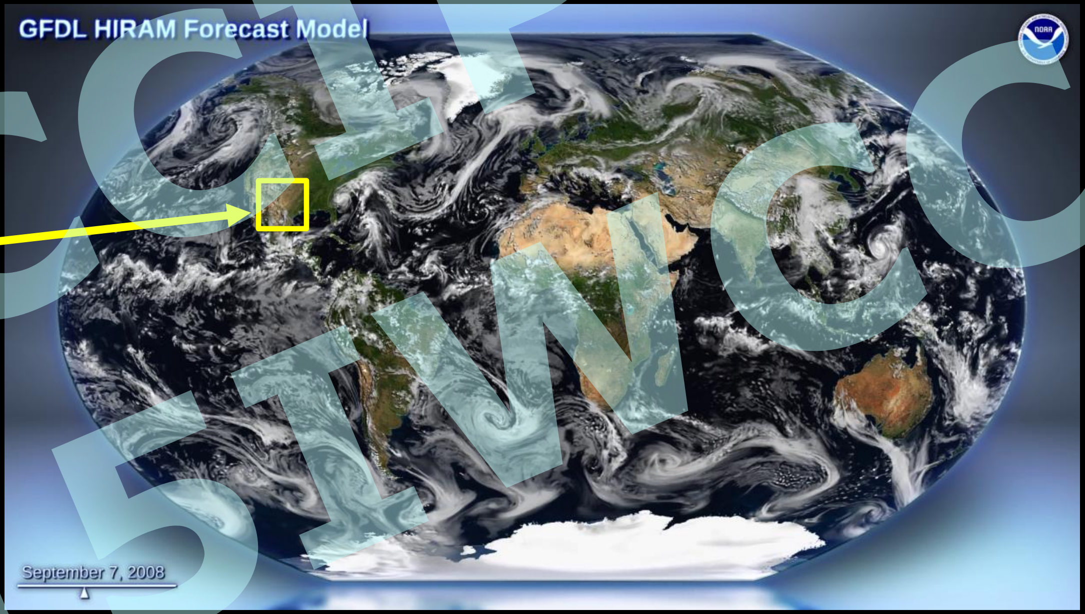
Business as usual development paths

The main challenge:

Simulations & predictions of high-impact weather-climate events from the smallest to the largest scale (tornadoes, thunderstorms, typhoons/hurricanes, MJOs, droughts, QBOs, ENSO etc.) within an "IPCC-class" climate modeling system

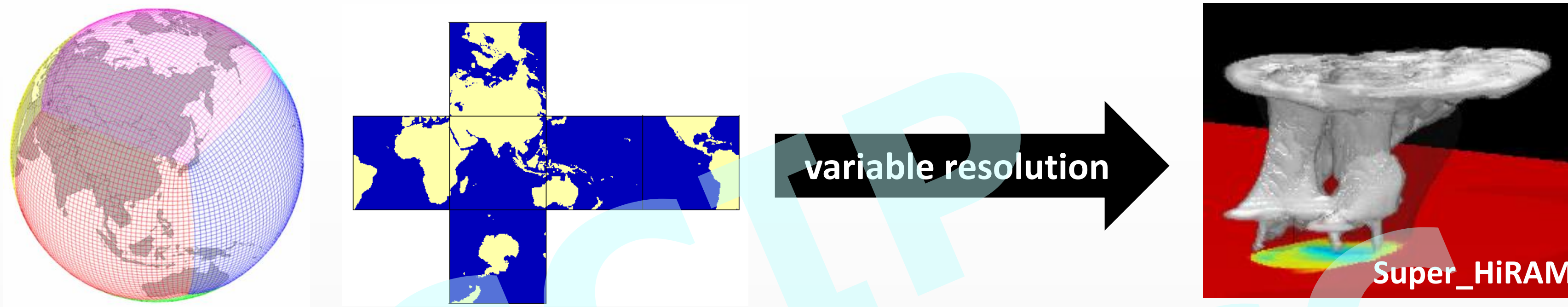


Non-hydrostatic HiRAM



- **Traditional IPCC-class climate models do not have either the correct dynamics or the physical parameterizations to represent storm-scale flows**
- **A new breed of "seamless" weather-climate model is needed**

The GFDL non-hydrostatic Finite-Volume core on cubed-sphere (FV3)



- Finite-Volume discretization & monotone advection of all prognostic fields (air mass, tracers, and Potential Vorticity) (Lin & Rood 1997)
  - Maintain dynamical consistency
  - Superior representation of vortical flows (e.g., tropical cyclones, super-cell thunderstorms, and tornadoes)

- Vertically Lagrangian discretization (Lin 2004)
  - Time step not limited by vertically propagating waves & strong updraft/downdraft ; big computational advantage for global cloud-resolving simulations

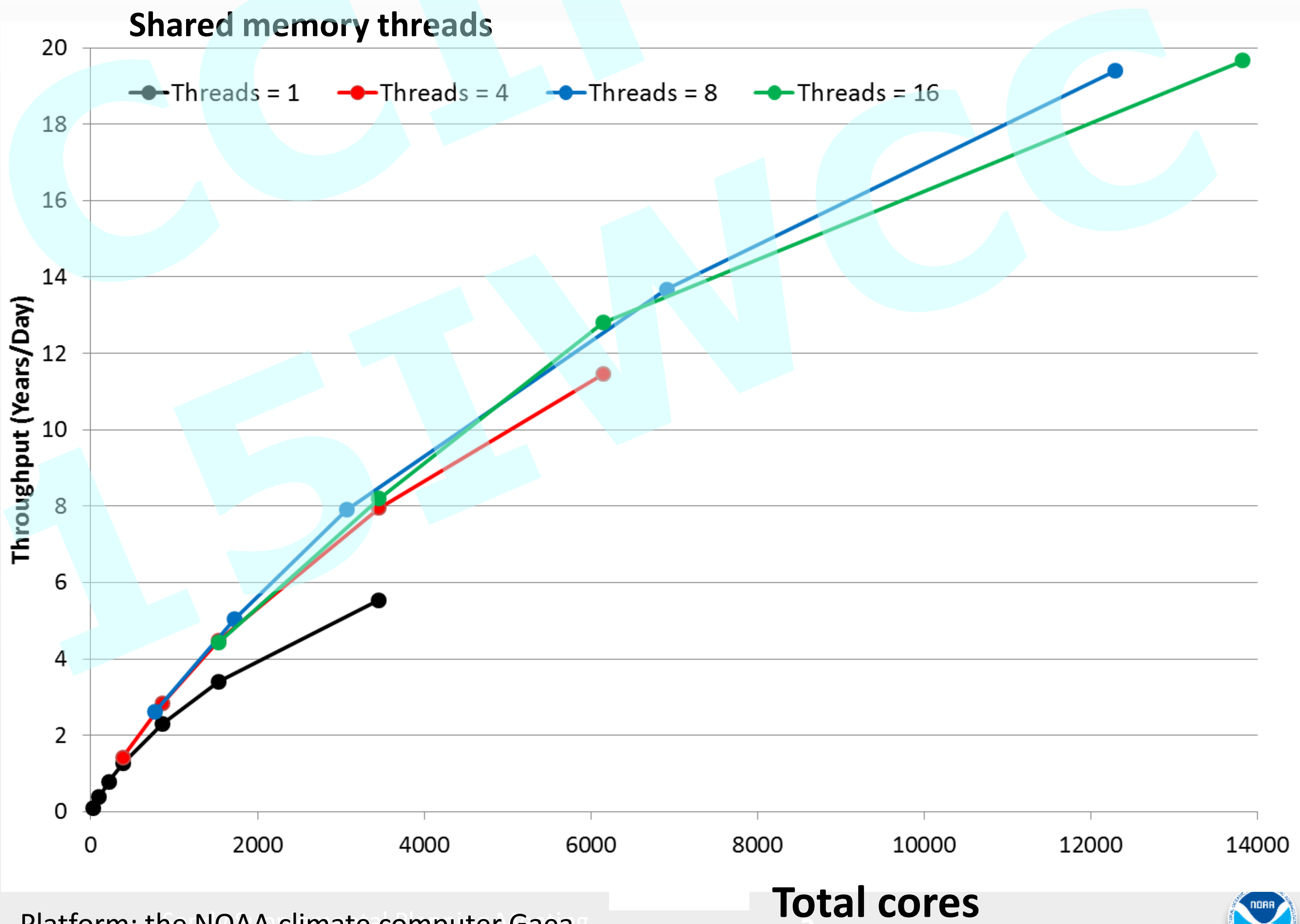
- Configurable as regional, global, or 2-way nested regional-global model (Harris & Lin 2014)

- Highly scalable with hybrid (shared & distributed memory) programming

Is it operationally feasible to use a global cloud-resolving model (~3 km or finer) for NWP within 5-10 years?

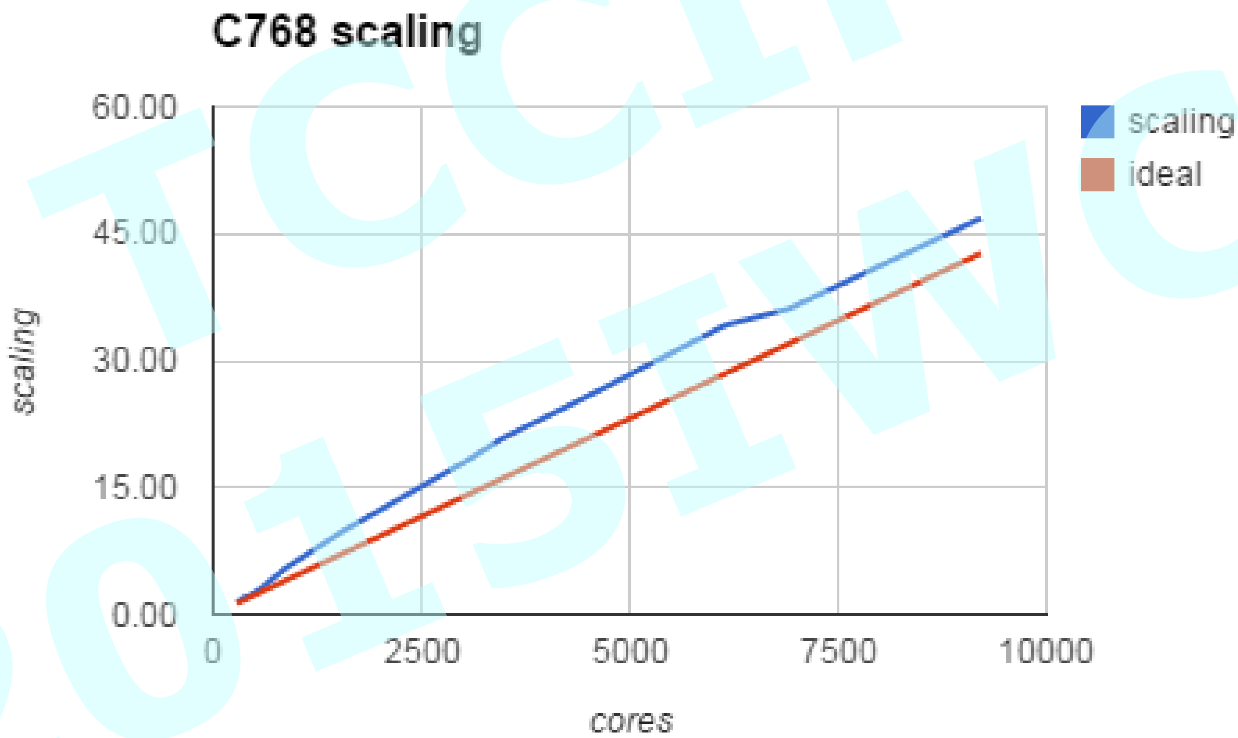
- The C192 AM4 prototype (50 km with 30 tracers) scales beyond 10,000 cores
- A FV3 based NGGPS model at 3 km should scale beyond 3 million cores

A C3072 NGGPS (3 km) cloud-resolving model has 256 times more computational points than the GFDL C192 AM4
Therefore the C3072 model will scale 256 times better



Platform: the NOAA climate computer Gaea

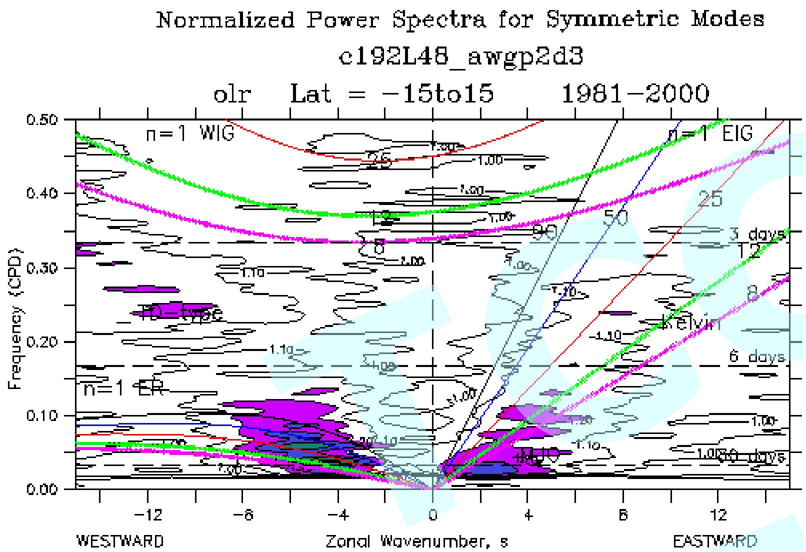
Scalability of GFDL FV3 at C768 (13 km) resolution

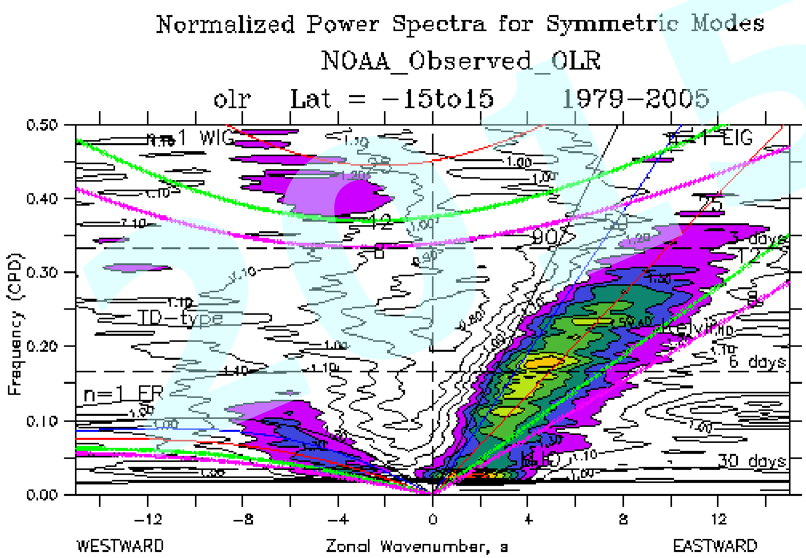


Platform: the NOAA climate computer Gaea

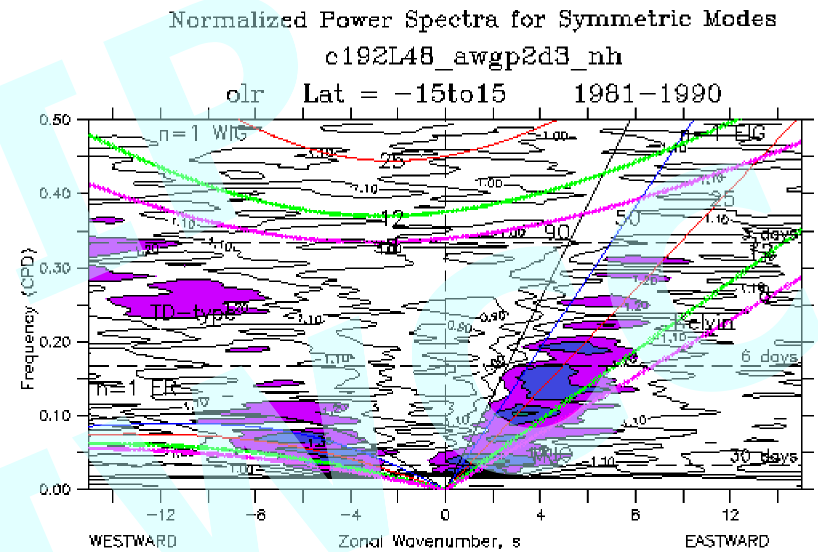
Impacts of non-hydrostatic dynamics are already significant at 50 km resolution

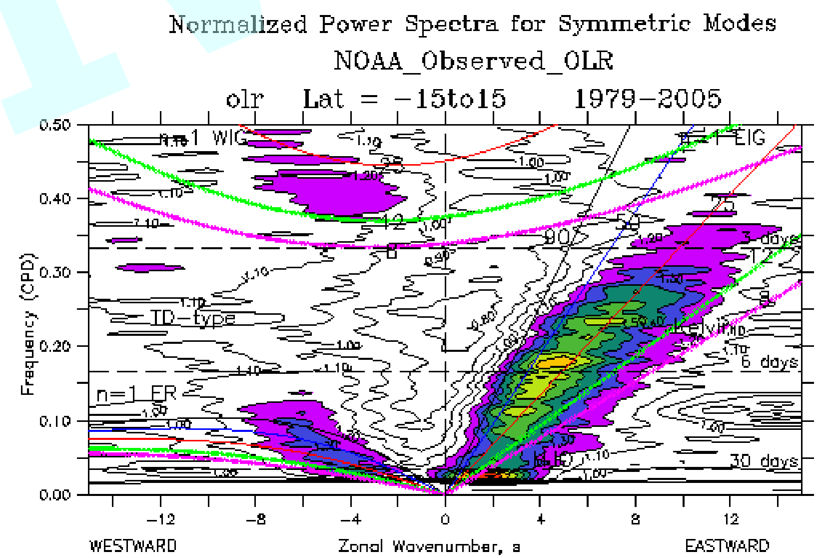
Hydrostatic AM4 prototype





Non-hydrostatic AM4 prototype

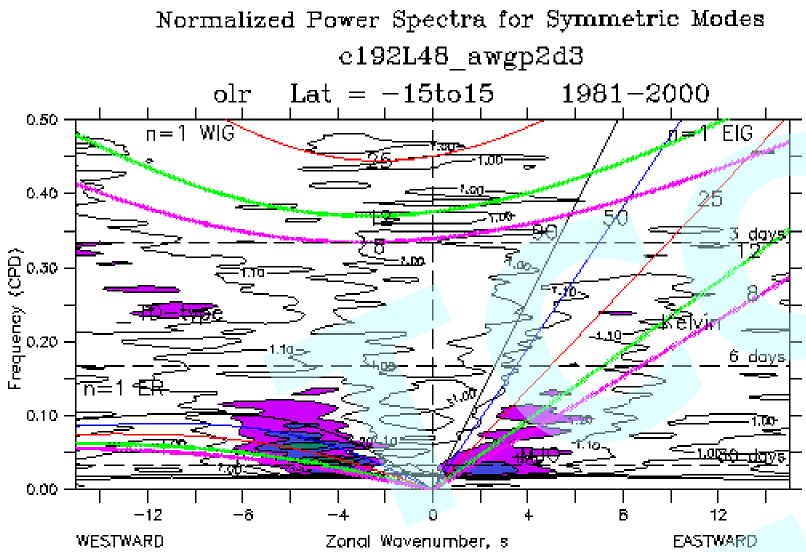


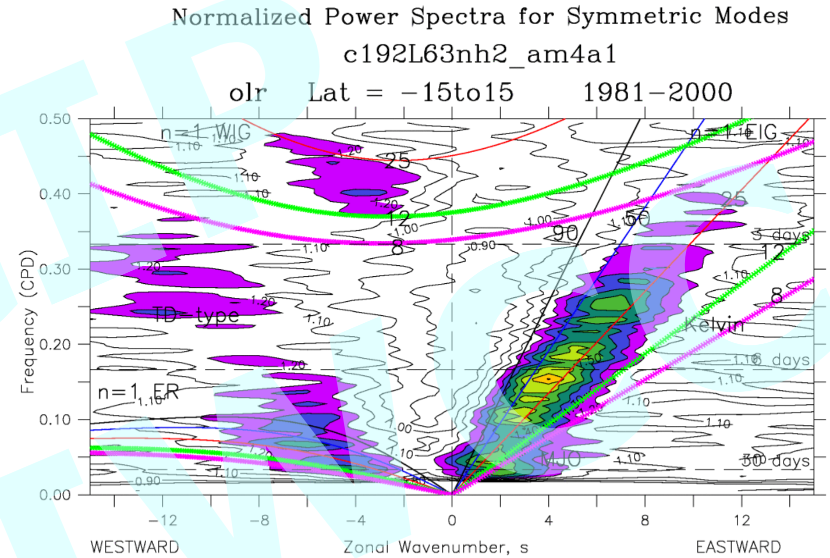


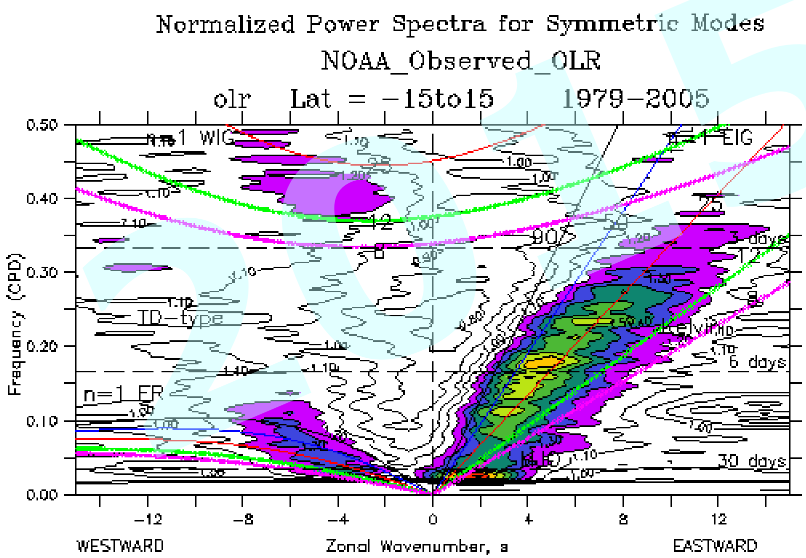
- **Kelvin waves can get much stronger with more entrained (i.e., diluted) plumes or by decreasing the divergence damping in the dynamics**
- **No QBOs if the Kelvin waves are too weak**

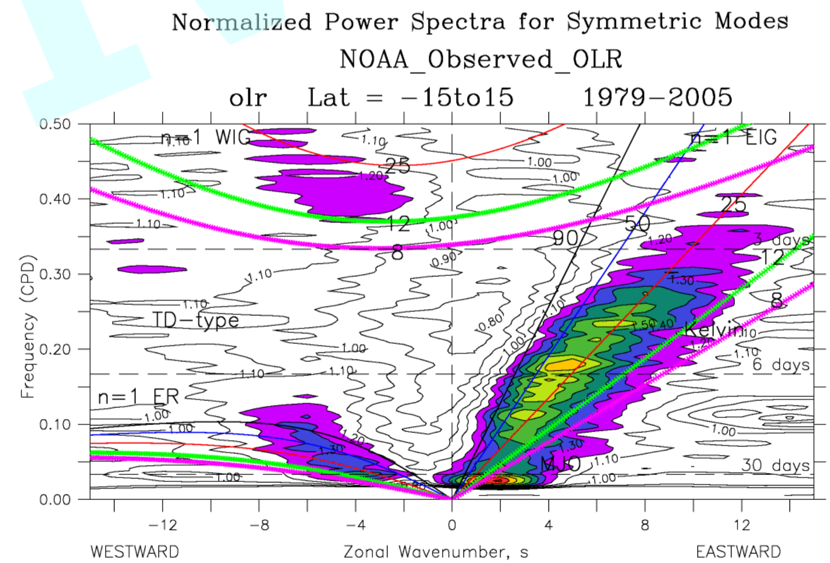
Hydrostatic AM4 prototype

Non-hydrostatic AM4 "tuned"

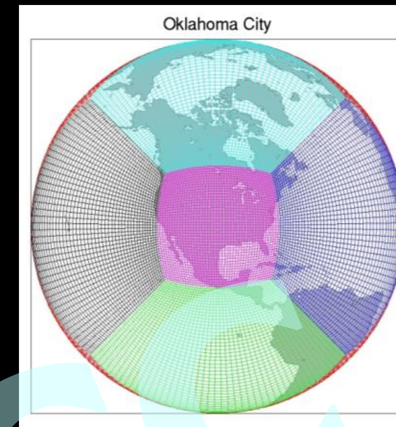


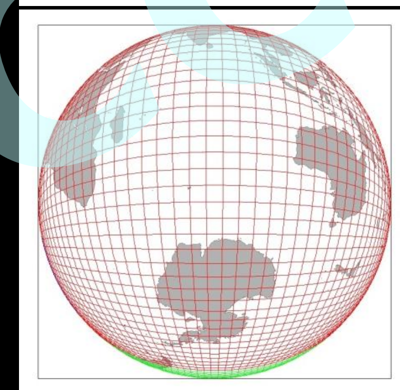






Strategies for variable resolution on the cubed-sphere

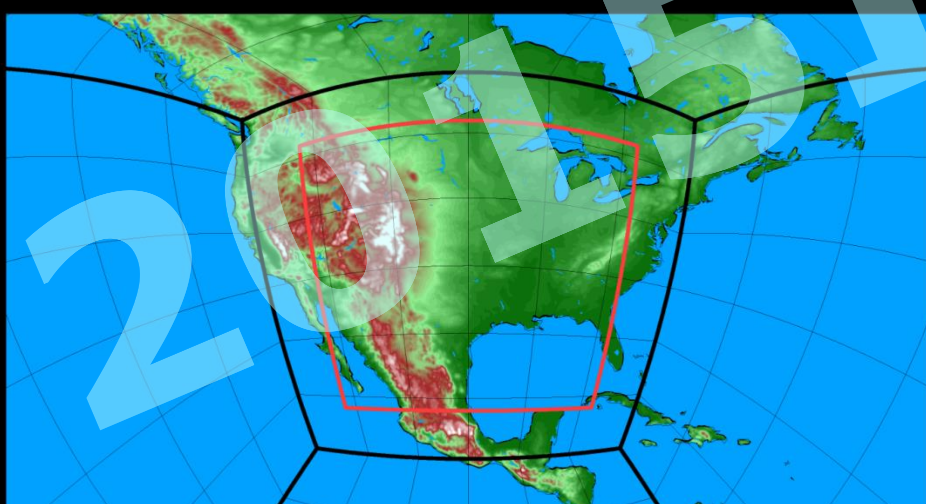




1) Grid **stretching** (via analytic transformation)
   - Moderate stretching (2.5 x) maintains integrity of global circulation – used for seasonal predictions or climate simulations
   - Aggressive stretching (20 x) – use this for short term severe weather predictions (super-cell & tornadoes)

2) 2-way **nesting** (Harris and Lin 2014)

3) Combination of the "**stretching**" and "**nesting**"



Example:

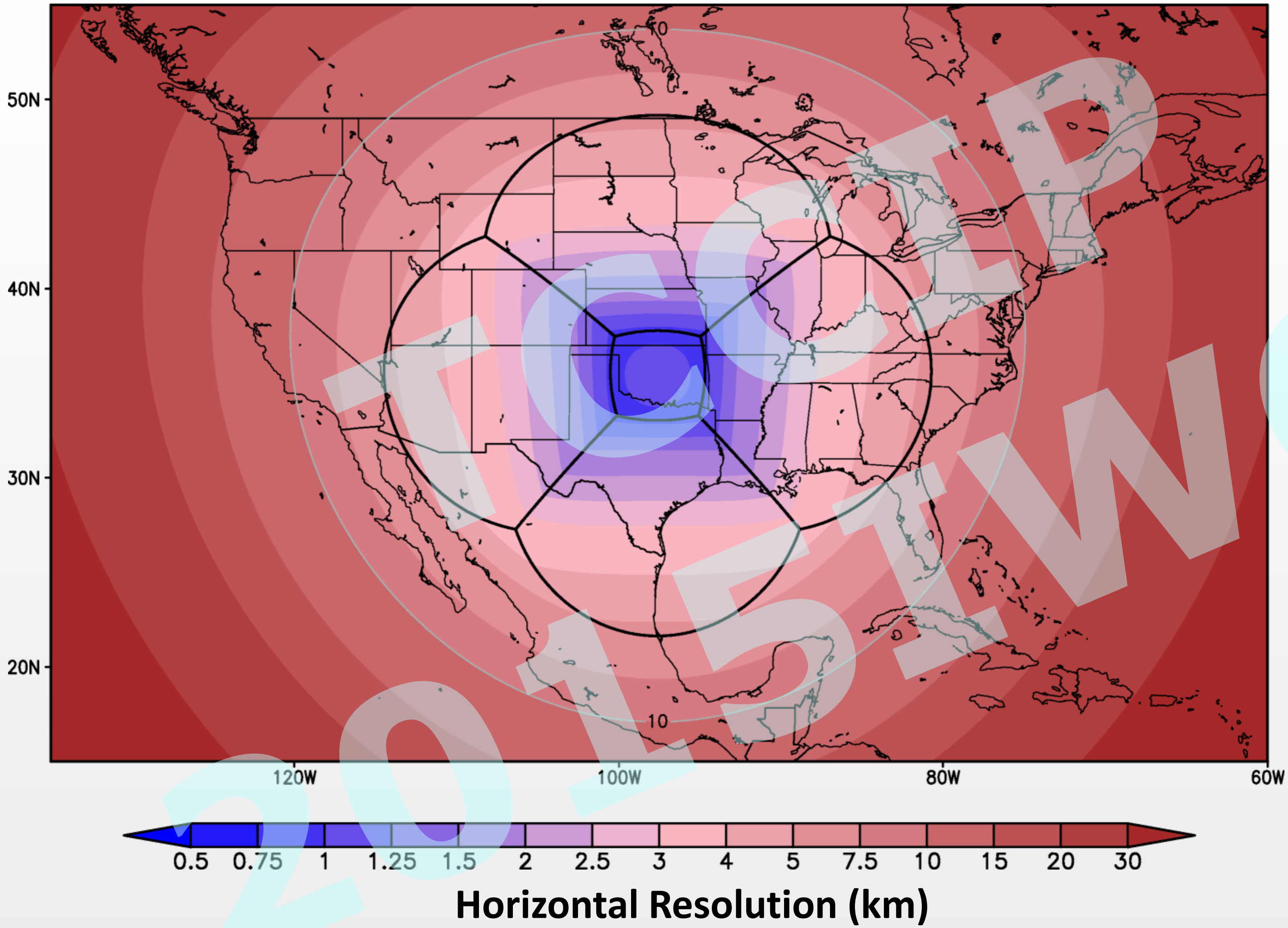
~ 3 km without the nest (black)
~ 1 km with a 2-way nest (red)

An example of a 2-way (global-regional) nested hurricane prediction model for the Atlantic basin

(8-km regional nest runs concurrently as the 25-km global grid)

(Harris & Lin 2014)

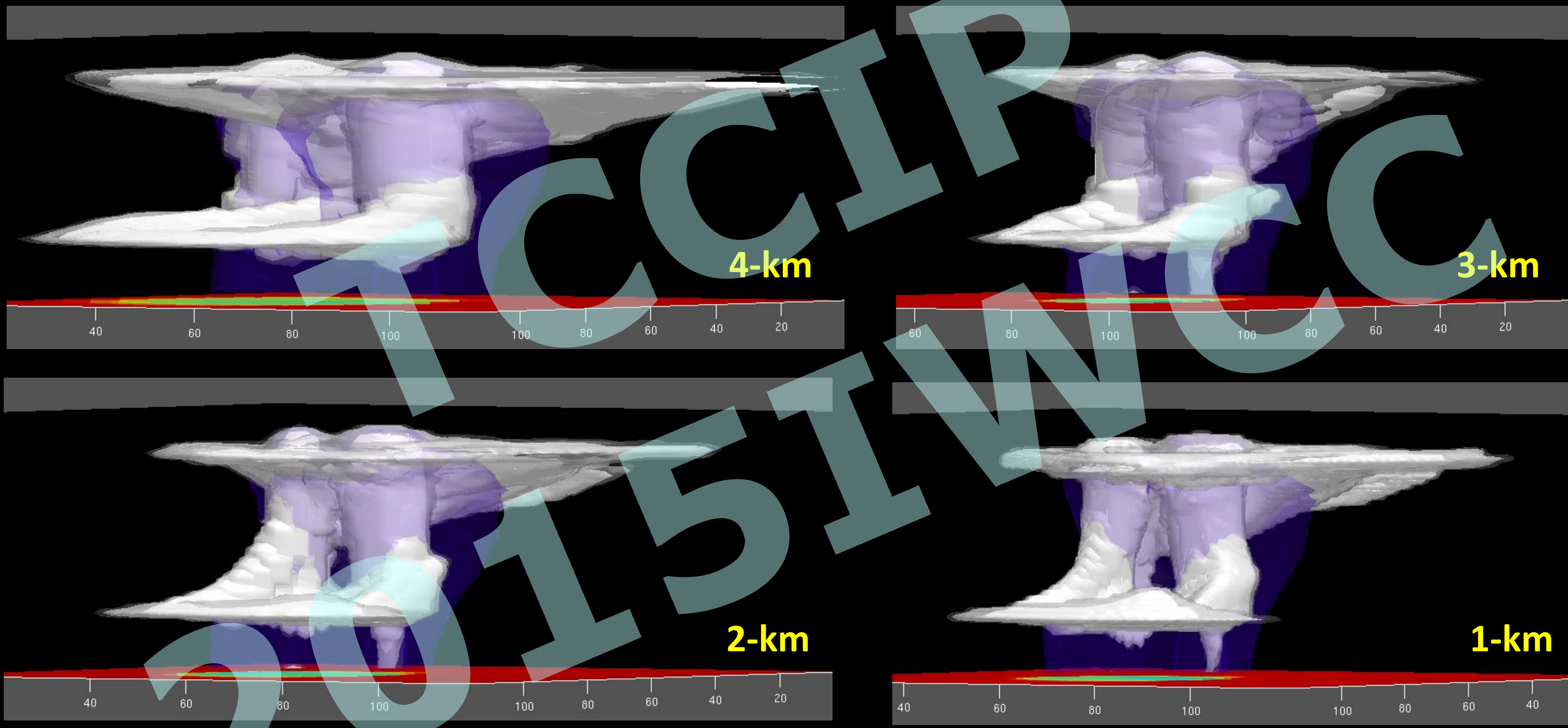
Distribution of horizontal resolution of the 20X-stretched configuration for super-cell & tornado simulations



Lin and Harris (2015 in preparation)

Resolution: averaged ~1 km resolution over Oklahoma, smoothly stretched to 400 km) over S. Indian ocean (antipodal point to OKC)

Simulations of tornado-producing super-cell storms with GFDL's super HiRAM with FV^3



Lin and Harris (manuscript in preparation)

The High Impact Weather Prediction Project (HIWPP) and NCEP's Next Generation Global Prediction System (NGGPS)

Goal: an inter-agency effort to develop a global non-hydrostatic model for NCEP's operational forecasts for the next 20 years

Dynamical core participants (the "contestants"):

- **GFDL FV3:** vertically Lagrangian finite-volume on the cubed-sphere, C-D grid
- **NCAR MPAS:** finite-difference/finite-volume on icosahedral grid, C-grid
- **NAVY NEPTUNE:** spectral-element on cubed-sphere, A-grid
- **NCEP NMMB:** finite-difference on latitude-longitude grid, B-Grid
- **ESRL NIM:** finite-difference/finite-volume on icosahedral grid, A-grid

Phase-1 comparisons:
idealized tests (similar to DCMIP) and speed/scalability benchmarks on various HPCs
Phase-2 comparisons:
Real-data forecast experiments at 13 km (operational FY15) and 3 km, global "uniform" resolution

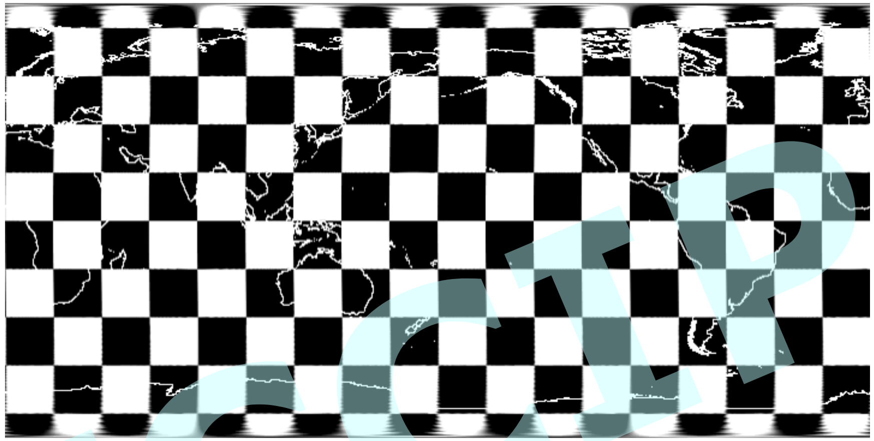
NGGPS: desirable attributes of a dynamical core for the next 5-10 year timeframe

- **Switchable (non)-hydrostatic**, applicable to all scales (from ENSO , MJO, to hurricanes, super-cell, and tornadoes)
- **Resolving more with less** (vertical & horizontal resolution):
  accurate & efficient scalar advection, crucial for cloud micro-physics
- **Excellent conservation properties (mass & total energy)**: prevent long-term (2-week to seasonal) drift
- **"One model to rule them all" (unification of regional-global system):** configurable as a regional model or a global model with 2-way "self-nesting" capabilities
- **Variable resolution** with a stretch-able and/or nest-able grid , **enabling a global model with thunderstorm resolving resolution within CONUS operationally feasible using HPCs available today**

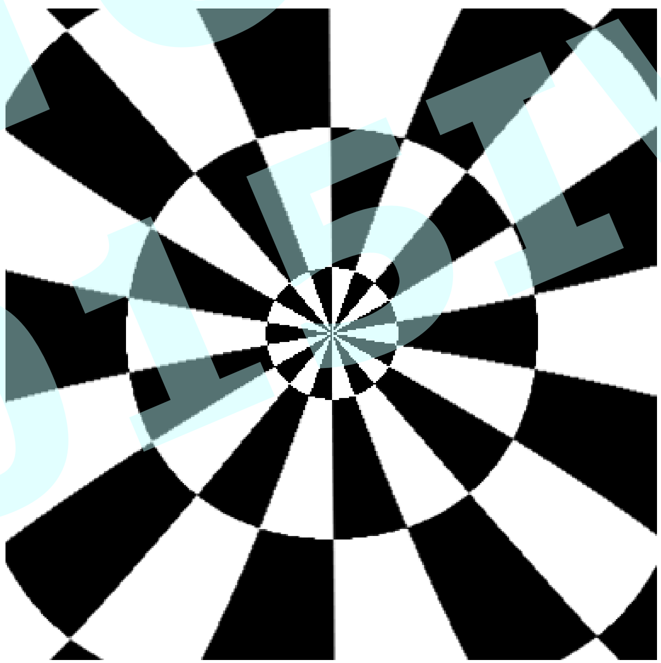
The “Jablonowski and Williamson Baroclinic-Wave” (B-W) test with a passive checker-board tracer (next slide)

C384 (25 km) FV3: Surface Pressure (0-10 days)

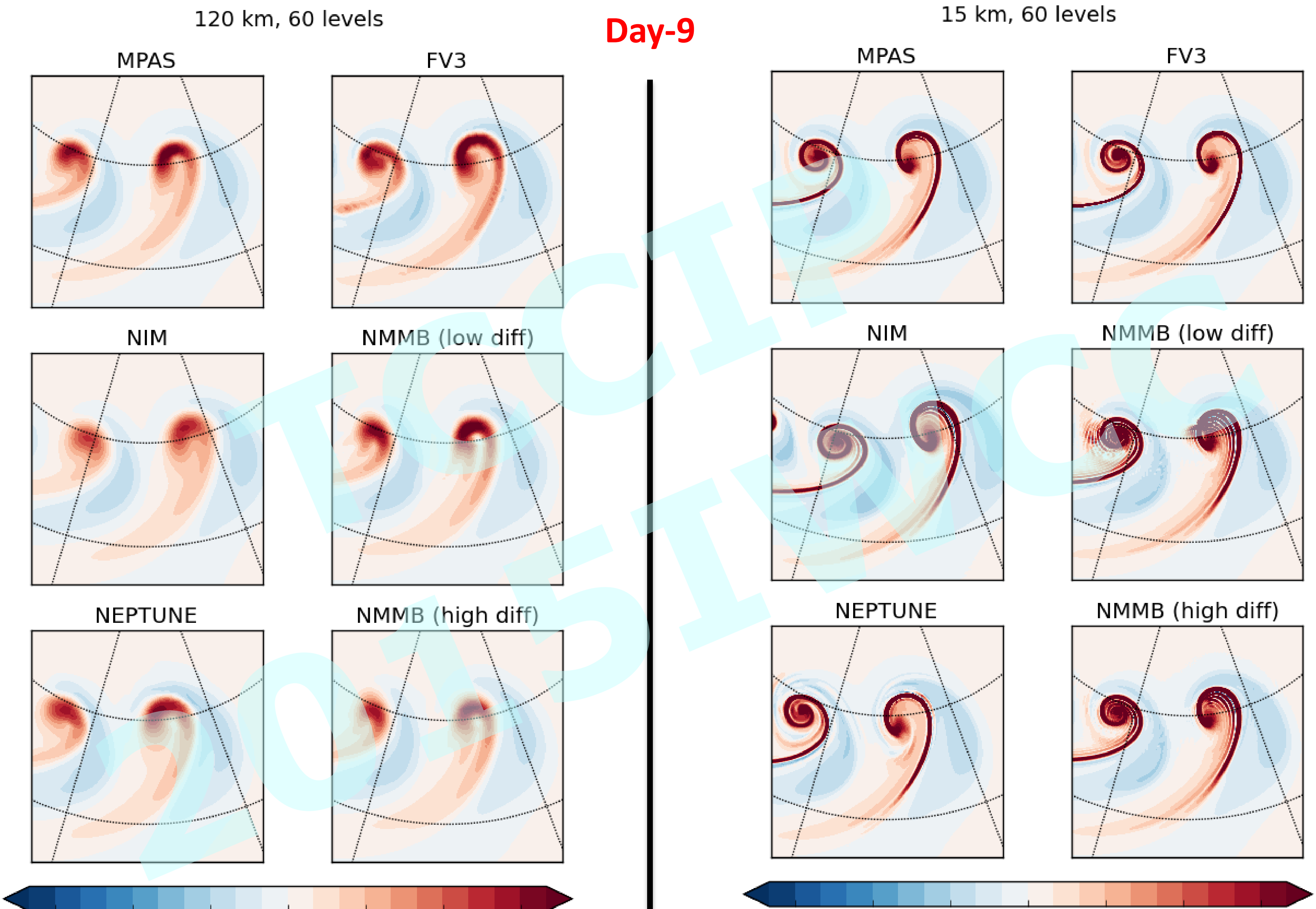
The B-W test: A passive "checker board" tracer



Tile-3 (North Pole at center)

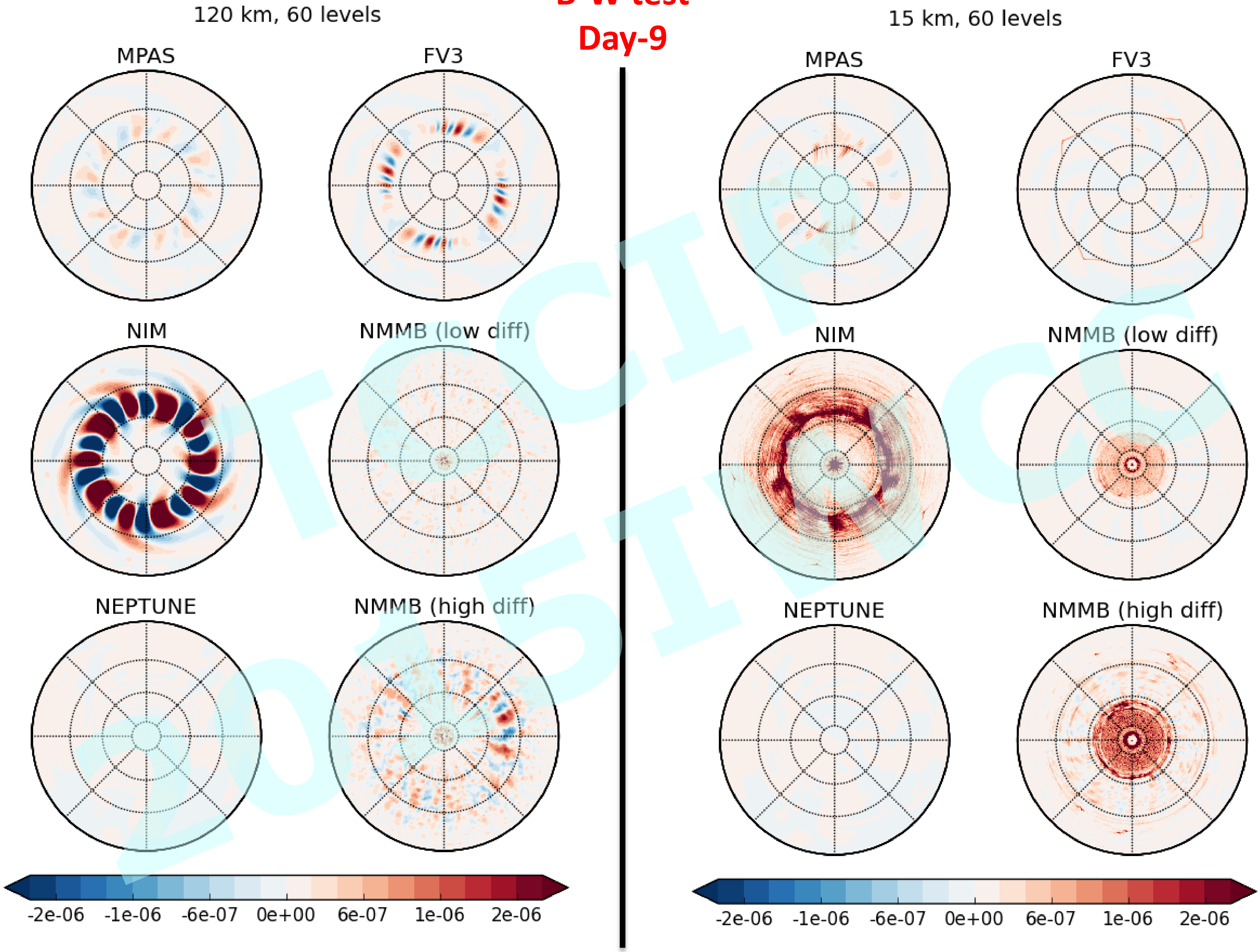


B-W test
Day-9



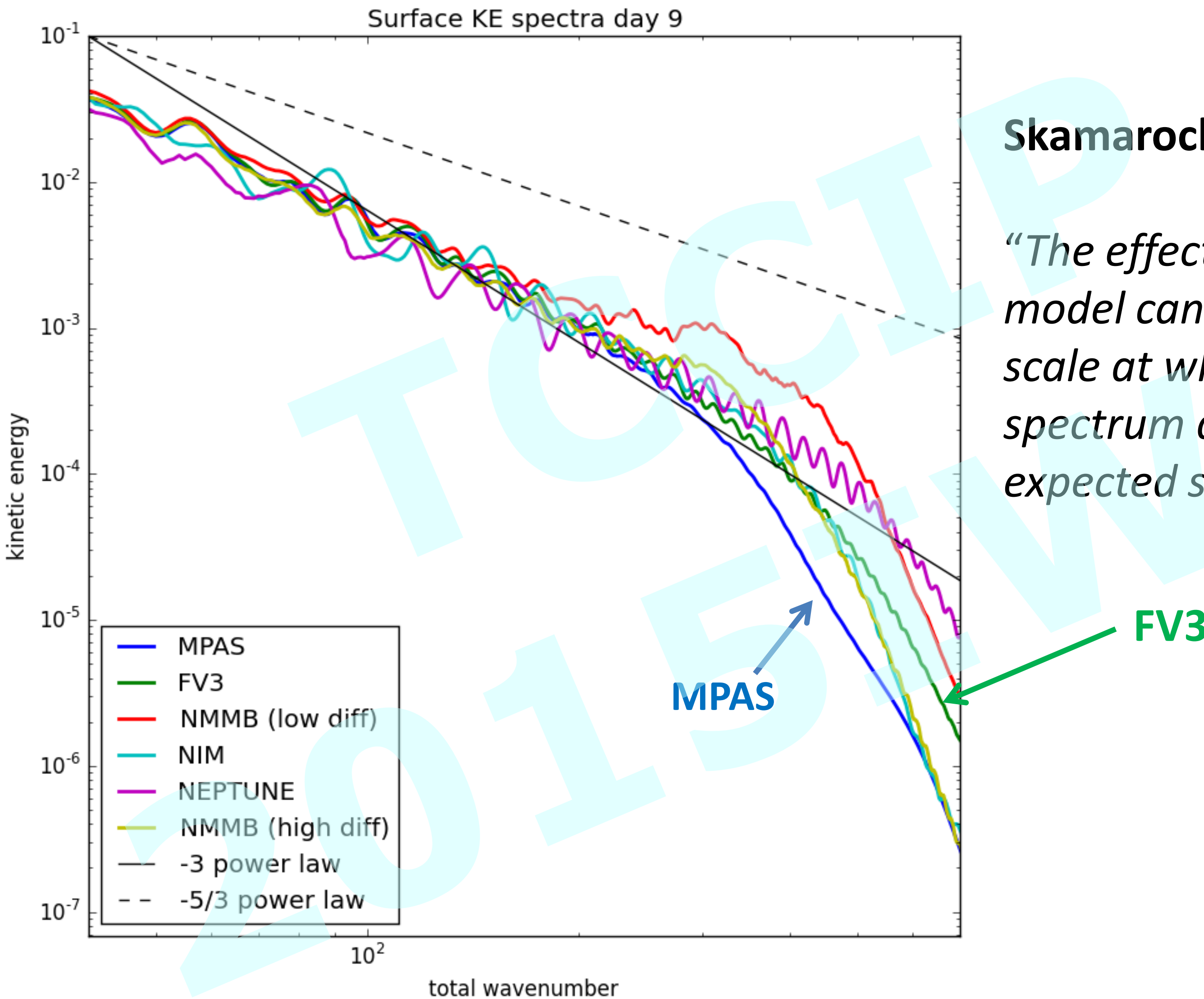
120 km, 60 levels
MPAS
FV3
NIM
NMMB (low diff)
NEPTUNE
NMMB (high diff)
-2e-04 -1e-04 -6e-05 0e+00 6e-05 1e-04 2e-04
15 km, 60 levels
MPAS
FV3
NIM
NMMB (low diff)
NEPTUNE
NMMB (high diff)
-2e-04 -1e-04 -6e-05 0e+00 6e-05 1e-04 2e-04

B-W test
Day-9



120 km, 60 levels
MPAS
FV3
NIM
NMMB (low diff)
NEPTUNE
NMMB (high diff)
-2e-06
-1e-06
-6e-07
0e+00
6e-07
1e-06
2e-06
15 km, 60 levels
MPAS
FV3
NIM
NMMB (low diff)
NEPTUNE
NMMB (high diff)
-2e-06
-1e-06
-6e-07
0e+00
6e-07
1e-06
2e-06

Lowest layer KE spectrum from the 30-km Baroclinic wave test (HIWPP report , J. Whitaker, 2014)

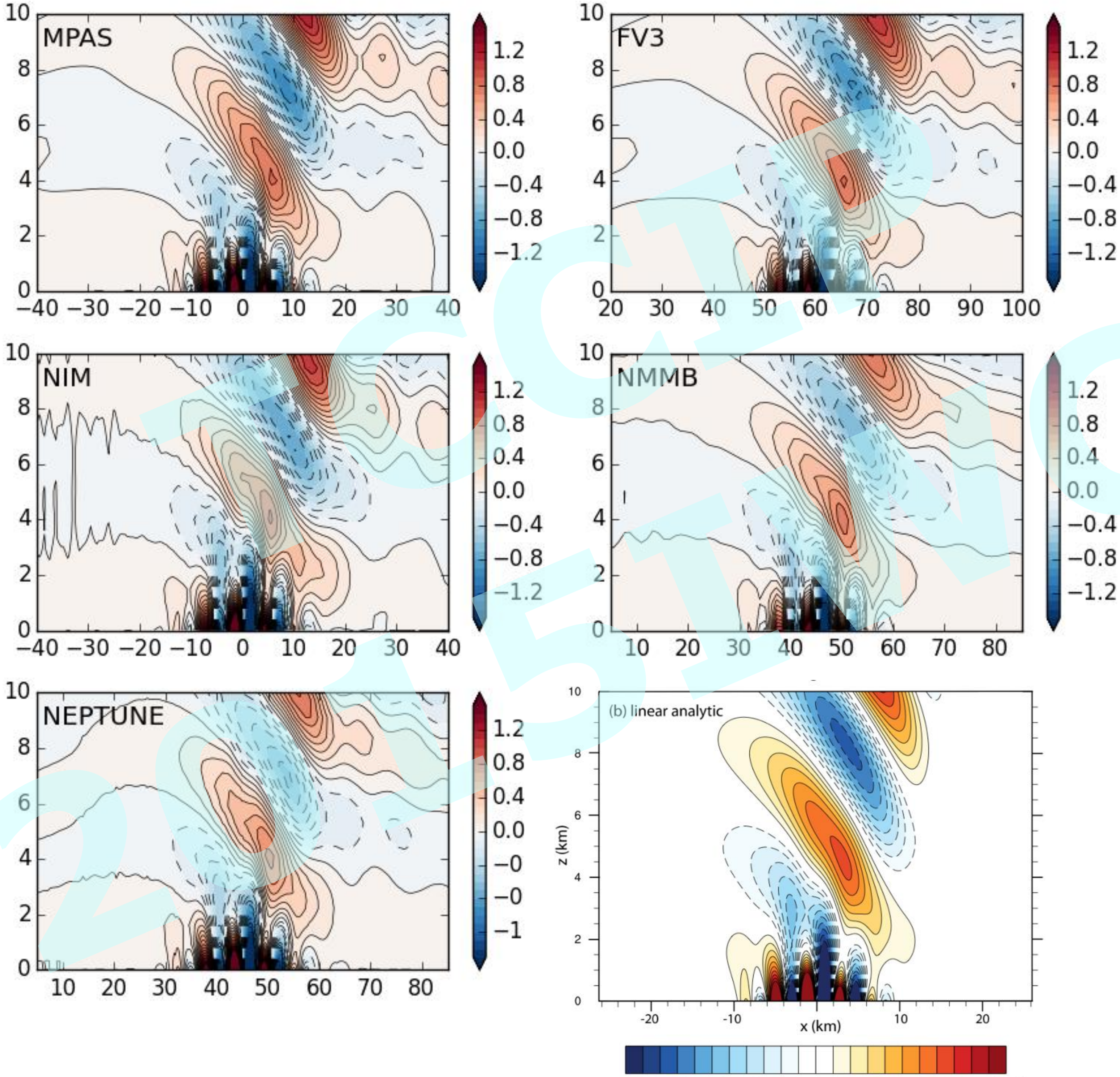


Skamarock (2004, MWR):

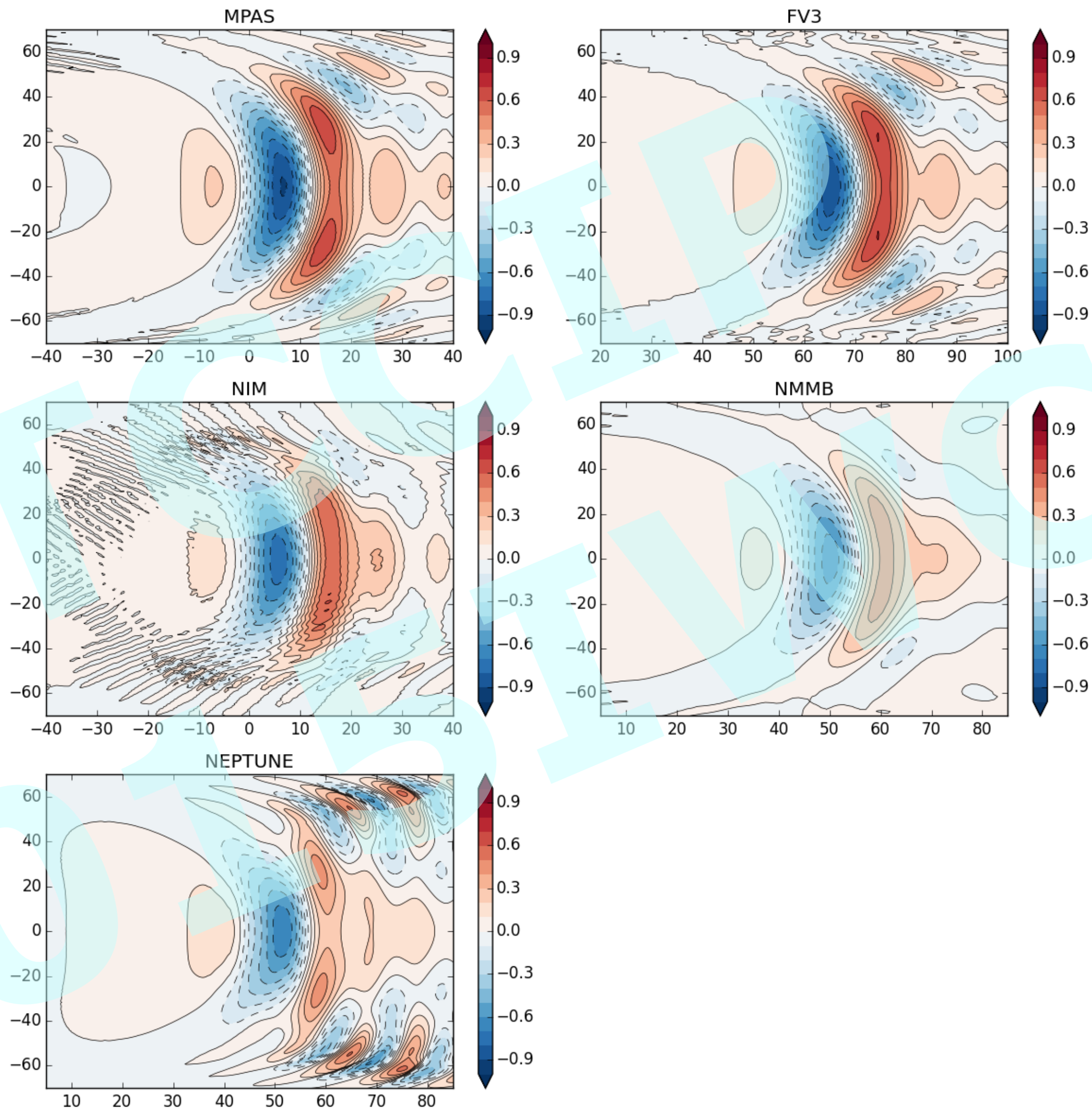
"The effective resolution of a model can be defined as the scale at which the model spectrum decays relative to the expected spectrum"

Mountain wave test (constant flow over ridge mountain)

Δx ~ 700 m
Δz ~ 500m

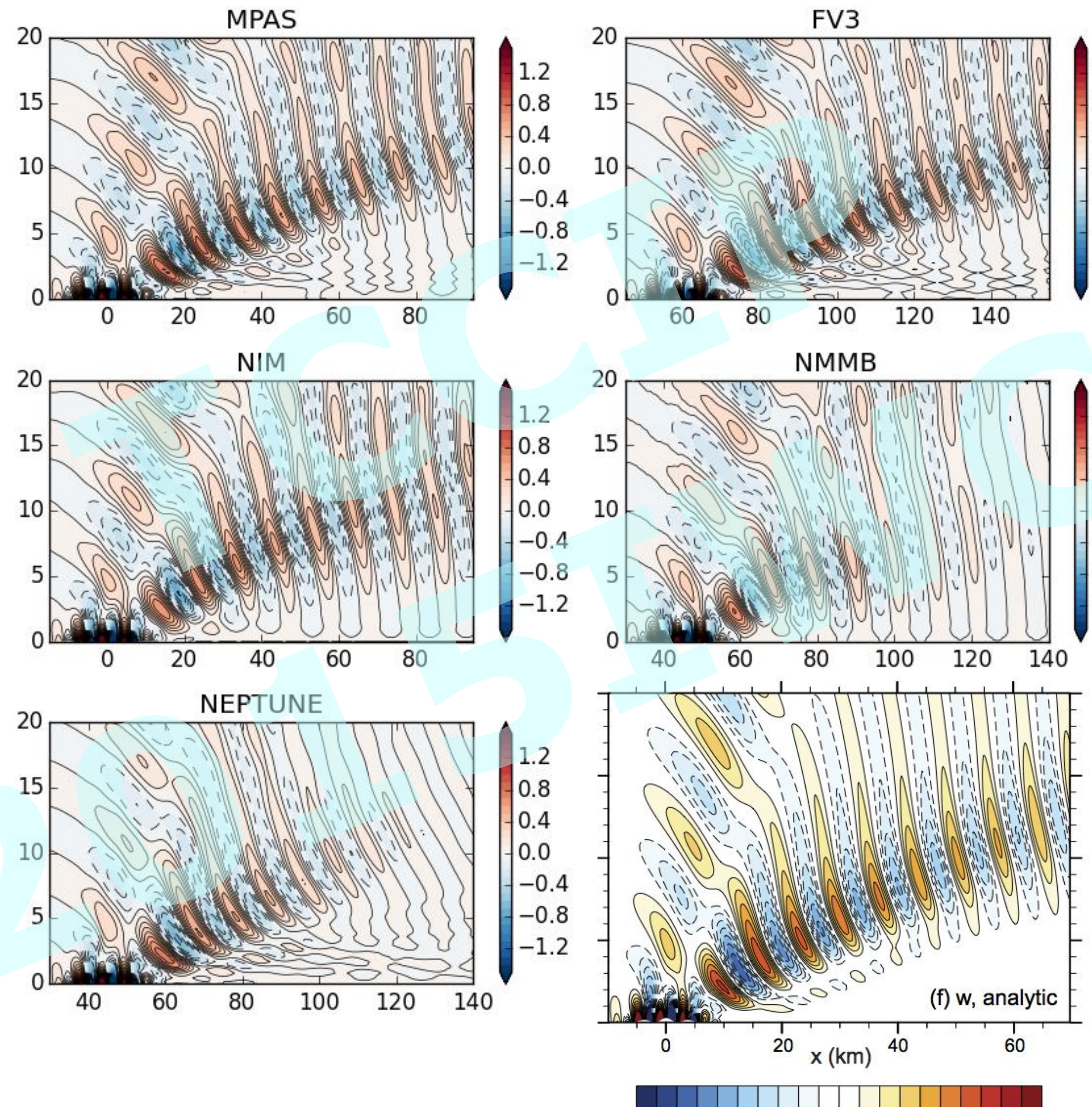


Mountain wave test (constant flow over ridge mountain)



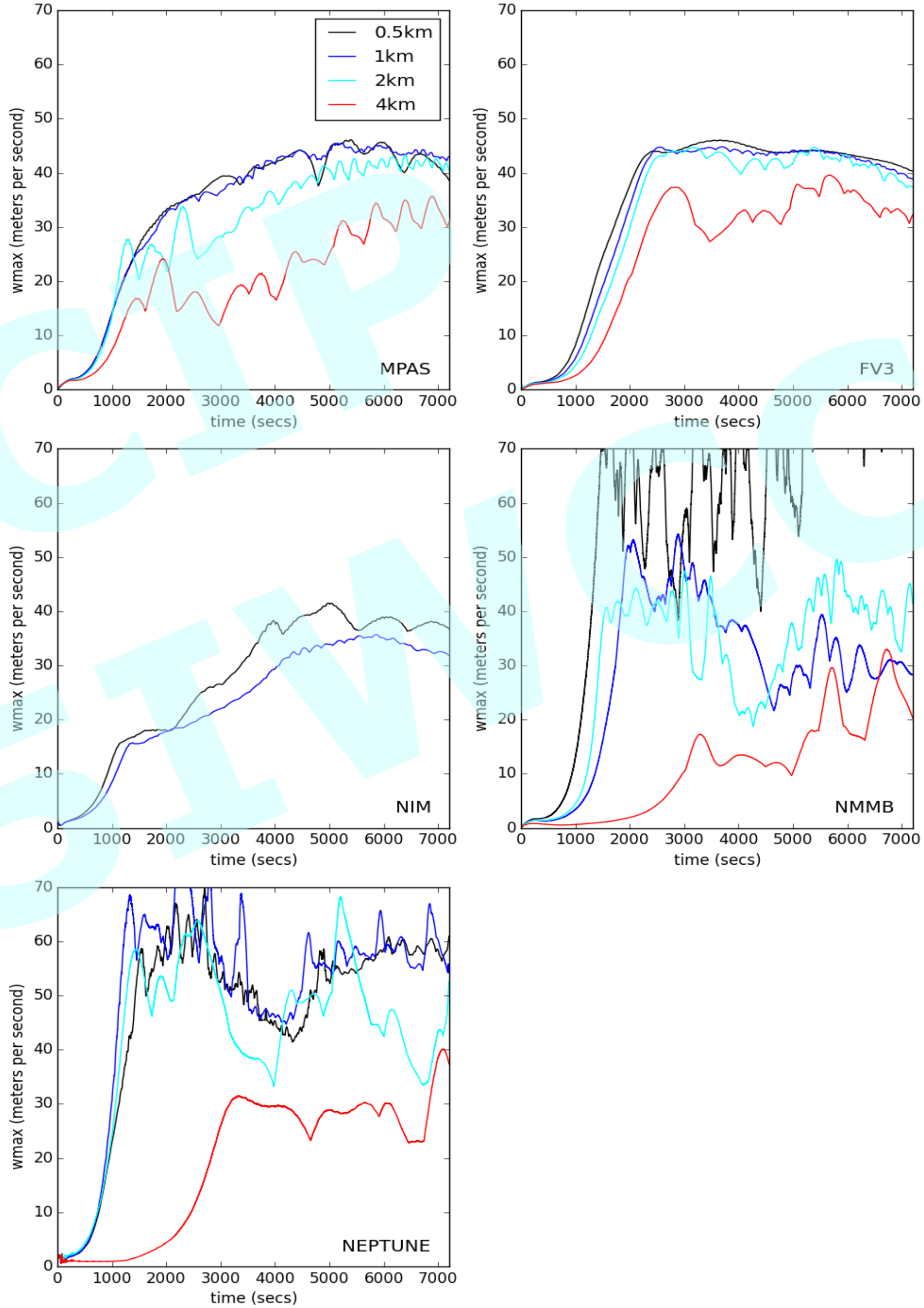
Mountain wave test (sheared flow over circular mountain)

$\Delta x \sim 350$ m
$\Delta z \sim 250$ m



Maximum updrafts (m/s)

HIWPP Super-cell test cases



Summary:

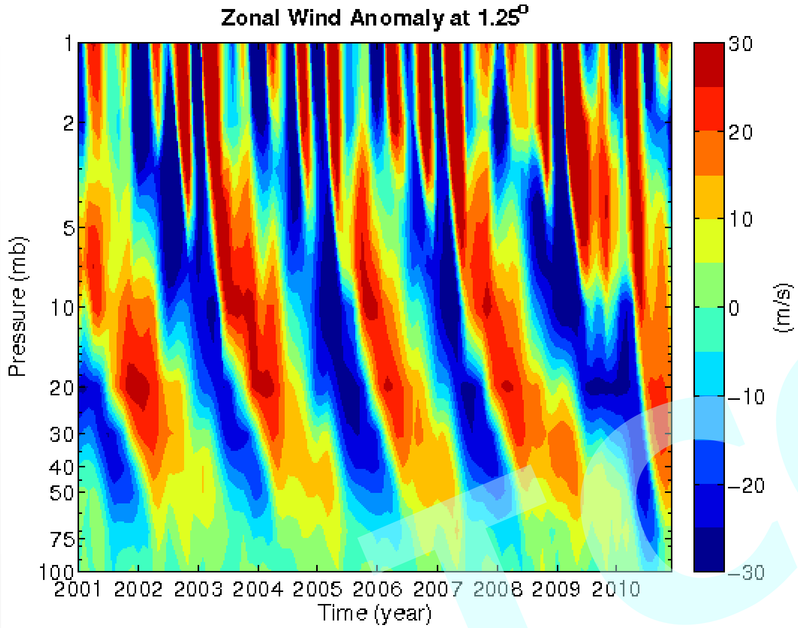
- GFDL is building a unified weather-climate modeling system based on the switchable non-hydrostatic FV3 dynamical core
- We plan to extend the FV3 dynamical core to use the “deep atmosphere equations” (instead of the current “shallow atmosphere” set)
- GFDL is an active participant of the OSTP funded project on the development of the Next Generation Prediction System (NGGPS) to be used operationally at NCEP for weather prediction from 0 to 30 days
- The HIWPP and NGGPS projects are extremely useful in revealing the strength and weakness of some of the well-known dynamical cores in the US – stay tuned!
- We are anticipating “the next big thing” in global weather-climate modeling – simulations and real-time predictions of supercell storms and tornadoes with a lead time of hours or even days

Extra slides

Multiple tornadoes simulated by GFDL's *variable-resolution* global model

- ~1 km resolution over Oklahoma, smoothly stretched to ~400 km over S. Indian ocean
- Warm-rain micro-physics
- Weisman & Klemp sounding (2002) with Toy (2012) quarter-circle hodograph wind profile
- 2^{o} C thermal bubble perturbation added to the mean state
- Computational cost: 3-hour simulation needs ~ 2 hours (wall clock) using 384 cores (on the NOAA climate machine: Gaea)

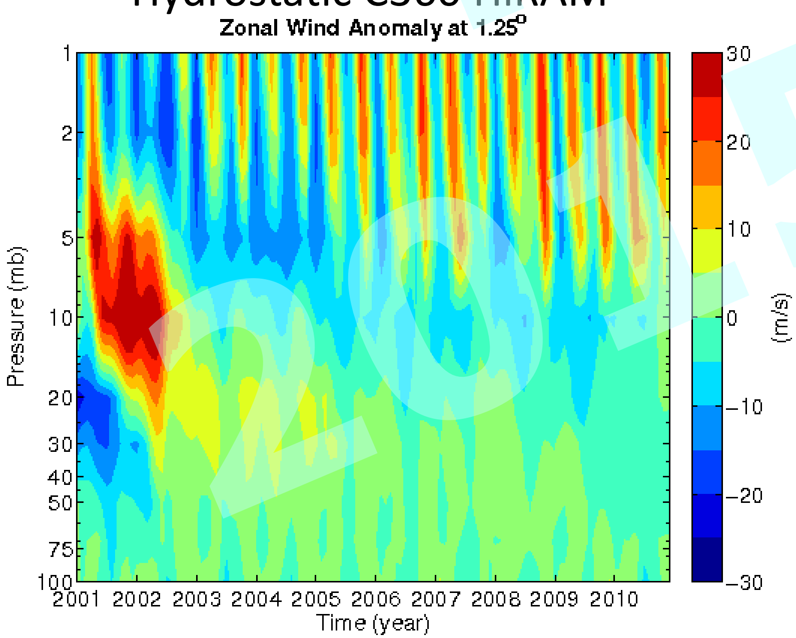
NASA Merra Data (analysis)



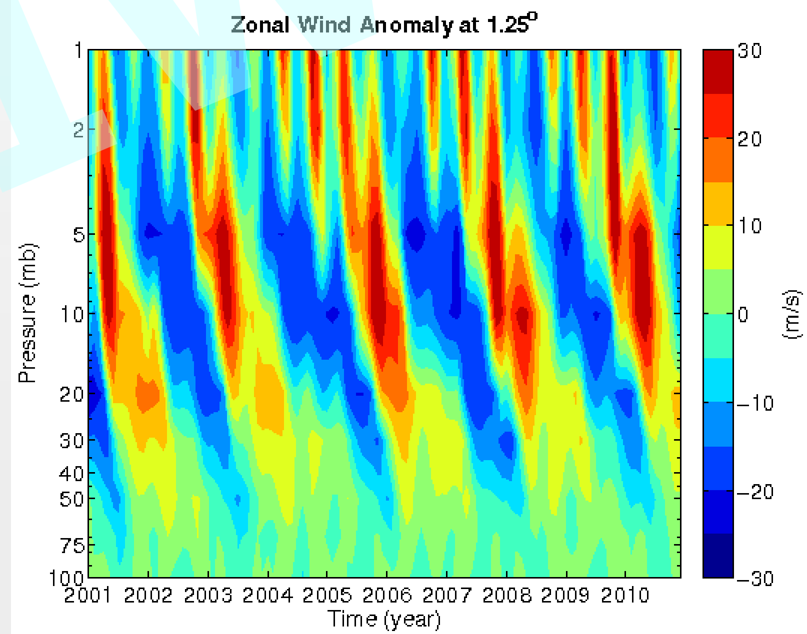
A dramatic (positive) impact of the non-hydrostatic dynamics:

- QBOs are extremely difficult to simulate in free-running GCMs with or without convective GWD
- QBOs are believed to have significant impacts to sudden warming, stratospheric ozone, and (some also believe) hurricanes & winter storms
- Decadal predictability is achievable with an initialized state and a good physical model

Hydrostatic C360 HiRAM

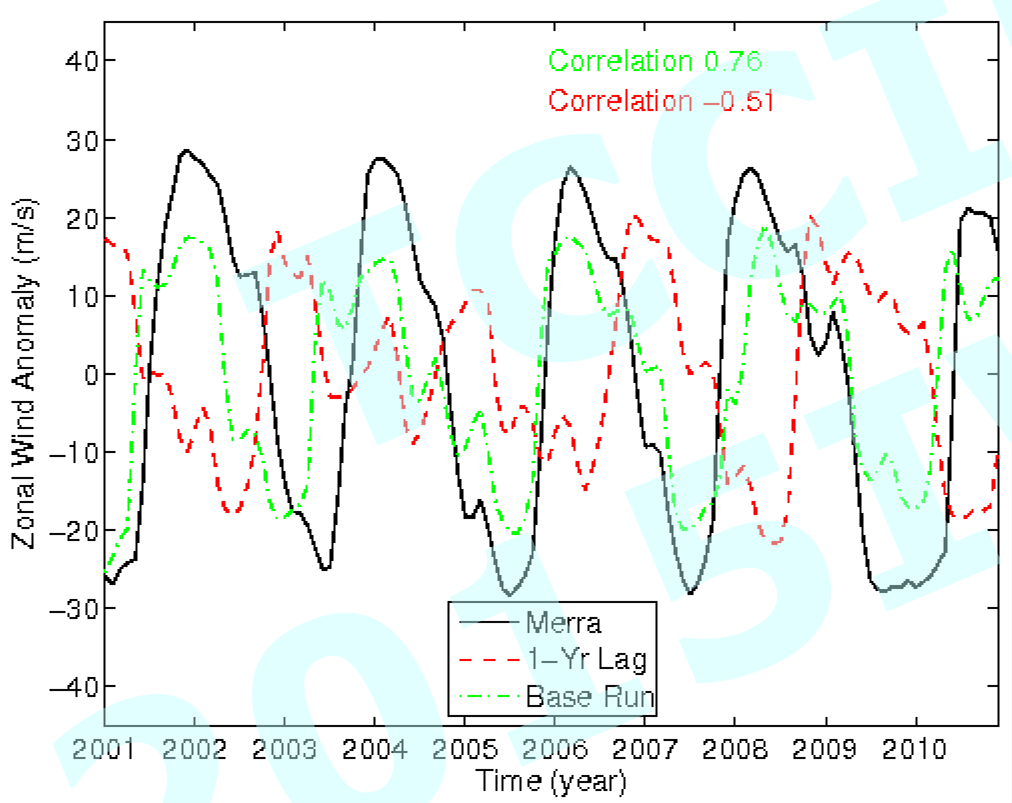


Non-hydrostatic C360 HiRAM



Zonal-wind: correlation (2001-2011):

model predictions vs. Observed (20 mb)



Obs (Merra analysis)

Initialized prediction

Prediction with 1-yr shifted IC (off-phase)