# HYCOM Global Ocean Forecasting and Data Assimilation

Contributions from
O.M Smedstad[1], E.J. Metzger[2], P.J. Hogan, P.G. Posey, A.J. Wallcraft[2], D.S. Franklin[1] , L. Zamudio[3] and M.W. Phelps[4]

[1]Vencore, Inc.
[2]Naval Research Laboratory
[3]Florida State University
[4]Jacobs Engineering

# *GOFS Descriptions and Status*

**GOFS 3.0:**

1/12° 32 layer HYCOM
NCODA-3DVAR
Modular Ocean Data Assimilation System (MODAS)
energy-loan ice

Operational system running on Navy DSRC IBM iDataPlex computers

**GOFS 3.1:**

1/12° 41 layer HYCOM (9 additional layers in the upper ocean)
NCODA-3DVAR
Improved Synthetic Ocean Profiles (**ISOP)**
Los Alamos Community Ice CodE (**CICE)**

Currently in operational testing mode (OPTEST)

**GOFS 3.5:**

1/25° 41 layer HYCOM **(Transition scheduled for Fall 2016)**
NCODA-3DVAR
ISOP
CICE
**tides**

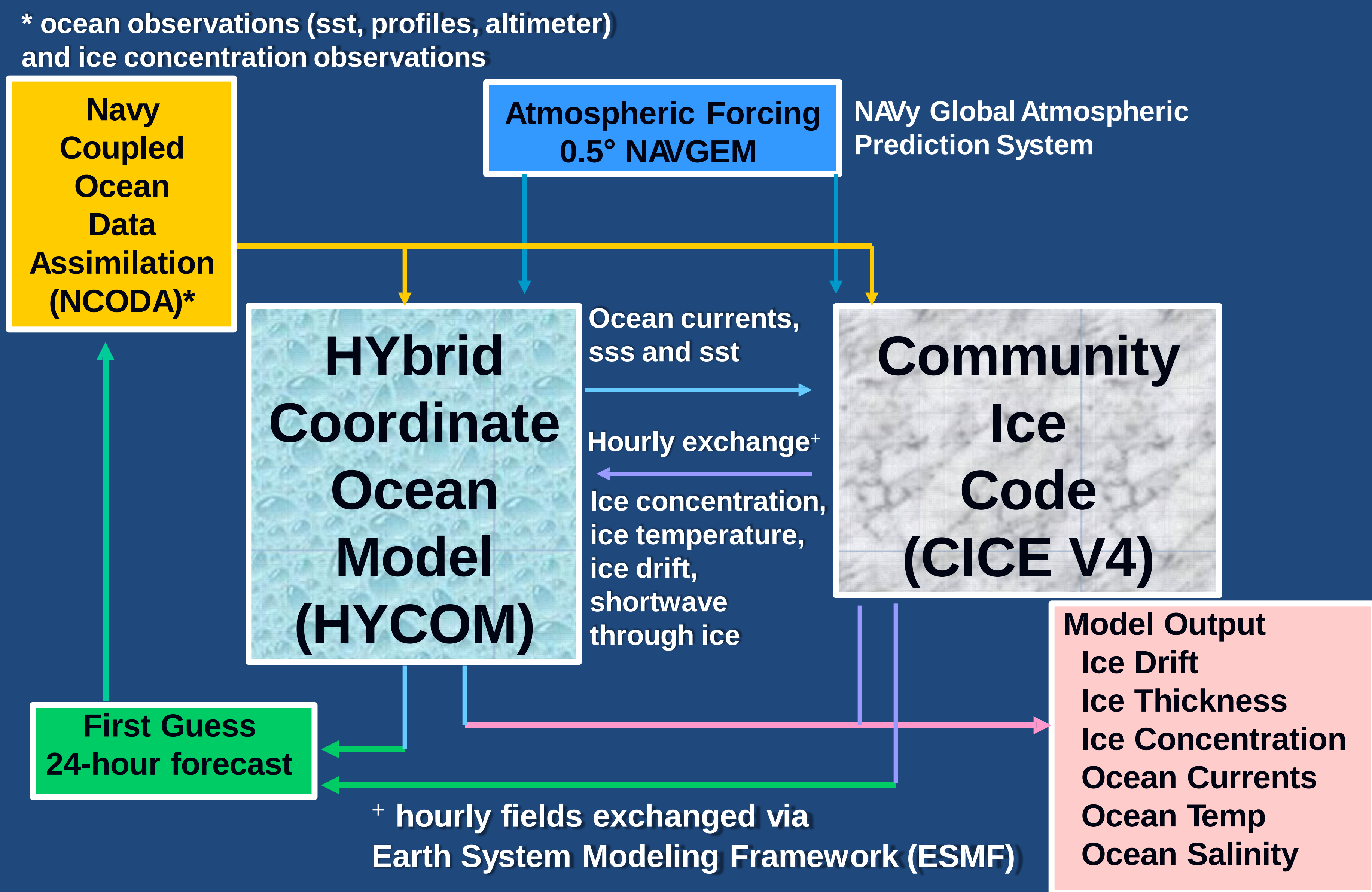
**Arctic Cap:**

**Sub region of GOFS 3.0 north of 40°N**
**CICE**

# GOFS 3.1 Configuration

- Horizontal grid: 1/12° equatorial resolution
  - 4500 x 3298 grid points, ~6.5 km spacing on average, ~3.5 km at pole
- Mercator 79°S to 47°N, then Arctic dipole patch
- Vertical coordinate surfaces: 41 for $\sigma_2$*
- KPP mixed layer model
- Community Ice CodE (CICE v4) sea-ice model
  Coupling between ocean and ice via the Earth System Modeling Framework (ESMF)
- Surface forcing: wind stress, wind speed, thermal forcing, precipitation, relaxation to climatological SSS
- Monthly river runoff (986 rivers)
- Initialize from January climatology (GDEM 4.2) T and S
  - No subsurface relaxation to climatology

# HYCOM/NCODA/CICE



# *Navy Coupled Ocean Data Assimilation*

Ocean Obs

Sequential Incremental Update Cycle
Analysis-Forecast-Analysis

SST: GAC/LAC
MCSST, GOES,
Ship, Buoy
Profile: XBT, CTD,
PALACE Float,
Fixed Buoy,
Drifting Buoy
Altimeter SSHA
SSM/I Sea Ice

Ocean QC

Innovations

3D Var

Increments

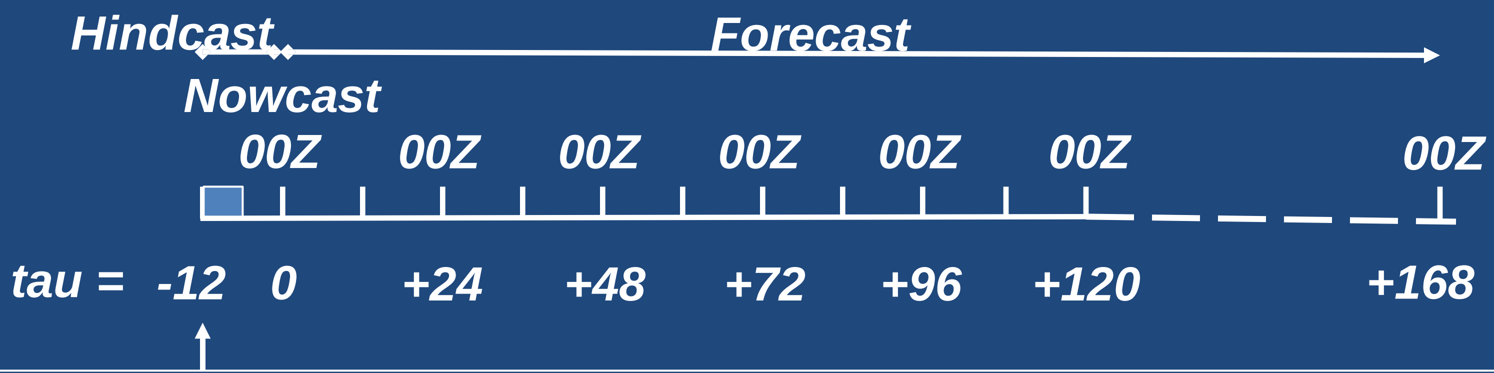
HYCOM
CICE

First Guess

**Improved Synthetic Ocean Profiles (ISOP) used as the vertical projection technique of the surface observations**

3Dvar - simultaneous analysis ice concentration and 5 ocean variables: temperature, salinity, geopotential, layer pressure, velocity (u,v)

# GOFS 3.1 Runstream



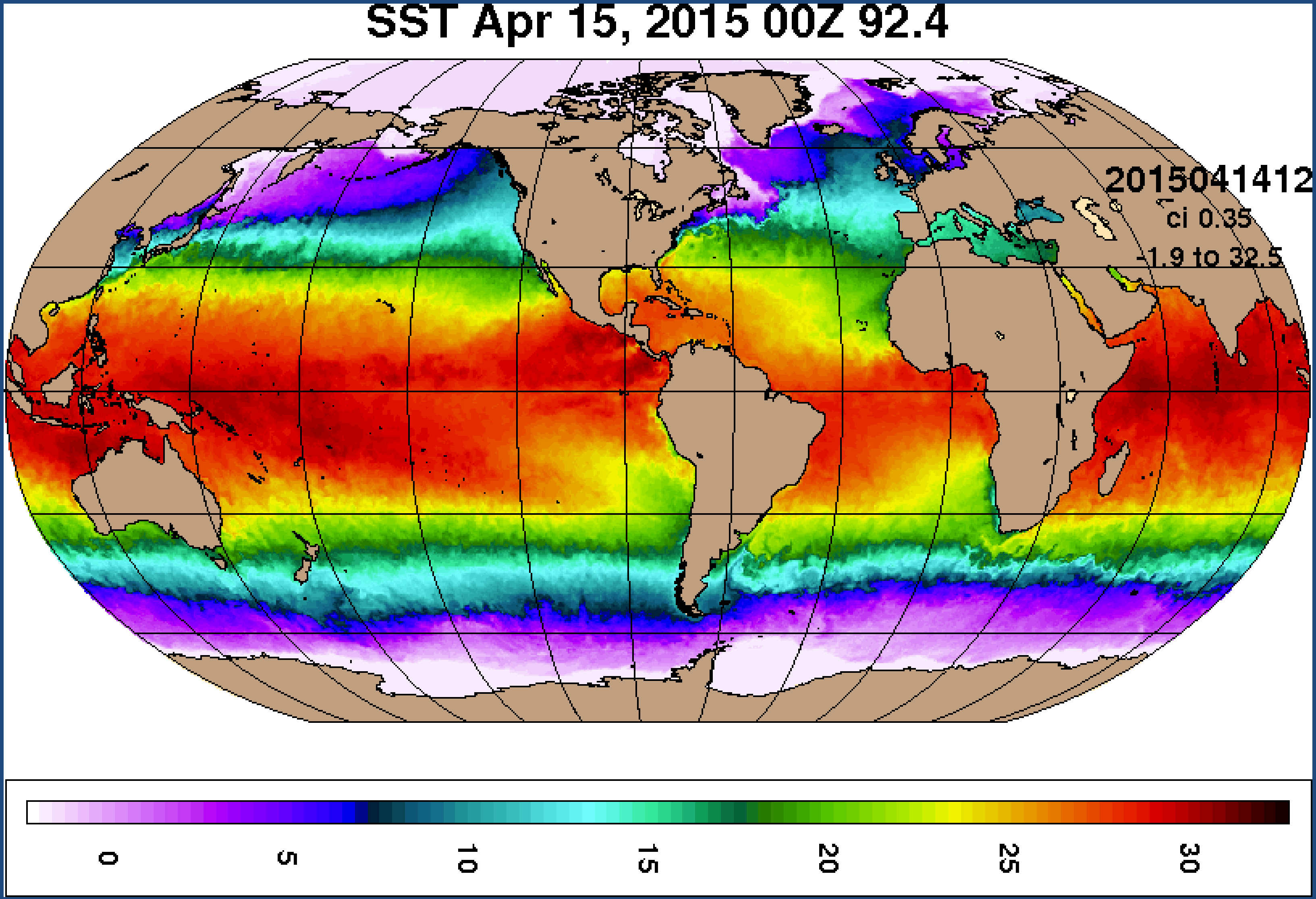

***NCODA analysis windows centered at this time using receipt time and FGAT using observations received since the previous analysis and looking back:***
***-96 hours for profile data***
***-120 hours for altimeter data***

1) *Perform first NCODA analysis centered on tau = -12*
2) *Run HYCOM using incremental updating ( ) over the first 6 hours*
3) *Run HYCOM in forecast mode out to tau = 168*

*FGAT – First Guess at Appropriate Time*

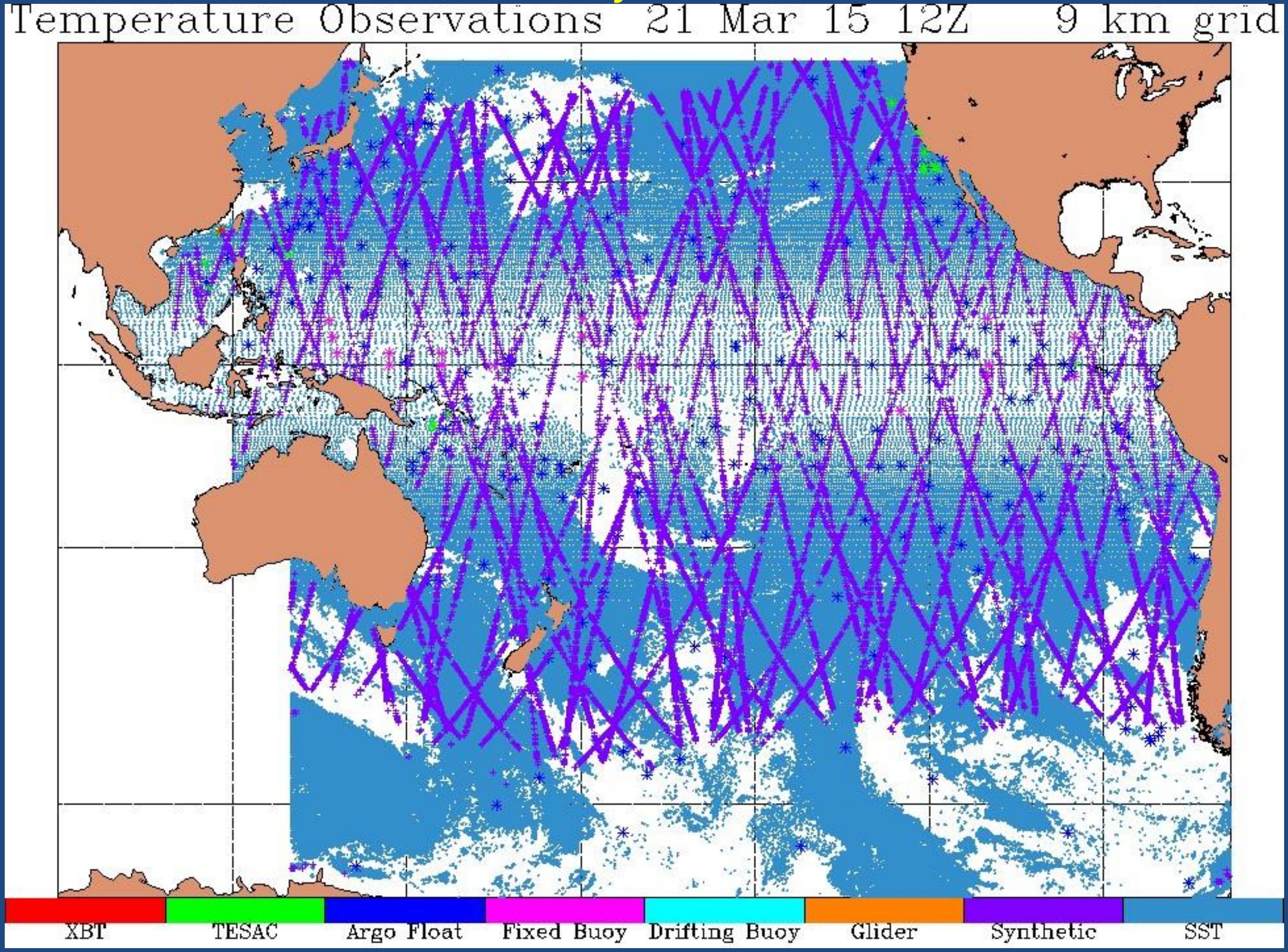
# 1/12° Global HYCOM/CICE

Snapshot of Sea Surface Temperature



# GOFS 3.1 Temperature Observations

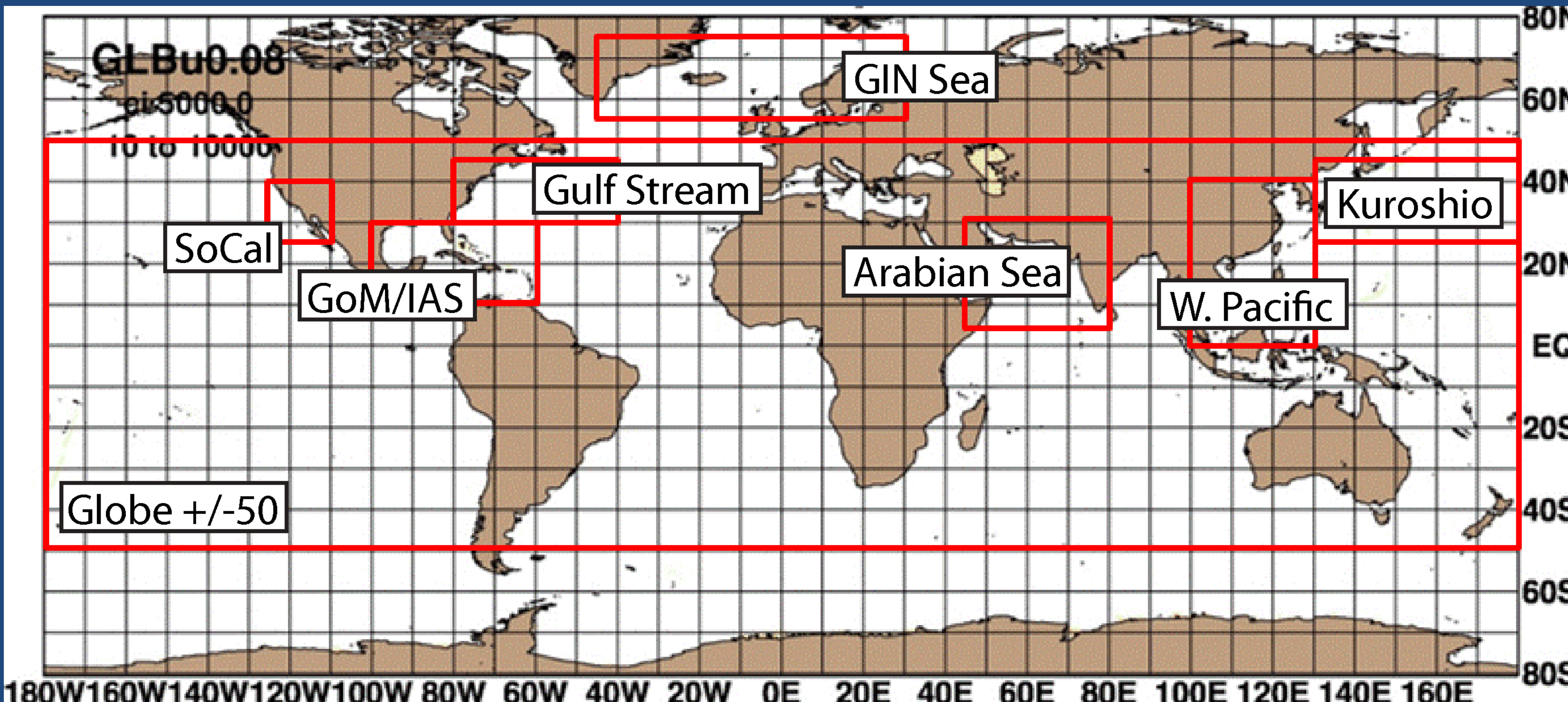
*Pacific Ocean*




Downward projection into the interior at all locations with SSH and SST (synthetics)

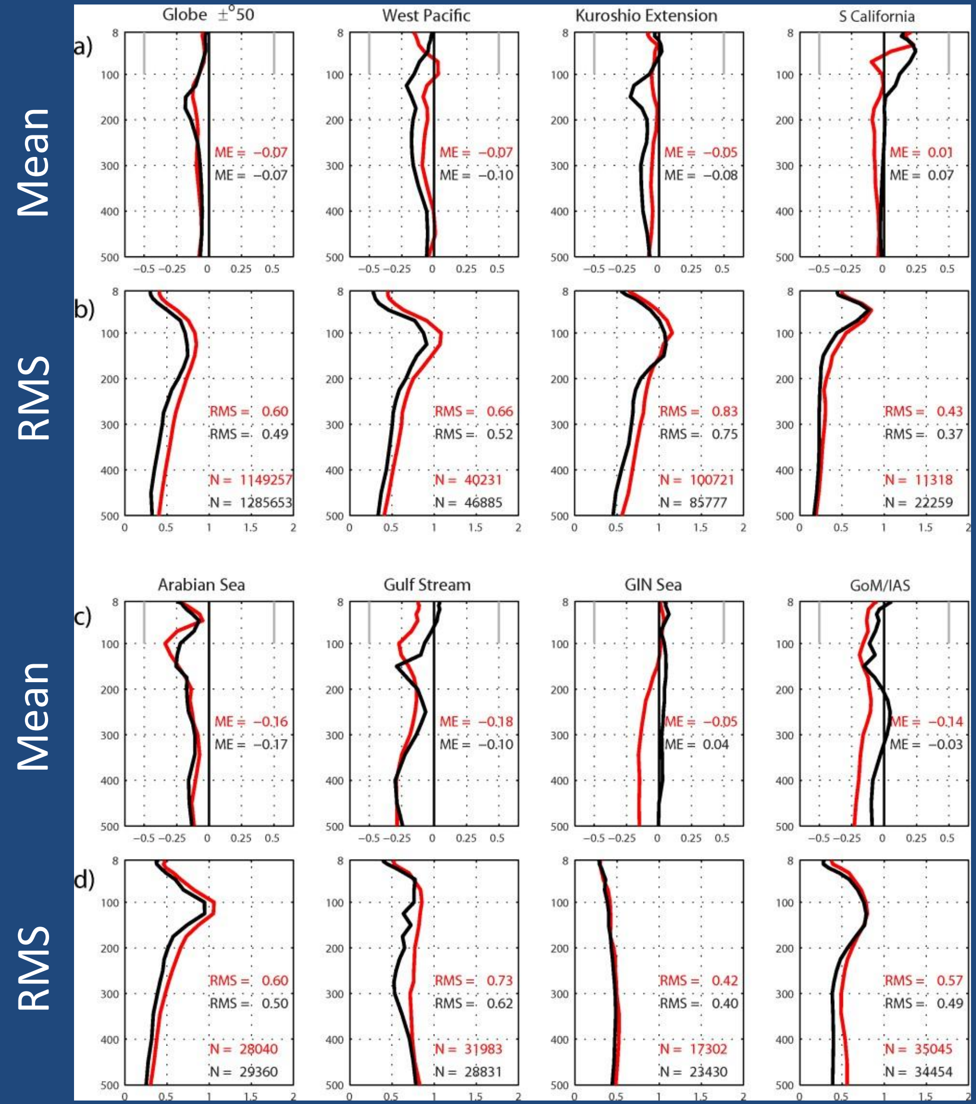
# *Ocean Validation Regions*

## *Used in the Validation Test Report (VTR)*




Validation regions are defined by the Naval Oceanographic Office

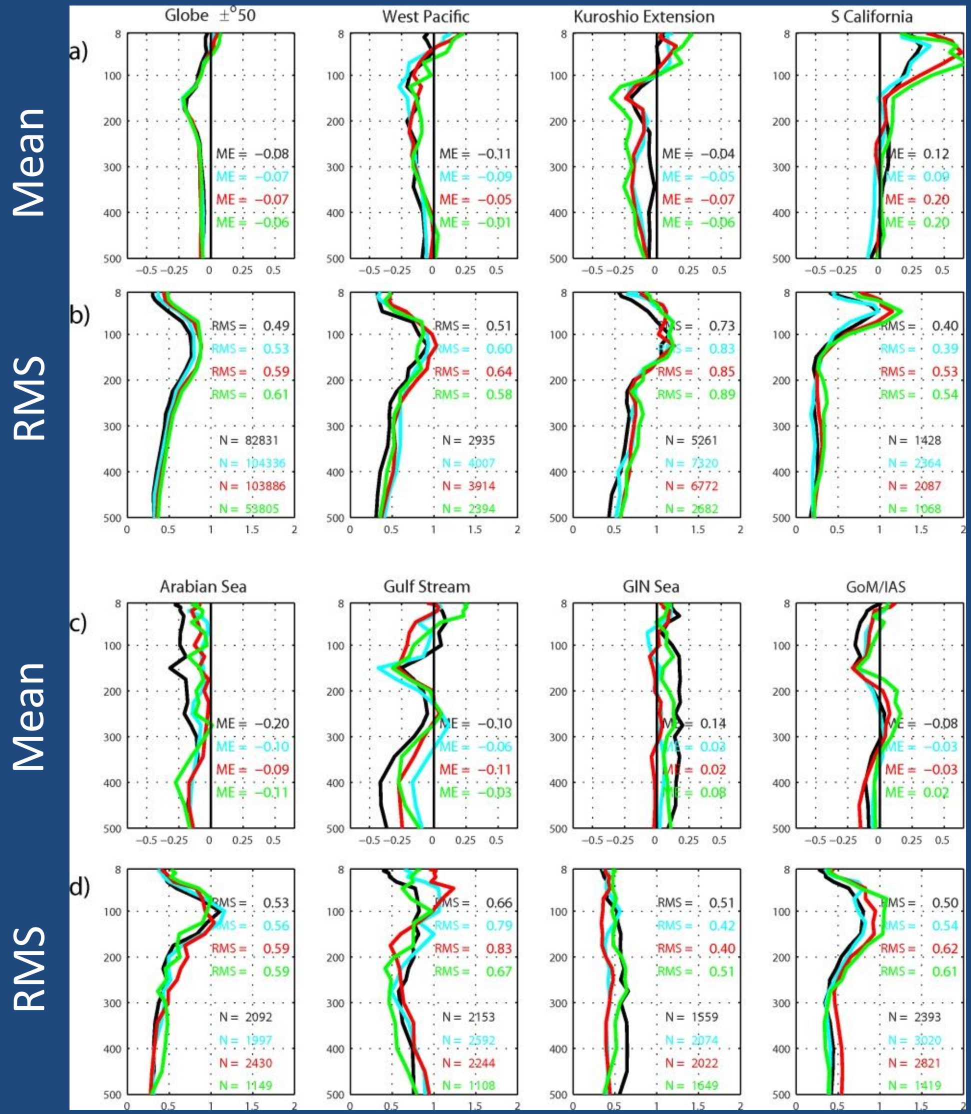
# Ocean Validation – Temperature Profiles
## GOFS 3.0 vs. GOFS 3.1 Nowcast Time




**Red curves:** **GOFS 3.0**
**Black curves:** **GOFS 3.1**

Temperature (°C) vs. depth error analysis in the upper 500 m against unassimilated profile observations at the "nowcast" time for the eight regions defined on the previous slide spanning the hindcast period August 2013 – April 2014. The gray lines in the ME plots are the tolerances set by NAVOCEANO for the temperature bias in the GOFS 3.0 OPTEST

# Ocean Validation – Temperature Profiles GOFS 3.1 Forecast Horizons (5,10,14 days)



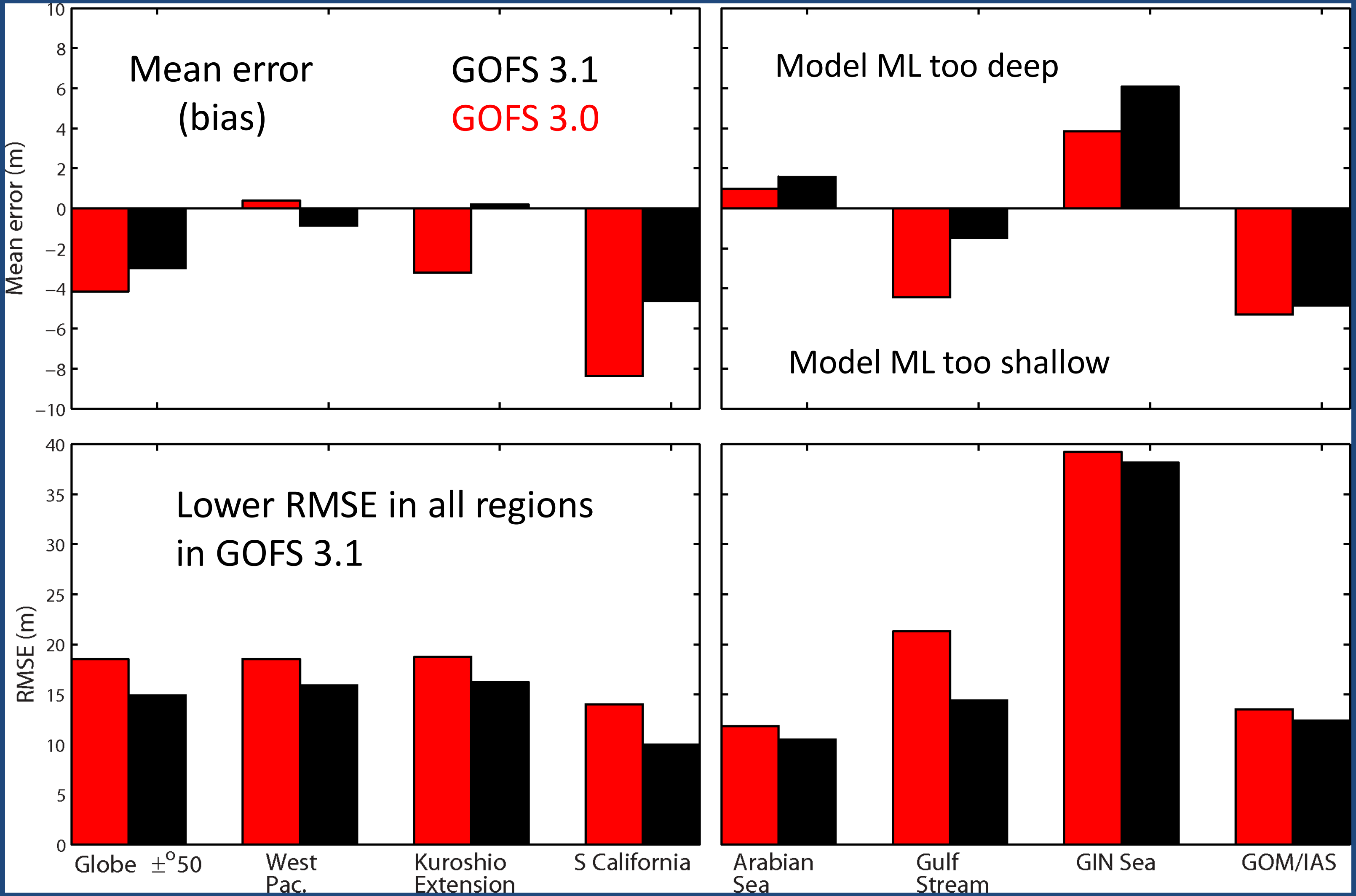

| | |
|---|---|
| **Black curves:** | **Nowcast** |
| **Cyan curves:** | **5-day forecast** |
| **Red curves:** | **10-day forecast** |
| **Green curves:** | **14-day forecast** |

Temperature (°C) vs. depth error analysis in the upper 500 m against **unassimilated** profile observations for the eight analysis regions for the 14-day forecasts initialized from the hindcast period August 2013 – April 2014.

Not a lot of forecast skill degradation Out to 14 day forecast horizon.

# Ocean Validation – Mixed Layer Depth

## GOFS 3.0 vs. GOFS 3.1Nowcast Time

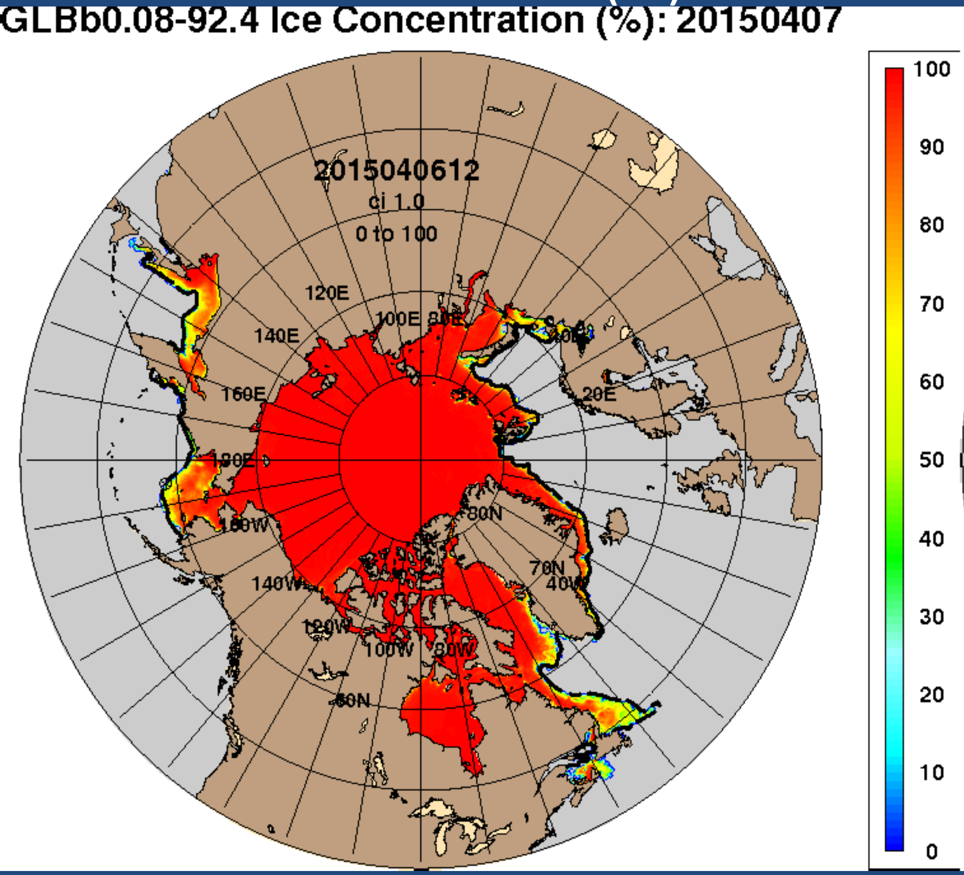



August 2013 – April 2014

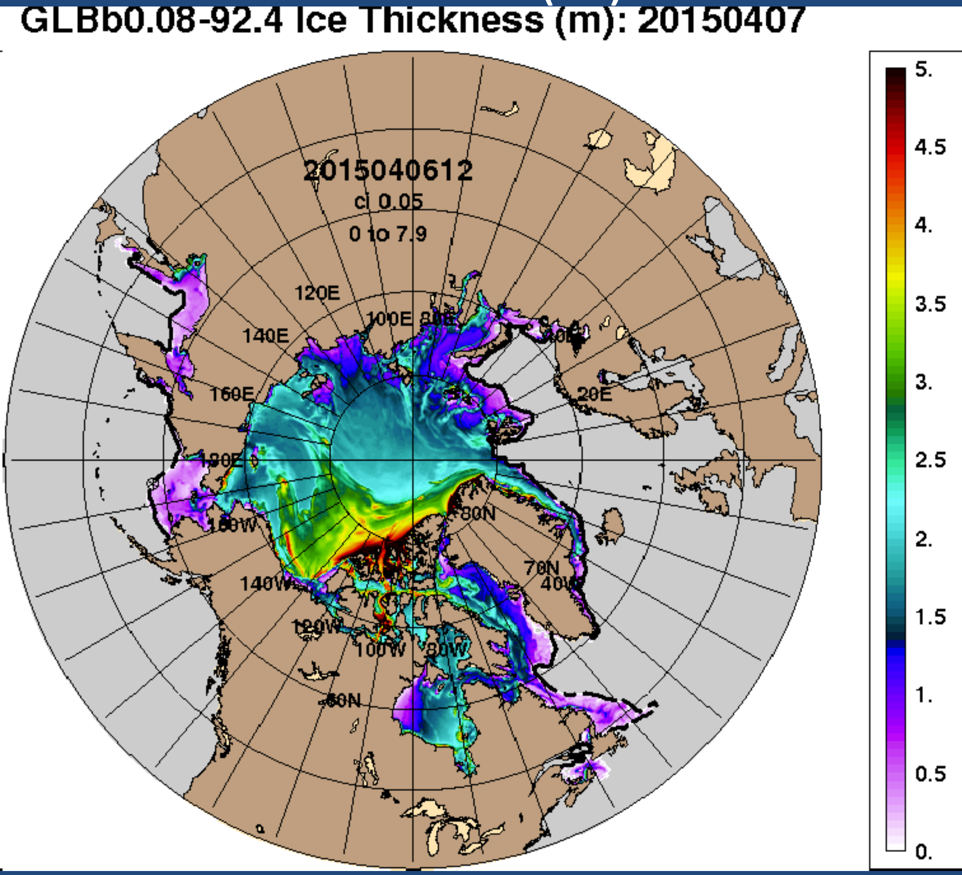
# *GOFS 3.1 includes 2-way nested CICE*

## 30-day animation starting on 7 April 2015

Ice Concentration (%)

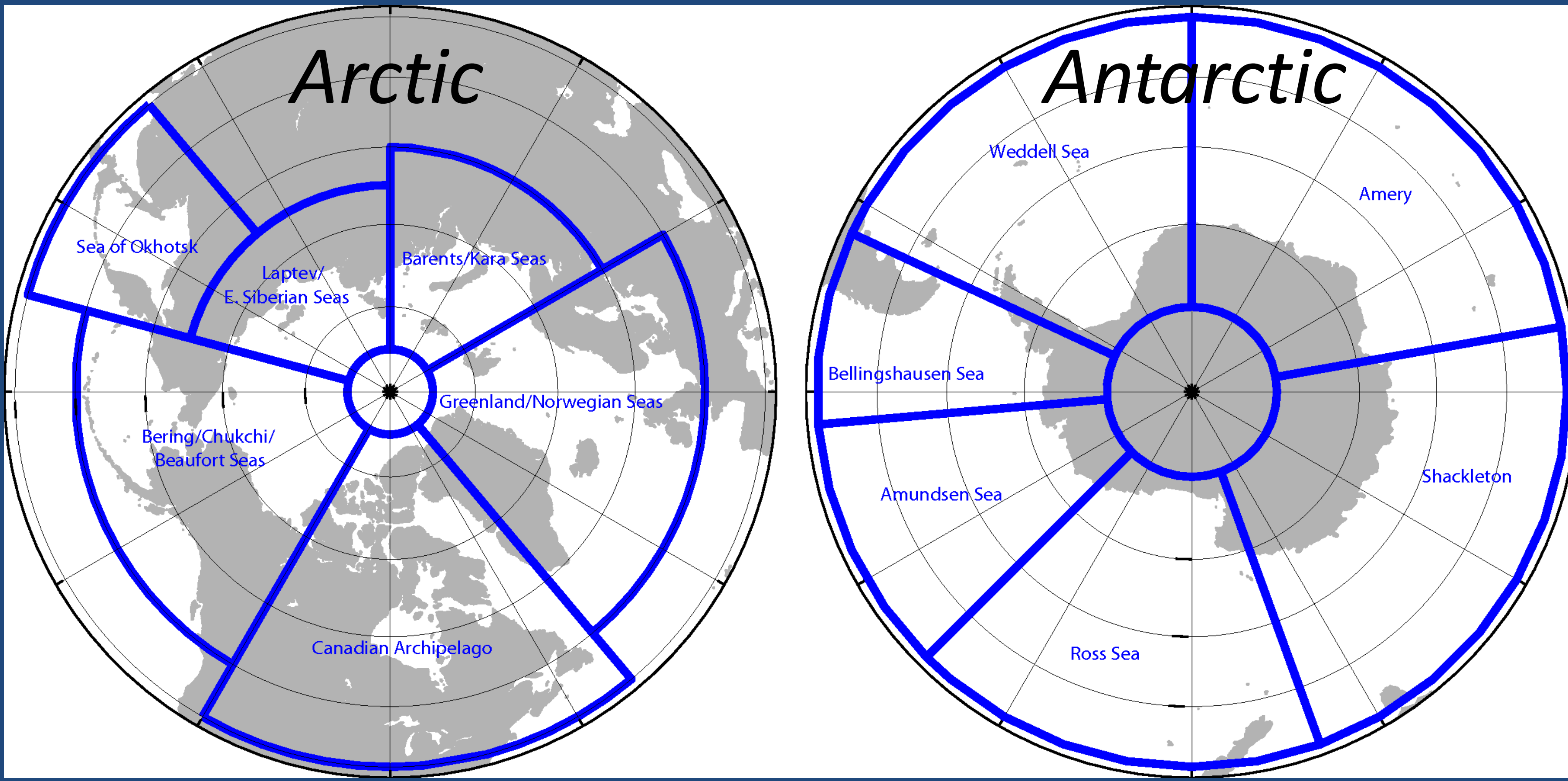



Ice Thickness (m)




Black line is the independent ice edge analysis from the National Ice Center (NIC)

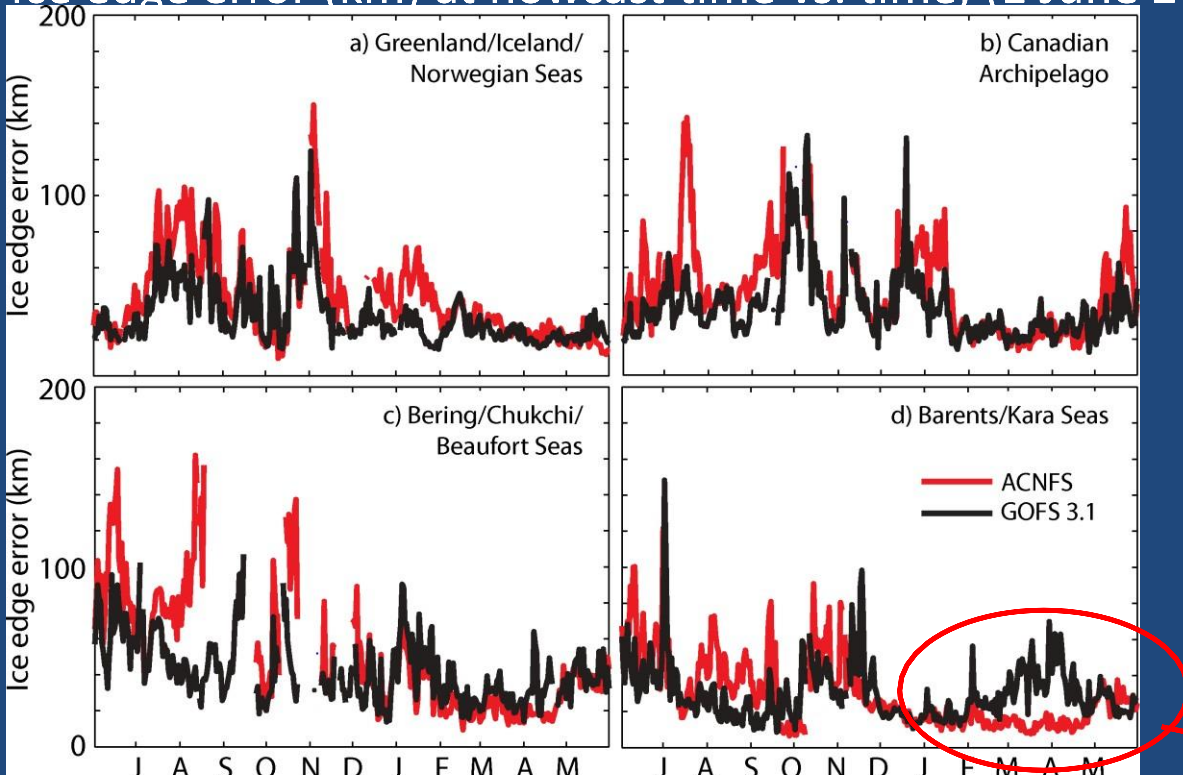
# Polar (Ice) Validation Regions




Compare independent observations against **GOFS 3.1 and ACNFS** hindcast output
(1 June 2012 – 31 May 2013)

# *Ice Edge Error*
## *Arctic*

Ice edge error (km) at nowcast time vs. time, (1 June 2012 – 31 May 2013)




Mean Error

| | |
|---|---|
| 28.4 km<br>36.4 km<br>22% | 38.4 km<br>43.6 km<br>12% |
| 38.9 km<br>44.9 km<br>13% | 28.8 km<br>25.6 km<br>-13% |

Due to an assimilation error that has been corrected

The GOFS 3.1 and ACNFS 5% ice concentration isolines are compared against the independent National Ice Center ice edge analysis

# *Mean Ice Edge Location Error (km)*

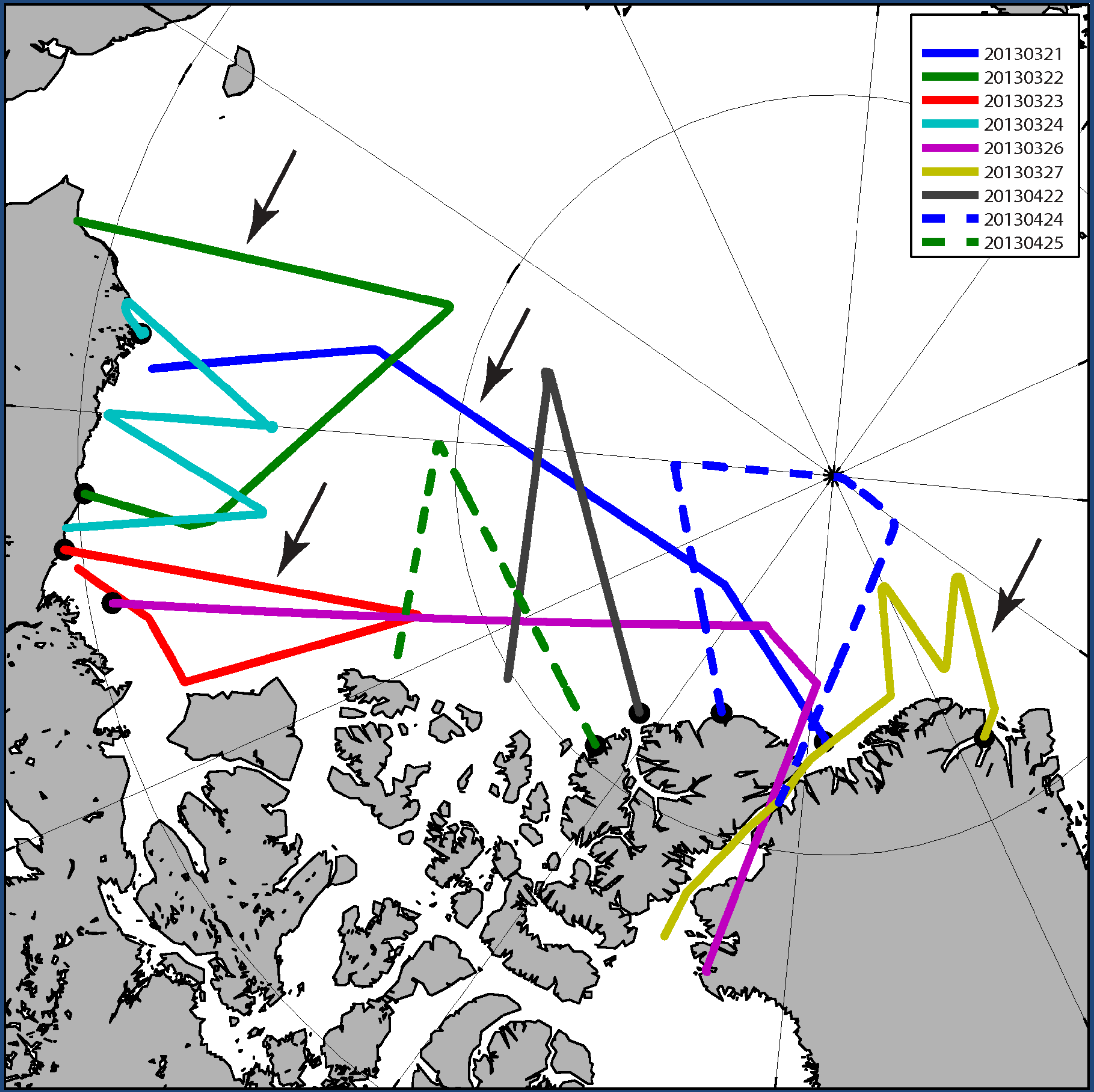
## *Antarctic*

| Region | GOFS 3.1 |
|---|---|
| Amery Sea | 34.2 |
| Shackleton Sea | 30.6 |
| Ross Sea | 29.2 |
| Amundsen Sea | 37.0 |
| Bellinghausen Sea | 39.9 |
| Weddell Sea | 47.3 |

*Validation period is 1 June 2012 – 31 May 2013*

**Take-home message: Ice edge errors in the Southern Hemisphere have similar magnitudes as ice edge errors in the Northern Hemisphere**

# “IceBridge” Flights (in lieu of satellite obs)

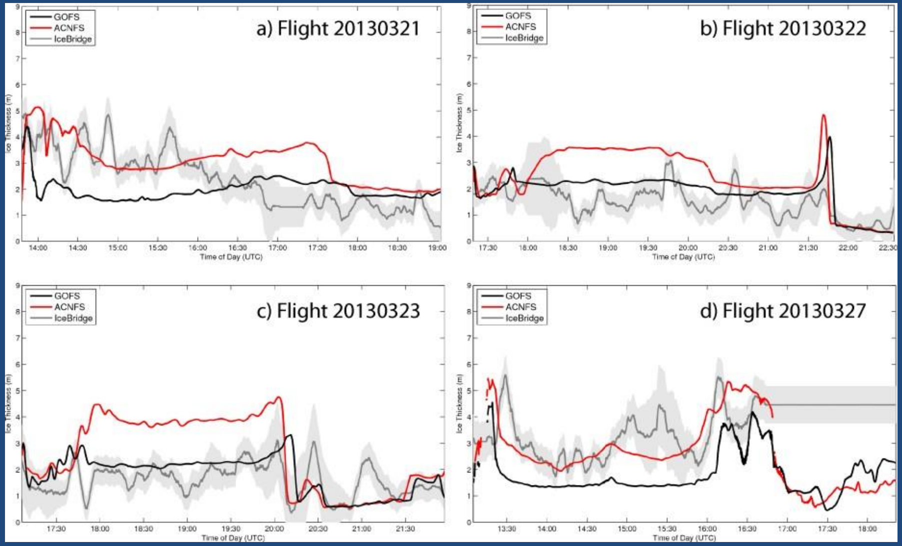



- Black arrows indicate flight data comparison shown on the next slide
- GOFS 3.1 has generally lower thickness error north of Alaska (Beaufort Sea) and the Canadian Archipelago
- ACNFS generally has lower thickness error north of Greenland

# *Ice Thickness vs. IceBridge*

## Select 2013 IceBridge Thickness Comparisons

IceBridge
GOFS 3.1
ACNFS

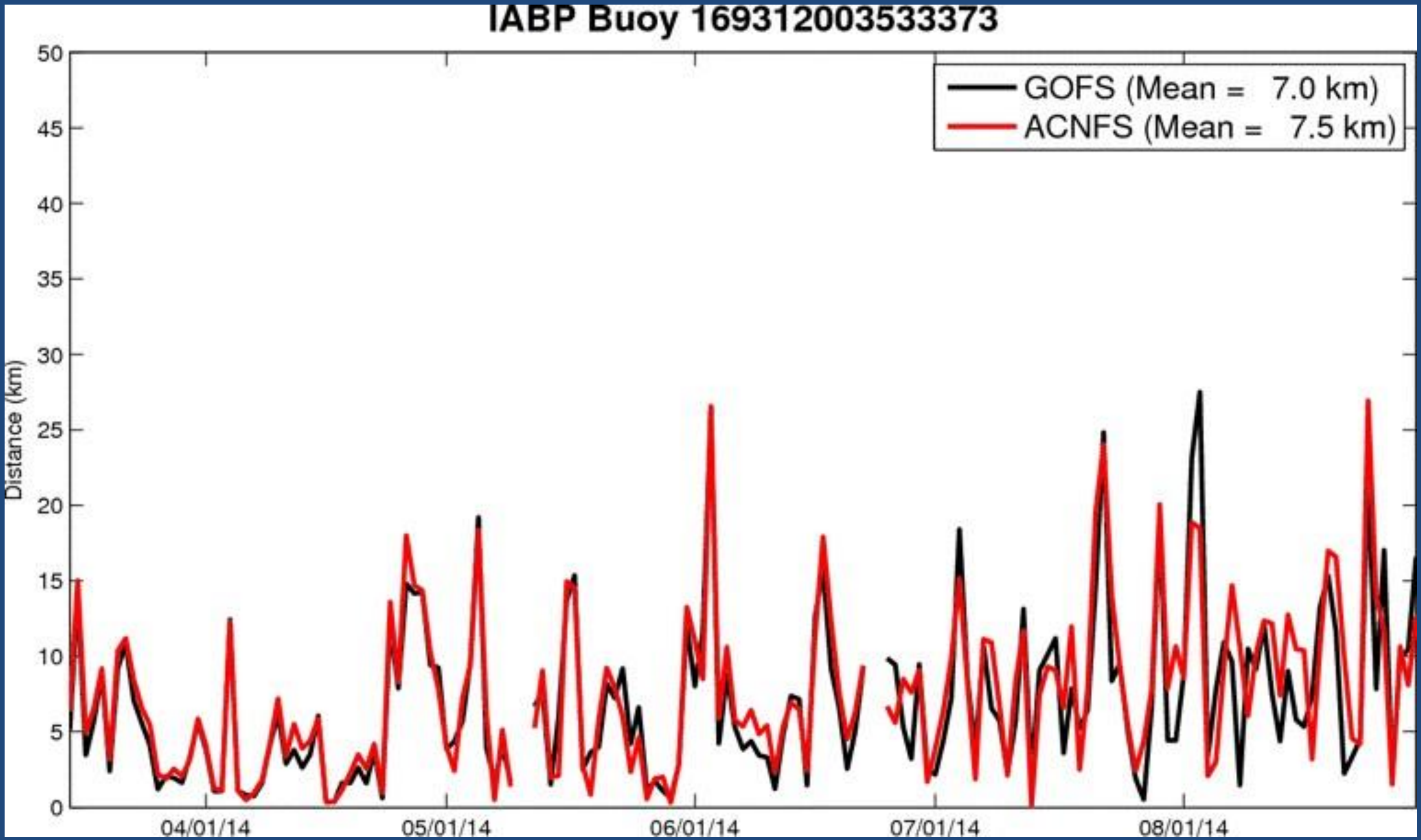



| Flight | Bias | | Absolute Bias | | RMS Difference | |
|---|---|---|---|---|---|---|
| | GOFS 3.1 | ACNFS | GOFS 3.1 | ACNFS | GOFS 3.1 | ACNFS |
| 20130321 | -0.43 | 0.60 | 0.98 | 0.90 | 1.22 | 1.09 |
| 20130322 | 0.39 | 0.98 | 0.54 | 1.08 | 0.67 | 1.33 |
| 20130323 | 0.23 | 1.04 | 0.55 | 1.33 | 0.77 | 1.59 |
| 20130324 | 0.59 | 0.82 | 0.82 | 1.01 | 1.05 | 1.32 |
| 20130326 | -0.76 | 0.76 | 0.96 | 1.09 | 1.23 | 1.32 |
| 20130327 | -1.89 | -1.11 | 1.91 | 1.45 | 2.14 | 1.93 |
| 20130422 | -0.57 | 0.80 | 0.83 | 0.85 | 1.00 | 0.99 |
| 20130424 | -1.33 | -0.11 | 1.40 | 0.62 | 1.87 | 0.94 |
| 20130425 | -0.28 | 1.46 | 0.63 | 1.47 | 0.79 | 1.55 |

# *Ice Drift*

- Compared 24-hour forecast ice drift against 129 International Arctic Buoy Program drifting buoys
- Initial results showed GOFS 3.1 was 35% too fast and ACNFS was 15% too fast
- GOFS 3.1 used ocean currents averaged over 3 m but ACNFS used currents averaged over 10 m
  - Options:
    - Use consistent depth for averaging ocean currents
    - Modify the ice-ocean drag coefficient
- Ice-ocean drag coefficient doubled and a new Jan-Aug 2014 hindcast was integrated to compute new ice drift errors

# *Drifting Buoy Comparison*




Twenty-four hour separation distance (km) between the International Arctic Buoy Program (IABP) ice drifting buoy 169312003533373 and GOFS 3.1 (black) and ACNFS (red) over the period 15 March - 3 September 2014. The mean separation distance for GOFS is 7.0 km and 7.5 km for ACNFS.

# *Ice Drift*

Observed and forecast ice speed (cm/s) against all IABP drifters

| Variable | Observed | GOFS 3.1 | ACNFS | GOFS - Observed | ACNFS - Observed |
|---|---|---|---|---|---|
| **Statistics over the period January-August 2014** | | | | | |
| **Speed** | 8.78 | 9.97 | 9.59 | 1.19 (14%) | 0.81 (9%) |
| **Statistics over the period January-March 2014** | | | | | |
| **Speed** | 7.90 | 9.43 | 9.96 | 1.53 (19%) | 2.06 (26%) |
| **Statistics over the period June-August 2014** | | | | | |
| **Speed** | 10.41 | 11.20 | 9.87 | 0.79 (8%) | -0.54 (-5%) |

- ACNFS has lower overall (Jan-Aug) error
- GOFS 3.1 has lower error in the winter (Jan-Mar)
- ACNFS has lower error in summer (Jun-Aug)
- Even though ACNFS slightly outperformed GOFS 3.1 in ice drift, the NIC agreed that in the net, GOFS 3.1 outperformed ACNFS (edge, concentration, thickness, etc.)

# *High resolution ice assimilation*

- SSMIS ≈ 25 km resolution
- AMSR2 ≈ 10 km resolution
- IMS ≈ 4 km resolution
- Implemented 2 Feb 2015 in real-time GOFS 3.1 runstream
- Significant improvement in edge location error

GOFS 3.1 ice edge location error (km) using various ice assimilation data sources

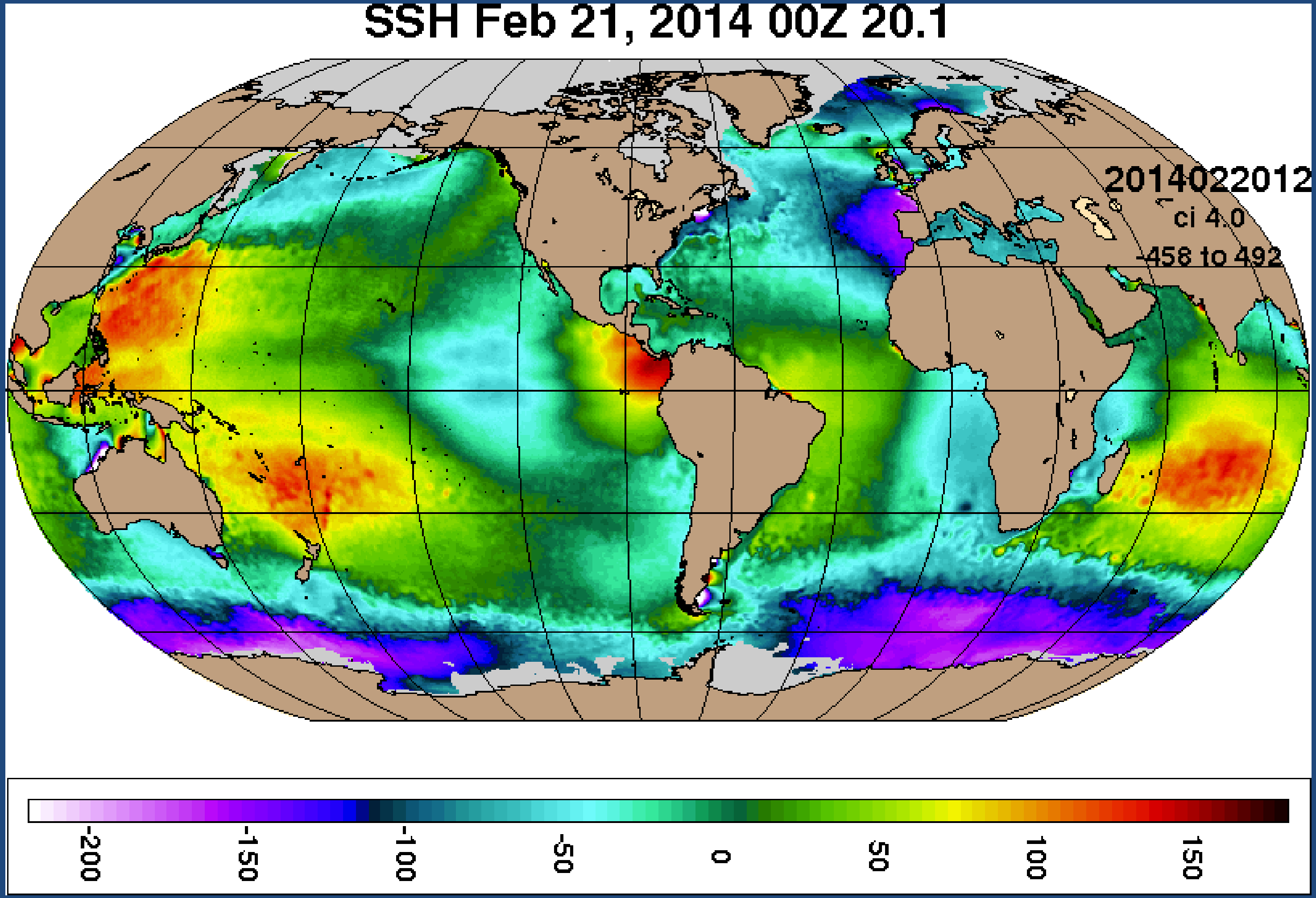
| Region | GOFS 3.1 | | |
|---|---|---|---|
| | SSMIS | AMSR2 and IMS | AMSR2 + SSMIS and IMS |
| **GIN Sea** | 72 | 19 | 19 |
| **Barents/Kara Seas** | 47 | 22 | 22 |
| **Laptev Sea** | 59 | 24 | 24 |
| **Bering/Chukchi/ Beaufort** | 57 | 22 | 22 |
| **Canadian Archipelago** | 83 | 31 | 31 |
| **Total Arctic** | 64 | 25 | 25 |
| **Percent improvement over SSMIS** | --- | 62% | 62% |

Hindcast period: Jun-Aug 2014

# *GOFS 3.5 Demonstration*

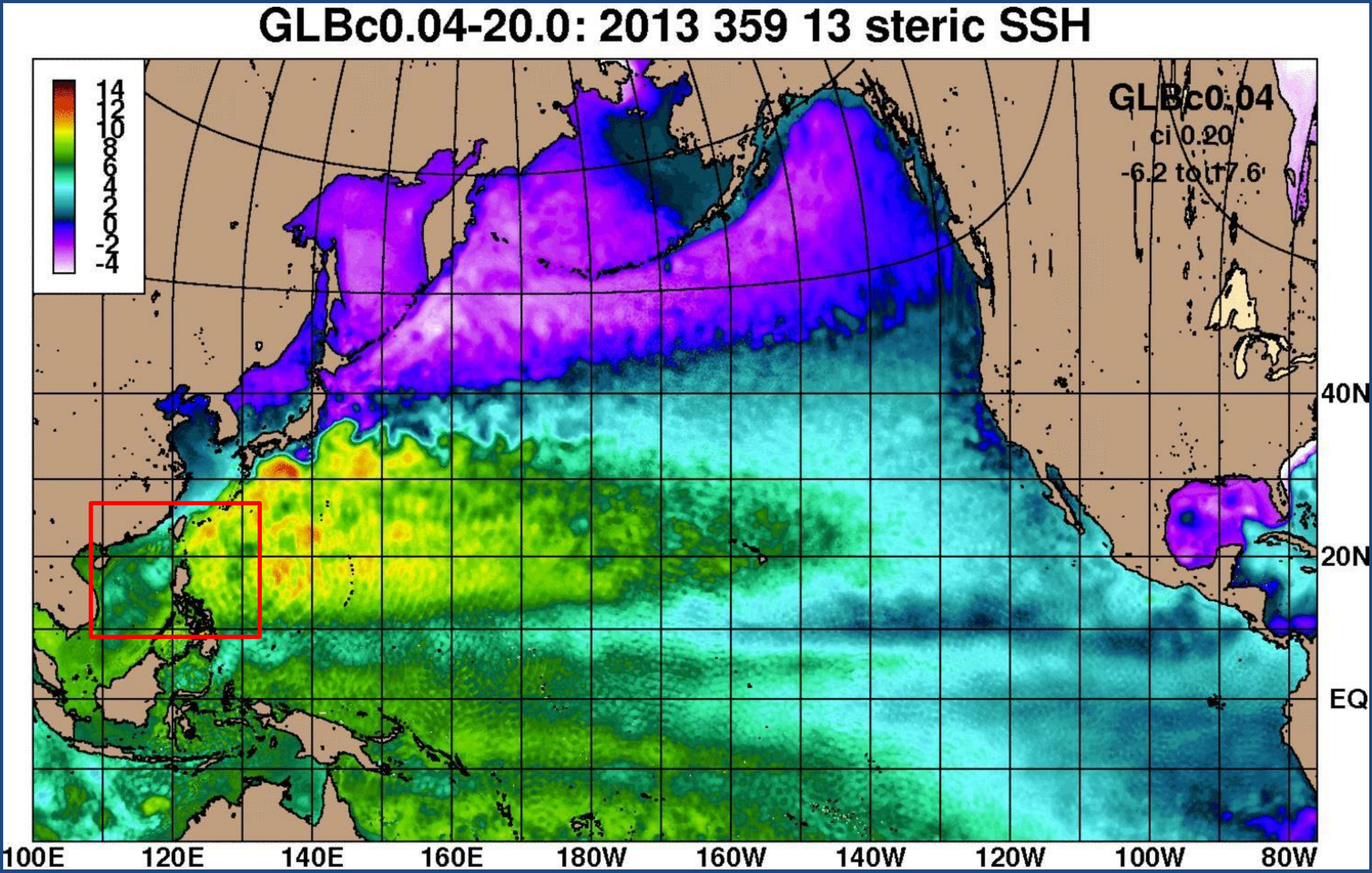
**1/25° HYCOM/CICE/NCODA with tides running in demonstration mode at Navy DSRC on Cray XC30**

**Total SSH (including the barotropic tidal signal)**



# *GOFS 3.5 Demonstration*

Steric SSH reveals the generation locations and propagation of internal waves

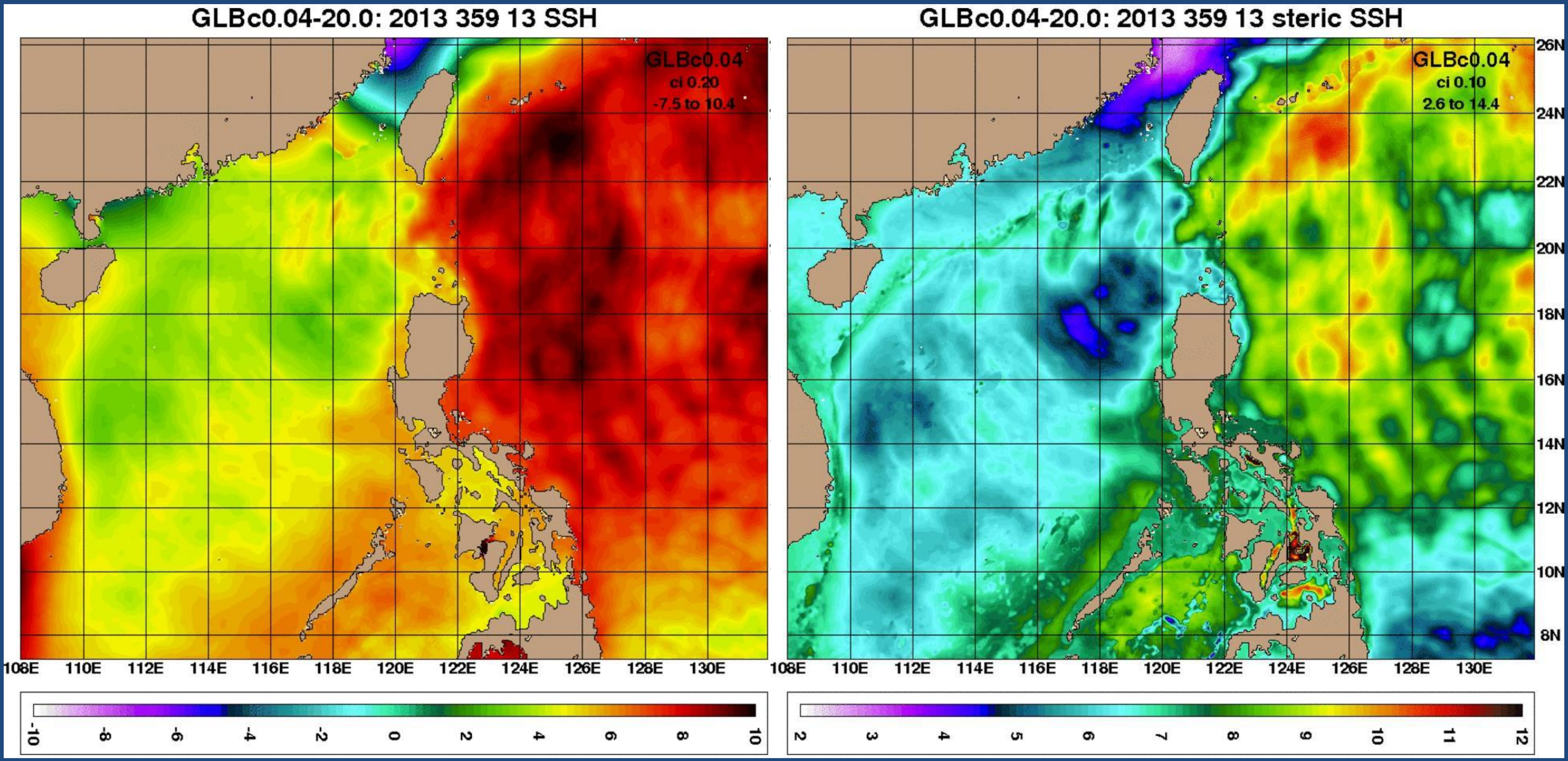


# GOFS 3.5 Demonstration

1/25° HYCOM/CICE/NCODA with tides running in demonstration mode at Navy DSRC on Cray XC30

Total SSH

Steric SSH




**Barotropic tides**

**Internal waves at tidal frequencies**

# HYCOM/NCODA Ocean Reanalysis

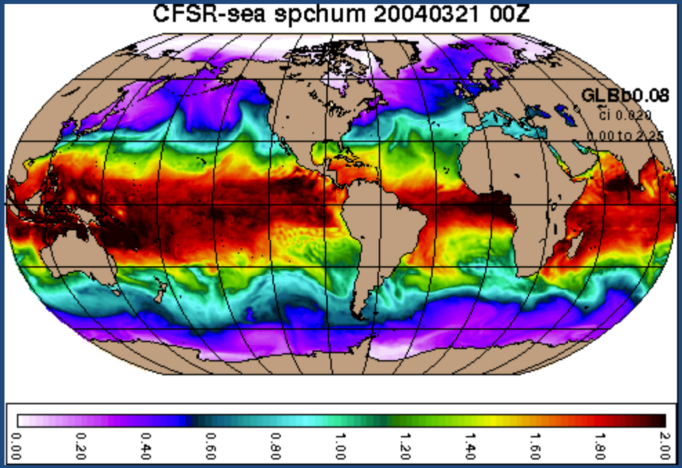
- Based on GOFS 3.0 (current operational system)
- Forced with NCEP Climate Forecast System Reanalysis (CFSR)
- Addresses the need for a long time period eddy-resolving ocean reanalysis (1993 to 2014, consistent with altimetry observations)
- Purpose is to provide physically consistent environmental scenarios for planning and scenarios to support Navy exercises and operations
- Numerous other applications and research opportunities

# Atmospheric Forcing

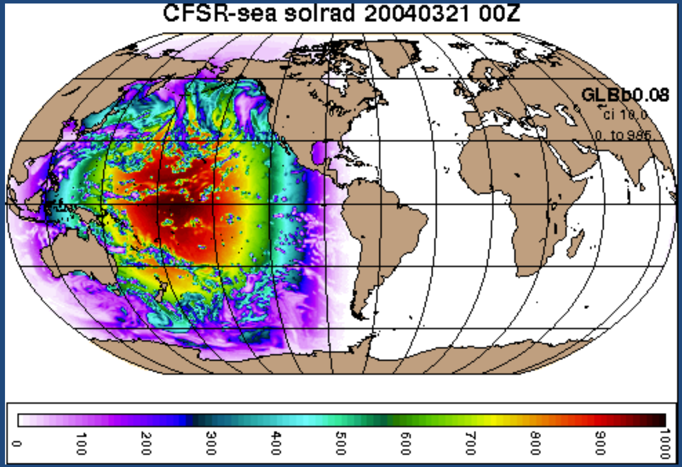
## NCEP Climate Forecast System Reanalysis (CFSR)

- Time frame: 1993-2012 (altimeter period)
- Horizontal resolution: 0.3125° gaussian
- Temporal resolution: 1-hourly
- Inputs:
  - Bulk-derived wind stress
  - Wind speed
  - Radiative fluxes
  - Thermal fluxes
  - Precipitation

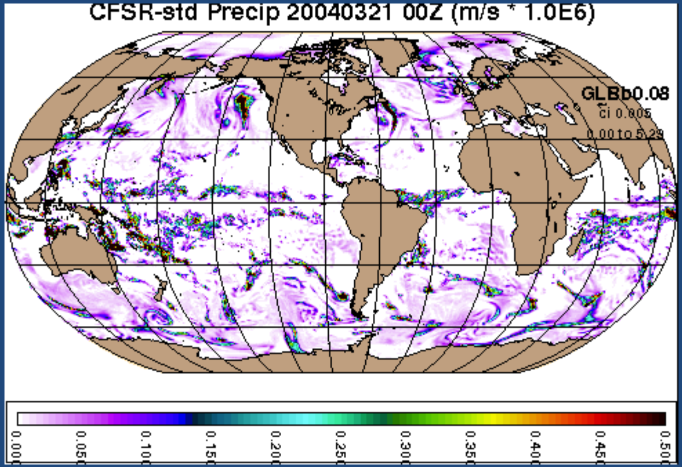
**Surface Specific Humidity (kg/kg x $10^2$)**




**Net Surface Shortwave (W/m²)**



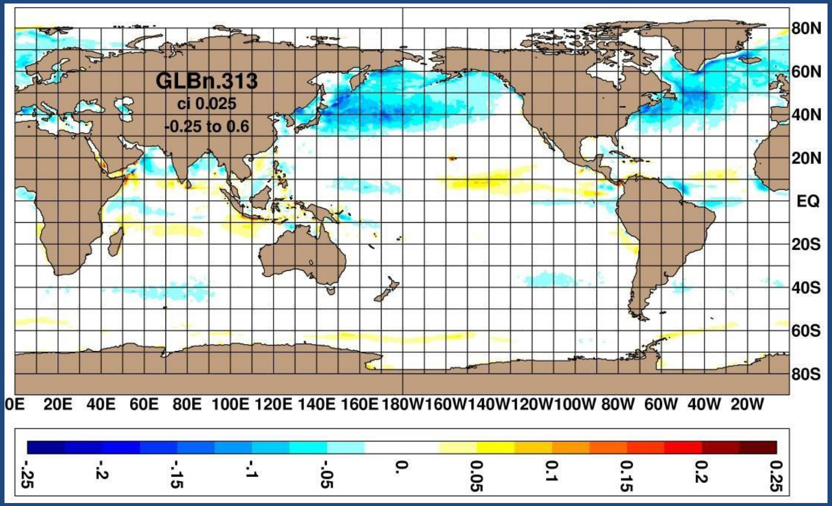

**Precipitation (m/s x $10^6$)**



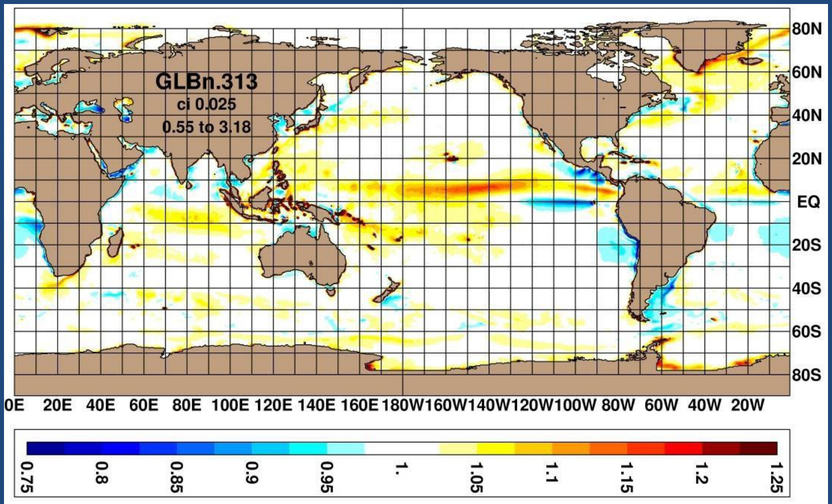
# Modifications to CFSR Wind Forcing

## QuikSCAT Scaling

**Offset**




**Bias**




Based on a regression analysis from 11 years (1999-2009) of monthly contemporaneous CFSR and QuikSCAT wind speed data

In addition a surface flux bias correction based on the annual mean SST error was applied (45 W/m**2 per 1°C)

# Output and Storage

- HYCOM 3D native grid archive files (compressed):
  - Single hour: ~7 GB
  - Saving 3-hourly output:
    - ~20 TB / model year
    - ~340 TB for the entire reanalysis
- HYCOM 3D constant .08° grid (±80° lat) netCDF files remapped to 40 z-levels (compressed):
  - Single hour: ~1.2 GB
  - Saving 3-hourly output:
    - ~3.5 TB / model year
    - ~59 TB for the entire reanalysis
- The 20-year run consumed ~5 million CPU hours
- Output is available on the **hycom.org** data server

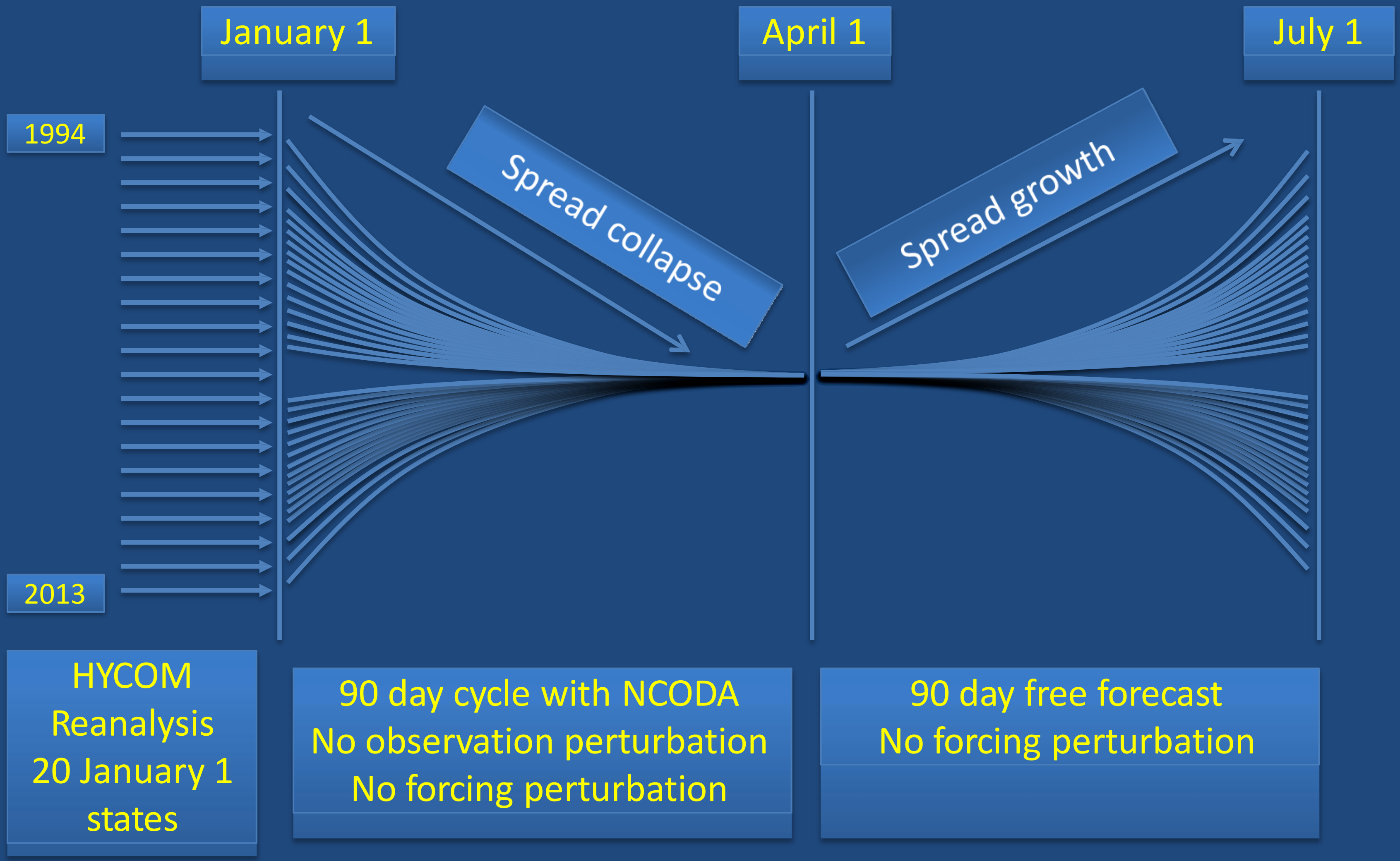
# Ocean re-forcasted ensembles

**Purpose: Use the 20-year reanalysis to generate perturbed initial conditions for ocean ensembles.**

- Address these questions:
  - What is the timescale of spread collapse without perturbed obs, and what is the background model variability? (Exp 1)
  - What is the rate of growth of ensemble spread from the model variability? (Exp 1)
  - What is the contribution of atmospheric model uncertainty? (Exp 2)
  - What is the contribution of perturbed observations in the analysis? (Exp 3)
  - What is the relative role of internal ocean dynamics vs. atmospheric forcing on uncertainty/spread in ocean variables, including mixed layer depth?

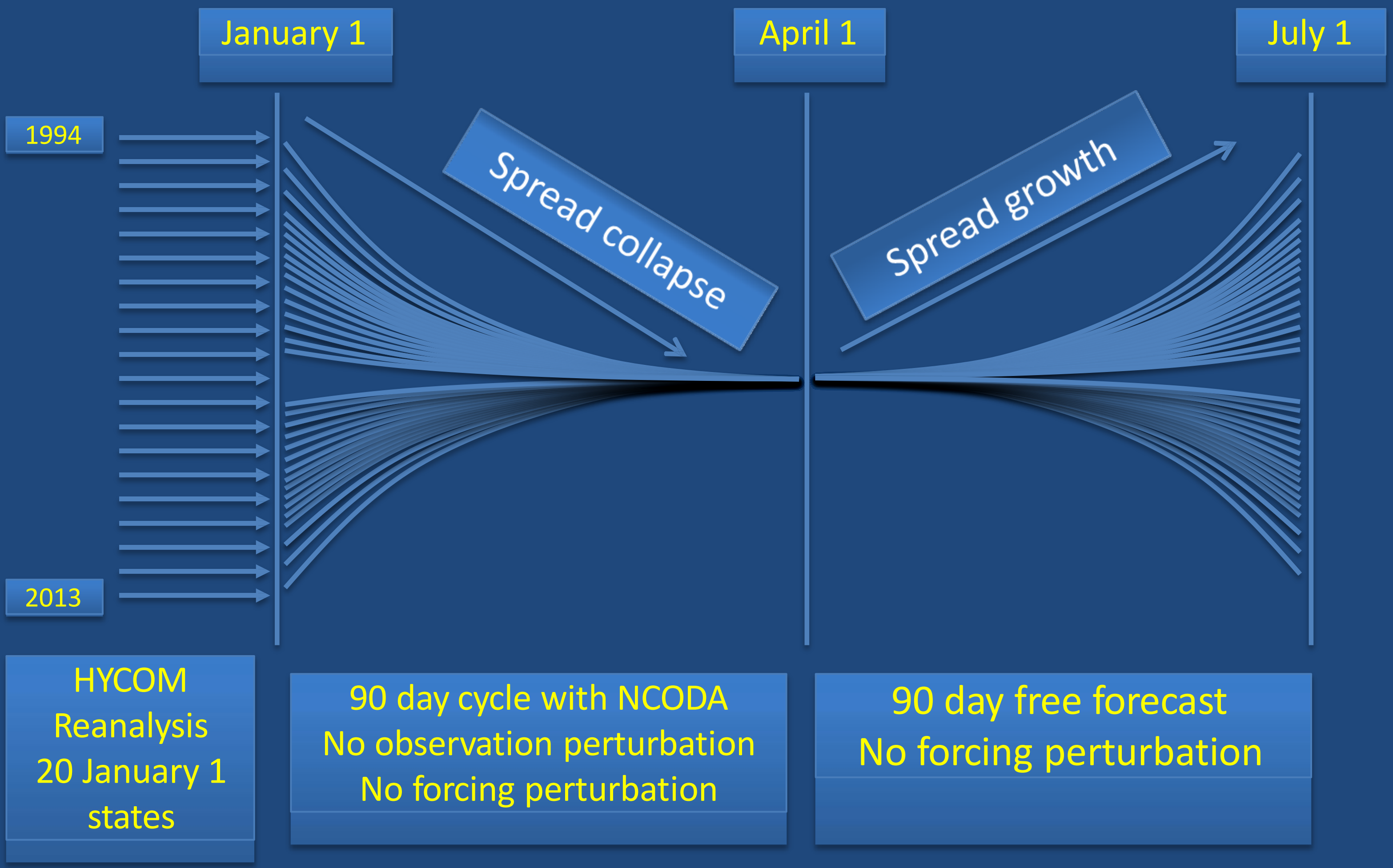
- Global HYCOM ensembles based on the 20-year HYCOM/NCODA reanalysis
- 20 different 01 Jan states from years 1994-2013 initialize 01 Jan 2014
- 10 different 01 July states from years 2003-2012 initialize 01 Jan 2014
  - Experiment 1: Initial perturbations only; 3 month reanalysis, 3 month forecast
  - Experiment 2: Add surface forcing variability
  - Experiment 3: Add perturbed observations
  - Experiment 4: Add perturbed physics (stochastic forcing)

# Ensemble Generation using the Reanalysis




Schematic of the setup of Experiment 1: Initialized from 20 different 01 January states from the 20-year reanalysis; cycled for 90 days with identical observations and no other perturbation; and a 90-day forecast run from the 90-day states.

# Ensemble Generation using the Reanalysis

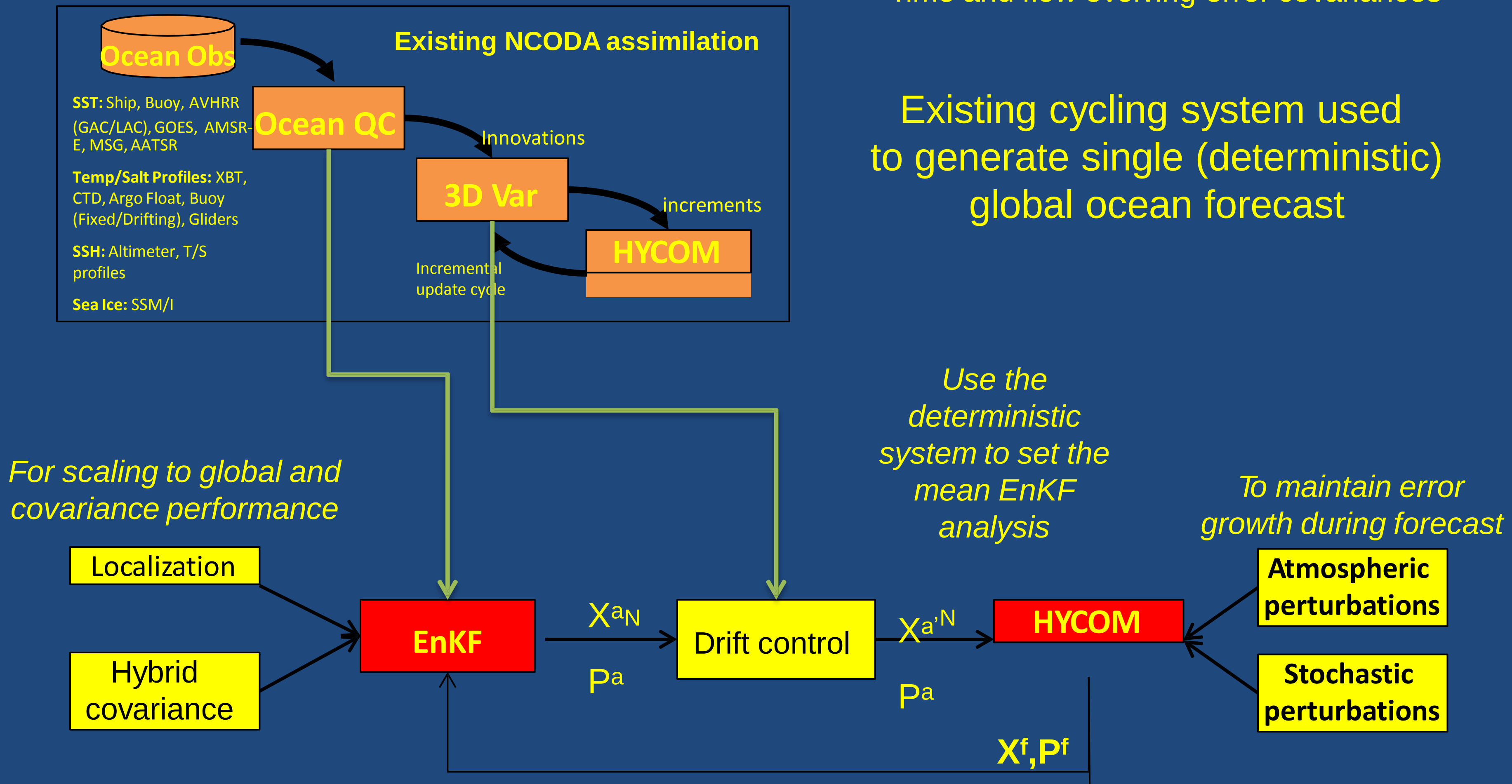



- Error spread collapse is rapid; model spread is underdispersive at end of 3-month analysis period, but not zero
- Error growth during forecast (due only to IC perturbations) is insufficient; additional sources of uncertainty need to be included (perturbed obs, perturbed atmosphere, perturbed model physics)

# EnKF Flow Chart

What's new:

- Using ensembles to generate uncertainty
- Time and flow evolving error covariances




EnKF for global uncertainty

N = number of ensemble members

# Earth System Prediction Capability (ESPC)

National ESPC
EARTH SYSTEM PREDICTION CAPABILITY

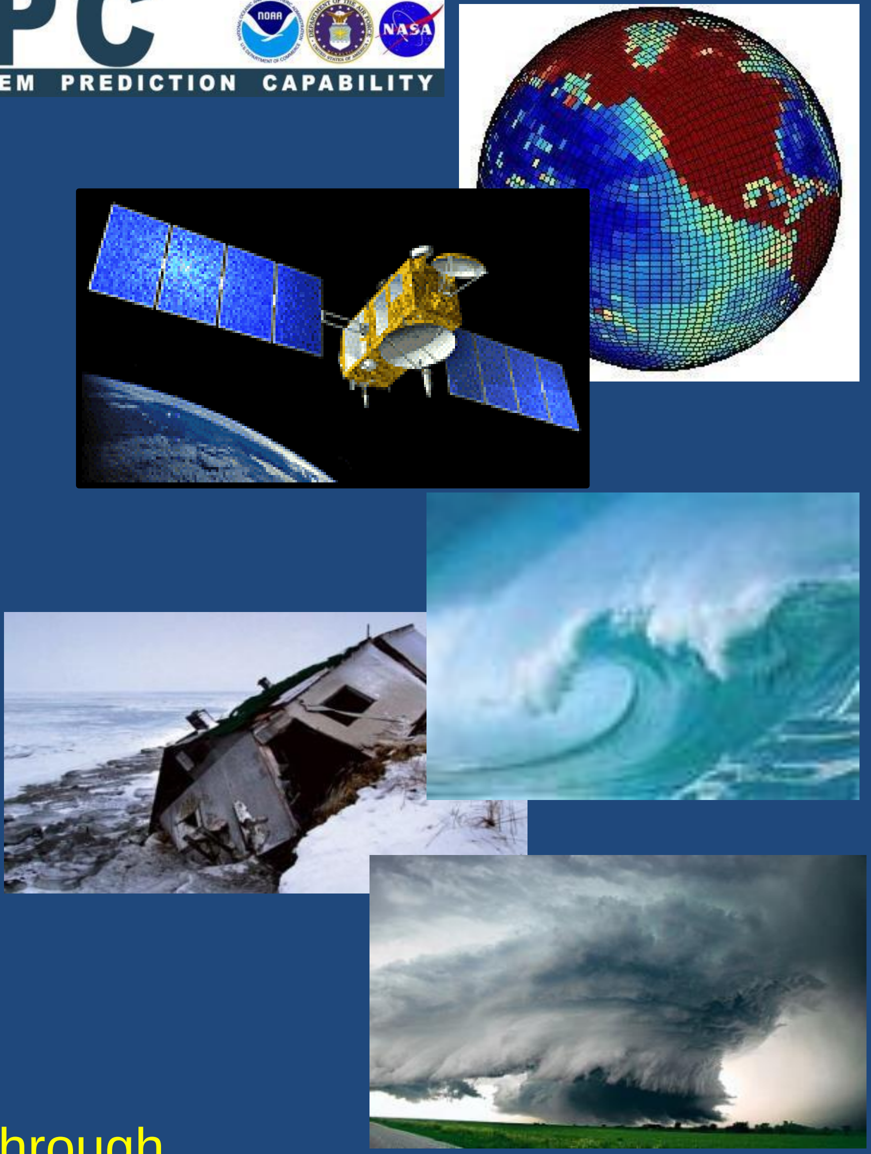
Coupled Global Forecast System

Improve Model Physics through
- Coupled modeling
- Improved parameterizations

Improve Data Assimilation through
- Joint observational retrievals
- New hybrid DA approaches

Increase Forecast Information through
- Stochastic prediction
- National Multi-model ensembles
- Seamless prediction

Increase System Resolution affordably through
- Efficient Computational Architectures
- Efficient Numerics/ Discretization



# Navy ESPC
## Initial Operational Capability 2018

- Not yet fully defined: initial working definition is NavESPC should be running in pre-operational mode at Navy DSRC under EOM with FNMOC-NAVO-DSRC cycling (uncoupled) DA and producing “prototype products”.

DRAFT

| Forecast | …e Scale, Frequency | Atmosphere NAVGEM | Ocean HYCOM | Ice CICE | Waves WW3 | Land-Surface NAVGEM-LSM | Aerosol NAAPS |
|---|---|---|---|---|---|---|---|
| …rministic short term | 0-16 days, Daily | T1025 (13 km) 100 levels | 1/25° (4.5 km) 41+ layers[1] | 1/25° (4.5 km) | 1/8° (14 km) | Module within NAVGEM | Module within NAVGEM |
| Seasonal Ensemble | 0-90 days, Weekly 28 members[2] | T681 (19 km) 80 levels | 1/12° (9 km) 41 layers | 1/12° (9 km) | 1/4° (28 km) | Module within NAVGEM | Module within NAVGEM |

[1]Vertical resolution of HYCOM still to be determined.

[2]Because the operational centers don’t get significantly more time on any one specific day of the week, the ensembles need to be broken up across the week. Run four ensemble members each day of the week.

***Thanks!***

***Questions?***