# Navy Sponsored Research Contributing to the U.S. National Earth System Prediction Capability (ESPC) Partnership

Daniel Eleuterio[1], Melinda Peng[2], Gregg Jacobs[3], James Richman[3], Tim Whitcomb[2], and Carolyn Reynolds[2]

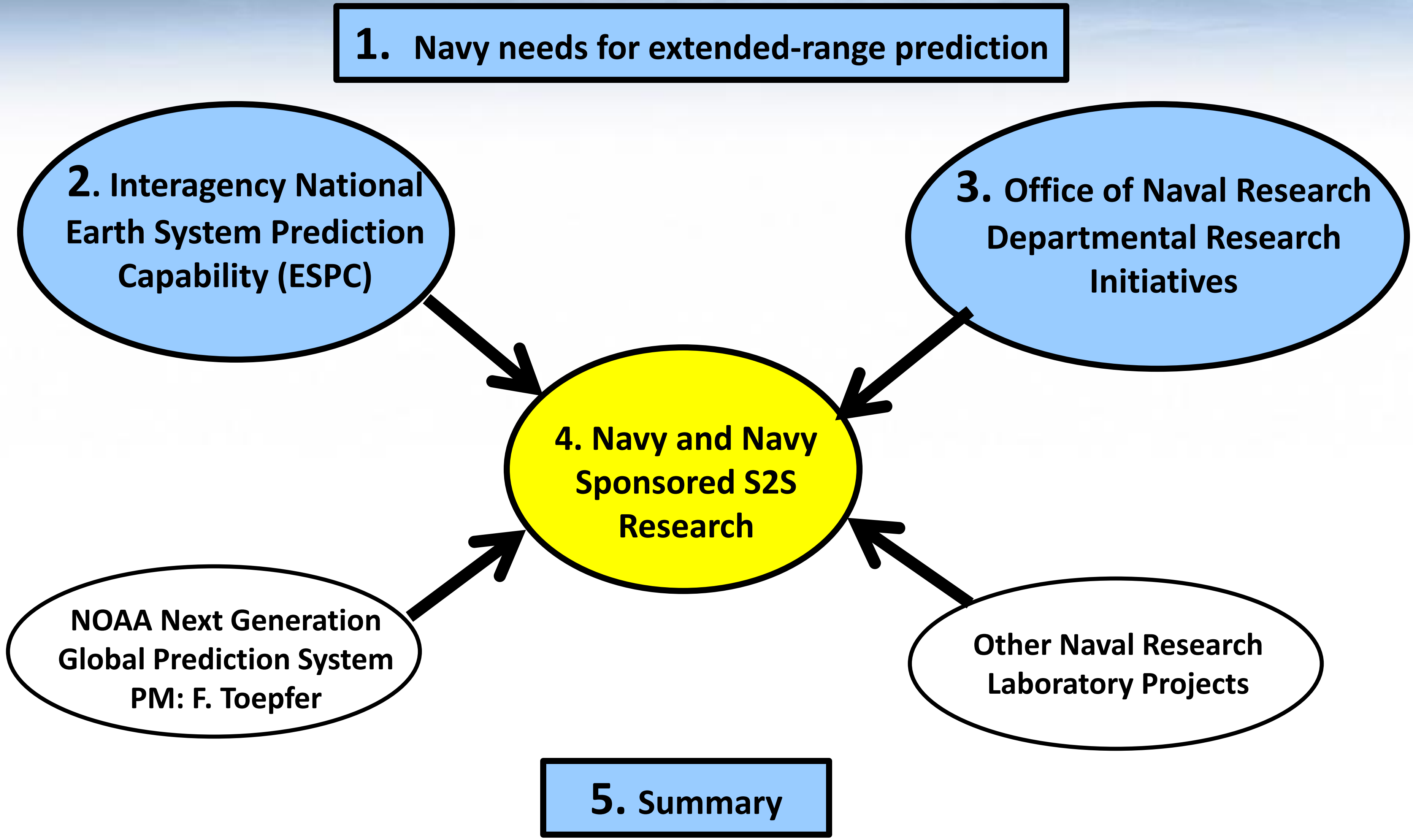
[2,3] **Naval Research Laboratory Monterey CA, and Stennis Space Center, MS**

[1] **ONR 322 Marine Meteorology, Arctic, and Global Prediction**

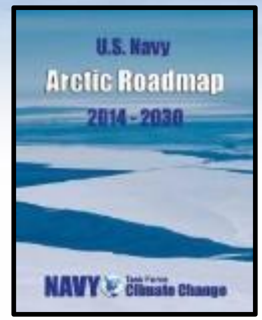
WGNE 30

March 2015

# Navy Extended-Range and Arctic Forecasting Research



# 1a. Challenges






***We provide worldwide forecasts to support DoD Operations – from the tropics to the poles, and from the depths of the ocean to the edges of space, across the coast to support stability operations, humanitarian assistance and disaster relief.***

# 1b. Opportunities

## *A National Earth System Prediction Capability*

TC Forecasts

Sea Level Rise

Aerosols & GHG

Extreme Weather
Floods, Droughts

Arctic Operations

National Security

***The time is now to accelerate research into operational capabilities for improved global medium range (to ~90 days) and long range (seasonal) forecasting skill to address national security and societal impacts of the environment through collaboration between the Research and Mission Agencies in the Dept. of Defense, NOAA, DoE, NASA and NSF.***

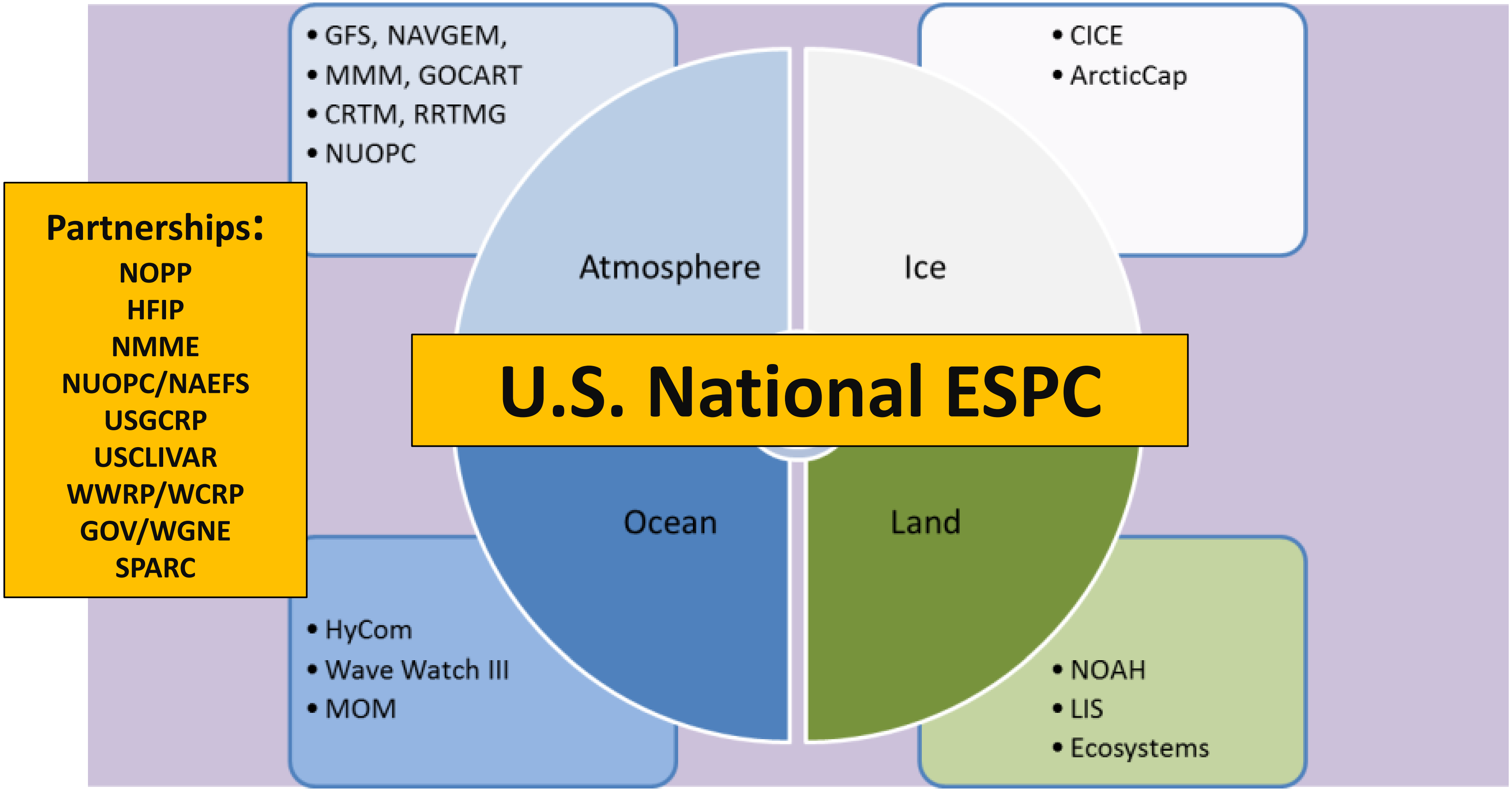
# 2. U.S. National ESPC Overview

An interagency collaboration since 2010, for coordination of research to operations of a National Earth System Model analysis and prediction capability.

Seeks improved coordination of global prediction of weather, ocean, and sea ice conditions at weather to seasonal timescales.

- Common prediction requirements and forecast model standards that enable agencies to improve leverage and collaboration.
- Cooperative focus projects to assess predictability of global scale high impact environmental conditions in research with an eye towards operations.
- Towards an multi-model, ensemble based, air-sea-land coupled global prediction capability.

# R2O Coordination for
## Earth System Modeling & Prediction



# Earth System Modeling Framework (ESMF) and the Earth System Prediction Suite (ESPS)

ESPS is a collection of NUOPC-compliant Earth system component and model codes

- interoperable, documented, available for integration/use.

Implementation is part of a NOPP project awarded under National ESPC: “An Integration and Evaluation Framework for ESPC Coupled Models”.

The NUOPC Interoperability Layer is:

- a set of rules for coding an ESMF-compliant Earth system components and downloadable model architecture.

ESPS website with draft inclusion criteria and list of candidate models (Coupled, Atmosphere, Ocean, Ice, and Wave):

http://www.earthsystemcog.org/projects/esps/

| Coupled Modeling Systems | NEMS | CFSv3 | COAMPS -TC | Navy ESPC | GEOS-5 | ModelE | CESM |
|---|---|---|---|---|---|---|---|
| | 2014 | 2014 | | | 2015 | 2015 | 2014 |
| **Atmospheres** | | | | | | | |
| GFS/GSM | | | | | | | |
| NMMB | | | | | | | |
| CAM | | | | | | | 2015 |
| FIM | 2015 | | | | | | |
| GEOS-5 FV | | | | | 2015 | | |
| ModelE Atm | | | | | | 2015 | |
| COAMPS | | | | | | | |
| NavGEM | | | | | | | |
| Neptune | | | | 2015 | | | |
| WRF | | | | | | | |
| **Oceans** | | | | | | | |
| MOM | | | | | | | |
| HYCOM | | | | | | | |
| NCOM | | | | | | | |
| MPAS-O | | | | | | | |
| POP | | | | | | | 2014 |
| **Ice** | | | | | | | |
| CICE | 2014 | 2014 | | | 2015 | 2015 | 2014 |
| **Wave** | | | | | | | |
| WW3 | 2015 | | 2015 | 2016 | 2015 | | 2015 |
| SWAN | | | 2014 | | | | |

LEGEND

Compliant | Completion date | In progress | Candidate

DeLuca et al. 2015 (in prep.)

# Coupled Geophysical Prediction (Models + Data Assimilation)

**1) NAVGEM** (Navy Global Environmental Model) next-generation global numerical weather prediction model; Major resolution and physics increase 2016.

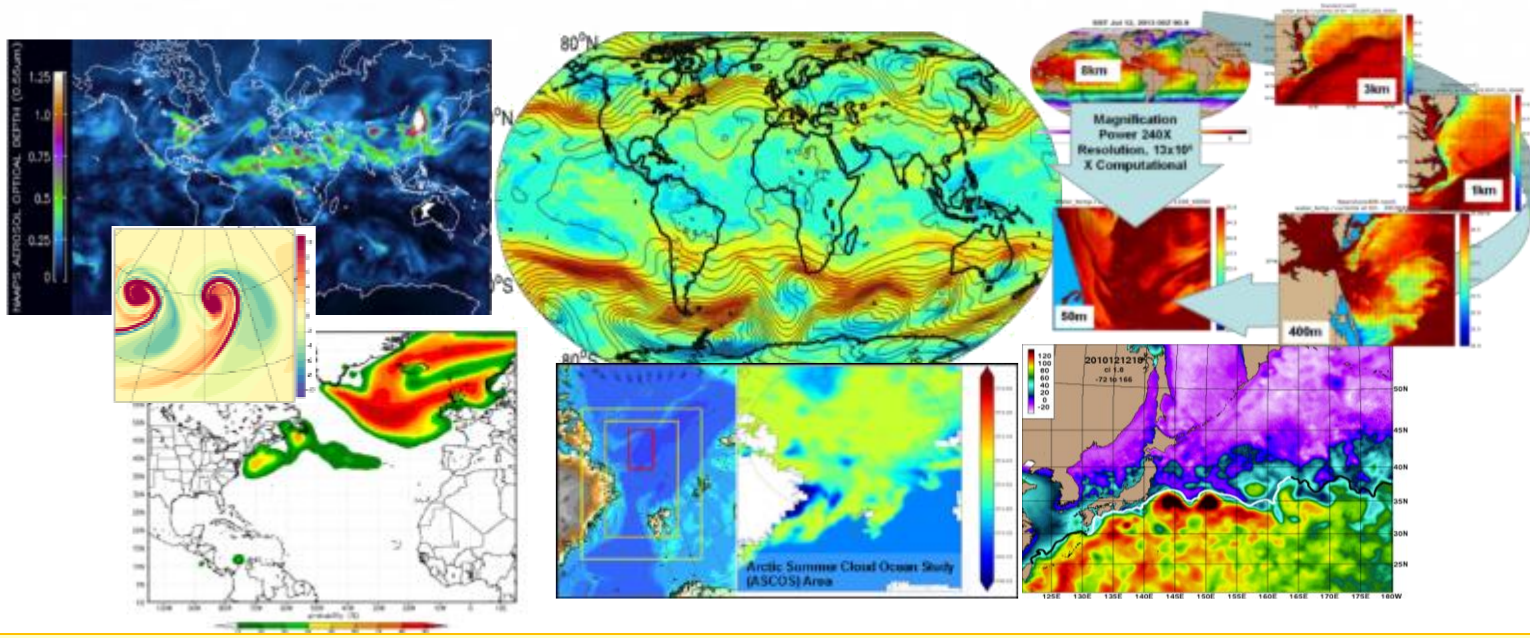
**2) COAMPS-TC** mesoscale tropical cyclone model. Predicts dynamically-driven TC intensity changes.

**3) GOFS** (Global Ocean Forecast System) Ver. 3.1 operational in **FY15.** [1/12º CICE with HYCOM, with tides]. GOFS 3.5 1/25º FY17.

**4) WaveWatch 3** (Global and Regional Wave Model) Ensemble operational in **FY14** [joint with NOAA and Canada].

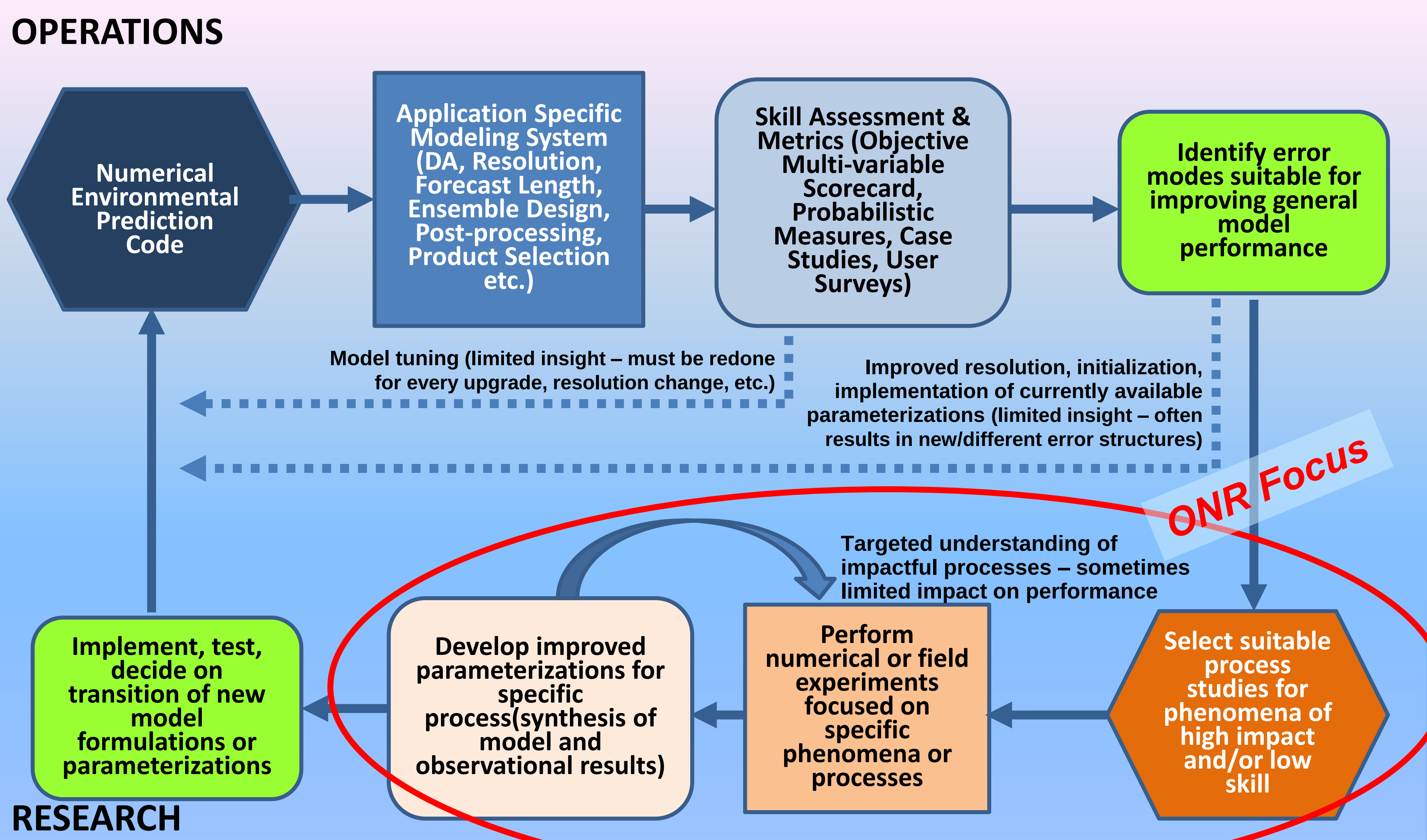
**5) Regional Arctic Coupled Forecast System** [Arctic COAMPS with HYCOM/CICE/WaveWatch3]

• **Future transitions: Coupled NAVGEM/ NAAPS/ GOFS via ESPC, COAMPS Ensemble, GOFS 3.5**.




Operational Predictions made by CNMOC Production Centers in Mississippi and California

# 3. Environmental Research in a Mission Agency




After Jakob, BAMS2009

# Department Research Initiatives (DRI)

**Since 1995, 52 Five Year Studies Completed (through end FY14)**

| DRI's by FY | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atmosphere-Ocean Processes for WestPac Tropical Storms | | | | | | | | | | | | | | |
| Tidal Flat Dynamics | | | | | | | | | | | | | | |
| Quantifying, Predicting, Exploiting Uncertainty | | | | | | | | | | | | | | |
| High Resolution Air-Sea Interaction Processes (CBLAST) | | | | | | | | | | | | | | |
| Impact of Typhoons in the Ocean (ITOP/ TCS-10) | | | | | | | | | | | | | | |
| Space Weather Forecasting Capability | | | | | | | | | | | | | | |
| Western Pacific Tropical Cyclone Structure (TCS-08/T-PARC) | | | | | | | | | | | | | | |
| Surf Zone Optical Variability | | | | | | | | | | | | | | |
| Scalable Lateral Mixing and Coherent Turbulence Program (LATMIX) | | | | | | | | | | | | | | |
| Internal Waves in Straits Experiment (IWISE) | | | | | | | | | | | | | | |
| Origins of Kuroshiro and Mindanao Currents (OKMC) | | | | | | | | | | | | | | |
| Inlet and River Mouth Dynamics (RIVET) | | | | | | | | | | | | | | |
| Littoral Air-Sea Processes (DYNAMO) | | | | | | | | | | | | | | |
| Vietnamese Shelf Variability | | | | | | | | | | | | | | |
| Parameterizations for Seasonal Predictions | | | | | | | | | | | | | | |
| Active Transfer Learning | | | | | | | | | | | | | | |
| Predictability of Seasonal and Intraseasonal Oscillations | | | | | | | | | | | | | | |
| Emerging Dynamics of the Marginal ice Zone (MIZEX) | | | | | | | | | | | | | | |
| Remote Sensing of Deltas | | | | | | | | | | | | | | |
| Bay of Bengal Freshwater Flux (ASIRI) | | | | | | | | | | | | | | |
| Fluxes Through the Ocean Boundary Layer (Langmuir Cell) | | | | | | | | | | | | | | |
| Increasing Open Water in the Arctic Ocean (Sea State Arctic) | | | | | | | | | | | | | | |
| Impact of Outflow on Tropical Cyclone Intensification & Structure (OUTFLOW) | | | | | | | | | | | | | | |
| Northern Arabian Sea Circulation - autonomous research (NASCar) | | | | | | | | | | | | | | |
| Flow Encountering Abrupt Topography (FLEAT) | | | | | | | | | | | | | | |
| The Inner Shelf | | | | | | | | | | | | | | |
| Propagation of Intra-Seasonal Tropical Oscillations (PISTON) | | | | | | | | | | | | | | |
| Coastal Land-Air-Sea Interactions (CLASI) | | | | | | | | | | | | | | |
| Stratified Ocean Dynamics in the Arctic (SODA) | | | | | | | | | | | | | | |

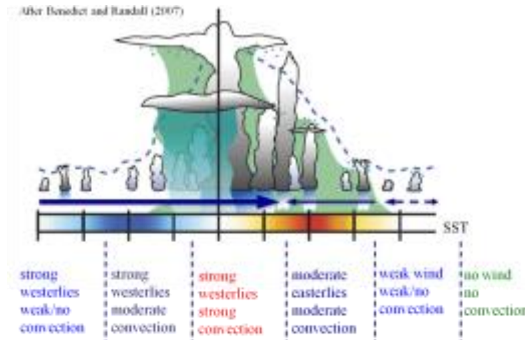
- New start DRI Candidates each year – allows programs to mount field or infrastructure intensive efforts beyond reach for individual core environmental science disciplines
- Responsive to top down guidance representing department strategic direction

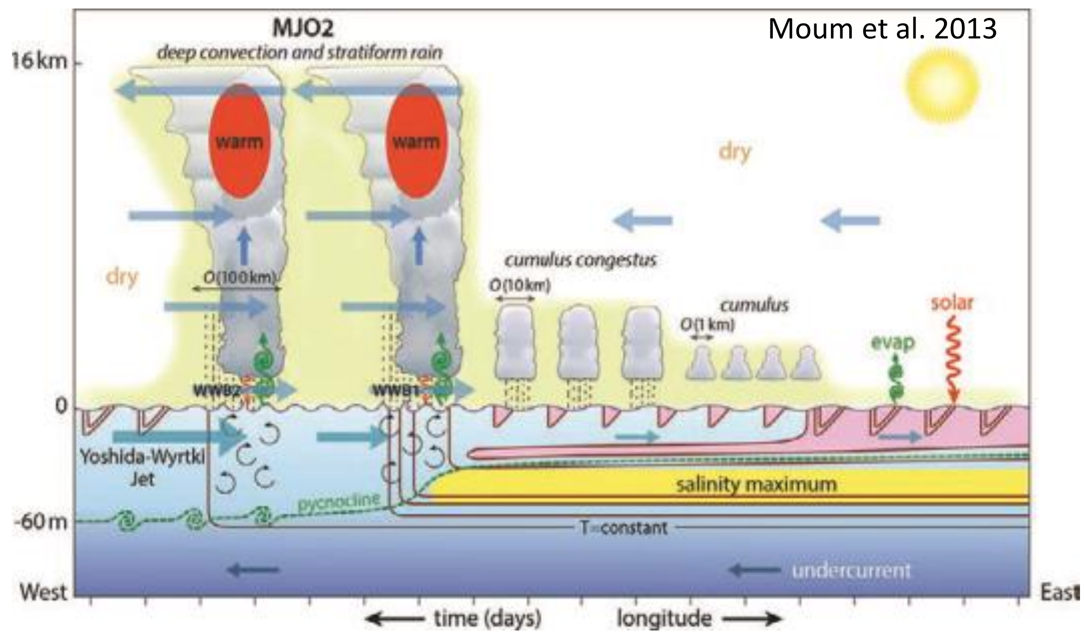
# ONR 32 Departmental Research Initiatives
# 3a. Dynamics of the MJO/ Air-Sea Processes (DYNAMO/LASP)
# 2010-2014

**Overarching DYNAMO Goal:**
**Advance our understanding of Madden-Julian Oscillation initiation processes for improved simulation and prediction of the MJO: air-sea interaction, convective initiation, cloud processes, and mid-tropospheric transport for climate and weather applications.**

***ONR-specific Goals:***

- ***A better understanding of physical processes and numerical representation of air-sea multi-scale coupled modes in MJO initiation and propagation.***
- ***Eventual improved operational prediction in the maritime tropics and subtropics.***

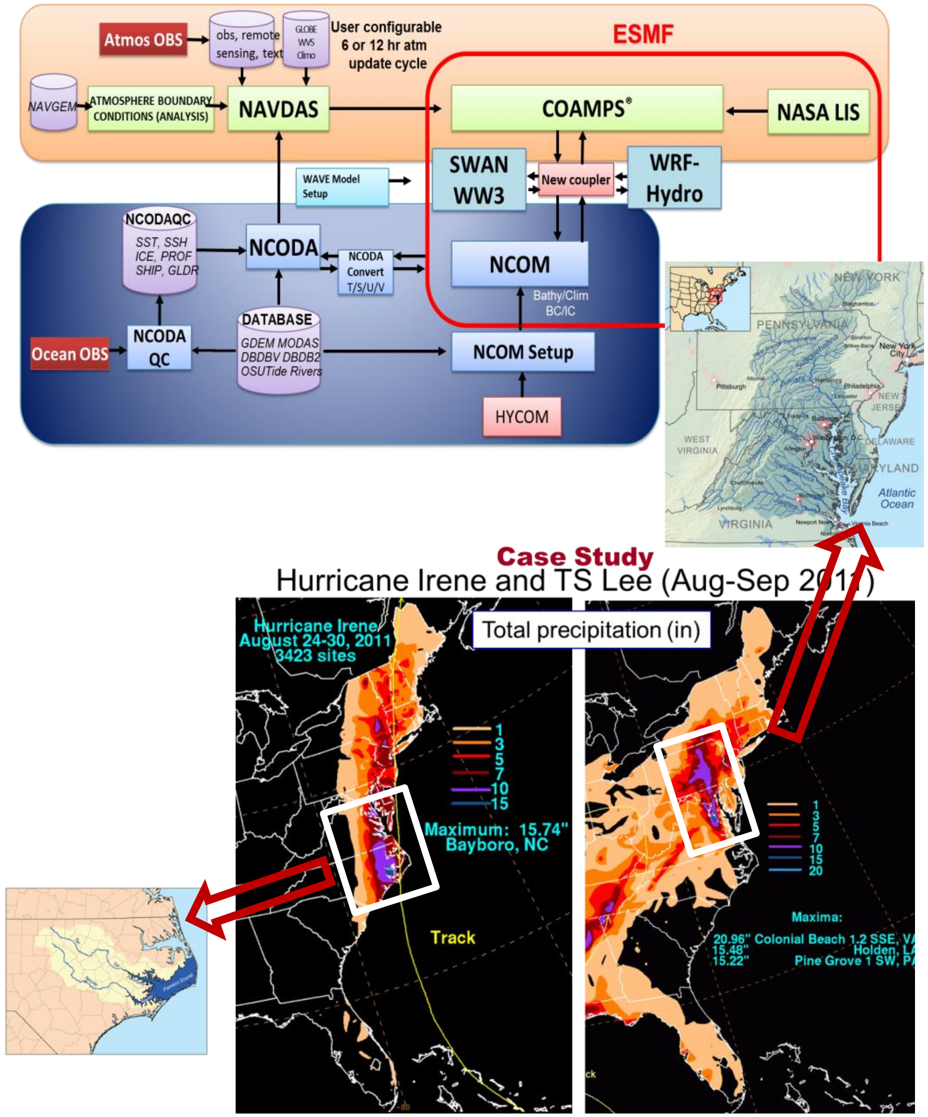


# 3f. Hydrology Coupled to COAMPS for Advanced Prediction (HyCCAP) (NOPP) 2015-2019

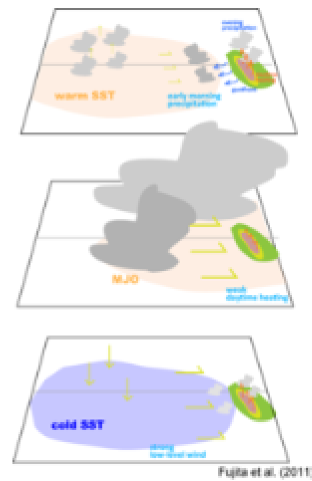
## S&T Objectives:

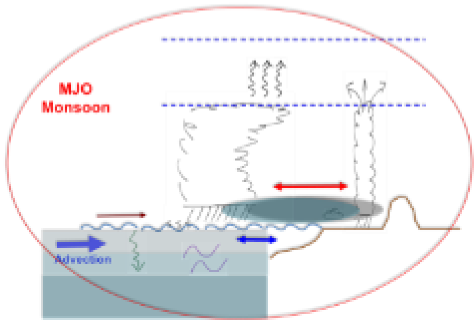
- Development of a mesoscale coupled atmosphere, land surface and hydrological forecast capability for improved skill in domains with large freshwater features as part of the scene.
- Leverage advanced development of ESMF compliant components in collaboration with partners at NCAR, NOAA, NCEP, USACE CRREL, and NASA.
  - Understand the water cycle impact on land surface dynamics, via the interactive feedback of land surface hydrology within the COAMPS land-surface model (LSM) framework.
  - Quantify the impact of enhanced cloud-microphysical processes via linkage with COAMPS moist physics parameterizations.
  - Quantify the feasibility of a “generalized” hydrological component within the COAMPS framework for use in ungauged basins.

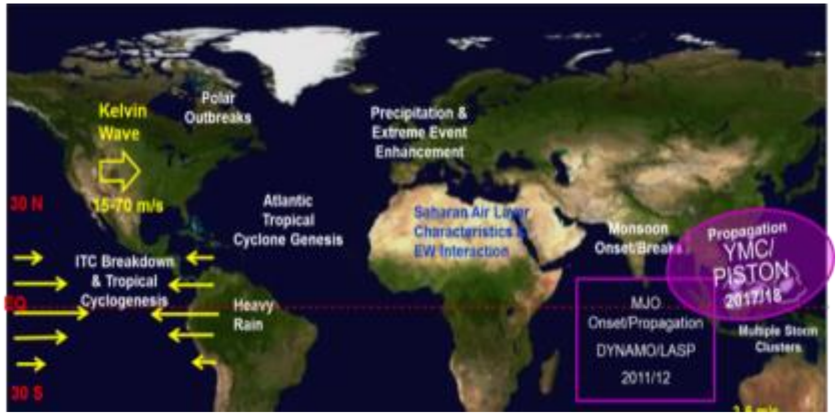


# 3f. Propagation of Intra-Seasonal Tropical Oscillations across the Philippines and the Maritime Continent (PISTON) 2016-2020

- **FY16/17: Planning, partnering, and numerical experimentation**
- **FY 18/19: Field efforts in collaboration with NASA CAMPEx and the International Year of the Maritime Continent (YMC).**
- **The PISTON Departmental Research Initiative will focus on the role of land-air-sea interaction and multi-scale convection in ISO propagation mechanisms across tropical archipelagos. An announcement of opportunity is expected to be released later this Spring for the Propagation of Intra-Seasonal Tropical Oscillations (PISTON) DRI in coordination with NASA's Cloud and Aerosols in Monsoon convection Processes Experiment (CAMPEx).**



# Proposed Timeline and Partnerships

Call for Proposals, Partnering

Instrument Development Pilot Study Final planning

Year of the Maritime Continent Apr 2017-2018

Data Quality Control & Analysis

| 2015 | | 2016 | 2017 | 2018 | 2019 | 2020 | |
|---|---|---|---|---|---|---|---|

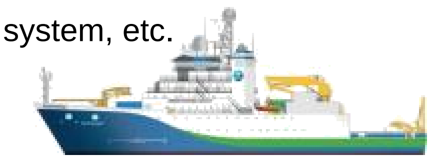
International Science Workshop Singapore (January)

Kick-off Meting

Analysis, Modeling, Synthesis & Publication

## Australia

| | |
|---|---|
| CAWCR | Numerical model, Ship-based observations, BoM sites |
| Monash Univ (C. Jacob) | Numerical model for MC |
| New Research Ship | ***R/V Investigator*** (available in 2015). Polarized C-band radar, sounding system, etc. |



## Indonesia

| | |
|---|---|
| BMKG (N. Hayati) , BPPT | Extensive ground based observational network, ***R/V Barunia Jaya 2&3*** |

## Japan

| | |
|---|---|
| JAMSTEC, Kyoto U. (K. Yonemaya) | ***R/V Mirai,*** TAO/TRITON & RAMA arrays, cooperative land-based observations with Indonesia, Philippines, Palau, NWP (NICAM), Sumatra Equatorial Atmos. Radar |

## France

| | |
|---|---|
| LMD (J.-P. Duvel) | Numerical model and Ship-based observations. Late 2015 /early 2016 collaborative cruise btwn JAMSTEC & French groups off Sumatra. |
| LEGOS (R. Roca) | Satellite (Megha-Tropiques) |

## Malaysia

| | |
|---|---|
| MMD (M. Rosaidi) | Extensive ground based observational network, upper air stations, air pollution stations, weather radar network |

## Philippines

| | |
|---|---|
| MO (G. Narisma) | Numerical model, land-based and (possibly) ship-based observations. |

## U.S.

| | |
|---|---|
| NASA (H. Maring) | CAMPEx Aircraft P-3/DC-8 atmospheric composition, dropsondes, significant ground network |
| ONR (D. Eleuterio) | ***R/V Sally Ride***, radar, soundings, possibly UAVs, ocean obs |
| NRL (J. Schmidt) | Numerical experiments, Equatorially Trapped Moist Modes |
| DoE | TBD |
| NOAA | TBD |
| NSF | TBD |

Possibility of Intensive Obs (ex. 8/day soundings for 6 months during the MJO season).

# 3. Summary: ONR DRIs

- *Recent Successes:*
  - *Long-range prediction of TC genesis facilitated by accurate tropical wave prediction*
  - *Improved QBO simulation given sufficient resolution and inclusive parameterizations*

- *Predictability Barriers:*
  - *High-resolution needed for Arctic, QBO, MJO*
  - *Further improvement in parameterizations needed*
  - *Long-range TC prediction depends on accurate equatorial wave prediction*

- *Potential Follow-on Efforts*
  - *Coordinated S2S multi-model intercomparison*
  - *Multi-scale interactions among MJO, ENSO, and high-frequency modes*
  - *Organized convection focus (expertise from several DRIs)*
  - *Maritime continent issues (leverage YMC, CLIVAR MJO-task force)*
  - *Arctic prediction (leverage YOPP, IARPC/SIPN, PPP)*

# 4. Navy Sponsored Research at NRL

- *NRL Research Priorities:*
  - *Coupled system development (NAVGEM/HYCOM/CICE/WW3)*
  - *NEPTUNE potential candidate for Navy and NOAA NGGPS*

- *Future Challenges/Opportunities:*
  - *Parameterization Development*
    - *Consistency across systems (e.g., A-O fluxes)*
    - *scale aware*
    - *account for uncertainty (probabilistic, stochastic)*
  - *Scalability, efficiency on new architectures.*
  - *Probabilistic system development (how many ensemble members, what resolution, etc.)*

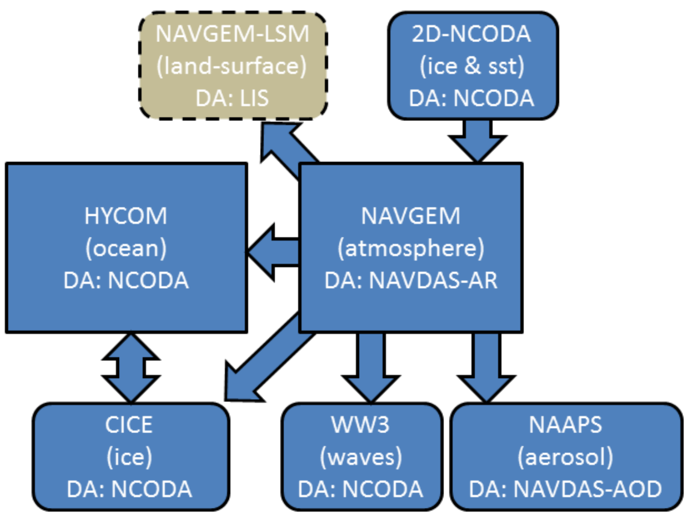
- *Priorities for improving S2S*
  - *Continued development of coupled system, next generation model, including DA*
  - *Identification of  Navy relevant metrics that also aid system development*
  - *Leverage work in wider community (e.g., NGGPS, NMME, CLIVAR MJO working group, YMC, etc.)*

***Please see talk by Carolyn Reynolds for the NRL Centre Report Update for more details***

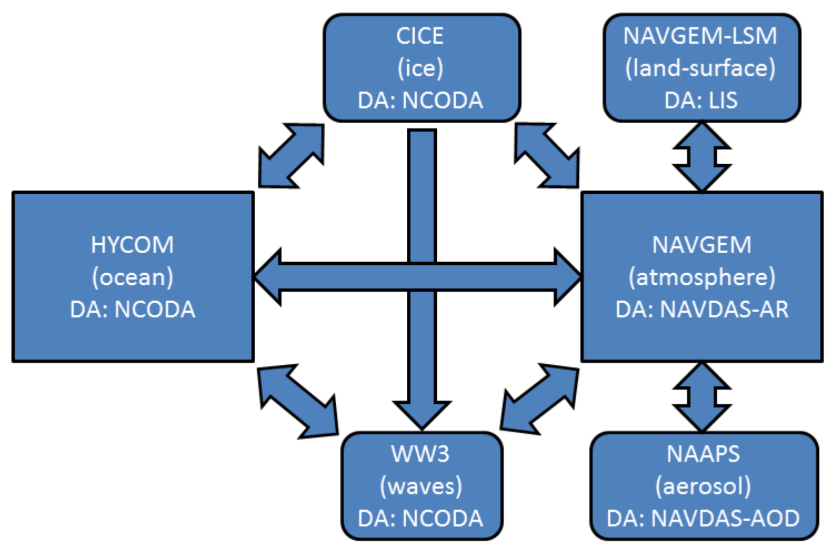
# 4. Navy Earth System Prediction Capability

- Contributes to the National, multi-agency collaborative effort to focus resources to develop the next generation earth prediction system
- Transitions research to operations, supports common components where feasible while accommodating unique Navy requirements
- Extend current global prediction capability beyond meso-synoptic ocean and weather prediction to sub-seasonal and seasonal lead times
- Develop data assimilating, cycling fully coupled global atmosphere-ocean-ice-wave systems

**Existing Uncoupled System**

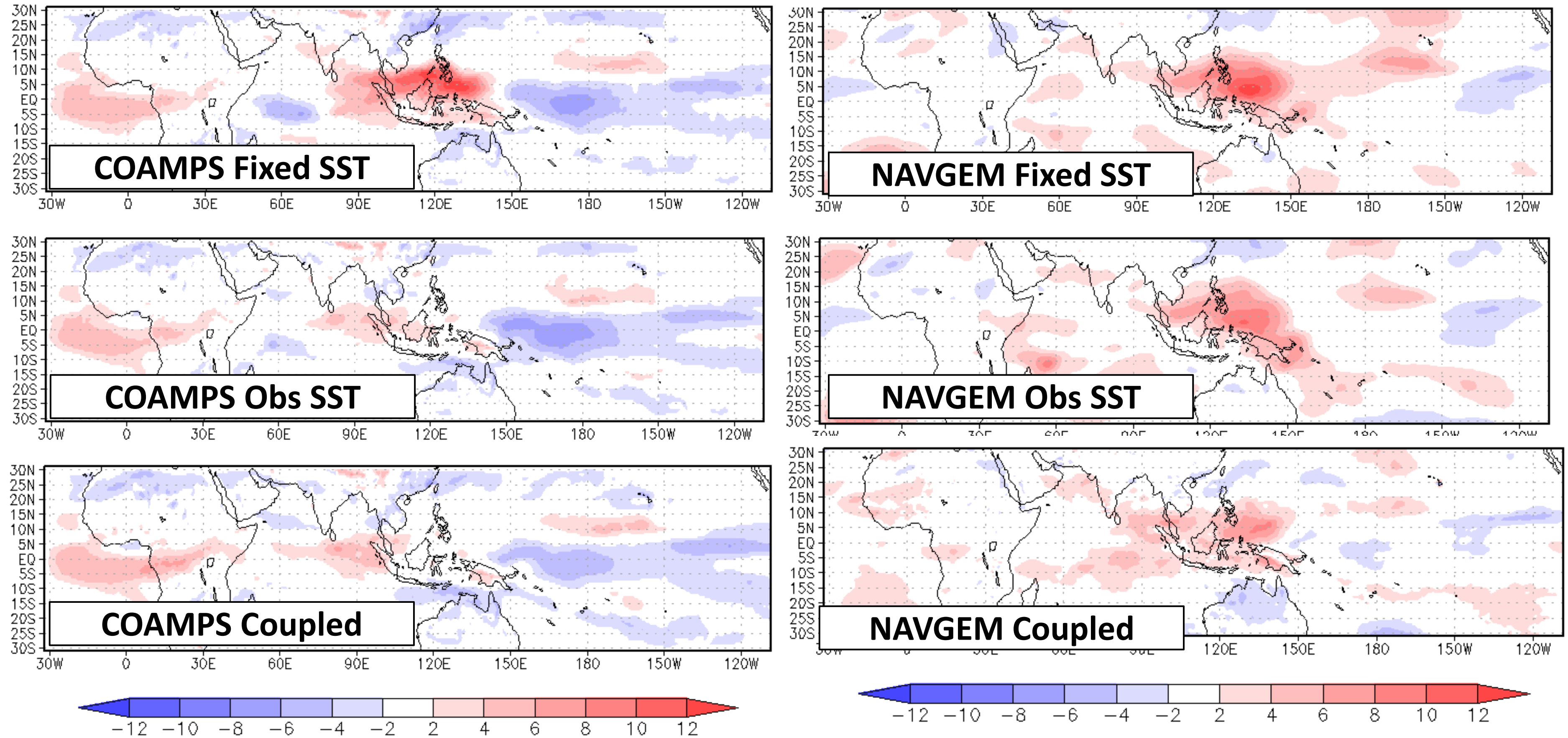



**Future ESPC Coupled System**



# 4. NRL Research: Biases in COAMPS and NAVGEM

## Average 850-hPa U Error (m/s) for 30-day forecasts from 1 NOV 2011




- *For both COAMPS and NAVGEM, low-level wind biases decrease when fixed SST (top) replaced by observed SST (middle)*
- *Bias is reduced even further in coupled system (bottom); encouraging since system have not been "tuned" for this application*

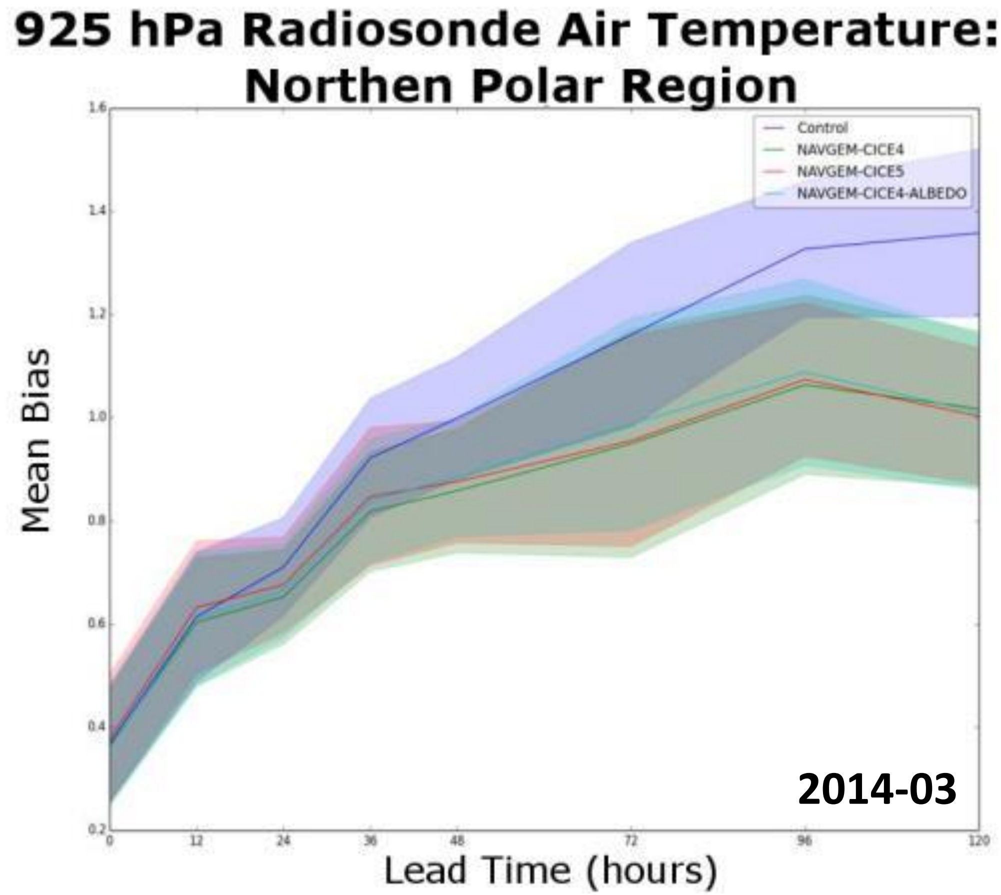
# 4. Navy ESPC Progress - Example

## Adding the Coupled Model to Atmospheric DA

- NAVGEM has a known polar temperature bias in the lower atmosphere during spring months.

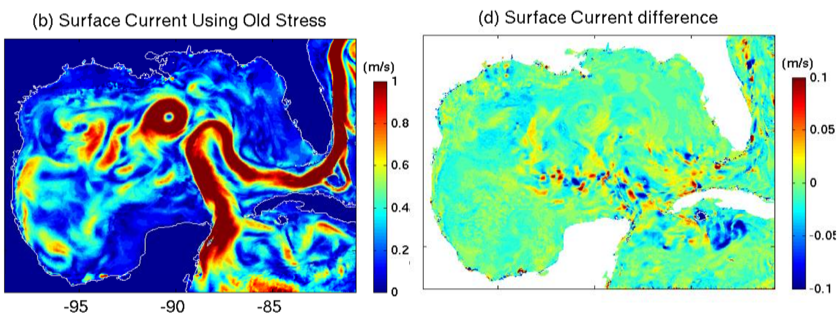
- NAVGEM – CICE are coupled and ran with NAVGEM-DA to test the effect of implementing  a new dynamic sea ice model to the known biases.

- All coupled runs have smaller biases in lower atmospheric temperatures compared with the control run.

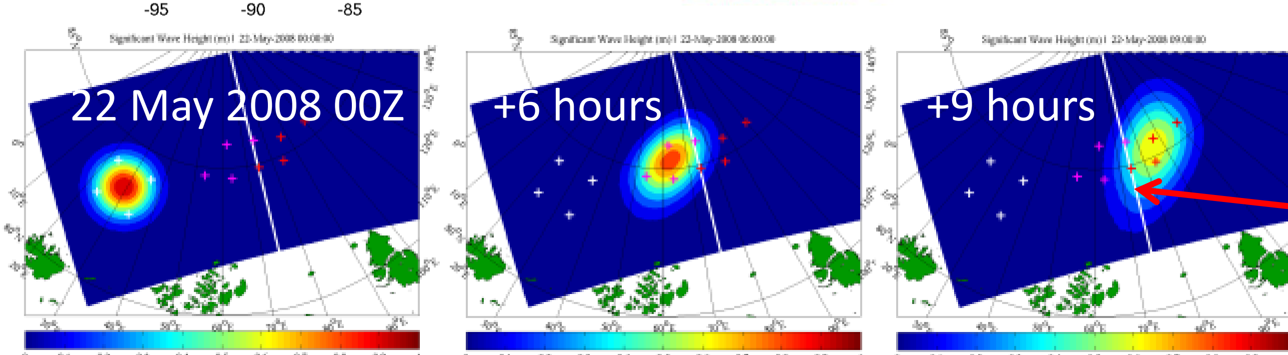


# 4. Navy ESPC Global Coupled System Wave Feedbacks

- Momentum transfers from the atmosphere primarily to the wave field and then through wave breaking and dissipation into the ocean. Momentum transfer from the wave field to the atmosphere is also included. These effects are implemented and undergoing testing.
  - Incorporation of wave effects into HYCOM
  - Momentum transfer between ocean / atmosphere through wave field dissipation physics
  - Extensions of WaveWatch III to incorporate tri-pole grid setup




Example of change in ocean surface currents (right) due to momentum transfer through surface wave field in fully coupled nested system



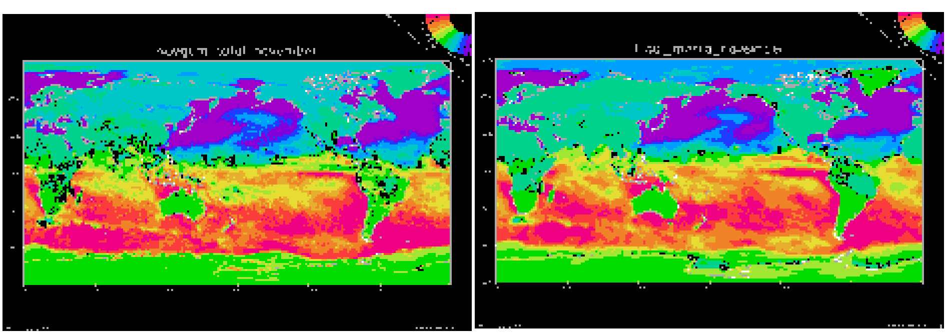

Testing of wave energy propagation across the Arctic seam of the tri-pole grid setup

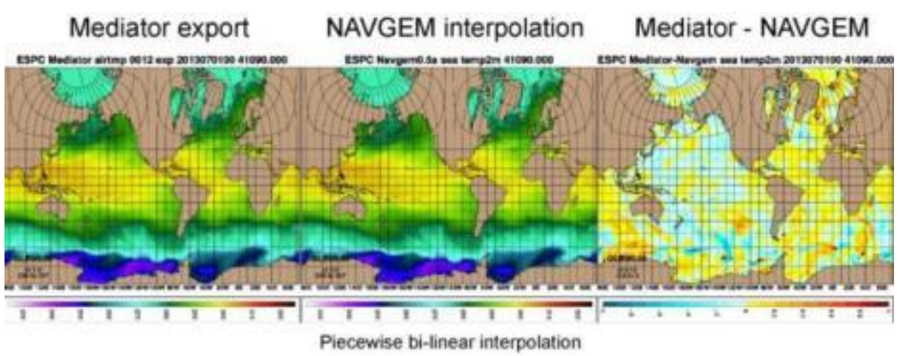
Difference between the two different ASEnKF predicted tides.

# 4. Navy ESPC Global Coupled System
# Verifying Mediator Performance

- Verifying the fluxes exchanged between the ocean and atmosphere in the coupled system
  - Standalone forecast systems for NAVGEM and HYCOM provide independent analyses
    - NAVGEM fluxes to the ocean reproduce the MERRA fluxes
  - With a data atmosphere, the fluxes to the ocean by the standalone forecast system and through the ESPC mediator with ESMF interpolation routines are compared
    - Broad scale patterns in the exchanged variables agree well, but fronts are diffused by the mediator
    - Wind speed and wind stress curl are poorly mapped by the mediator
    - Changes in the ESMF interpolation routines are being implemented to correct the problem

NAVGEM fluxes compare well with the MERRA fluxes

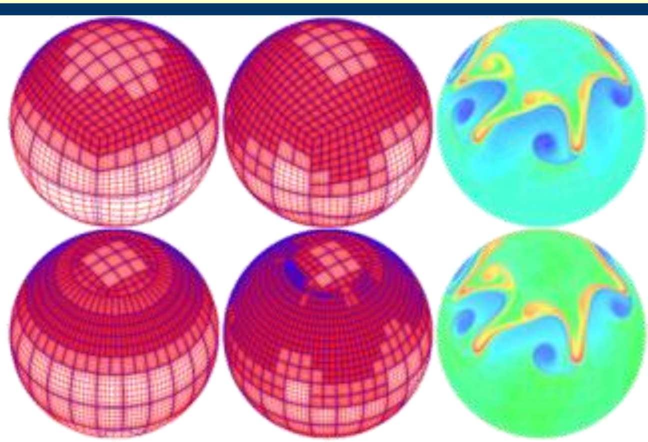




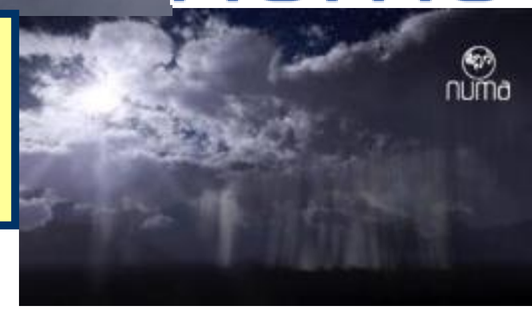

ESMF interpolation used in the Mediator reproduces the broad scale patterns in the scalar variables such as air temperature, but the fronts are poorly mapped. The errors occur on scales much larger than the grid differences between the ocean and atmosphere.

# Navy Environmental Prediction SysTem Utilizing the NUMA CorE (NEPTUNE)

NUMA is the dynamics solver inside NEPTUNE, a next-generation NWP Model for all scales

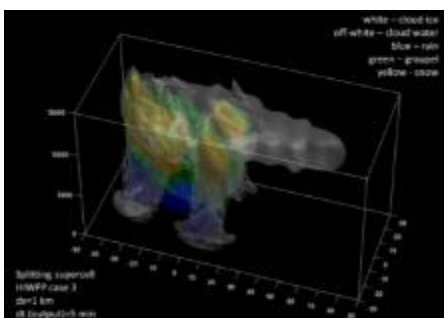



Thunderstorm Quantitative Numerical Simulation with Clouds and Rain



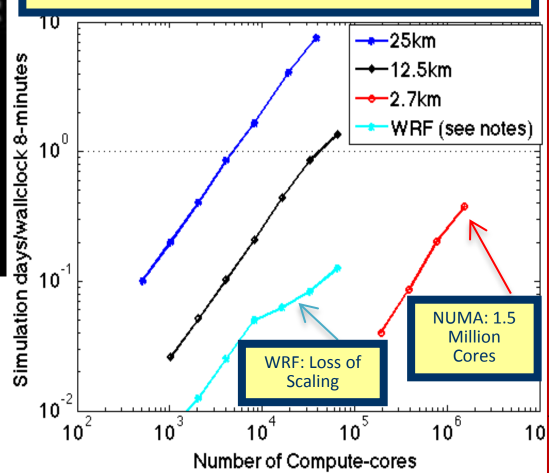

*J. Doyle (NRL), F. Giraldo (NPS)*

Dynamically Adaptive Grids: Could make forecasting hurricane path easier, faster, and more accurate.



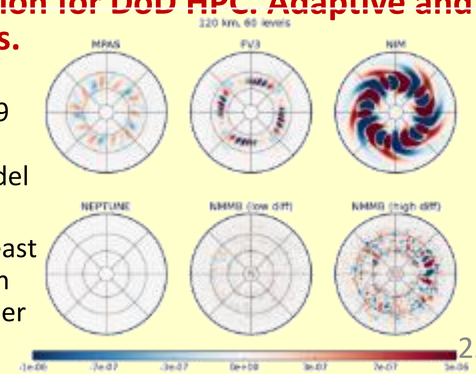

Example of a 6-class microphysics scheme in NEPTUNE for an idealized splitting supercell case.

Performance/ Scalability of NUMA on PetaScale Computers




## NUMA/NEPTUNE Plans

- **FY15: Completion of multi-model evaluations in idealized simulations with other research groups and Initiation of real-data simulations for specific high-impact case studies.**
- **FY16: Advancement of NEPTUNE infrastructure and physics. Code optimization for DoD HPC. Adaptive and Variable resolution tests.**




- Baroclinic wave test case after 9 days, perturbations grow due to the grid imprinting from the model meshes.
- In this test, NEPTUNE has the least imprinting errors of U.S. research dynamic cores due to higher-order accuracy dynamics

# Navy ESPC – Summary of Recent Progress and Ideas for GOV/WGNE Collaboration

- Coupled architecture: Implemented using the National unified ESMF (NUOPC standard)
- HPC platforms: Designed and tested scripts for coupled system with different complexity (Data-ATM, Data-ICE, Data-OCN) and on HPC platforms with different architectures.
- Fidelity improvements:
  - Fully coupled NAVGEM/HYCOM demonstrated significantly improved capability of simulating MJO
  - Improved model physics reduces excessive tropical cyclone genesis events at longer (Week 3-4) lead times
  - Fully coupled NAVGEM/CICE reduces Arctic low level temperature biases
- Recent NUMA/NEPTUNE results in NGGPS Dynamic Core project show excellent scalability, accuracy and virtually no grid imprinting.

***How can Navy ESPC and ONR Field Projects better link to HIWeather, S2S, PPP and other WWRP/WCRP Initiatives and WGNE Modeling Centres?***

# *Questions?*

# 3b. ONR DRI Unified Physical Parameterizations 2011-2015

**1) Current parameterizations are <u>inadequate</u>**

**2) New parameterizations are required to capture globally important phenomena controlled by:**

- **-Clouds**
- **-Convection**
- **-Radiation**
- **-Turbulence**

**- New approaches and a new multiscale modeling framework for development, testing and evaluation**

**3) Improved parameterizations are necessary to couple to ocean, land and ice and to extend NWP skill to longer times (~10-day to seasonal)**

IN BOX
INSIGHTS and INNOVATIONS

## Parameterization of the Atmospheric Boundary Layer

### A View from Just Above the Inversion

BY J. TEIXEIRA, B. STEVENS, C. S. BRETHERTON, R. CEDERWALL, J. D. DOYLE, J. C. GOLAZ, A. A. M. HOLTSLAG, S. A. KLEIN, J. K. LUNDQUIST, D. A. RANDALL, A. P. SIEBESMA, AND P. M. M. SOARES

One of the main components of the climate system is the atmospheric boundary layer, which mediates the interactions between the ocean/land surface and the free atmosphere. Several boundary layer processes are known to have a profound influence on the climate system. Relevant examples include the feedbacks between boundary layer clouds and climate. However, in weather and climate prediction models, in spite of some advances, the boundary layer is still not represented realistically. Figure 1 illustrates an aspect of this problem by showing the opposing response of boundary layer (low) clouds to perturbation experiments (e.g., double $CO_2$) in current climate models.

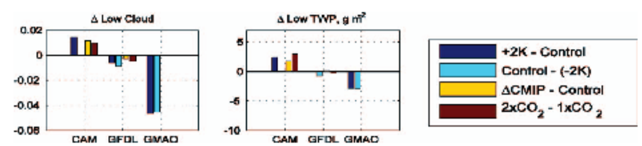



**FIG. 1. Changes in low (below 700 hPa) cloud cover and low liquid + ice path (TWP) for different perturbation experiments and for three U.S. climate models (CAM, GFDL, and GMAO). Note the opposite signs, in terms of the low cloud and low TWP sensitivities, between the different models. Three SST perturbation experiments were performed with spatially uniform perturbations of +2 and −2 K and with a spatially and monthly varying SST perturbation (ΔCMIP) (adapted from Wyant et al. 2006).**

The general problem of parameterization in fluids dates back to the first modern studies of turbulence during the nineteenth and early twentieth centuries. By then, it was already clear that for turbulent flows such as the atmosphere, it was not feasible (or even relevant) to try and follow every parcel of fluid in its turbulent trajectories. Instead, research should concentrate on trying to understand the statistical properties of turbulent flows. With the advent of computers came the possibility of developing numerical models for weather and climate prediction. Numerical discretizations imply a limit for the temporal/spatial scales below which the flow cannot

AFFILIATIONS: TEIXEIRA—Naval Research Laboratory, Monterey, California, and NATO Undersea Research Centre, La Spezia, Italy; STEVENS—University of California, Los Angeles, Los Angeles, California; BRETHERTON—University of Washington, Seattle, Washington; CEDERWALL, KLEIN, AND LUNDQUIST—Lawrence Livermore National Laboratory, Livermore, California; DOYLE—Naval Research Laboratory, Monterey, California; GOLAZ—Naval Research Laboratory, Monterey, California, and Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey; HOLTSLAG—Wageningen University, Wageningen, Netherlands; RANDALL—Colorado State University, Fort Collins, Colorado; SIEBESMA—Royal Netherlands Meteorological Institute, De Bilt, Netherlands; SOARES—University of Lisbon, Lisbon, Portugal, and Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal
CORRESPONDING AUTHOR: João Teixeira, Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 169-237, Pasadena, CA 91109
E-mail: Teixeira@jpl.nasa.gov

DOI:10.1175/BAMS-89-4-453

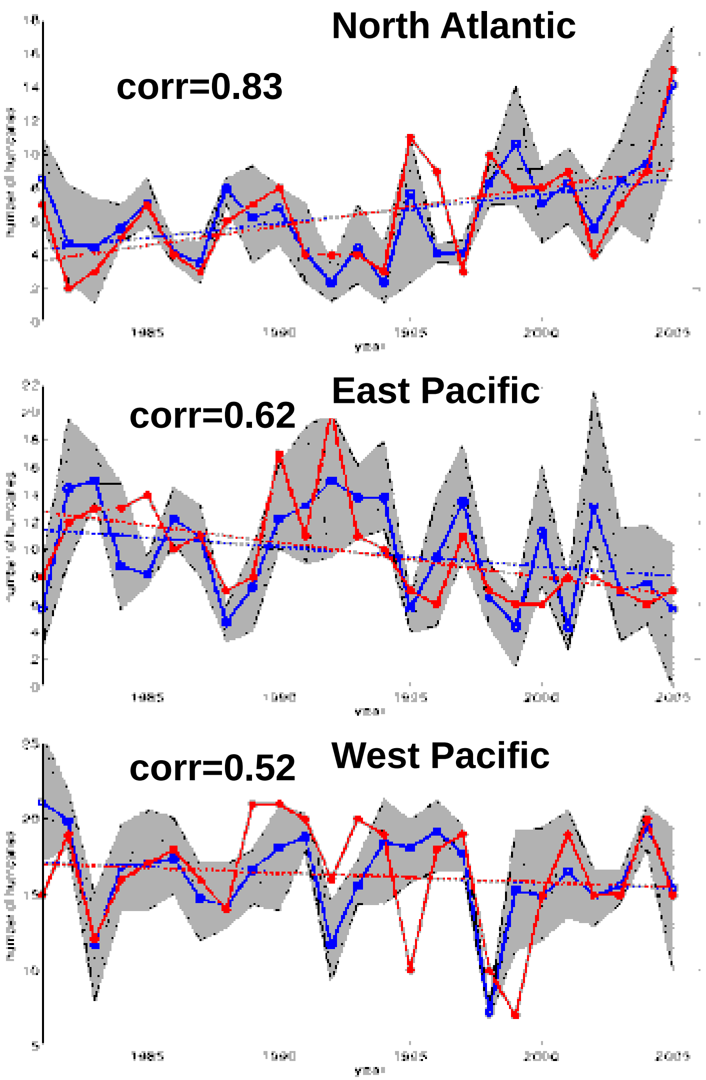
# 3c. ONR DRI Seasonal Prediction 2012-2016

## Predictability Barriers

1. High resolution over Arctic needed to resolve diabatic intensification of tropopause polar vortices which in turn are needed to predict Rossby wave breaking and accurate sea ice prediction (Cavallo, U. Oklahoma and Skamarock, NCAR) – extra slide

2. Increased vertical resolution, reduced diffusion, and improved gravity wave parameterizations required for QBO simulations (S. Eckermann, NRL) – extra slide

3. Long-range TC prediction related to equatorial atmospheric waves (T. Li, U. Hawaii)



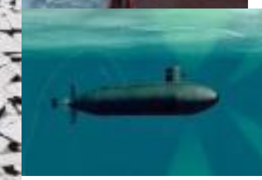
# ONR Arctic Research Program

*To Better Understand and Predict the Arctic Environment*

*Program Initiated in FY2012*

## Major Program Thrusts:

- Improved **Basic Physical Understanding** of the Arctic Environment
- **New technologies** to enable persistent Arctic observations
- Development of new fully-integrated **Arctic System Models**
- **Exploitation of Remote Sensing** for both Basic Understanding and to constrain the new Arctic System Models



### 3d. 2012-2016: Marginal Ice Zone DRI

• Study the physics of the marginal ice zone during the summer break-up and melt season

• Major field experiment in 2014 using buoys and UUVs

### 3e. 2013-2017: Arctic Sea State DRI

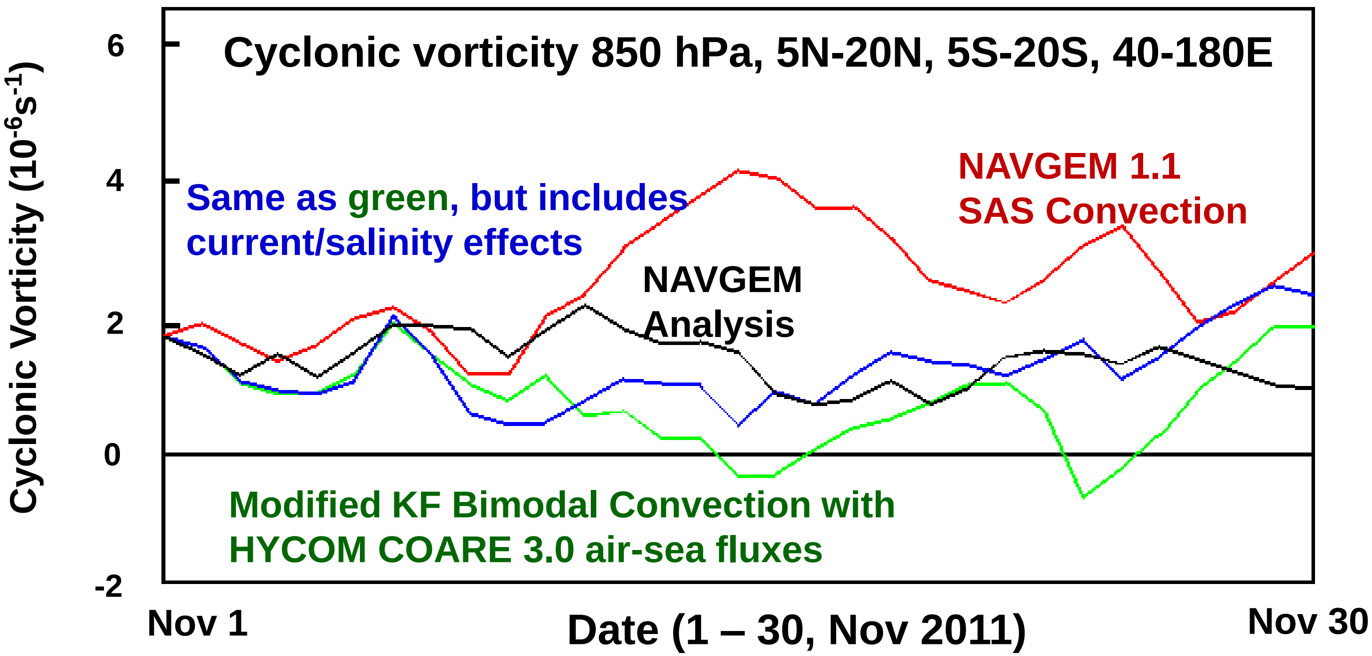
• Study the impact of waves on air-sea interaction in the Arctic, and the propagation and interaction of waves and swell on sea ice in the Arctic

**Payoff: Safer, more efficient naval operations in the Arctic through better Arctic domain awareness, improved sensing and communications, and international coordination and collaboration**

# 4. NRL Research: Improving NAVGEM parameterizations and A-O flux consistency

- Excessive cyclonic vorticity reduced through physics upgrades
- Results sensitive to treatment of surface fluxes, including effects of ocean surface current/salinity variability

**NAVGEM-HYCOM 30-day Integrations from 1 Nov 2011**




***Equatorial circulation characteristics improve through implementation of parameterizations that are consistent between different system components***

*J. Ridout, M. Flatau, C. Reynolds, J. Richman, T. Jensen, J. Shriver (NRL), J. Chen (SAIC): ESPC, ONR DRI, NRL*