U.S. Navy Mesoscale Forecast System and HPC Attributes

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COAMPS Research and Development Team

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Outline

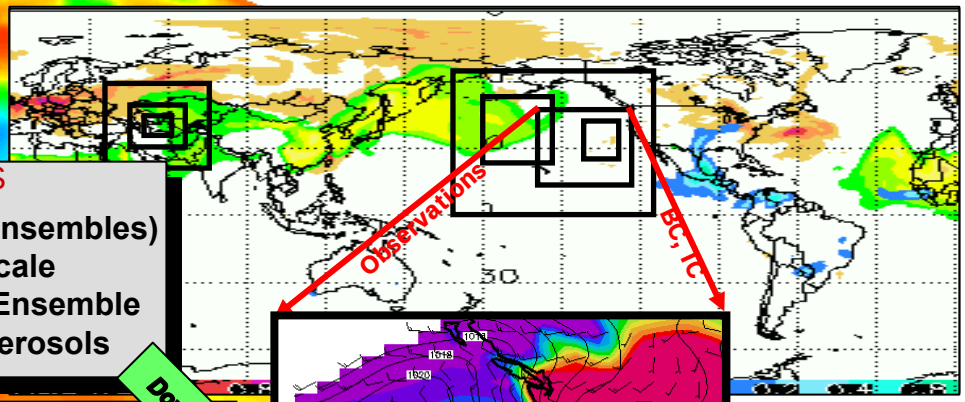
- Computational Aspects
- Coupled Modeling
- Tropical Cyclone Prediction
- Adjoint and Ensemble Kalman Filter
- Next-Generation High-Resolution Models

U.S. Navy Models and Tools

Telescoping Strategy

Navy Operational Global Atmospheric Prediction System

NRL Aerosol Analysis and Prediction System



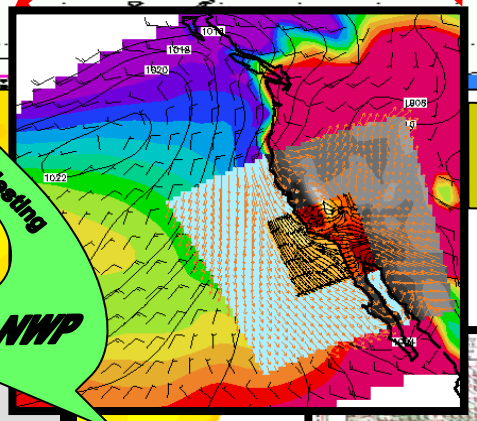
NRL Atmospheric Variational Data Assimilation System

Data Assimilation

NOGAPS & NAAPS
- *Global Coverage (Ensembles)
- *Meso- to Synoptic Scale
- *1-5d Guidance/ 10d Ensemble
- *Weather, Ice, SST, Aerosols

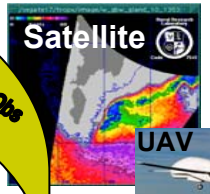
NAVDAS
- *4DVAR/3DVAR
- *Observation Space
- *Global to Local

Down-Scale Nesting

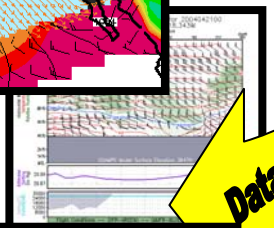


NWP

Through-the-Sensor Obs



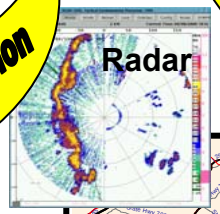
COAMPS® & COAMPS-TC
- *Nested Regional Coverage
- *Nonhydrostatic Scale
- *0-120h Guidance (Ensembles)
- *Weather, Ocean, and Aerosols

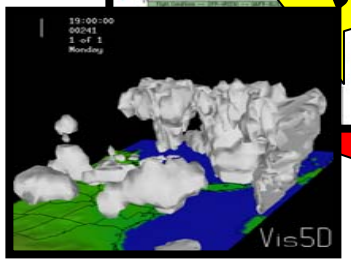


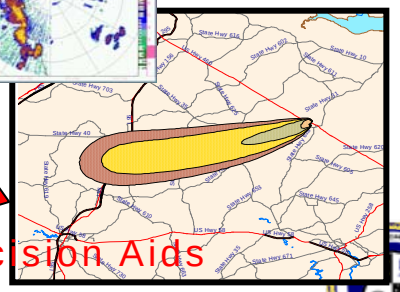
COAMPS-OS®
- *Nested Local Coverage
- *Tactical Scales
- *0-24h Guidance, on-demand
- *On-Scene, local data assimilation

Coupled Ocean/ Atmosphere Mesoscale Prediction System

Data Fusion







Decision Aids

NOWCAST
- *Rapid Environmental Assessment
- *Warfighter Time & Space Scales
- *0-6h Guidance, Rapid Update
- *Real-time, Automatic, Data Fusion

Computational Platforms
NRL, DoD HPC, FNMOC

NRL Marine Meteorology Division research is conducted on a mix of computers:

- **NRL-Monterey Based Systems**
  - 176 and 44 cores Linux Clusters
- **DOD HPC Network systems**
  - IBM P6 (4800 cores), Cray XT5 (12736 cores),
  - SGI Altix 4700 (9216 cores), Altix Ice (15360 cores)
  - 17 Large HPC Systems (2000-16000+ cores)
  - 12 Petabytes of single copy storage
- **Fleet Numerical Meteorology & Oceanography Command**
  - Linux Clusters (3720 cores), IBM (486 cores)
  - SGI File Systems (512 cores)

Computers

COAMPS®

Coupled Ocean/Atmosphere Mesoscale Prediction System

Atmospheric Analysis

- Complex Data Quality Control
- NAVDAS 3D-Var: **u, v, T, q**
- TC Analysis: **Synthetic obs., 3D-Var**
- Initialization: **Hydrostatic Constraint on Analysis Increments, and/or Digital Filter**
- Ensembles: **ET, EnKF (DART)**

Ocean Analysis

- Navy Coupled Ocean Data Assimilation **(NCODA)** System
- 2D OI: **SST**
- 3D MVOI: **T, S, SSH, Sea Ice, Currents**
- Complex Data Quality Control
- Initialization: **Stability check**

Atmospheric Model

- Numerics: **Nonhydrostatic, Scheme C, Nested Grids, Sigma-z, Flexible Lateral BCs**
- Physics: **PBL, Convection, Microphysics, Radiation, LSM, Sfc. Fluxes, Ensembles**
- Aerosols: **Transport, Deposition**
- TC Option: **Moving Nests, TC Physics**
- Adjoint: **Nests, PBL, Microphysics**

Ocean Models

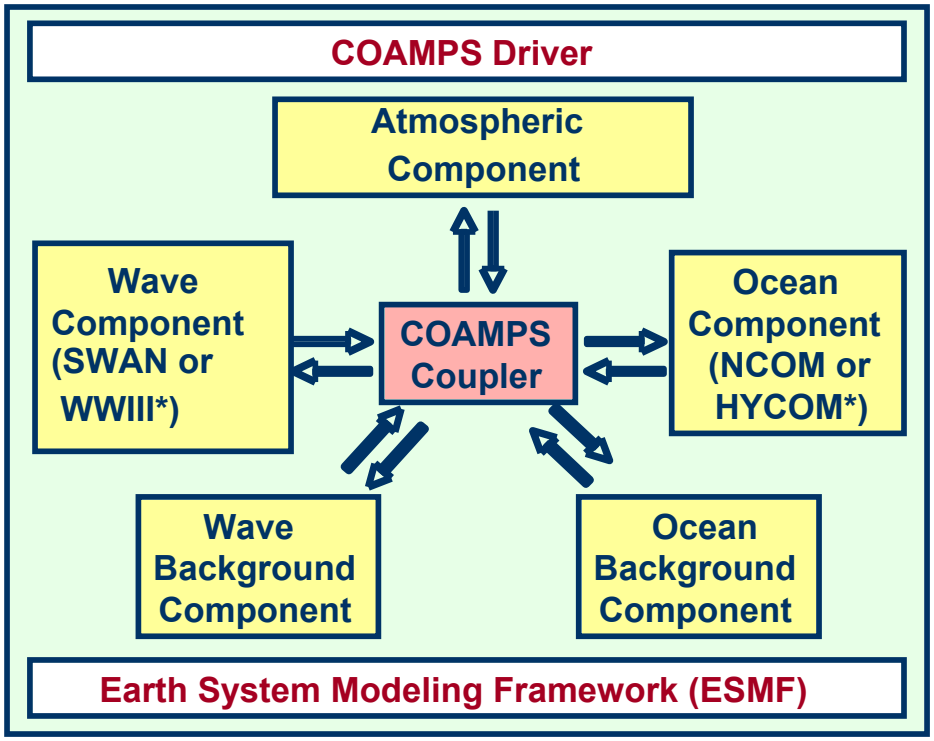
- NRL Coastal Ocean Model **(NCOM)**
- Numerics: **Hydrostatic, Scheme C, Nested Grids, Hybrid Sigma/z**
- Physics: **Mellor-Yamada 2.5**
- Wave Models: **WWIII and SWAN**
- Generalized Coupler: **Earth System Modeling Framework (ESMF)**

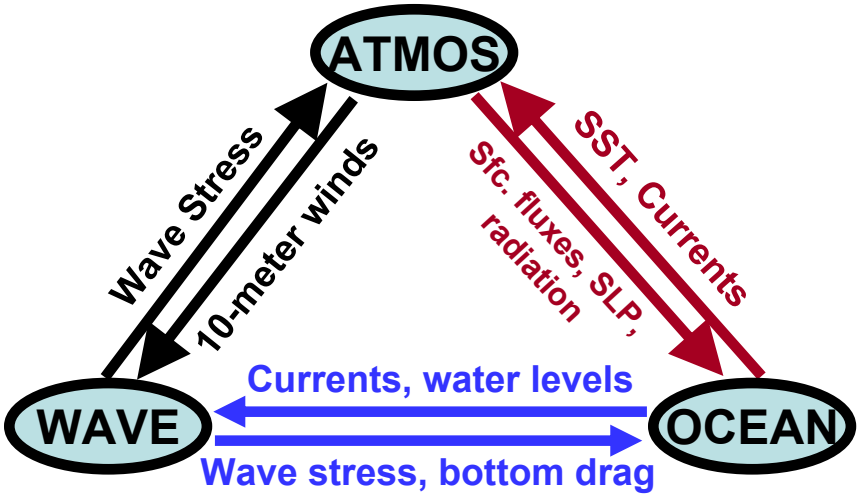
Features

- COAMPS-OS® Turnkey Automated System with GUI
- Globally Relocatable: **5 Map Projections**
- Single Configuration Managed System for All Applications
- Operational FNMOC for over 50 areas per forecast watch (2-27 km resolution)
- Operational at FNMOC since 1998: Over *200,000* Operational Forecasts

Fully Coupled Air-Ocean-Wave Prediction Capability

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)



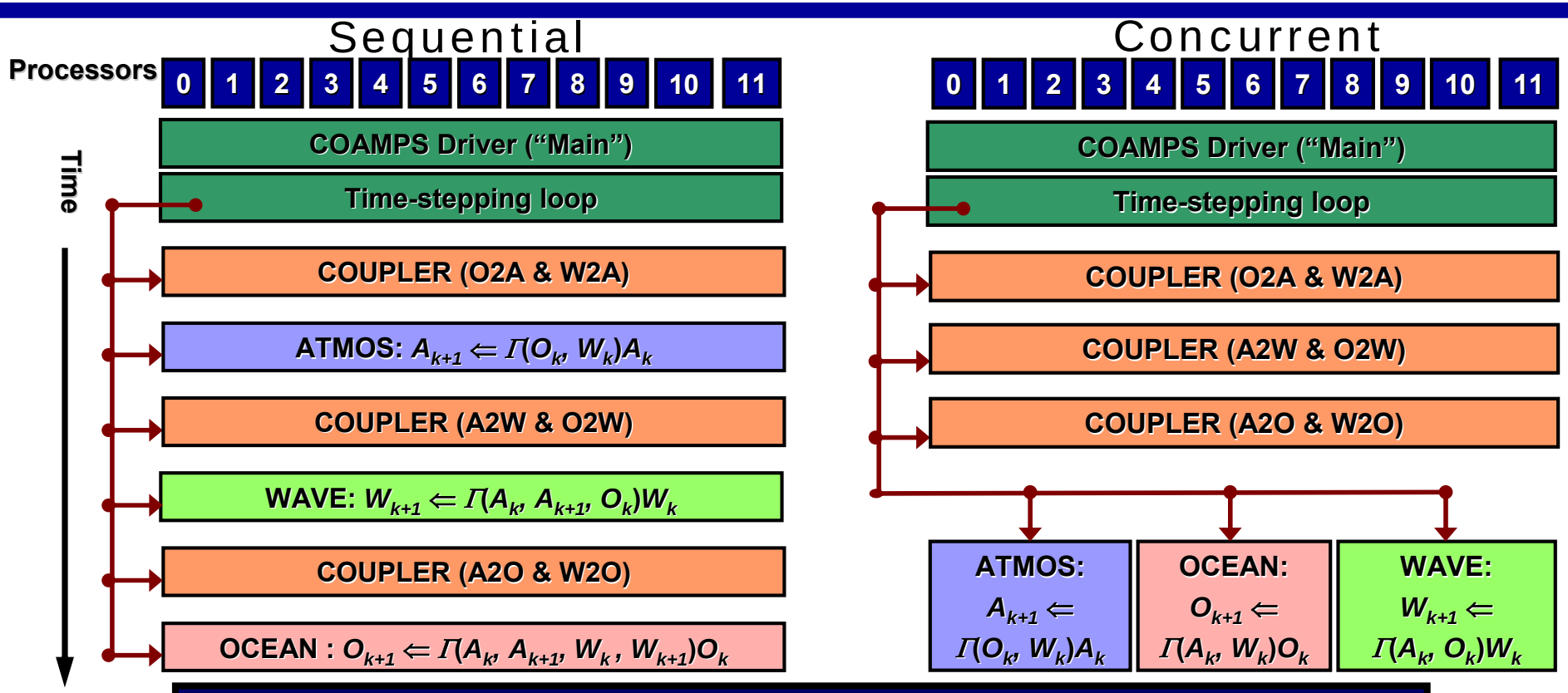


- Component-specific exchange grid is used facilitate interactions between the model components and grid meshes.
- Atmospheric model domain encompasses both wave and ocean domains.
- Transition to Navy operations in FY11.

Chen S., T.J. Campbell, H. Jin, S. Gaberšek, R. M. Hodur, and P. Martin, 2010: Effect of two-way air-sea coupling in high and low wind speed regimes. *Mon. Wea. Rev.*, 138, 3579–3602

Coupling Modes

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

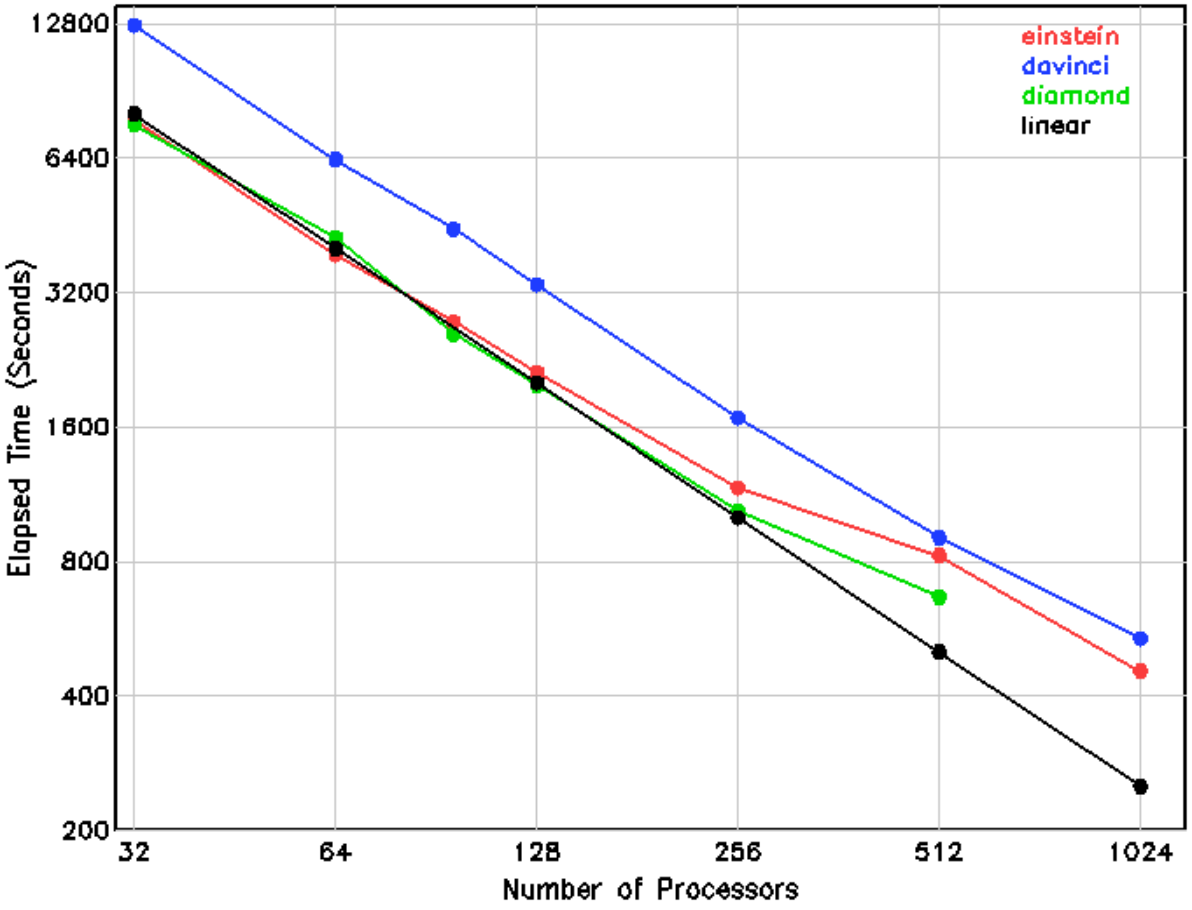


- Sequential
  - Coupler and all components execute on full set of processors
  - Components sequentially integrate forward in time
- Concurrent
  - Each component executes on a different set of processors
  - Coupler executes on full set of processors
  - Components concurrently integrate forward in time.

COAMPS Scalability on DoD HPC Platforms

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

Einstein (Cray XT5), Davinci (IBM P6) and Diamond (SGI Altix Ice)
COAMPS (640x640x40) 12 h Forecasts



Code is Scalable to 1000+ Processors for Typical Operational and Research Applications

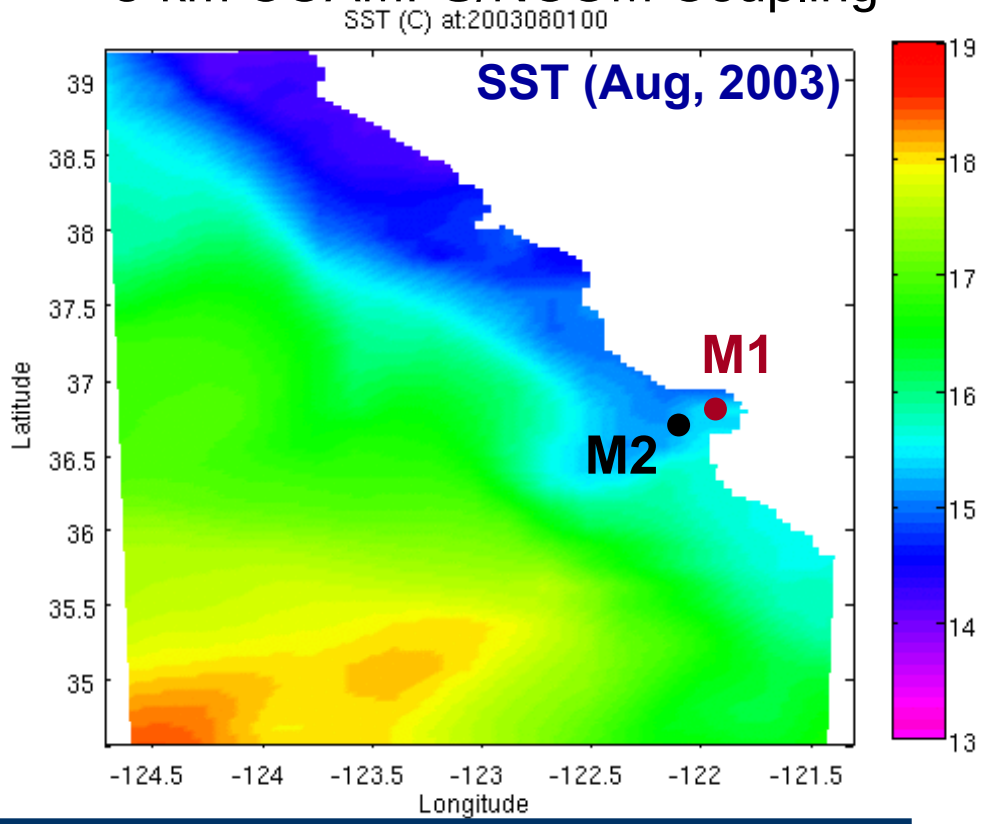
COAMPS Air-Sea Interaction Research

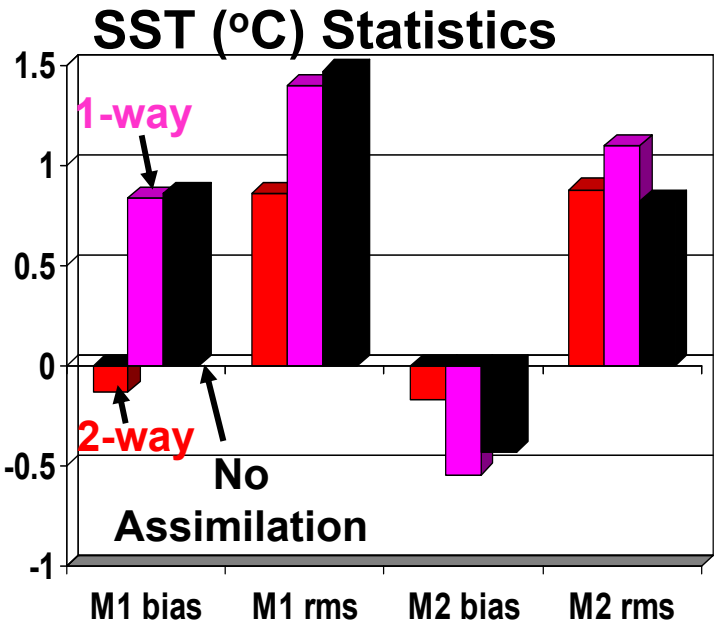
Coupled Atmosphere-Ocean-Wave Coupling

Model Configuration

- One month continuous data assimilation in atmosphere & ocean, using 3 km resolution
- Adaptive (AOSNII) ocean glider observations from assimilated.

3-km COAMPS/NCOM Coupling





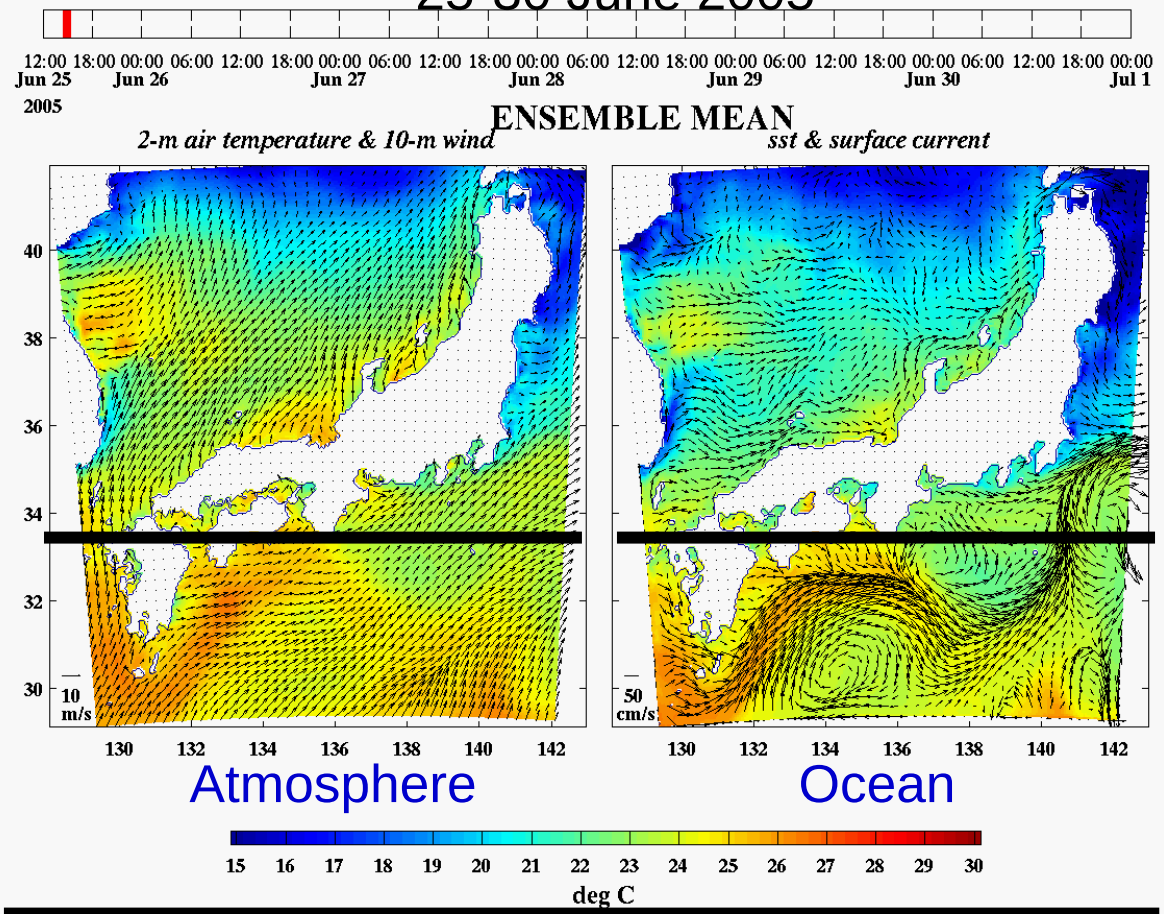
The 2-way coupled simulation has a smaller mean SST bias and RMS compared to the 1-way and no data assimilation runs.

COAMPS Ensembles

High-Resolution Ensemble Transform Coupled Ensembles

21 members (Δx=5 km), 12-h Forecasts

25-30 June 2005

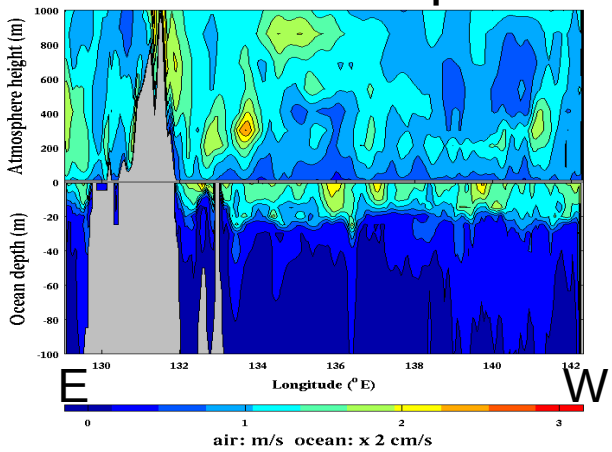


Maximum ensemble spread is located near atmospheric BL top & ocean ML bottom

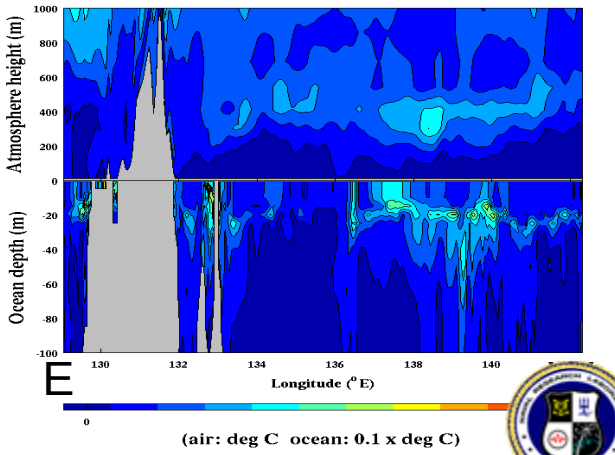
Ensemble Spread

21Z 27 June 2005 (9 h)

Atmospheric u-wind component
Ocean u-current component



Atmospheric potential temperature
Ocean temperature



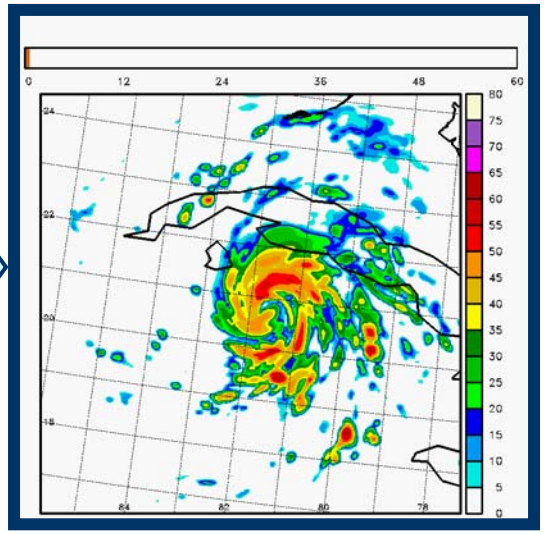
Tropical Cyclone Prediction Using COAMPS-TC

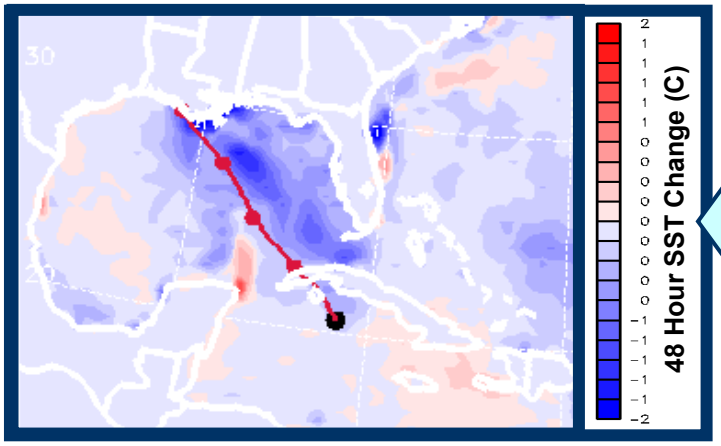
COAMPS-TC Air-Ocean Coupled Prediction of Hurricane Gustav

Initial Time: 1200 UTC 30 August 2008

COAMPS Forecast Track (red) and Official Warning Positions (black) plotted every 12 hours (dots) in uncoupled run

Animation of COAMPS predicted radar reflectivity every 30 minutes on 5 km moving grid





SST cooling of approximately 1°C-2°C is found to the right of the predicted path of Hurricane Gustav (Initial position is black dot, red dots represent every 12 hours)

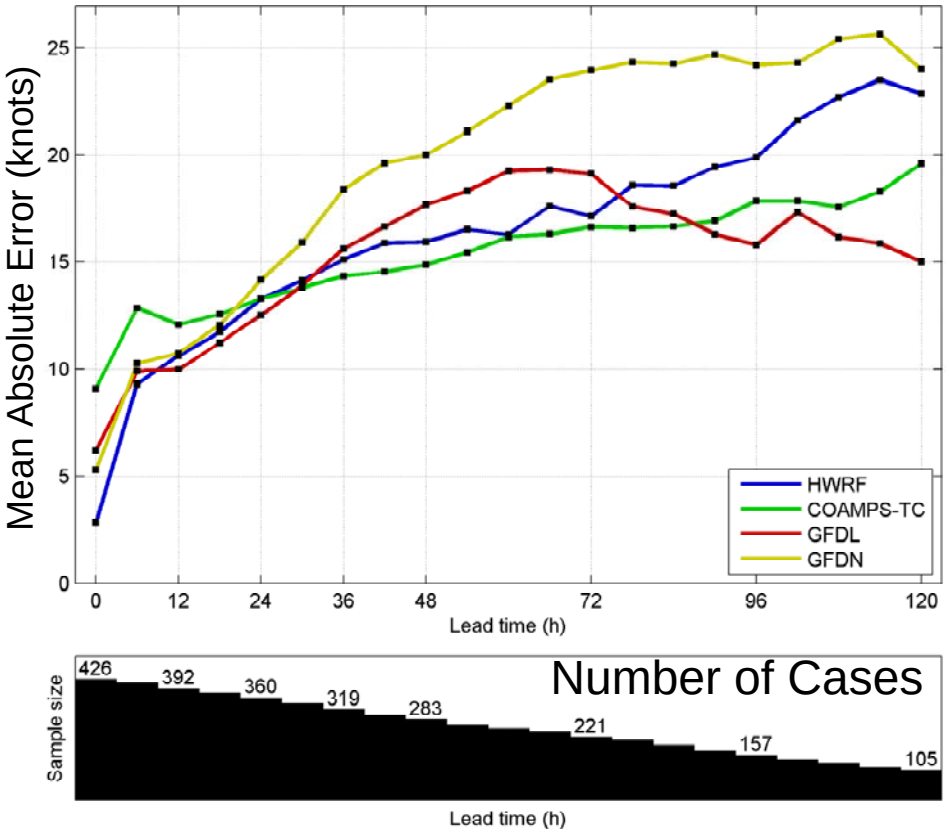
New version of COAMPS developed to predict tropical cyclone track, structure and intensity: COAMPS-TC.

Hurricane Forecast Improvement Project (HFIP)

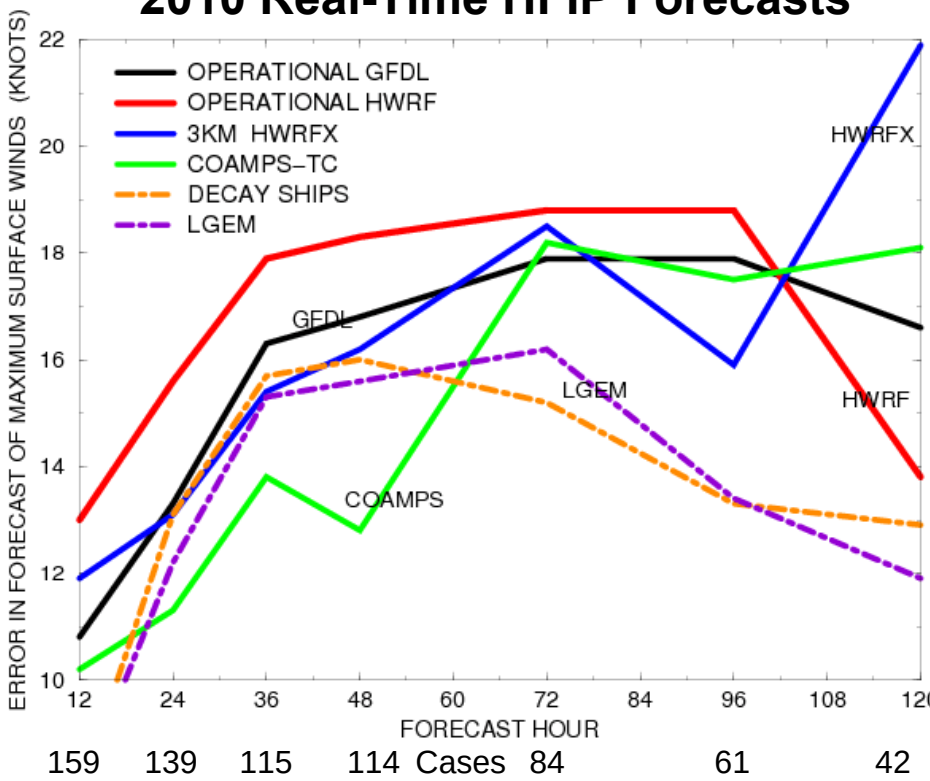
COAMPS-TC Retrospective Tests (2008/2009 Seasons)

W. Atlantic Homogeneous Intensity Forecast Error (kts)

Retrospective Tests (2008/2009)



2010 Real-Time HFIP Forecasts

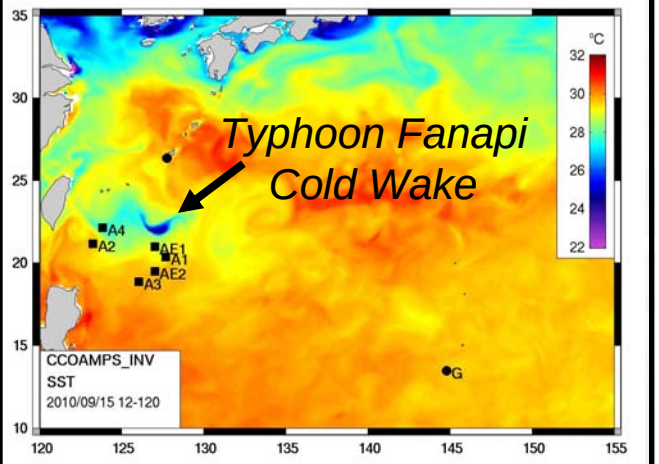


- HFIP: NOAA, Navy, Academia Effort to Improve Hurricane Intensity and Track Forecasts
- COAMPS-TC Intensity Skill is Superior to HWRF, GFDN, GFDL, NCAR AHW (30-84h).
- COAMPS-TC is the Leading Intensity Model and Shows Skill to 60 h for 2010.

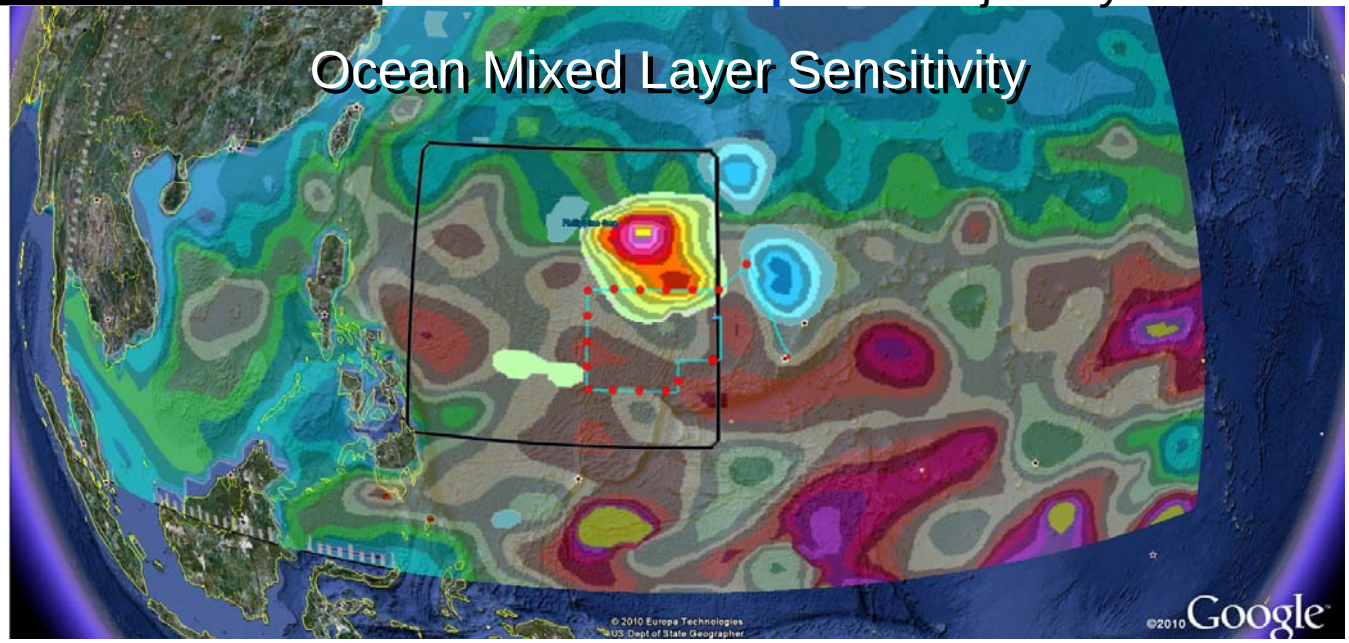
Impact of Typhoons on the Ocean in Pacific (ITOP)

2010 Field Campaign in W. Pacific: COAMPS-TC Adjoint Targeting

Air-Sea Coupled COAMPS-TC



- **Fully coupled forecasts in support of ITOP.**
- **Real-time adjoint forecasts for targeting.**
- **Adjoint allows for the mathematically rigorous calculation of forecast sensitivity of a response function to changes in the initial state**
- **COAMPS® Moist Adjoint Model**
  - **Dynamics:** nonhydrostatic, nested
  - **Physics:** PBL, surface flux, microphysics, Kuo
  - **Ocean:** Two-way coupled mixed layer model
  - **Parallel I/O option:** Trajectory written every time step

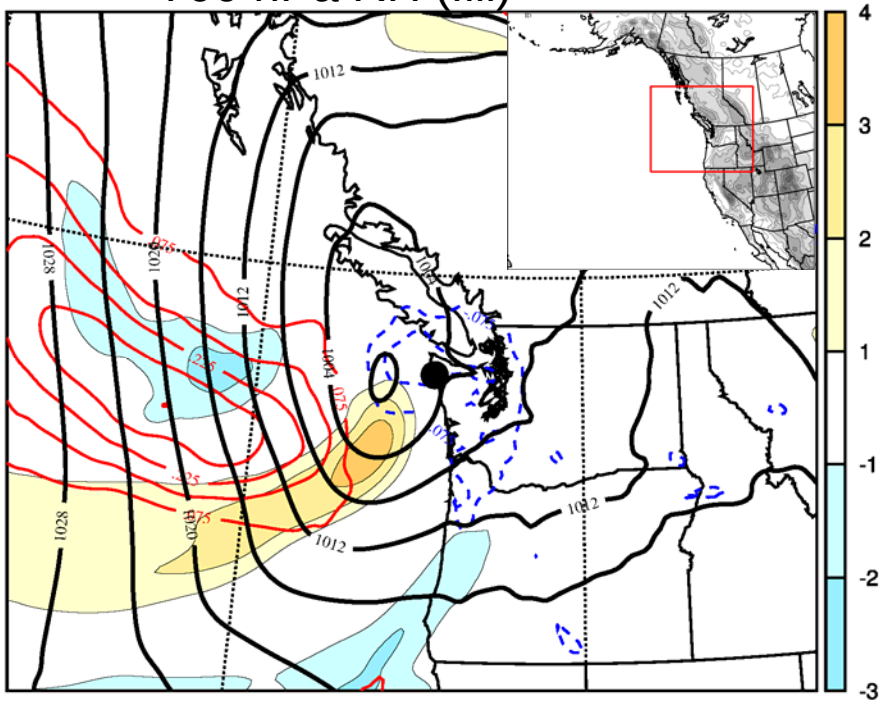


Ensemble Data Assimilation and Predictability

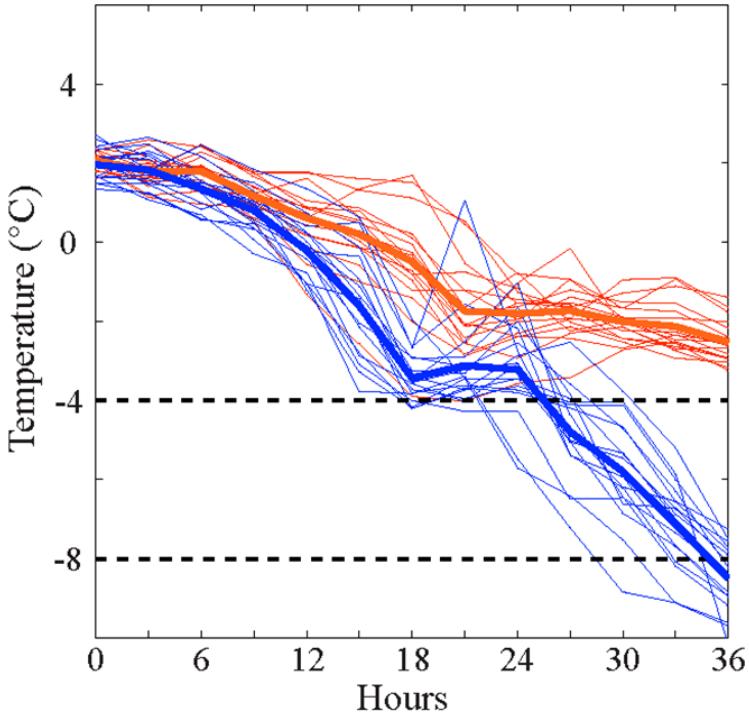
Application of COAMPS EnKF to a Pacific NW Snow Event

100-member EnKF Data Assimilation System (27 and 9-km)

Covariance between SLP and
700 hPa Temp (contours)
700 hPa RH (fill)



Puget Sound 850 hPa Temp
17 Warm and Cold Members

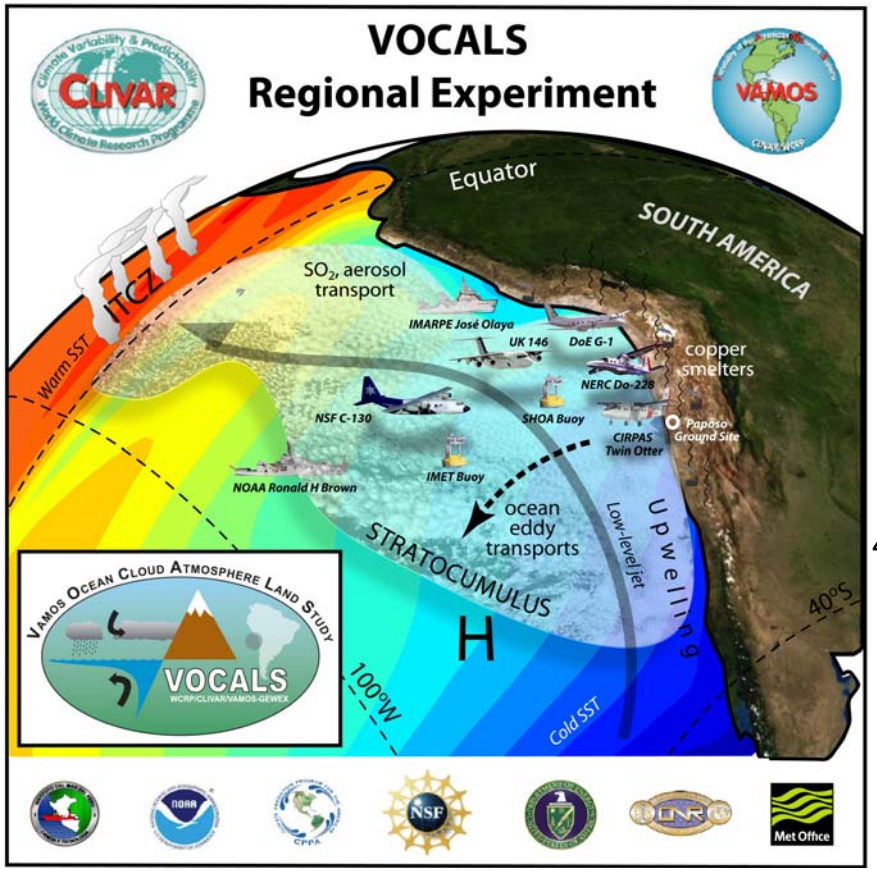


- **Flow dependent mesoscale covariances**
- **Mesoscale cyclogenesis (500 km difference in low position)**
- **Rapid error growth; 36-h temperature differences of 6°C.**

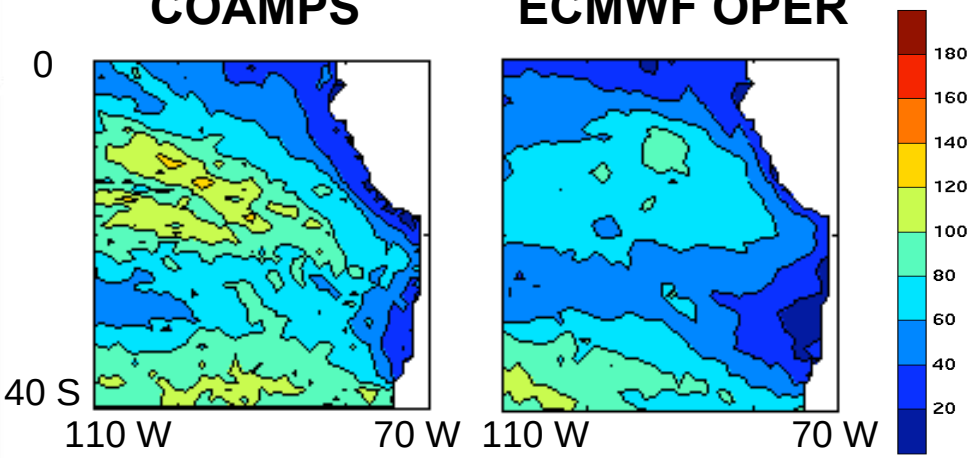
A. Reinecke

Clouds, Aerosols, Turbulence Interactions

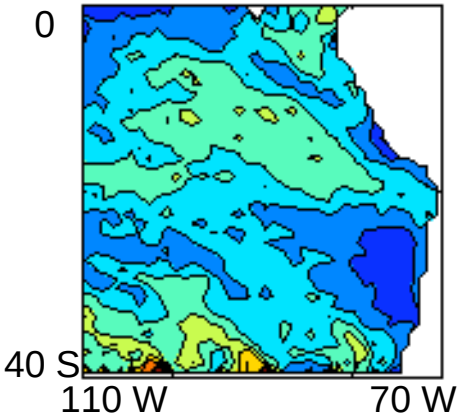
VAMOS Ocean Cloud Atmosphere Land Study (VOCALS)



Oct. 2006 Average Liquid Water Path (g/m²)



TRIMM Microwave Imager (TMI)

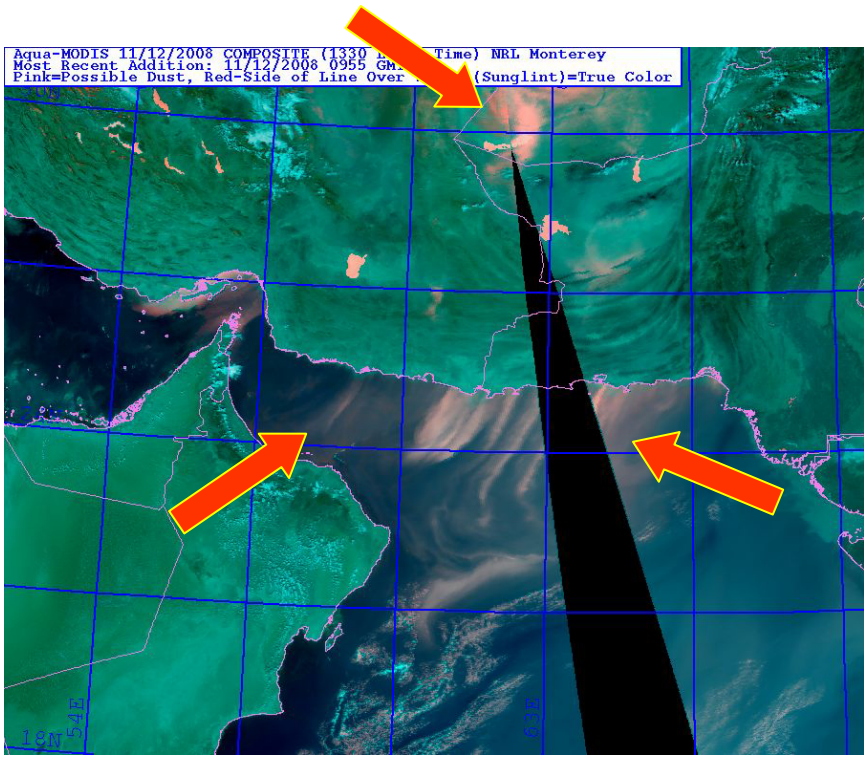


- Real-time COAMPS guidance during VOCALS.
- Pre-VOCALS model intercomparison.
- New insight into cloud-turbulence- aerosol interactions & cloud variability.

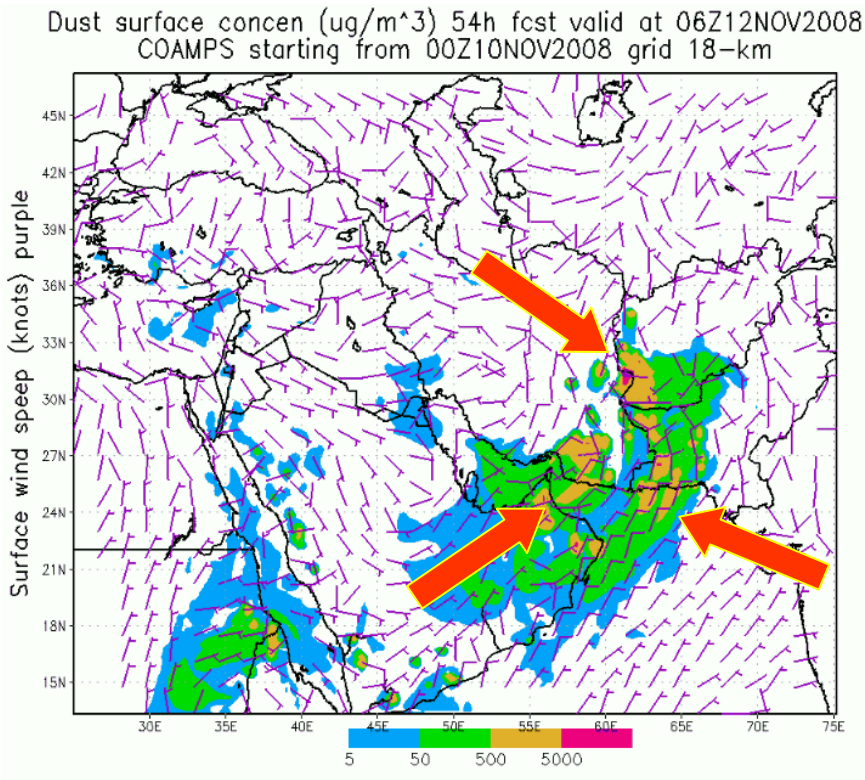
S. Wang

COAMPS Aerosol Modeling
Coupled Aerosol Modeling Capability

NRL DEP 0955 UTC 12 Nov 2008



COAMPS 54 h Surface Dust Forecast
valid 0600 UTC 12 Nov 2008



- Fully integrated aerosol transport model within COAMPS.
- Improved dust source database (DSD) resolves dust plumes.
- Aerosol data assimilation development is underway.

D. Westphal, M. Liu, A. Walker

High-Resolution Modeling Over Complex Terrain

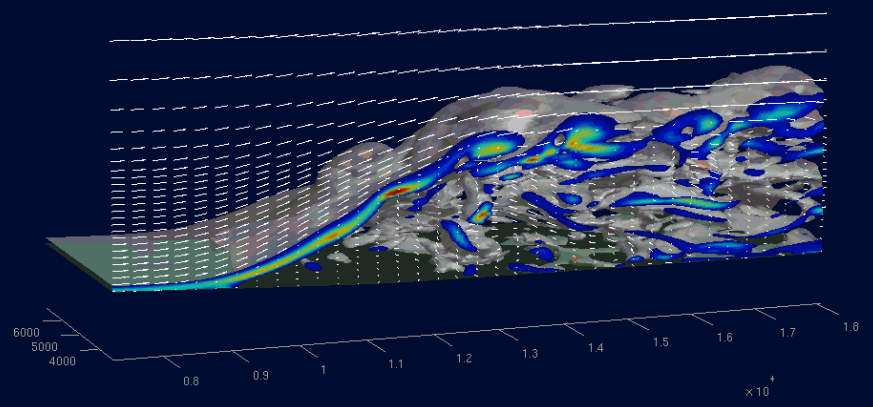
Terrain-Induced Rotor Experiment (T-REX)

- Ultra high-resolution simulations of intense subrotor vortices.
- Lidars observed similar structures.
- Models can guide our search for new fine-scale phenomena.

COAMPS-LES: Subrotor Vortices

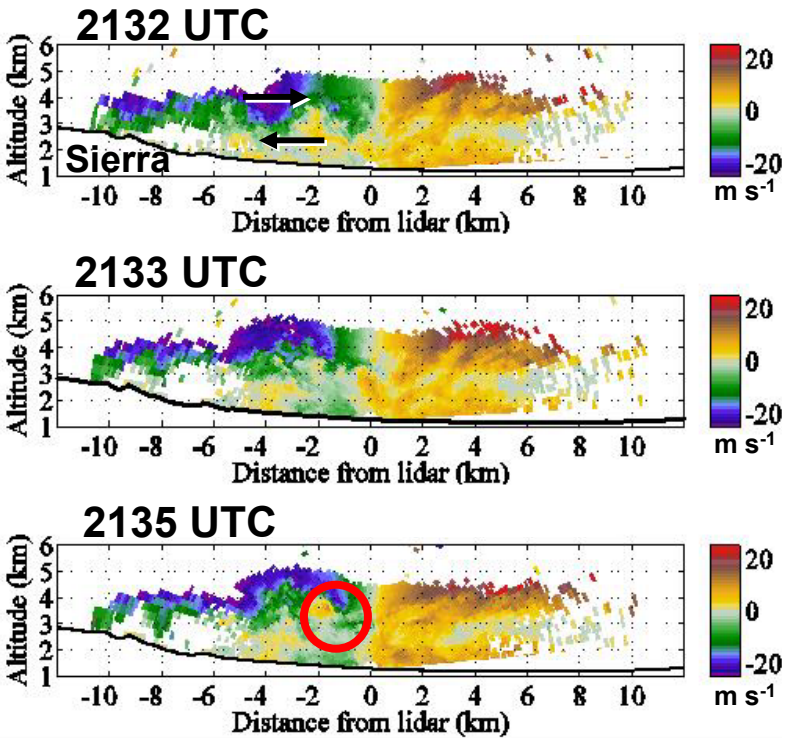
Δx=60 m

2100 UTC 16 April 2007



η Vorticity (color)
η = 0.15 s-1 (red)
η = 0.02 s-1 (gray)

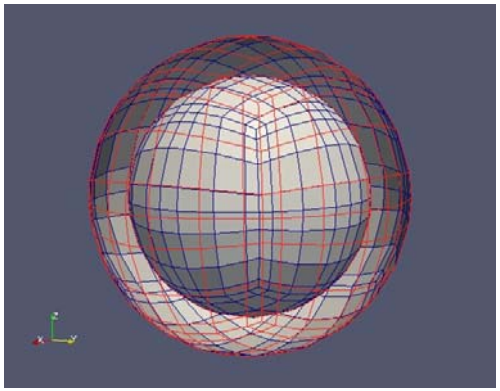
DLR Doppler Lidar Velocities

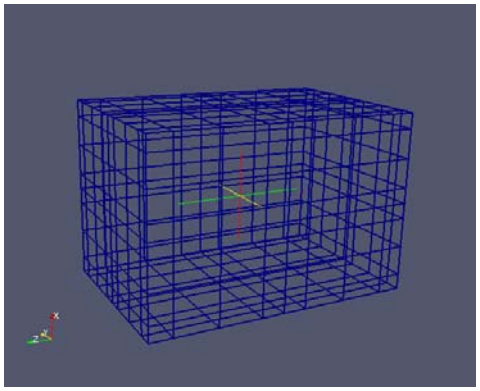


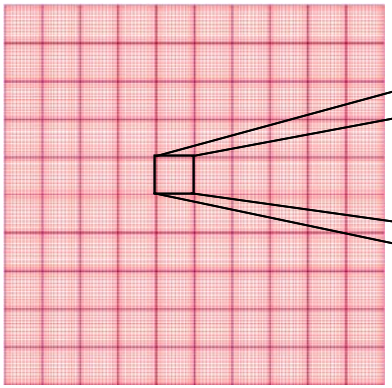
Doyle et al. (2009) JAS

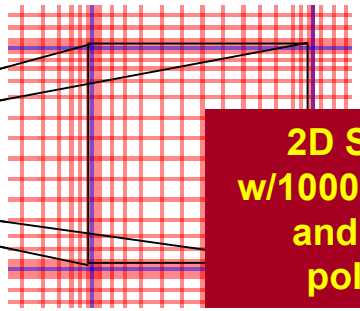
Next Generation High-Resolution Modeling
Nonhydrostatic Unified Model for the Atmosphere (NUMA)

- **Spectral Element Dynamical Core:**
  - High order accuracy
  - Highly scalable
  - Mesoscale, Global options (w/ MPI)
  - Semi-implicit solver
  - Incorporation of physics underway

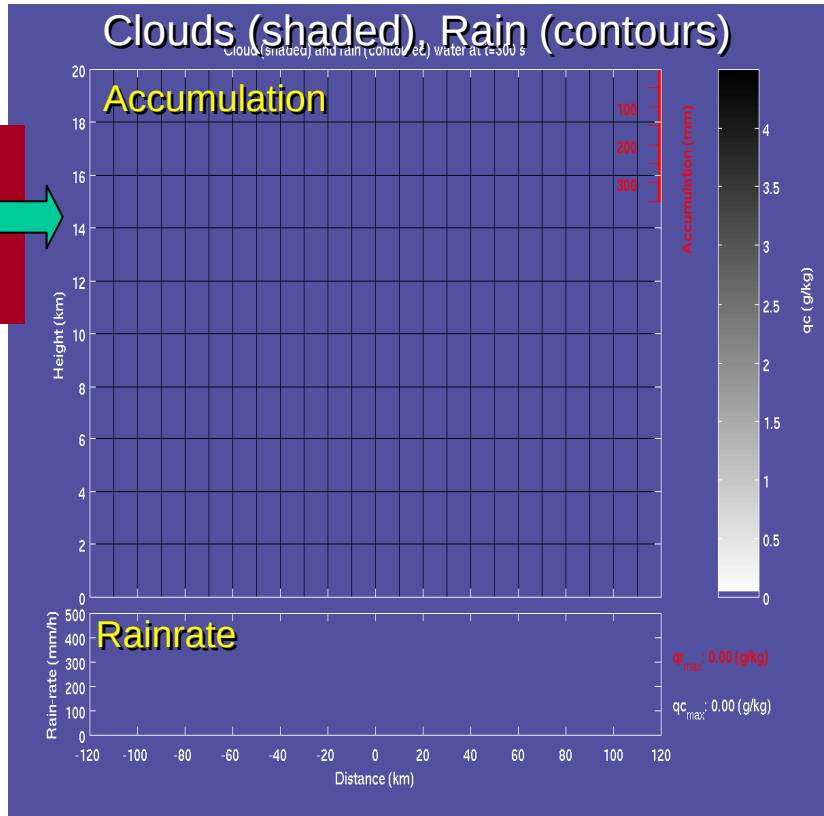








2D Squall Line w/1000 m resolution and 10th order polynomials



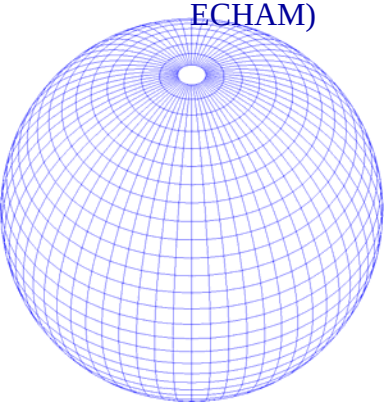
Density Current w/50 m resolution and 8th order polynomials

Frank Giraldo, Jim Kelley (NPS), Sasa Gabersek (NRL)

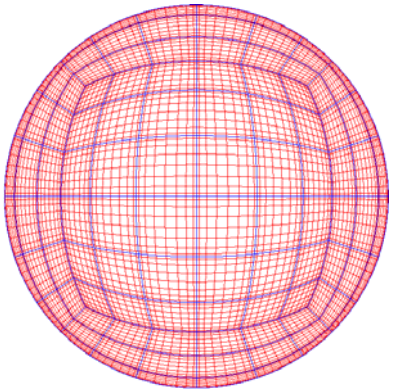
Nonhydrostatic Unified Model for the Atmosphere

NUMA Grid Capabilities

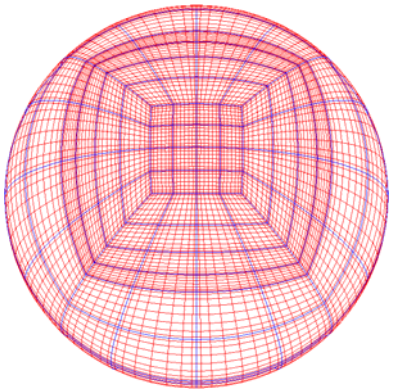
Lat-Lon
(IFS, GFS, NOGAPS, UM, CAM, ECHAM)



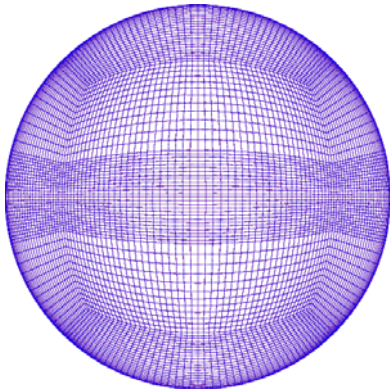
Hexahedral
(HOMME, NSEAM, FV-Cube)

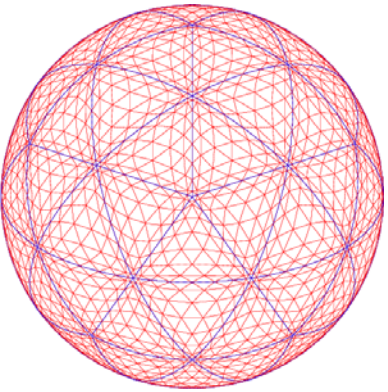


Telescoping

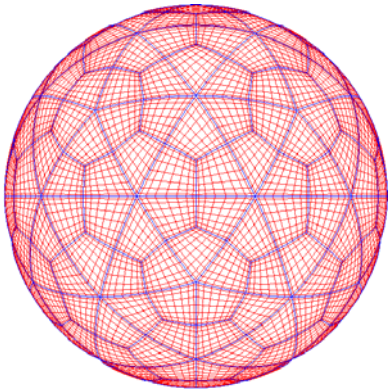


Banded

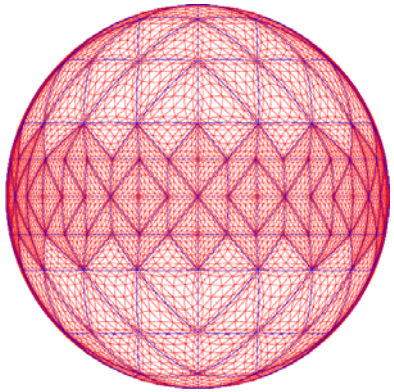




Icosahedral
(NICAM, ICON, FIM, MPAS)



Icosahedral



Adaptive

Adaptive

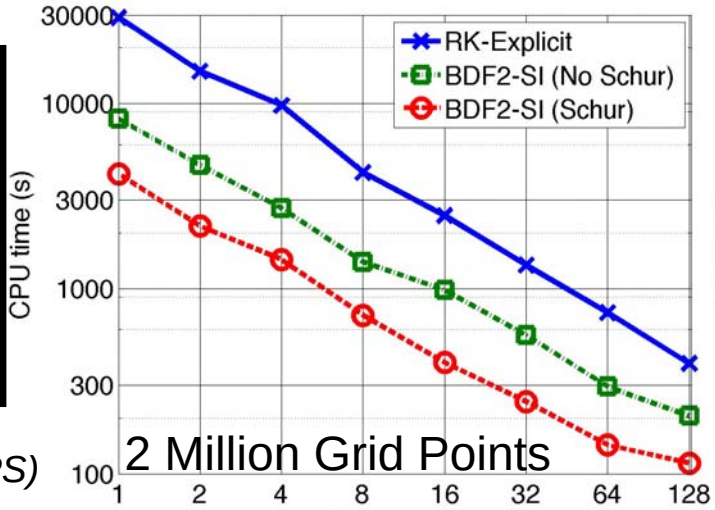
Frank Giraldo, Jim Kelley (NPS)

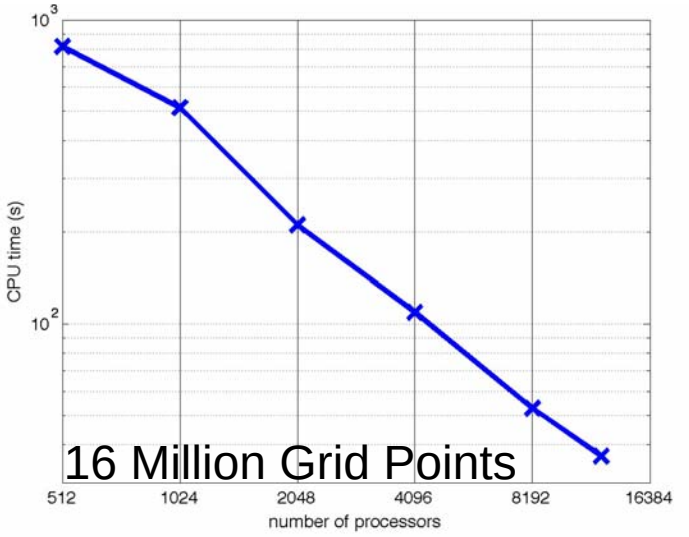
Nonhydrostatic Unified Model for the Atmosphere

NUMA Scaling Performance and DG Adaptivity

- Spectral Element Models are Highly Scalable.
- Option for Domain Decomposition in Vertical.

Frank Giraldo, Jim Kelley (NPS)





Nonhydrostatic Adaptivity using a Discontinuous Galerkin Method.

Müller, Behrens, Giraldo, Wirth 2010

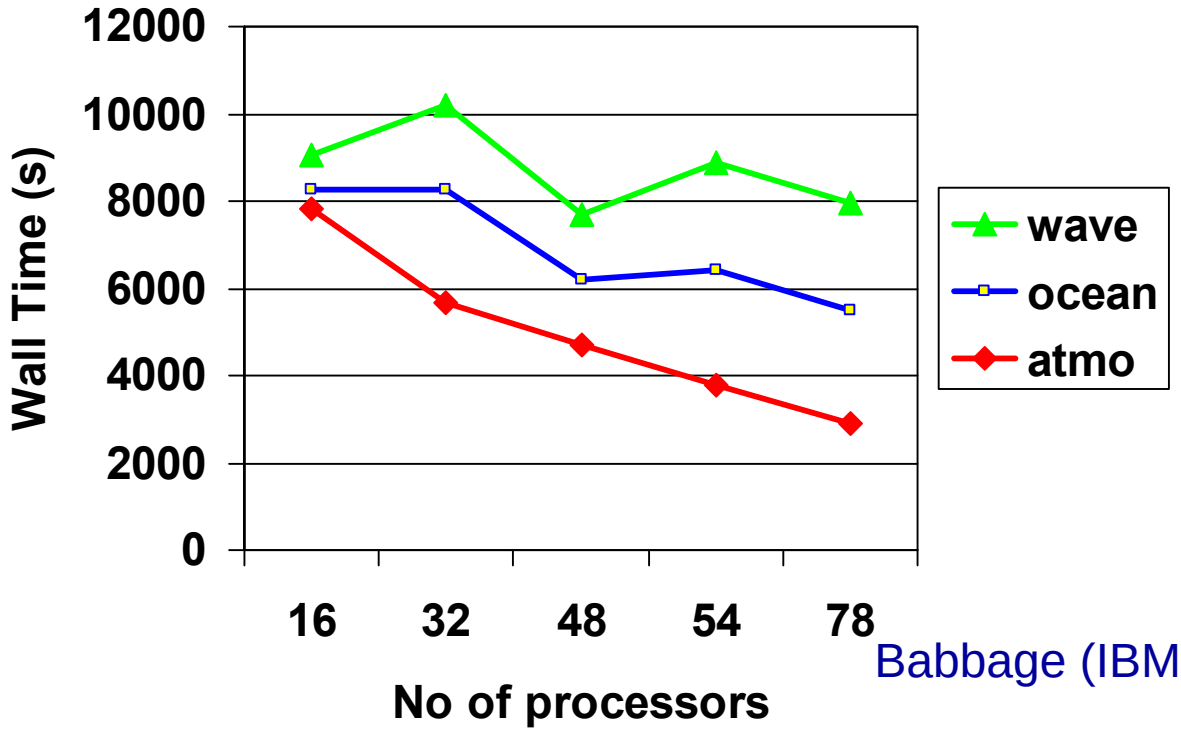
Challenges and Future Directions

- **High-Resolution Coupled Modeling:**
  - Representation of key environmental interactions (air, sea, wave…)
  - High resolution needed to resolve key processes, however gray areas exists
    - convection (Δx~1-4 km), gravity waves (~2 km), turbulence (5-100 m)
  - Motivates need for new physics algorithms (turbulence, clouds, spray...)
  - Coupled mesoscale ensembles provide estimates of the uncertainty
  - New model development underway (nonhydrostatic SE, semi-Lagrangian)
  - New data assimilation methods for the cloud scale (hybrid)
  - Community efforts: HFIP, Earth System Prediction Capability, NUOPC

- **Computational Attributes and Challenges:**
  - Faster cores and greater number of cores (resolution, physics, ensembles)
  - Fast I/O (ensembles, post processing)
  - New paradigms (SE) may be needed for scaling across 10,000+ cores
  - Adaptive load balancing for embedded meshes
  - Challenges for coupled codes (balancing)
  - Grid / cloud computing challenges for ensembles (post processing)
  - Visualization / data management challengesre

Three-Way Coupled COAMPS Scaling (Concurrent)

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS®)



Babbage (IBM SP5)

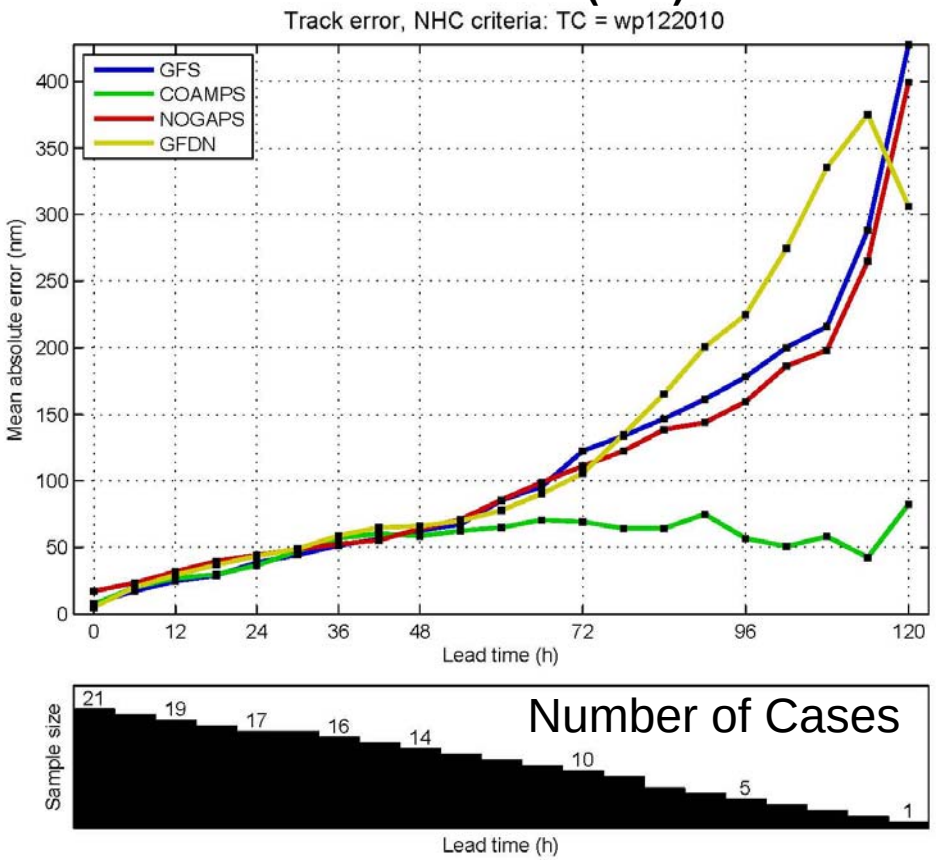
Total no. of proc.	No. of atmos proc./run-phase wall time(s)	No. of ocean proc./ run-phase wall time(s)	No. of wave proc./ run-phase wall time(s)	Component run-phase wall time ratio
78	72 / 2908	2 / 2600	4 / 2449	1.18 : 1.06 : 1
54	48 / 3799	2 / 2601	4 / 2468	1.54 : 1.05 : 1
48	36 / 4271	4 / 1466	8 / 1491	2.91 : 1 : 1.02
32	24 / 5649	2 / 2624	6 / 1922	2.94 : 1.33 : 1
16	16 / 7814	16 / 462	16 / 788	16.91 : 1 : 1.69

COAMPS-TC Forecast Skill

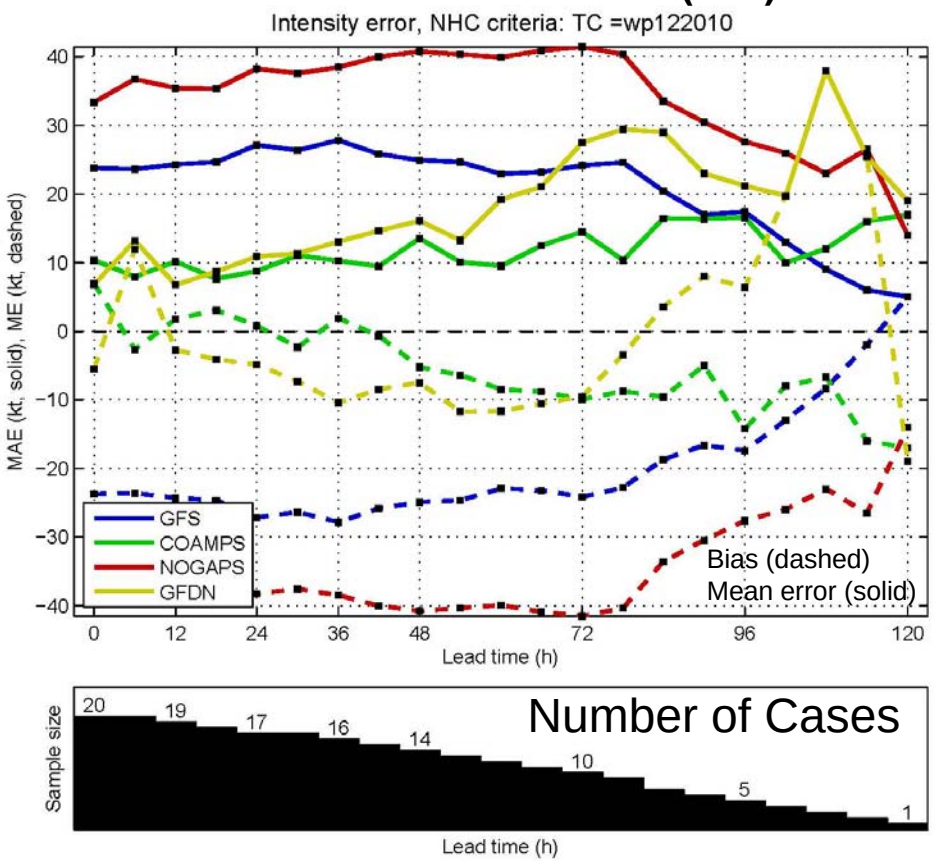
Real-Time Forecasts for Typhoon Fanapi (12W) (2010)

Homogeneous Comparison

Track Error (nm)



Wind Forecast Error (kts)



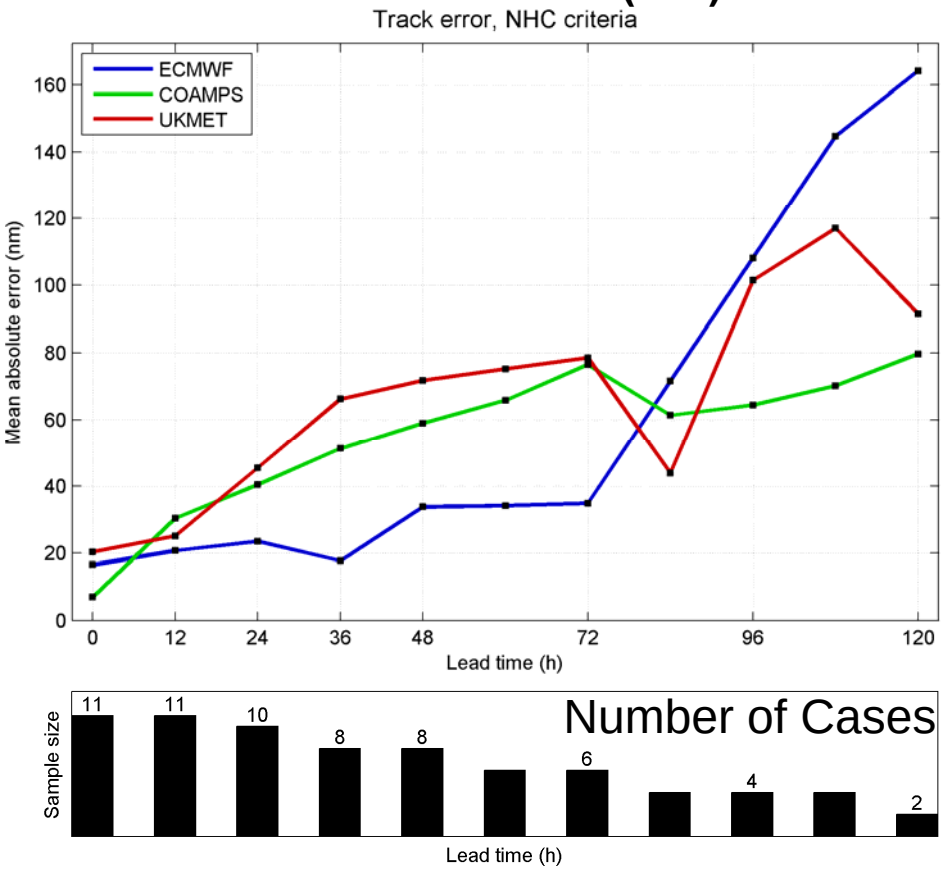
COAMPS-TC Track and Intensity Skill is Significantly Better than the Global (GFS, NOGAPS) and Regional Models (GFDN) for Typhoon Fanapi.

COAMPS-TC Forecast Skill

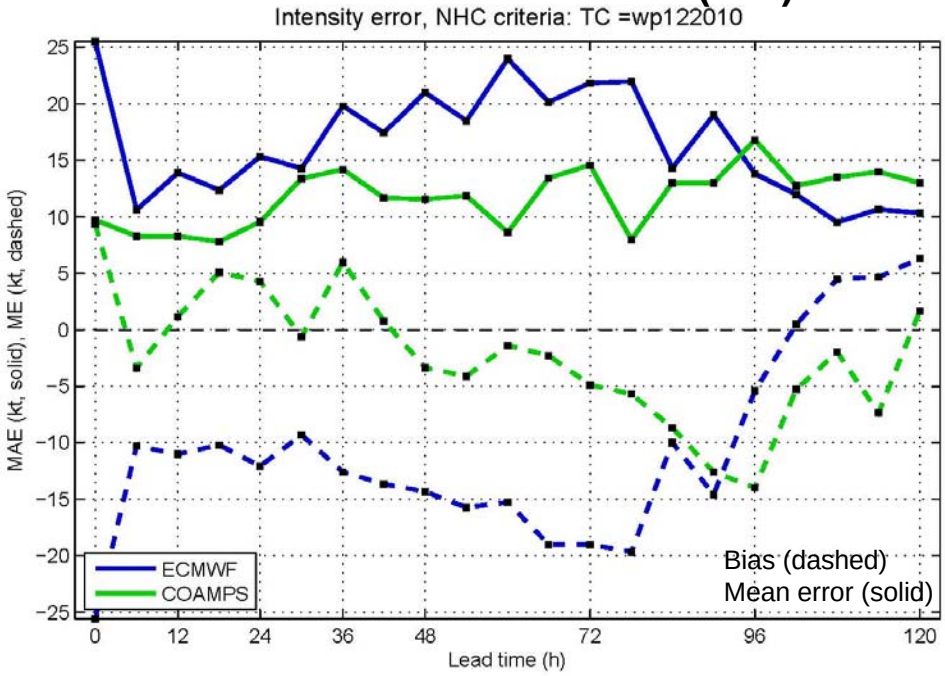
Real-Time Forecasts for Typhoon Fanapi (12W) (2010)

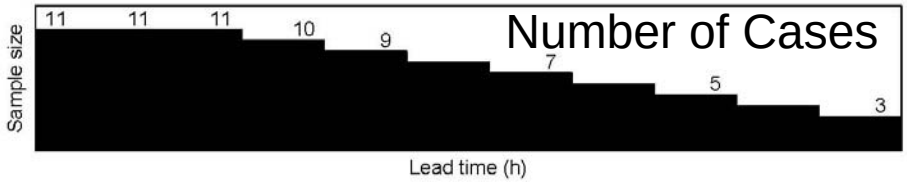
Homogeneous Comparison with ECMWF and UK Metoffice

Track Error (nm)



Wind Forecast Error (kts)





- **COAMPS-TC Track Skill is Comparable to UKMET and Slightly Lags ECMWF.**
- **COAMPS-TC Intensity Skill is Greater Than ECMWF.**