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Research and Development in Numerical Weather Prediction at NRL

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16th Conference on Weather Analysis and Forecasting
Central Weather Bureau
Oct 2016

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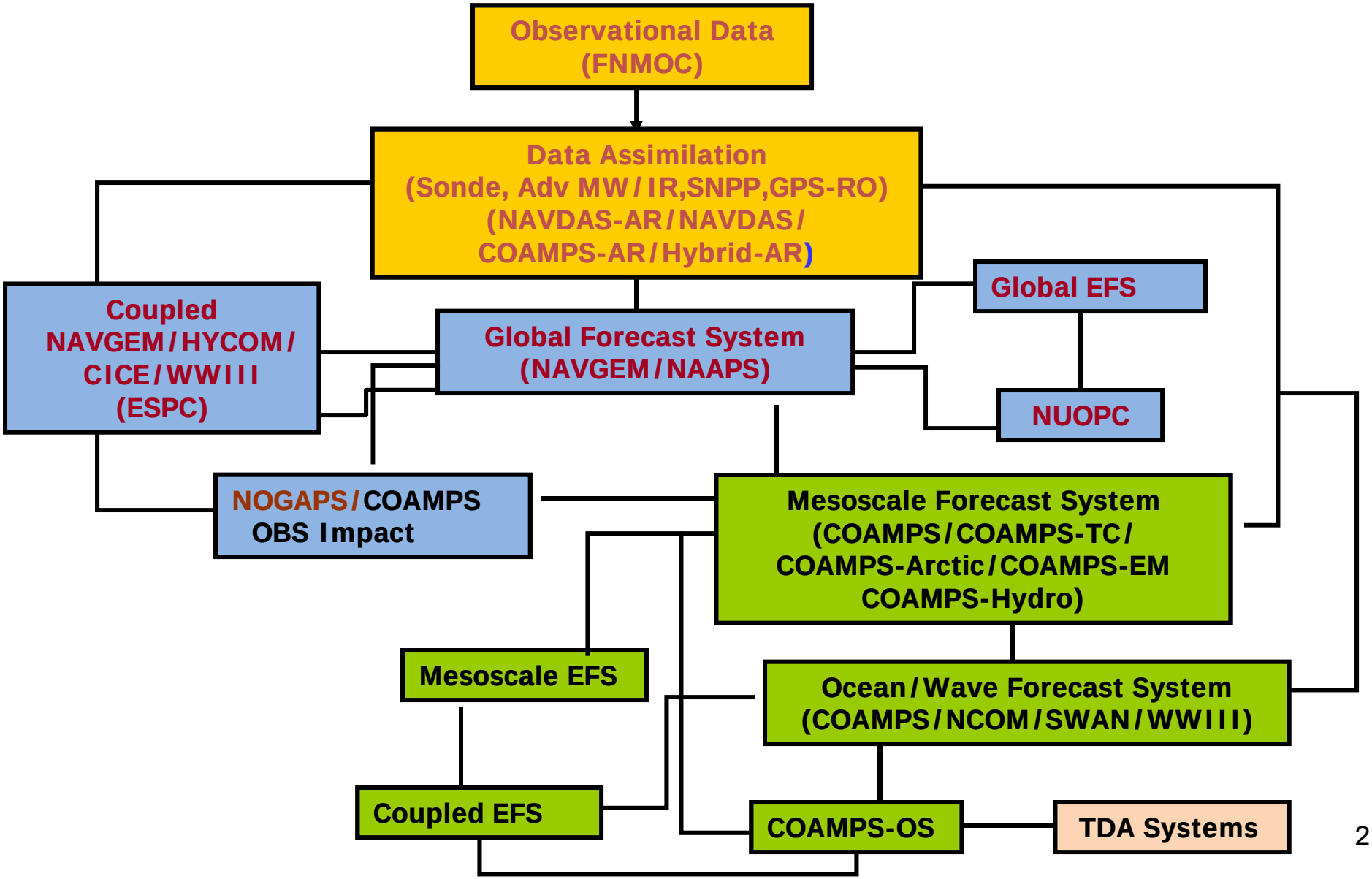
Overview of NRL/FNMOC Systems



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Recent and Future DA and NWP Development

- Hybrid 4D VAR DA in operational test
  - Combination of ensemble DA and 4D-VAR system
- NAVGEM v1.3.1 (Oct 2015)
  - T425L60 (31km)
  - GeoCSR assimilation (GOES-13 and -15, Meteosat-07 and -10, and MTSAT2)
  - CrIS assimilation
- NAVGEM V2.0 (Oct 2017)
  - T681L80 (19km)
  - Computational efficient
- NAVGEM V3.0 (Oct 2018)
  - T1035L100 (13km)
  - GFS physics
  - Reordering of physics
- COAMPS-TC
  - Operation since 2013
  - Upgrade of the system every year
- Navy global coupled system under ESPC
  - Fully coupled NAVGEM/HYCOM/CICE/WWIII
  - For extended range prediction
- Next generation model NEPTUNE
  - Spectral element dynamic core

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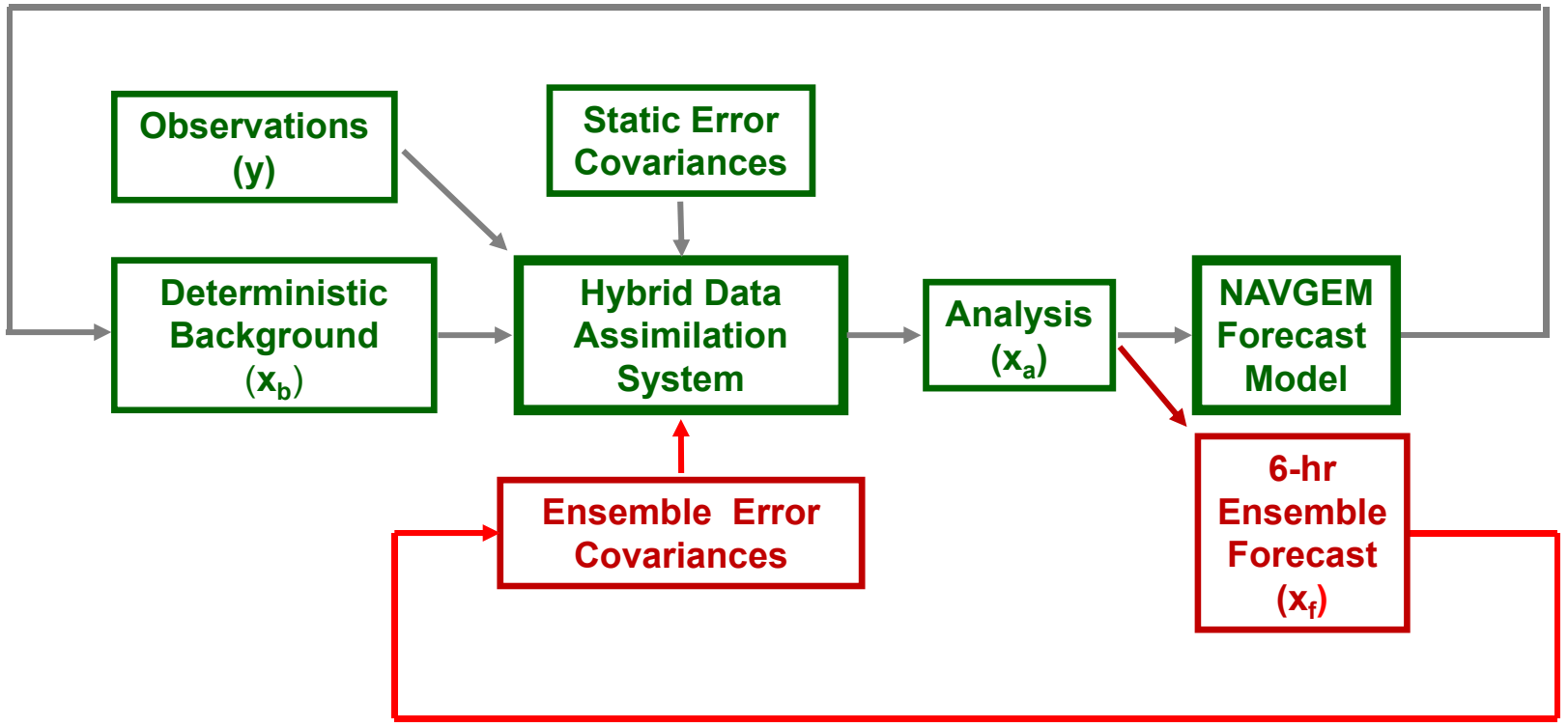
Hybrid 4DVar System

Model forecast becomes the Background for subsequent DA cycle



*New components for **Hybrid 4DVar** are shown in **red**

"Hybrid Data Assimilation system" includes finding an optimal way to combine static and *flow-dependent* ensemble error covariances.

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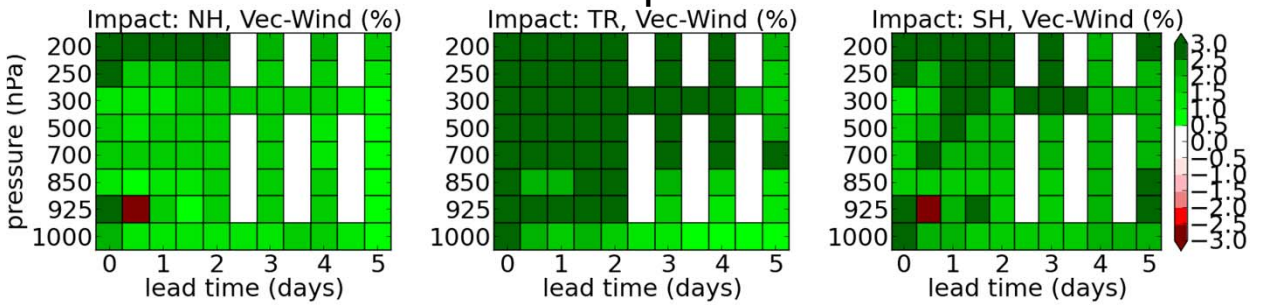
Hybrid-4DVAR

Fall/Winter 2014: Oct. 10, 2014-Jan. 7, 2015
90-day Benchmark Testing: NAVGEM 1.4 hybrid DA system
Comparison between NAVDAS-AR 1.3.1 and NAVGEM 1.4 (α =0.25)

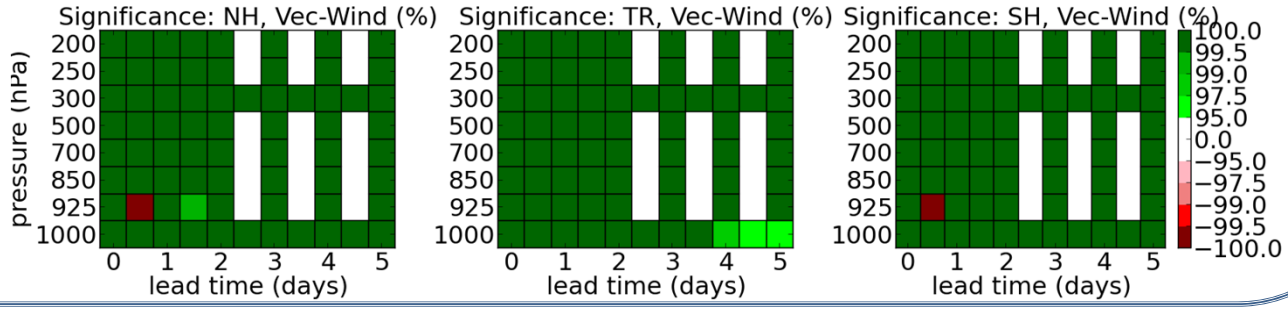
$$\mathbf{P}^{\mathbf{f}} = \alpha \mathbf{P}^{\mathbf{f}}_{ENS} + (1-\alpha)\mathbf{P}^{\mathbf{f}}_{CONV}$$

NAVGEM 1.3.1 vs. NAVGEM 1.4 Hybrid-AR α =0.25
Vector-Winds verified with ECMWF analysis

Forecast Impact



Statistical Significance



Green Shading ➔ NAVGEM 1.4 is better; Red Shading ➔ NAVGEM 1.3.1 is better

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Performance of Hybrid DA

FNMOC NAVGEM Scorecard

Comparison of 1.3.1 vs. 1.4

Fall/Winter 2014/15 (~OND) α=0.25

Total Score=8

Self Analysis/Radiosonde Verification

Reference	Level	Region	Variable	Lead time	Level type	Metric	Weight	Score
Fixed Buoy	None	Northern Hemisphere	Wind Speed	72	surface	Mean Error	2	0
Fixed Buoy	None	Southern Hemisphere	Wind Speed	72	surface	Mean Error	2	0
Fixed Buoy	None	Tropics	Wind Speed	72	surface	Mean Error	2	0
Radiosondes	100.0	Global	Geopotential Height	72	pressure	RMS Error	1	+1
Radiosondes	250.0	Global	Air Temperature	72	pressure	RMS Error	1	0
Radiosondes	250.0	Global	Wind	72	pressure	Vector RMS Error	1	0
Radiosondes	500.0	Global	Geopotential Height	72	pressure	RMS Error	1	0
Radiosondes	850.0	Global	Air Temperature	72	pressure	RMS Error	1	0
Radiosondes	850.0	Global	Wind	72	pressure	Vector RMS Error	1	0
Self Analysis	200.0	Northern Hemisphere	Wind	72	pressure	Vector RMS Error	1	0
Self Analysis	200.0	Tropics	Wind	72	pressure	Vector RMS Error	1	0
Self Analysis	500.0	Northern Hemisphere	Geopotential Height	96	pressure	Anomaly Correlation	4	+4
Self Analysis	500.0	Southern Hemisphere	Geopotential Height	96	pressure	Anomaly Correlation	1	+1
Self Analysis	850.0	Northern Hemisphere	Wind	72	pressure	Vector RMS Error	1	0
Self Analysis	850.0	Tropics	Wind	72	pressure	Vector RMS Error	2	0
Self Analysis	1000.0	Northern Hemisphere	Geopotential Height	96	pressure	Anomaly Correlation	1	+1
Self Analysis	1000.0	Southern Hemisphere	Geopotential Height	96	pressure	Anomaly Correlation	1	+1

5% RMS error thresholds apply to all scores except anomaly correlation

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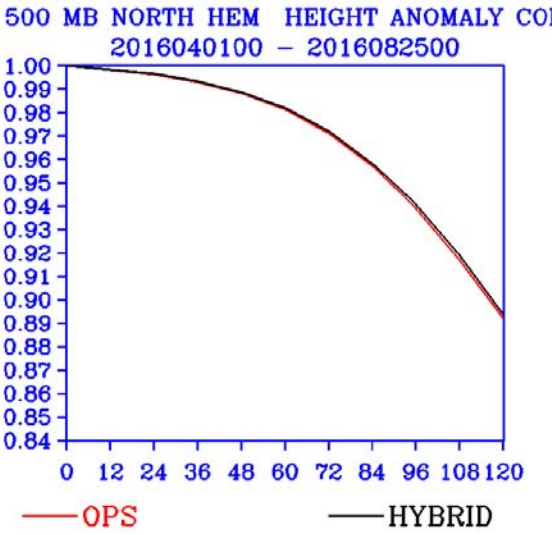
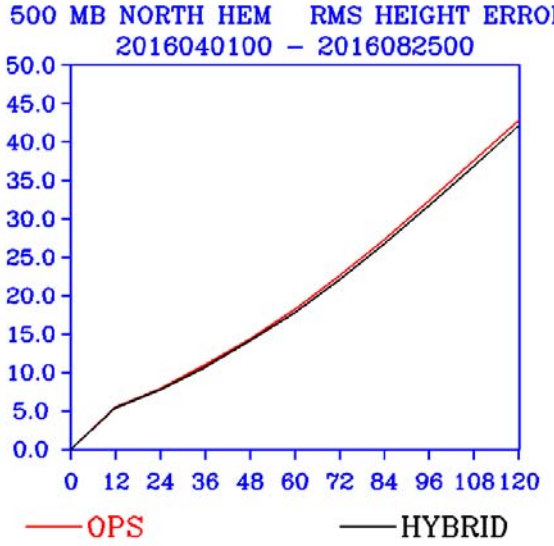
T425L60 NAVGEM (version 1.4)

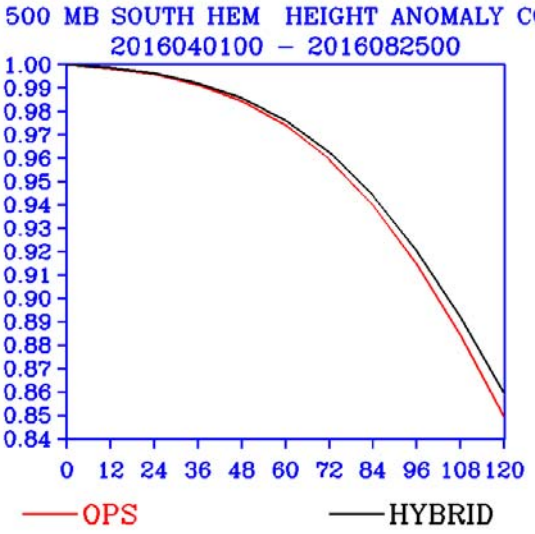
OPS VERSUS HYBRID ANALYSIS

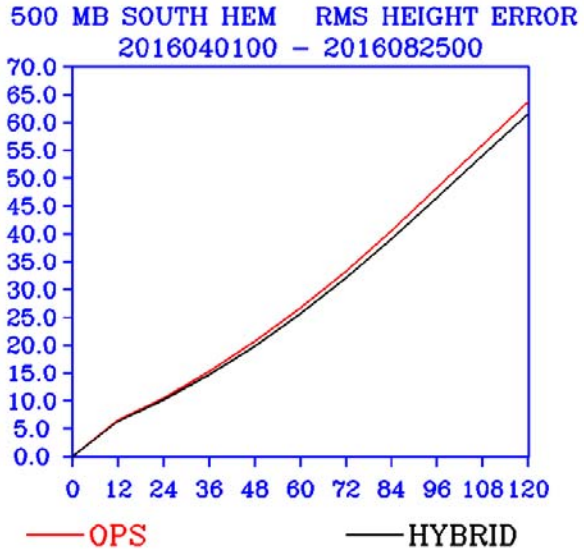
500 mb Northern Hemisphere Height Anomaly Correlation and RMS Error

April 1, 2016 – August 25, 2016









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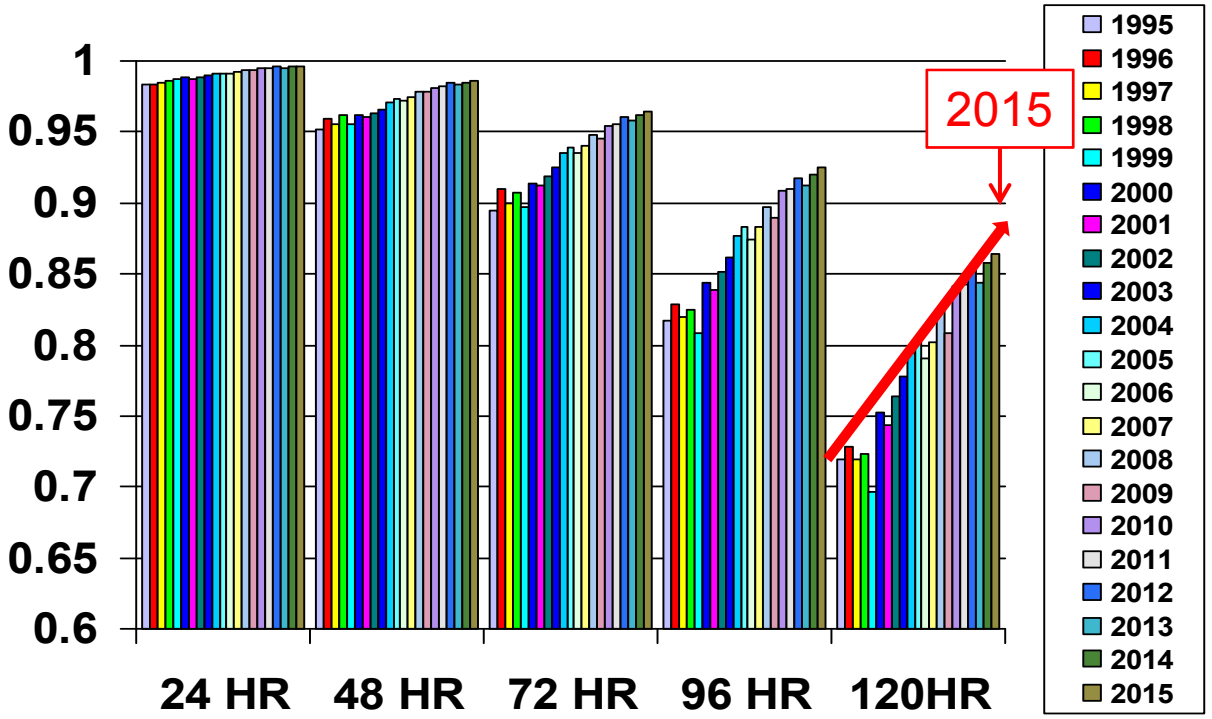
NOGAPS/NAVGEM

NOGAPS/NAVGEM Annual Mean Forecast Statistics

N. Hemisphere 500 hPa Heights

Anomaly Correlation



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NAVGEM

FY15-16 Accomplishments

- NAVGEM 1.3 operation June 2015 (T425L50)
- NAVGEM 1.3.1 operation Oct 2015
- NAVGEM 1.2.3 EPS operation May 2015
- NAVGEM 1.3.2 EPS currently OPTEST
- ESPC Coupled NAVGEM/HYCOM/CICE system
- NAVGEM 1.4 T425L50 with Hybrid-4DVar (OPS test now)
- NAVGEM 1.4.1 Correlated obs error and new data

FY17-18 Plans

- NAVGEM 2.0 T681L80 (19km) 4Q FY17
- NAVGEM 1.3.2 T325L50 EFS transition 2Q FY16
- NAVGEM 3.0 T1025L100 (13km) 4QFY18 (RTP)
- Interactive Aerosol System 4QFY18
- ESPC Fully Coupled NAVGEM/HYCOM/CICE system IOC 4QFY18

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NAVGEM Version 1.3 (operation in Oct 2015)

Data Assimilation

- SSMIS Upper Atmosphere Sounding (UAS) data assimilation
- GPS-RO addition of GRACE-B and TanDEM-X
- SNPP VIIRS Atmospheric Motion Vectors

Forecast Model

- T425L60 resolution (31km)- Reduced Gaussian grids
- Advection of perturbation potential temperature
- Zenith angle correction for more accurate solar radiation
- Improved turbulent mixing scheme EDMF and cloud scheme
- LIS soil moisture initialization
- New snow albedo
- New stratospheric water vapor photochemistry
- Stratospheric humidity quality control
- New non-orographic gravity wave drag

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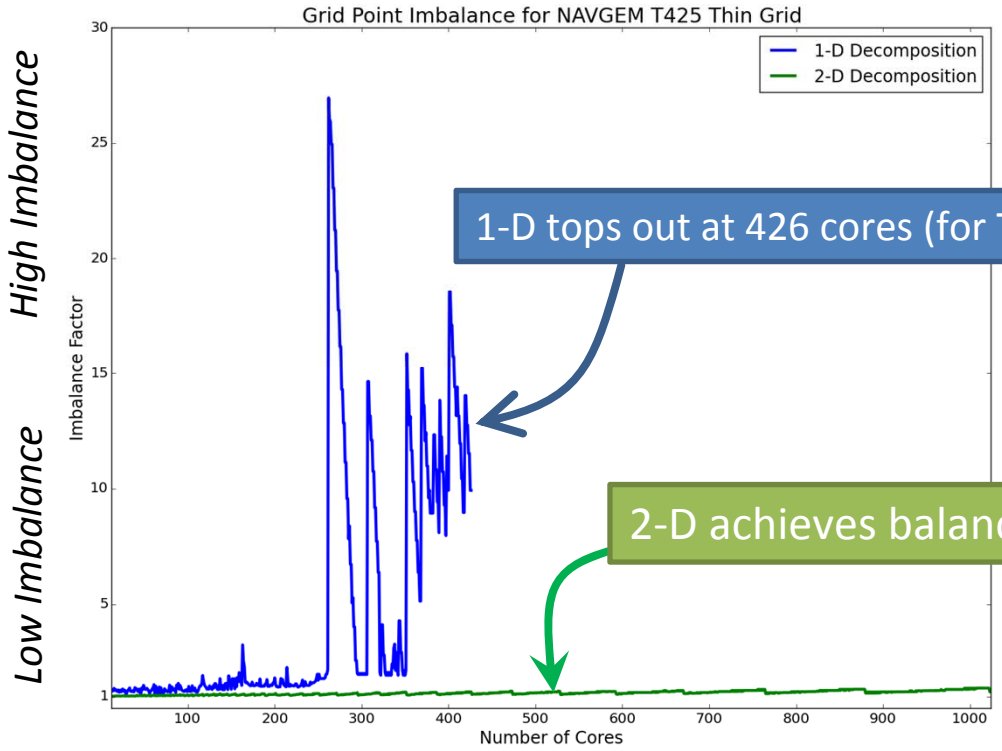
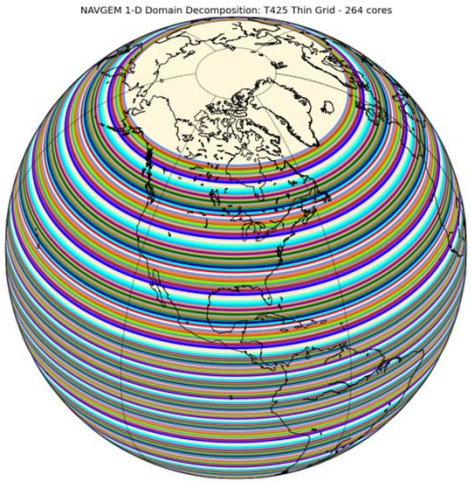
High-Resolution NAVGEM

T425 Load Balance





Current 1-D domain decomposition shows significant challenges to grid point load balancing after 264 cores which is almost entirely mitigated with the 2-D decomposition.

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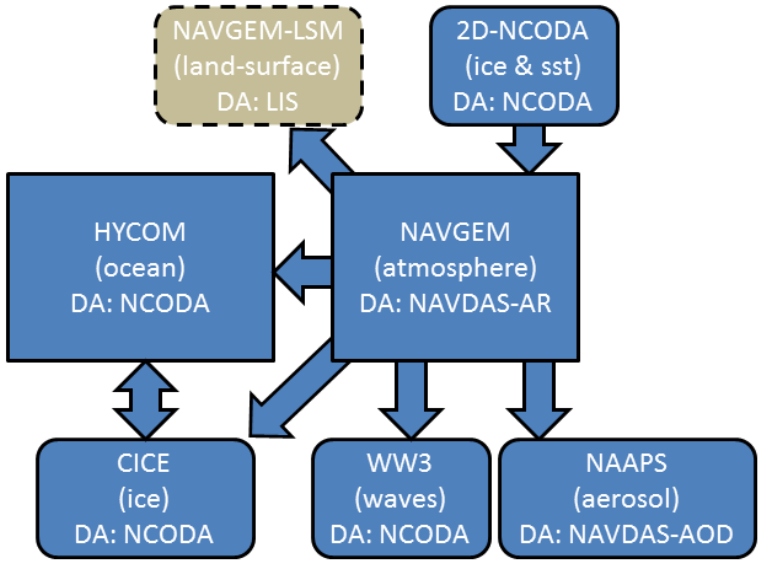
Navy ESPC Coupled System

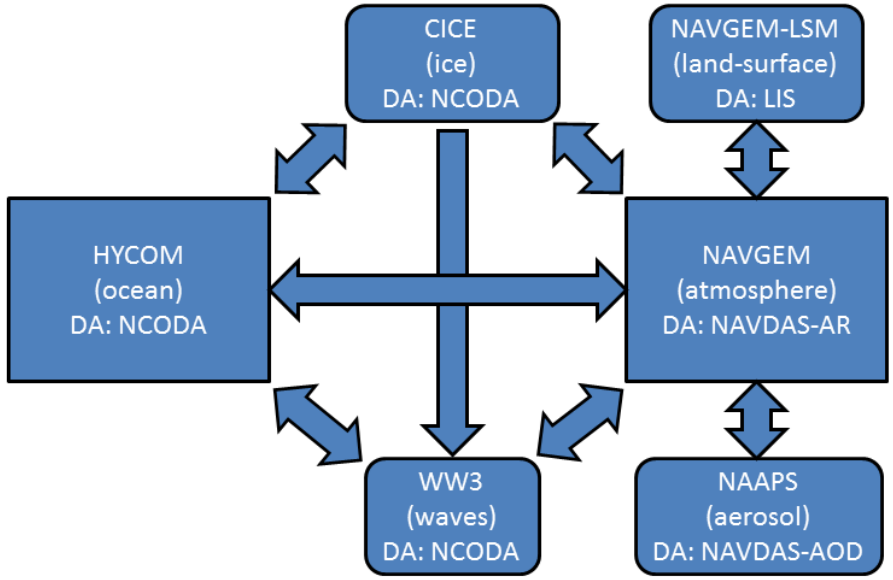
Infrastructure for the Fully Coupled System

- Define implementation across operational systems, architecture requirements, cycling setup including DA

Current Uncoupled System



Fully Coupled System



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MJO Hindcast Experiments – ESPC Coupled System

November 2011 Rainfall

Rainfall Hovmöller Plots (Time/Longitude)

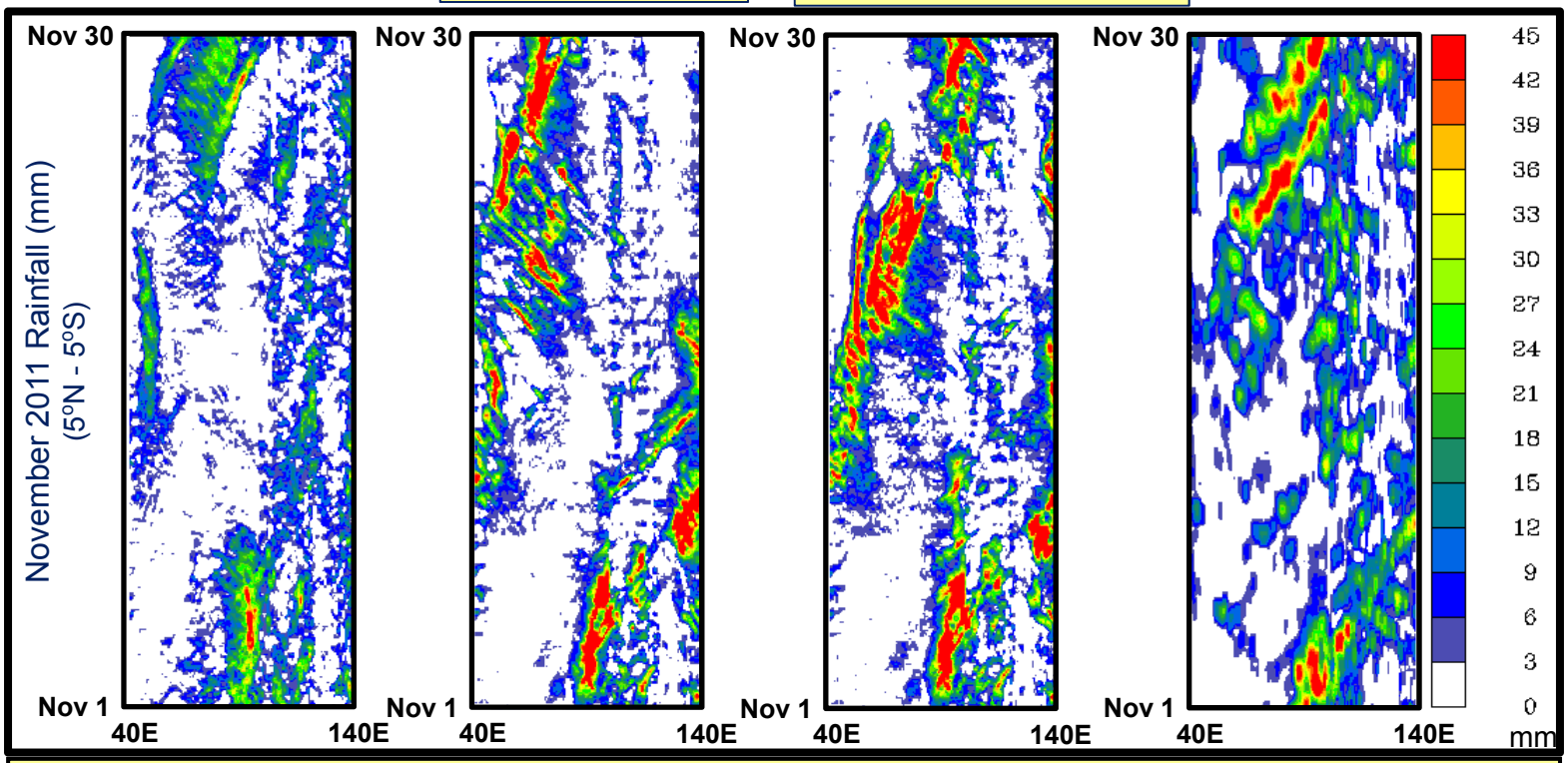
Simplified Arakawa-Schubert (NAVGEM 1.1)

Modified Kain-Fritsch / updated EDMF and Xu-Randall Cloud Fractions

With NAVGEM Louis et al. (1982) air-sea fluxes

With HYCOM modified COARE 3.0 air-sea fluxes

TRMM Retrieval



MJO hindcast performance for our DYNAMO period tests has continued to improve through physics development.

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ESPC Operational Implementation Design

Projected horizontal and vertical resolutions of the individual ESPC system components at IOC in 2018

Forecast	Time Scale, Frequency	Atmosphere NAVGEM	Ocean HYCOM	Ice CICE	Waves WW3	Land-Surface NAVGEM-LSM	Aerosol NAAPS
Deterministic short term	0-10 days, daily	19 km 80 levels (T681L80)	1/25° (4.5 km) 41 layers	1/25° (4.5 km)	1/8° (14 km)	3/16° (19 km)	3/16° (19 km)
Deterministic long term	0-30 days, weekly	19 km 80 levels (T681L80)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	3/16° (19 km)	3/16° (19 km)
Probabilistic long term	0-90 days, weekly	37 km 50 levels (T359L50)	1/12° (9 km) 41 layers	1/12° (9 km)	1/4° (28 km)	1/3° (37 km)	1/3° (37 km)

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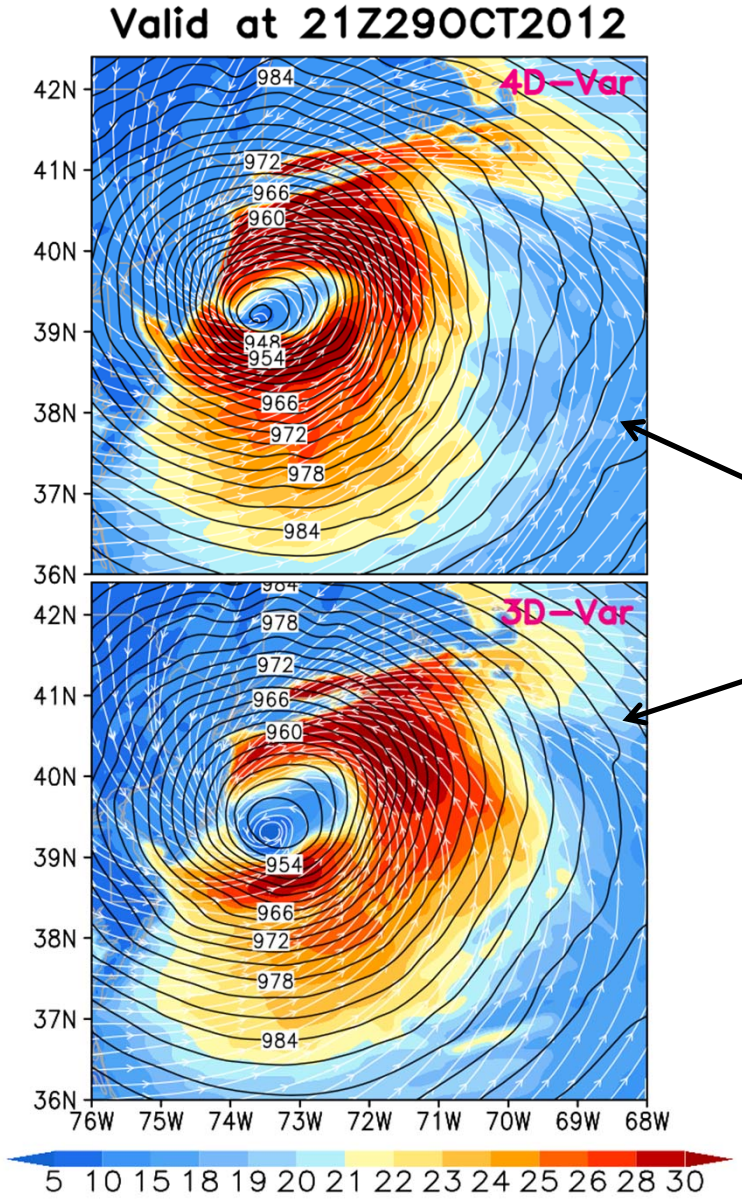
Atmospheric Data Assimilation

COAMPS-AR Analyses for Sandy



- COAMPS-AR → better intensity analysis and forecasts

- Warning info at 2012102912 is 945 mb at 36.9N and 71.0W
- Warning info at 2012102921 is 943 mb at 38.8N and 74.0W

- Top panel: COAMPS-AR (4D-Var) analysis minimum SLP of 945 mb, 9-hr forecast minimum SLP of 943 mb
- Bottom panel: NAVDAS (3D-Var) analysis minimum SLP of 960 mb, 9-hr forecast minimum SLP of 949 mb

- Sea Level Pressure (SLP) (black contours), 10m windspeed (shaded), and streamlines (white lines)
- Triple nested COAMPS run with 45 km (121x91x30), 15 km (121x121x30), and 5 km (151x151x30) grid-sizes

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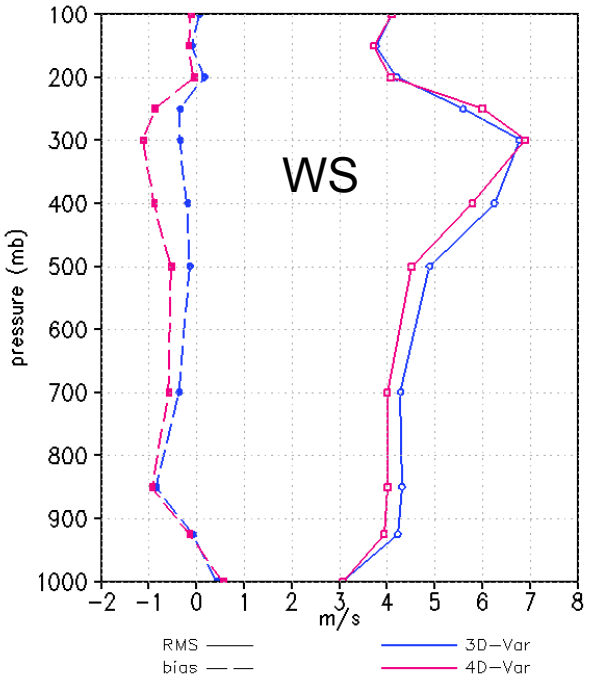
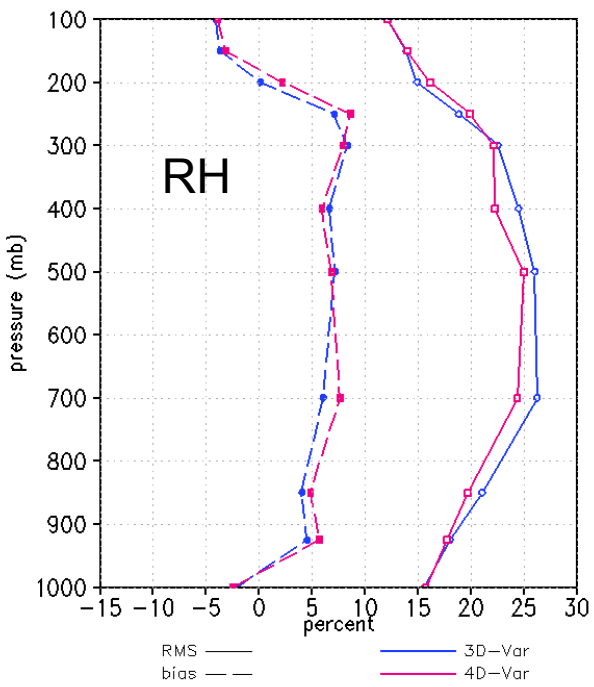
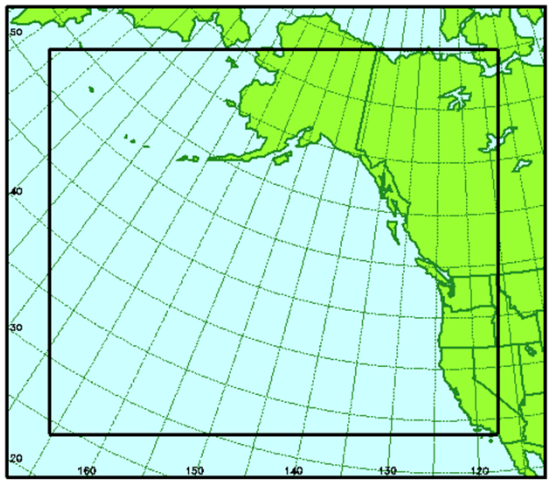
COAMPS 4DVar Verification







Nested domain used for evaluation

24 h COAMPS atmospheric model error measured against RAOBS for forecasts originating from 4DVar and 3DVar analyses. March 1-10 2016.

Consistent improvement out to 24 h in midlevel moisture and wind forecasts

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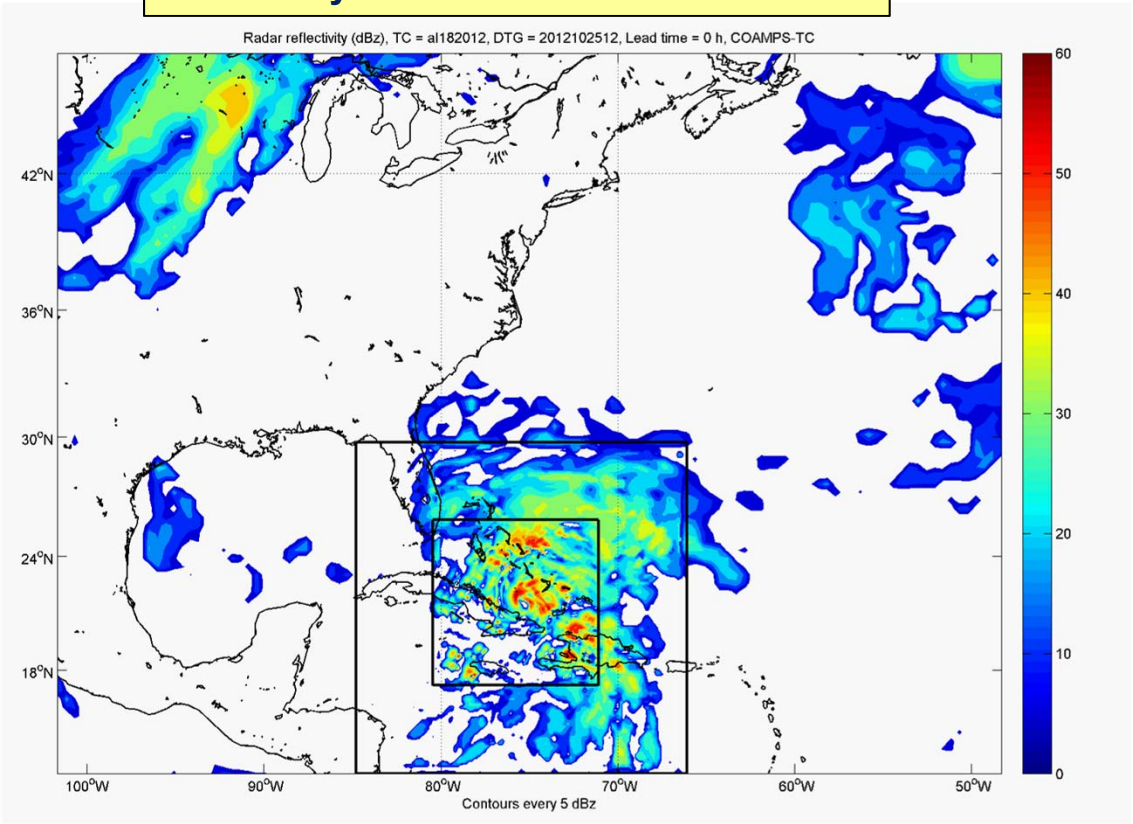
COAMPS-TC System Overview

- **Analysis:** Cold start from NAVGEM on large scale, insert balanced TC vortex
- **Atmosphere:** Three nests at 45/15/5 km, nonhydrostatic dynamics, TC physics
- **Ocean:** 3D-Var (NCODA), ocean (NCOM), wave (SWAN, Wave Watch III)
- **Ensemble:** COAMPS-TC EnKF DART, Coupled Ensemble Transform

Sandy (2012) simulated radar reflectivity from real-time forecast



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Key Scientific Accomplishments

- **COAMPS-TC is the top dynamical model in WPAC in 2015**
  - Remarkable improvements in COAMPS-TC in the past 3 years.
- **Improved initialization for TC vortex and larger scales**
  - Flexible vortex initialization method improved intensity spin-down issues.
- **Improved physical parameterizations for TCs**
  - Advancements to the PBL to better represent the surface drag at high winds.
  - Experimentation with high-resolution version, different physics & init.
  - New land surface parameterization implemented (NOAH).
- **Air-ocean coupling for COAMPS-TC in 2016**
  - Improved and evaluated COAMPS-TC coupling with NCOM.
- **COAMPS-TC ensemble system development**
- **COAMPS-TC Awards/Recognition**
  - NASA Group Achievement Award: NASA HS3 Team (2015)
  - Technology Transfer Royalty Award for COAMPS-TC (2015)
  - Arthur E. Bisson Prize for Naval Technology Achievement (2015)

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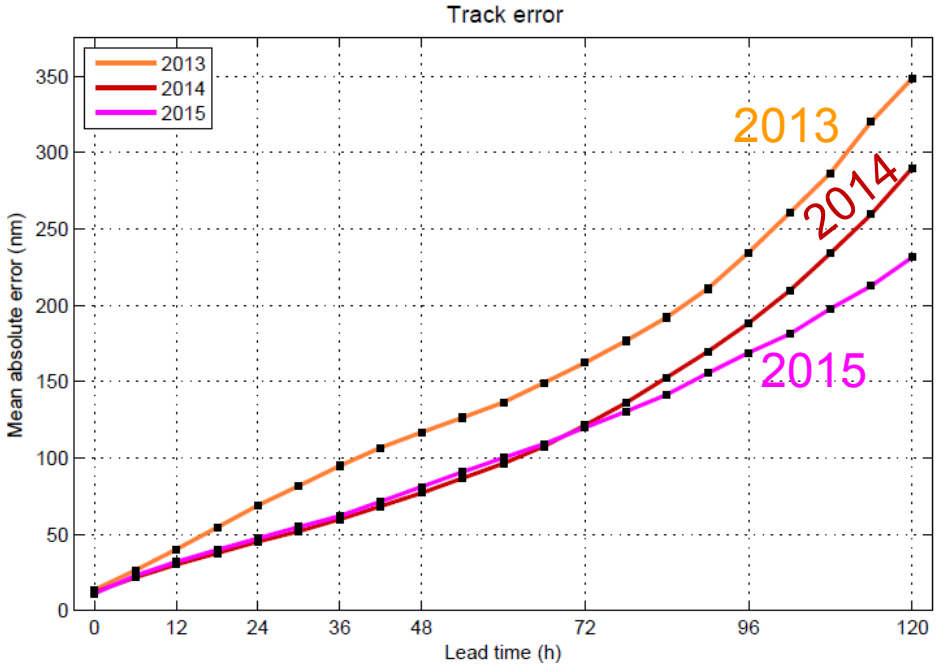
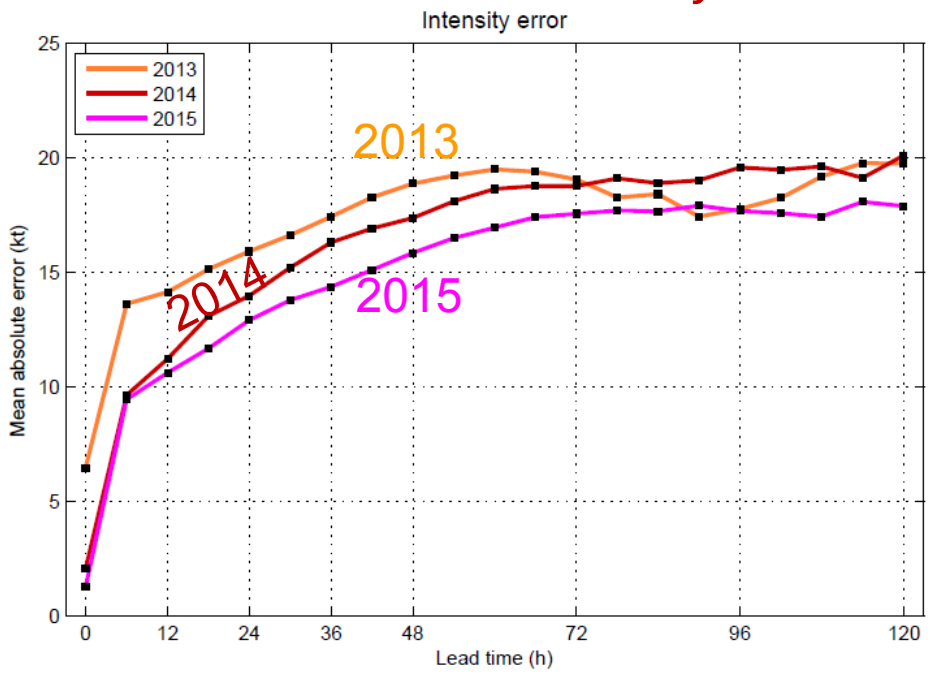
Significant Improvements

COAMPS-TC Track Error



COAMPS-TC Intensity Error



Significant improvements in COAMPS-TC in the past 3 years.

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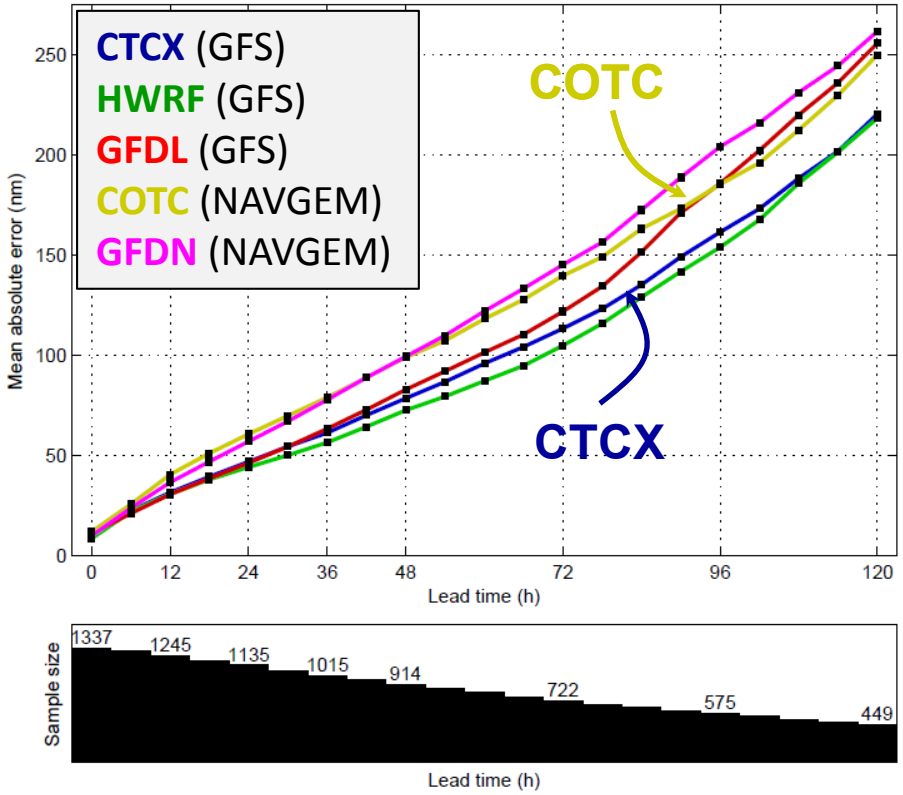
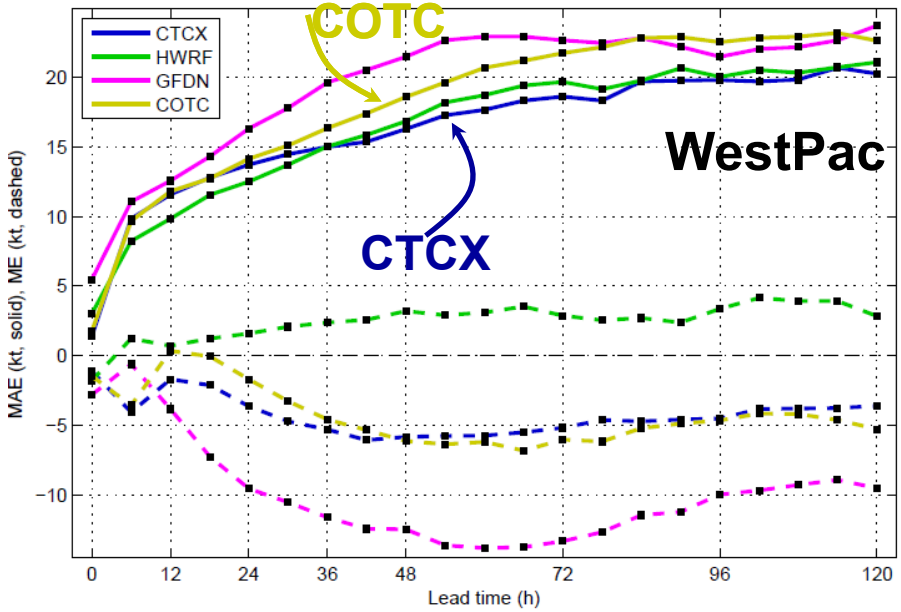
2015 Operational Statistics

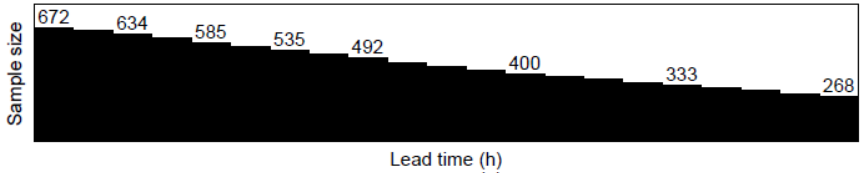
Atlantic, WestPac, CentPac, and EastPac

Position Error



Intensity Error & Bias





- For position, CTCX errors similar to HWRF and lower than GFDL. COTC track errors are similar to or better than GFDN.
- For intensity, CTCX has lowest errors for lead times beyond 48 h. COTC outperformed GFDN. Bias closer to zero than in 2014.
- Extremely large sample of cases in 2015 due to El Niño

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New Surface Drag Parameterization

Issue

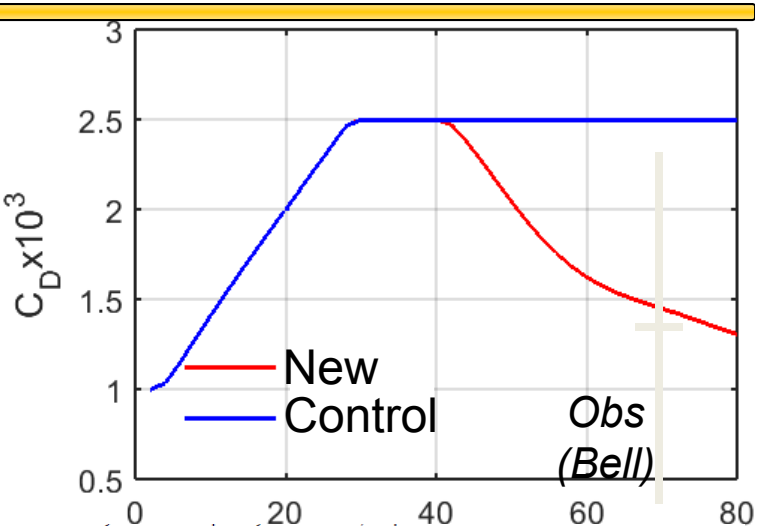
- Negative intensity bias for strong storms.
- Large uncertainties in Cd in high wind regime.

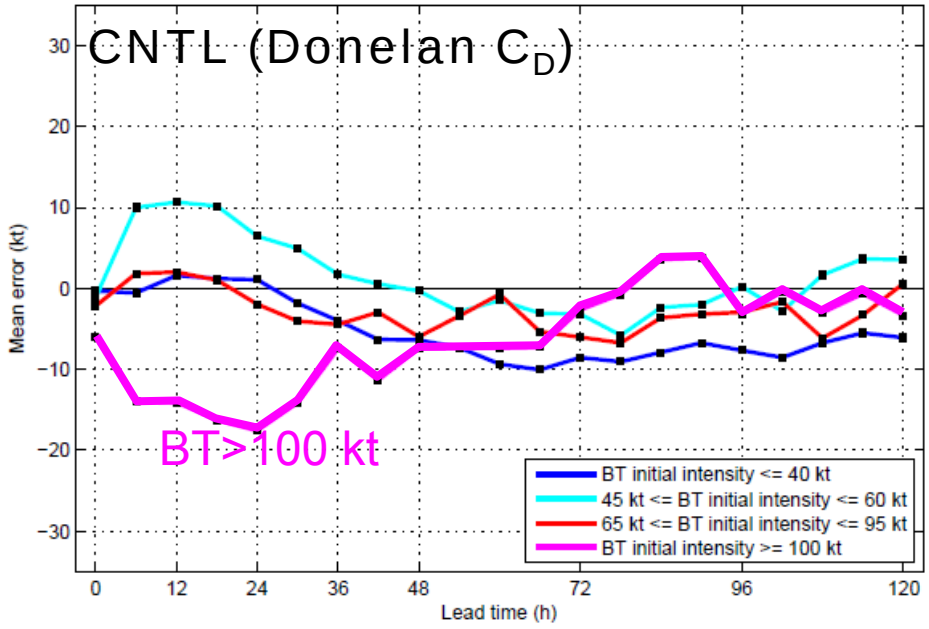
Solution

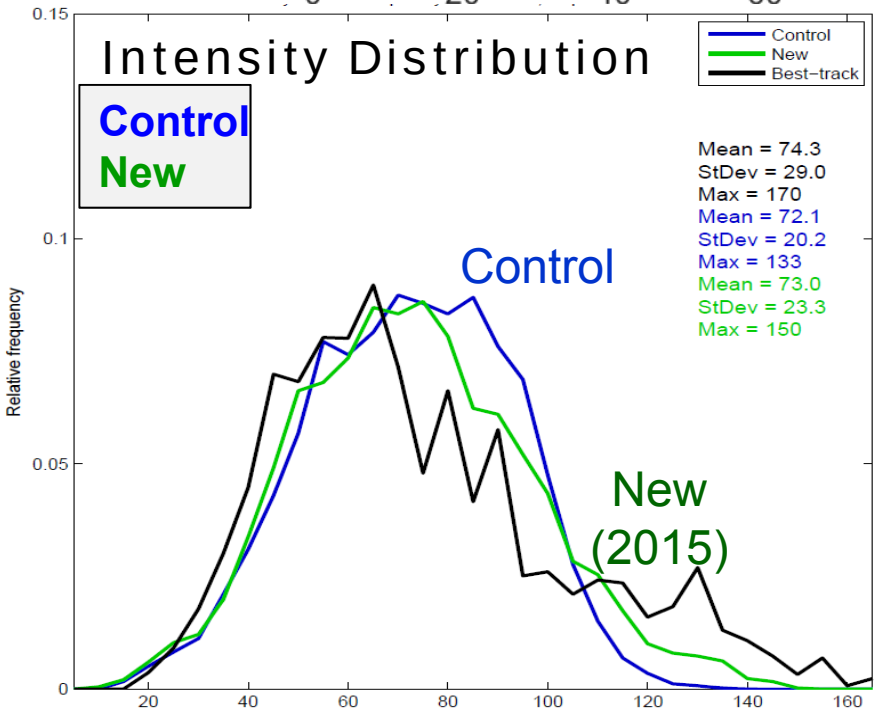
- New Cd parameterization for high wind regime (partially based on CBLAST, Bell, Soloviev)

Key Findings

- Intensity bias for strong storms reduced
- Intensity dist. & P-W relation improved







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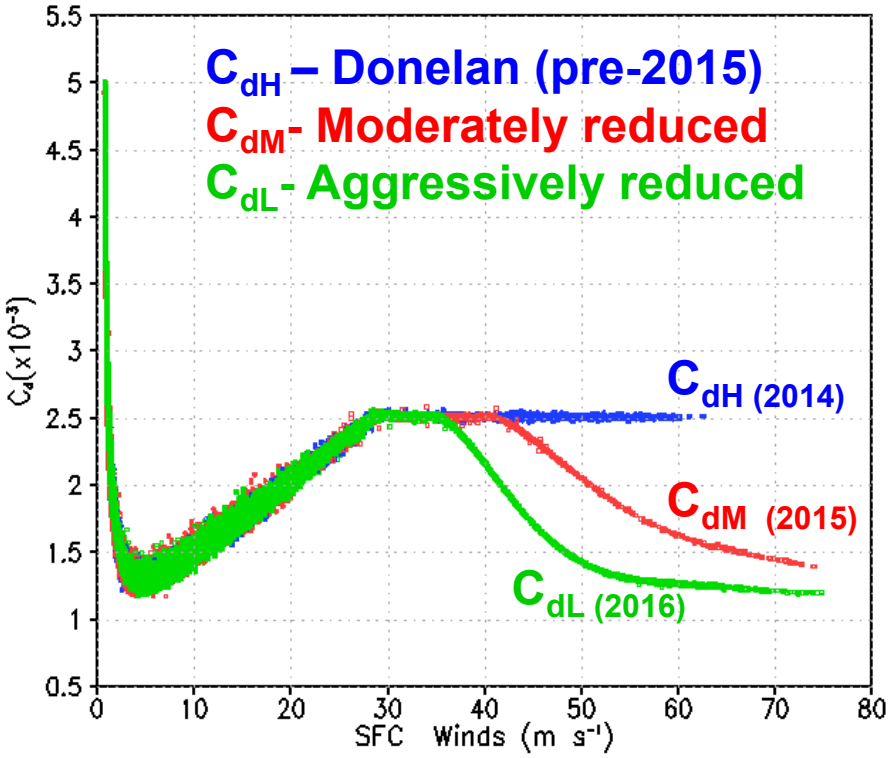
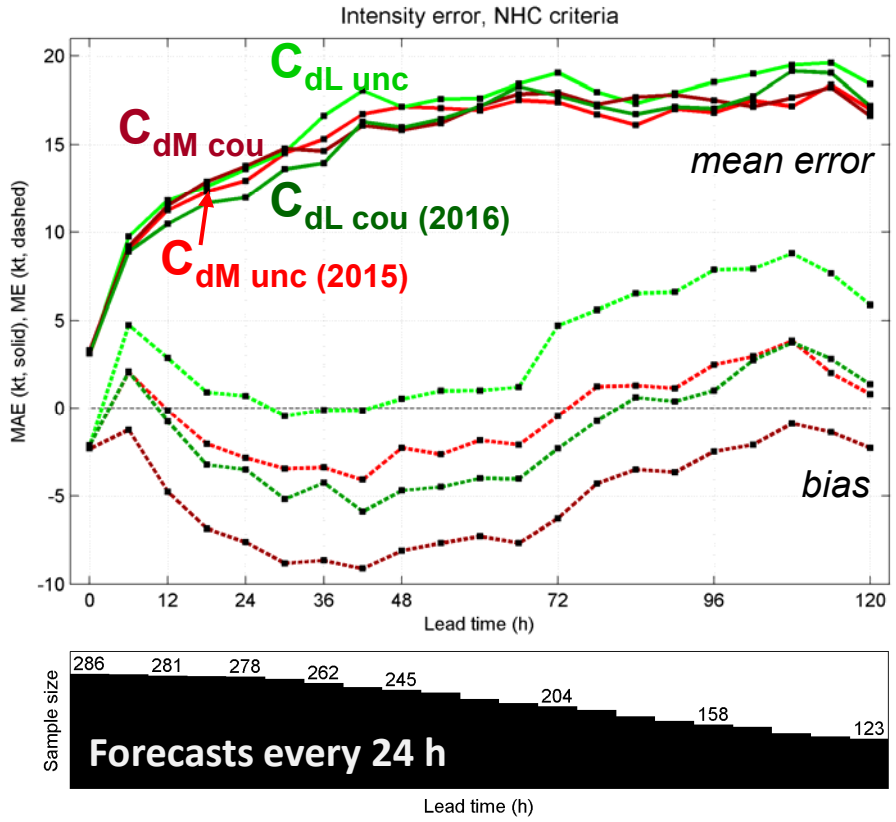
Evaluation of Cd for Pre-retro Sample

A series of C_d formulations have been evaluated for a large retrospective sample, including 44 TCs during 2012-2015 in the ATL, WPAC and EPAC basins.





- The C_{dM} performs best for intensity for **uncoupled forecasts**
- The C_{dL} performs best for intensity for **coupled forecasts (basis for 2016 COTC)**
- The C_d has significant impact on intensity distribution and pressure-wind relation

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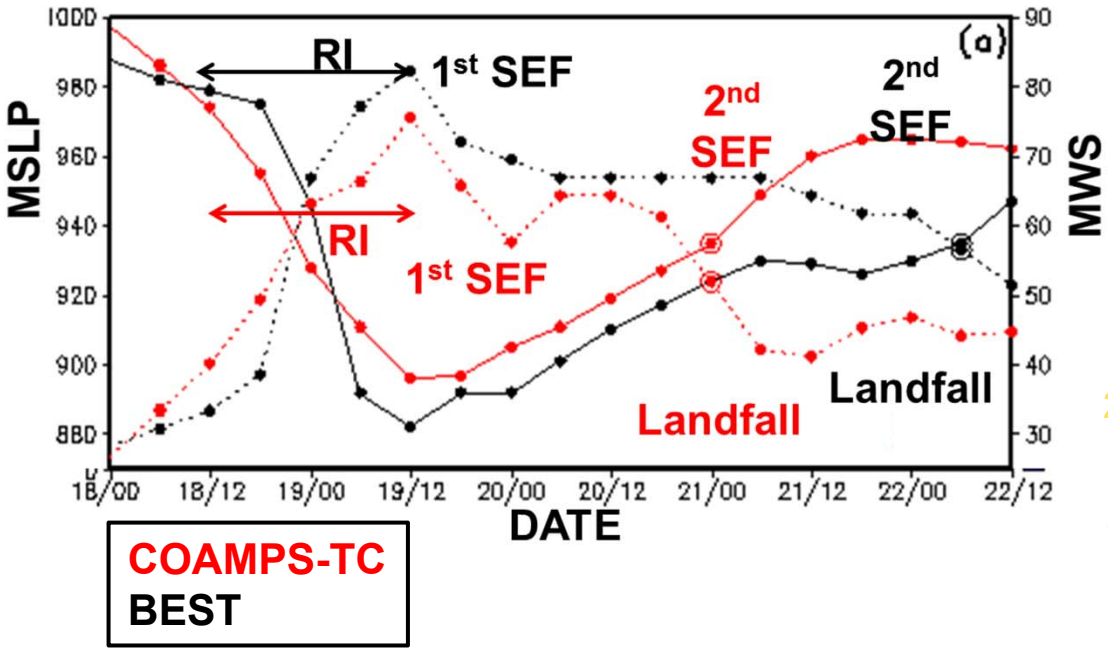
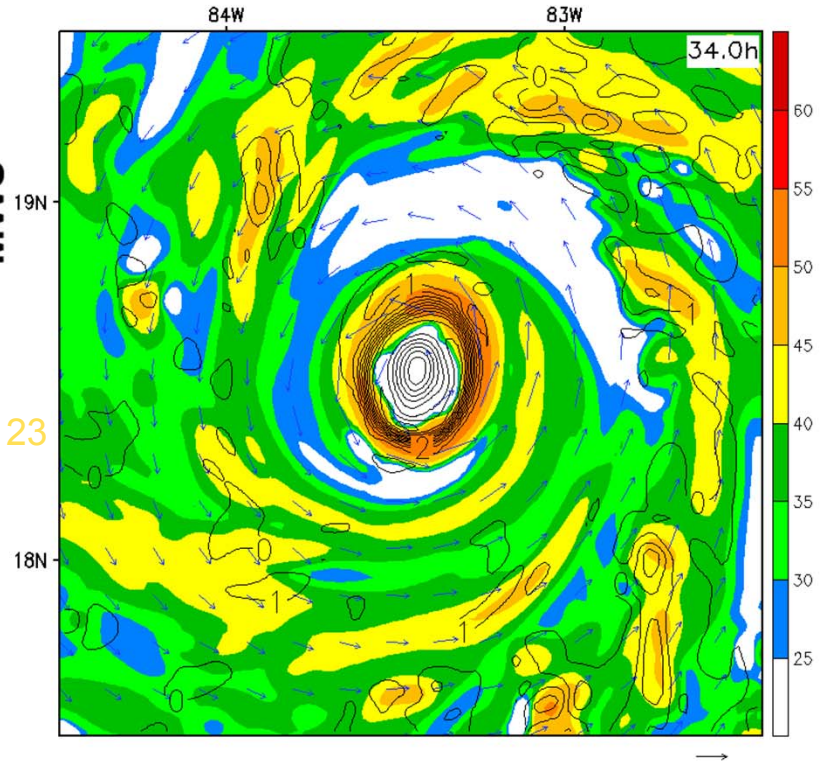
High-Resolution (1.7 km) Version

Simulations of Hurricane Wilma's (2005) RI and SEF



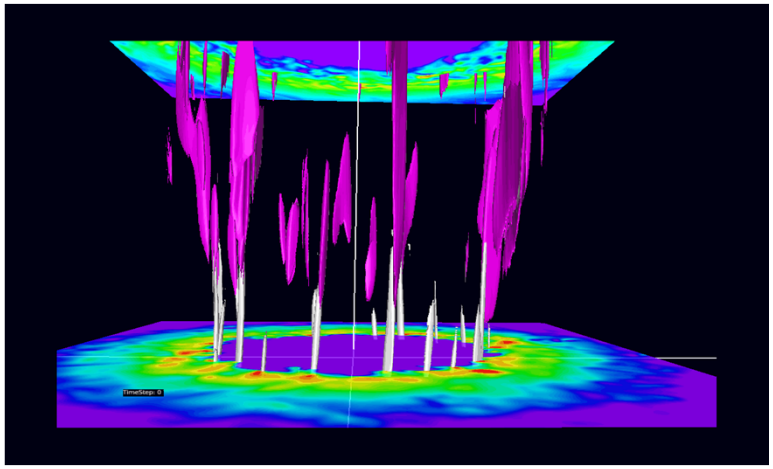


- **High-resolution COAMPS simulation (1.7 km) with new (next-gen type) physics (Thompson microphysics, different PBL etc.) and initialization captures Wilma's *challenging* RI & secondary eyewall formation (SEF)**
- **Current ops version (at 5 km & 1.7 km) does not capture RI and SEF**

Accomplishments and Future Plans

➢Achievements and Key Findings:

- COAMPS-TC intensity & position forecasts one of the top in the world in 2015
- Improved initialization, physics (Cd), terrain, all improved TC position forecast.
- New air-ocean coupling, physics, and initialization planned for 2016



Large Eddy Simulation (dx=60m) of idealized TC [Dan Stern & George Bryan]

Future Plans

- Advanced DA needed, initial moisture critical
- Improve air-ocean-wave interaction
- Advanced TC model physics, particularly PBL
- High-res. multi-model ensembles (RTP)
- TCI high-resolution obs. for assimilation & eval.
- LES to guide PBL development

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Navy Next Generation Modeling

- **NRL is developing a new NWP system**
  - **Using NUMA (developed by NPS) as the dynamical core**

- **NEPTUNE**
  - **Navy Environmental Prediction sysTem Utilizing the NUMA CorE**

  - **3D spectral element model**
  - **Highly accurate and scalable**
  - **A suite of physical parameterizations has been added**
  - **Real data initialization capability**
  - **Flexible grids (cube sphere, icosahedral, etc.)**
  - **Eventually, with have Adaptive Mesh Refinement**
  - **Coordinating with both DCMIP and HIWPP**

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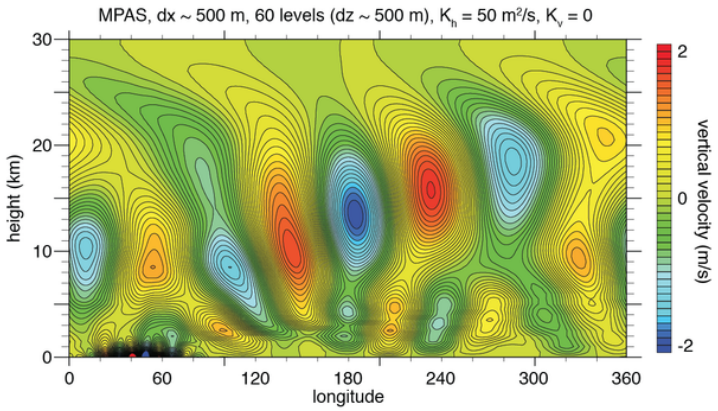
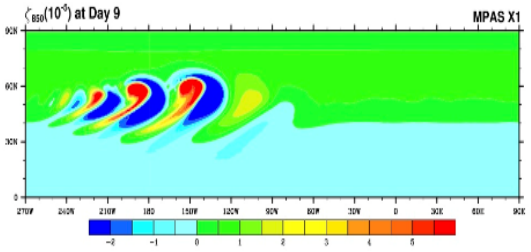
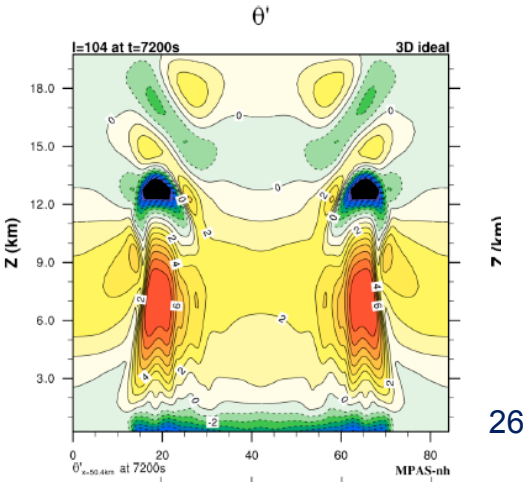
Idealized Test Cases

- Coordinating with NOAA HIWPP next generation nonhydrostatic model group- Pre-NGGPS
- FY14 test cases follow the DCMIP (dynamical core model inter. project)
  1. Baroclinic Wave on Sphere (basically completed except 60L tests)
  2. Nonhydrostatic mountain waves on small planet (mostly complete)
  3. Supercell on small planet
  4. Tropical Cyclone (optional)
- FY15 test cases (real data)
  - 1 year of real-data retrospective runs on sphere
  - Limited number of high-resolution tests on sphere







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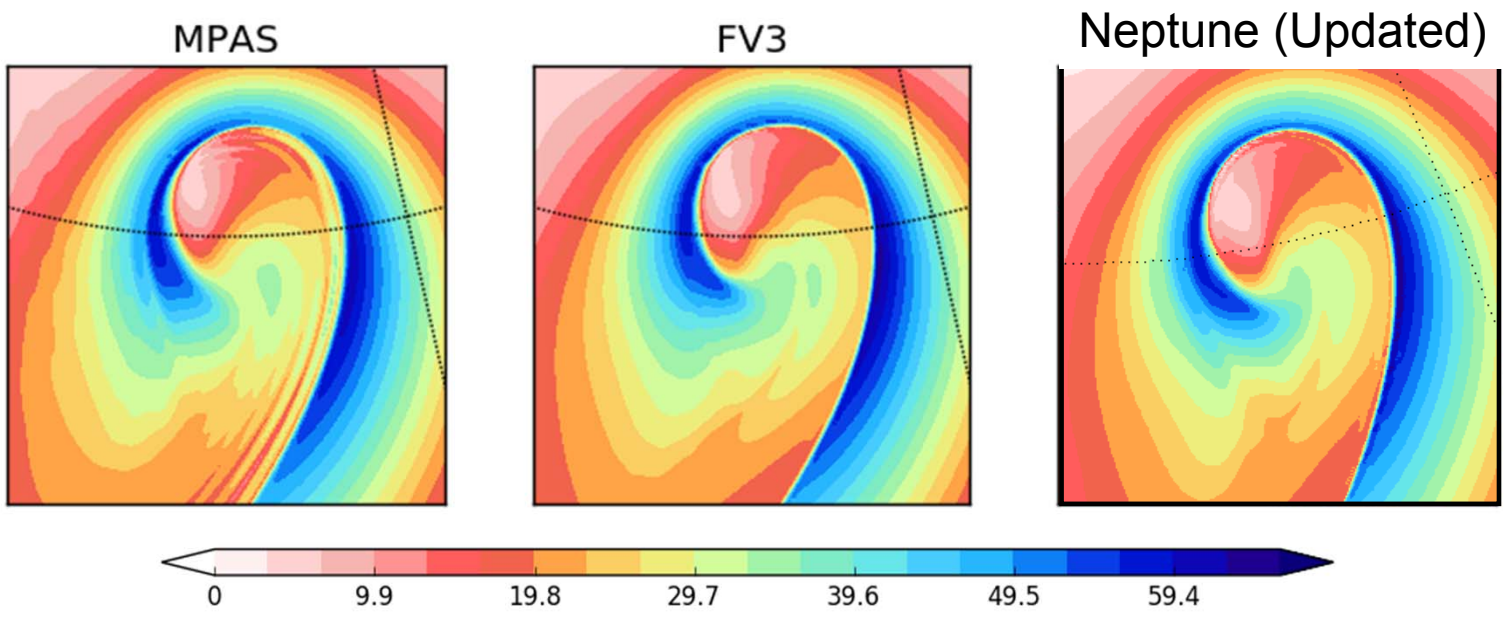
DYCORE Test: Baroclinic Wave

(sfc wind at day 9, 15-km resolution)



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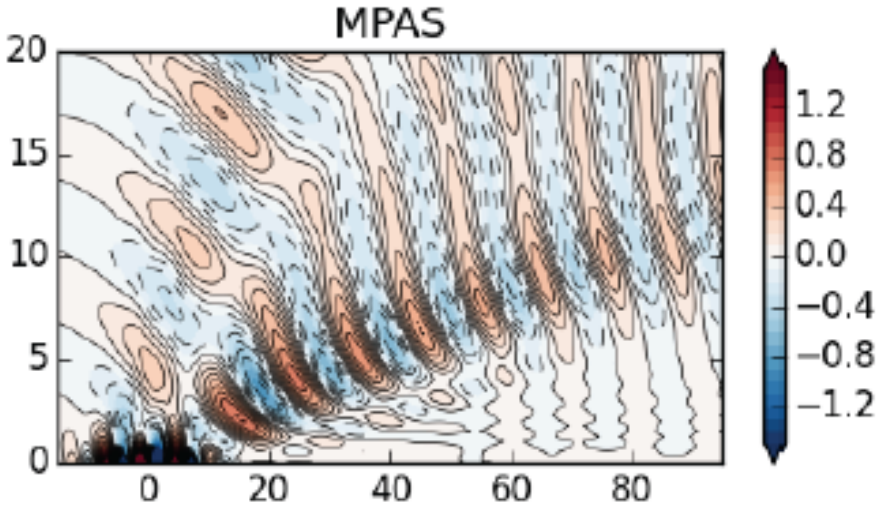
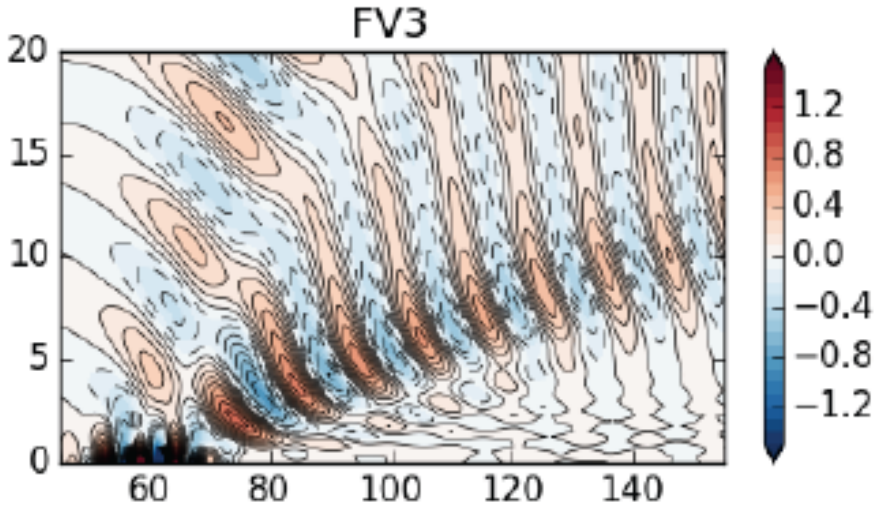
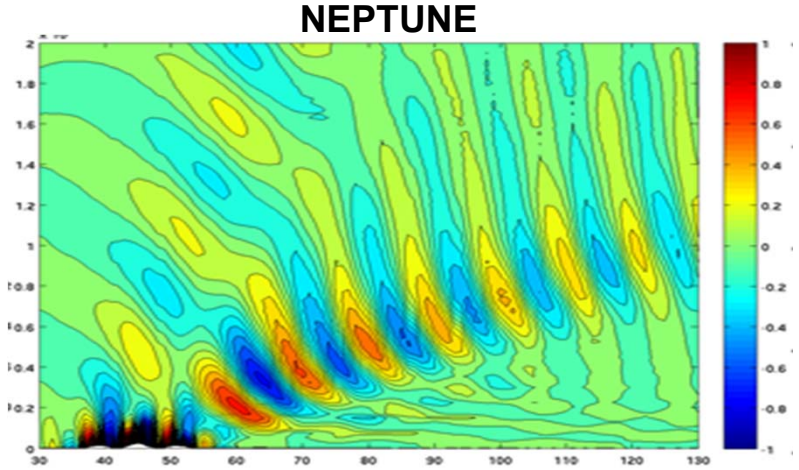
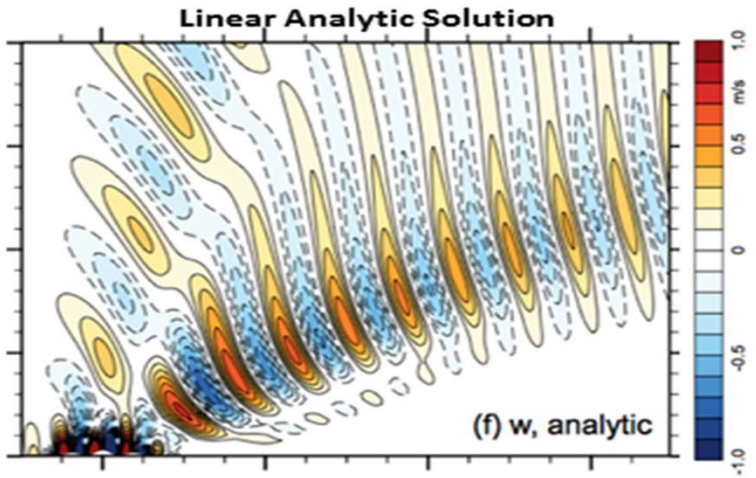
Mountain Wave in Sheared Flow









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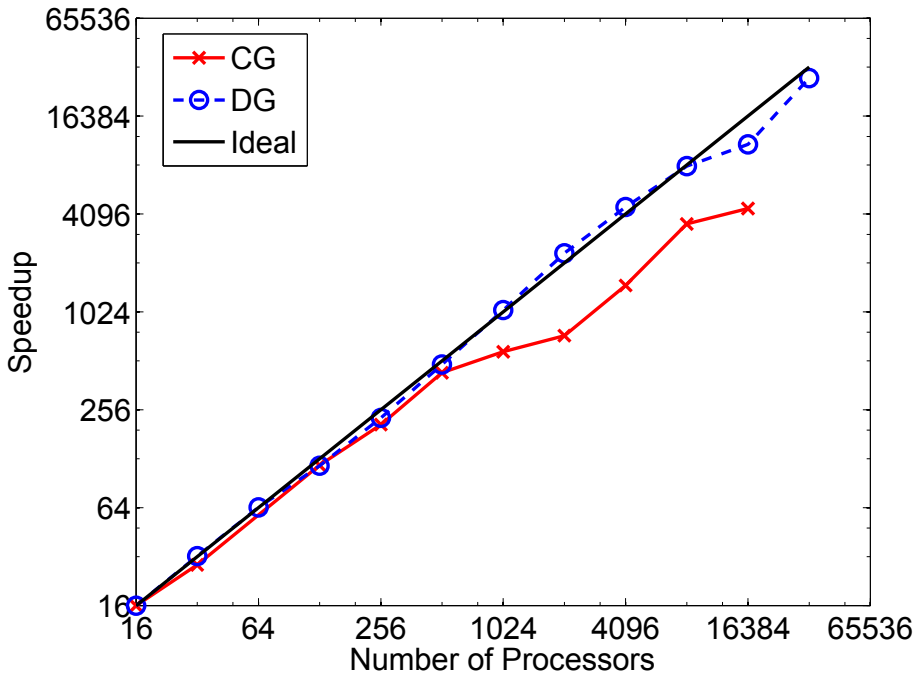
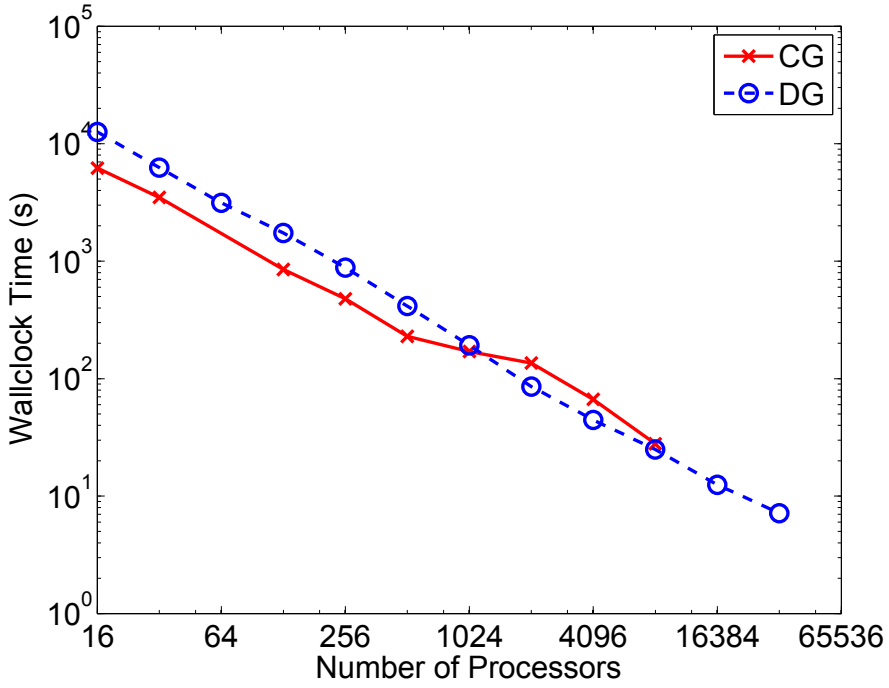
NUMA Scaling





- **Both Continuous Galerkin (CG) and Discontinuous Galerkin (DG) methods scale well up to 8,000 processors. DG method scales up to 32,000 processors.**
- **Each processor contains only one single element which illustrates the fine-grain parallelism of both methods.**
- **Scales well on GPU architecture (DG).**

Kelly and Giraldo (2012)

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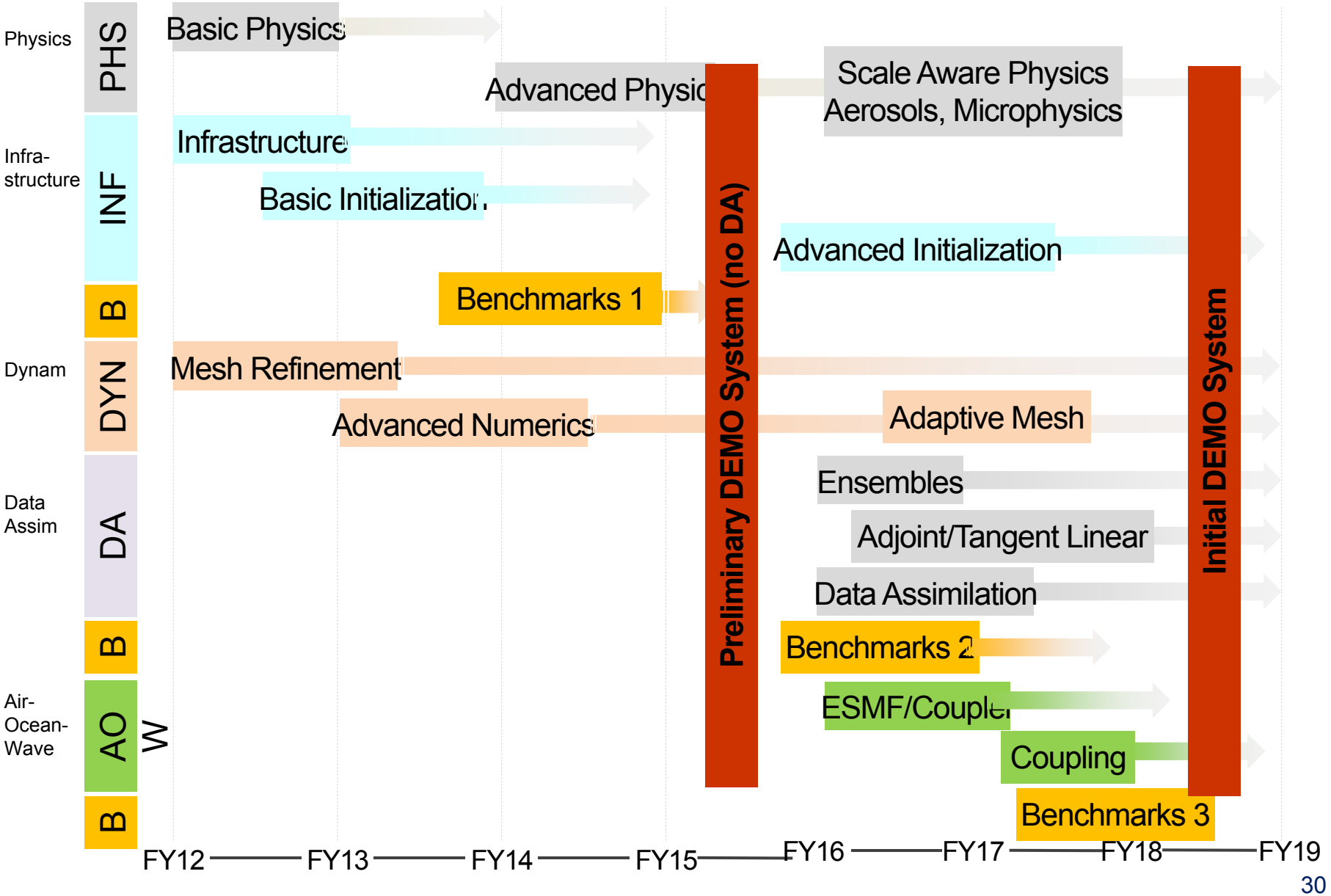
NEPTUNE Roadmap



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Summary of Long Term Plans

- New operational requirement for 1-90 day forecast.
- Navy operational productions are reinvigorated by accelerated multi-year HPC procurements.
- Development of NAVGEM will continue and a global 4-way coupled NAVGEM/HYCOM/CICE/WW3 is on track towards a 2018 demonstration of sub-seasonal to seasonal forecast capability.
- Event following, fully air-sea-wave-ice coupled COAMPS will be run at ~1 km spatial resolution with 4DVar possibly in 2017.
- Hybrid 4DVar and ensemble hybrid 4DVar.
- NEPTUNE as the candidate for a unified global and regional modeling framework.

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Research and Development in Numerical Weather Prediction at NRL

Thank you!