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Sea Ice Assimilation in Navy Modeling Systems

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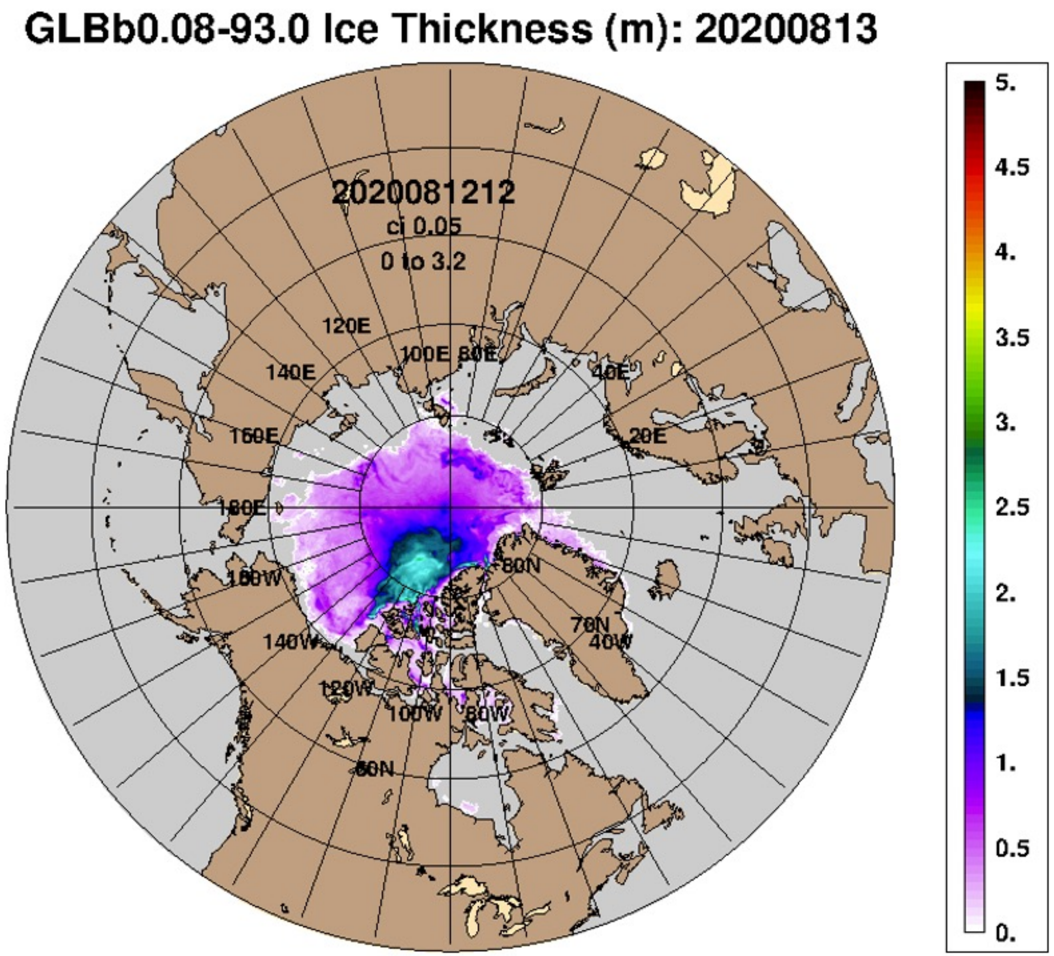
Outline

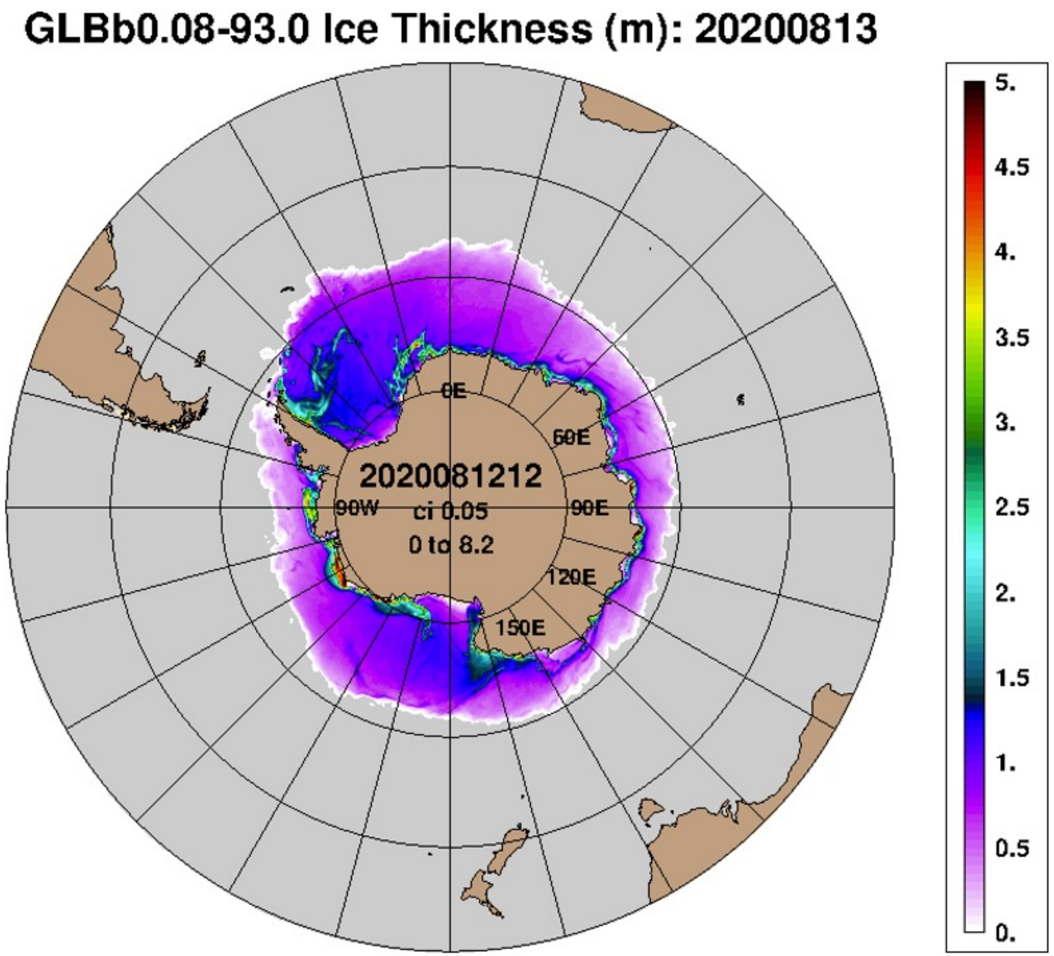
- Navy Ice Modeling Systems
  - GOFS 3.1
  - GOFS 3.5
  - Navy ESPC
- Ice Concentration Assimilation
- Use of CryoSat-2 to initialize models
- Testing assimilation of CryoSat-2 data in GOFS 3.5

Global Ocean Forecast System (GOFS 3.1)

- Global Ocean Forecast System (GOFS) 3.1 was declared operational on 7 November 2018
- Navy's global ocean prediction system to provide first look information "anywhere, anytime"
- Provides boundary conditions to regional (ice and ocean) models
- 1/12° HYCOM two-way coupled to Community Ice CodE (CICEv4)
- Uses the Navy Coupled Ocean Data Assimilation (NCODA) to assimilate available real-time observations: satellite altimeter, SST and sea ice concentration data, in-situ SST, profile data (Argo profiles, XBTs, CTDs, gliders, marine mammals)
- Atmospheric forcing from NAVy Global Environmental Model (NAVGEM)
- Runs daily at Navy DSRC under FNMOC control: 7-day forecasts

Global Ocean Forecast System (GOFS 3.1)





https://www7320.nrlssc.navy.mil/GLBhycomcice1-12/skill.html

HYCOM output available at hycom.org

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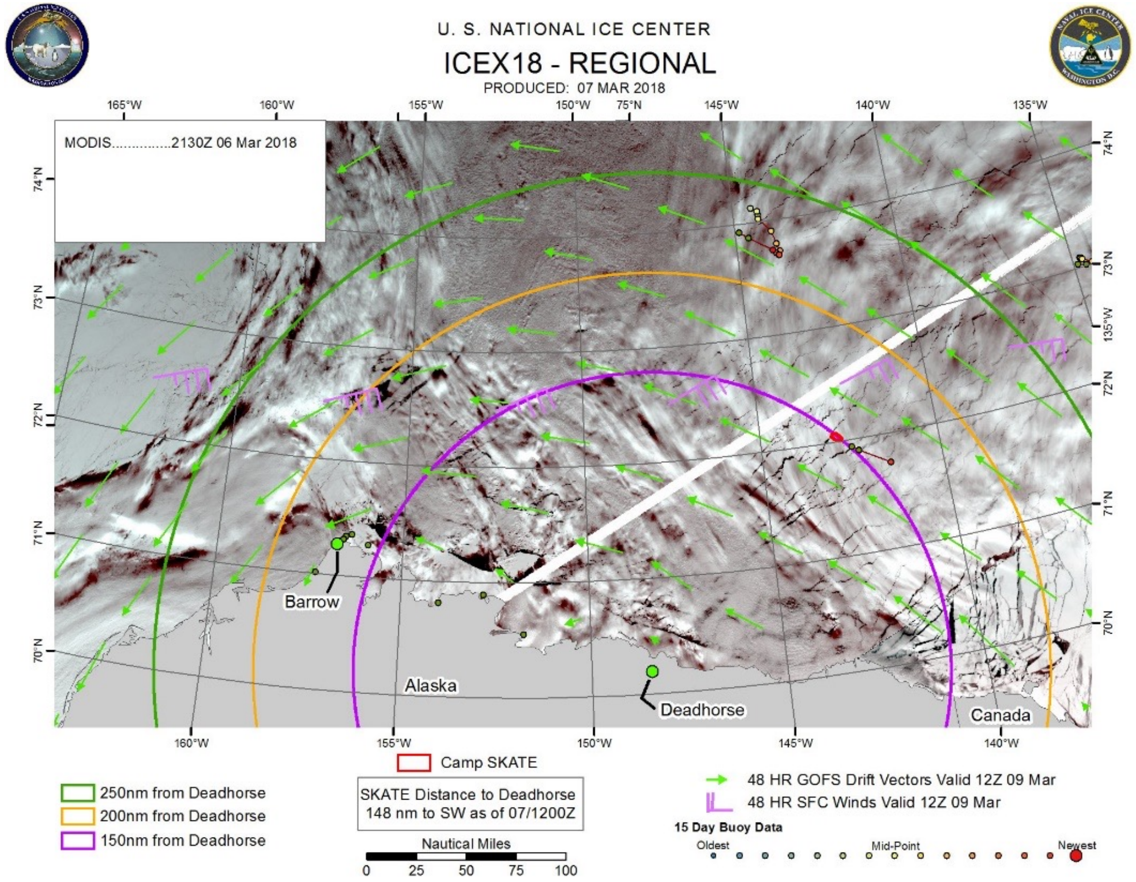
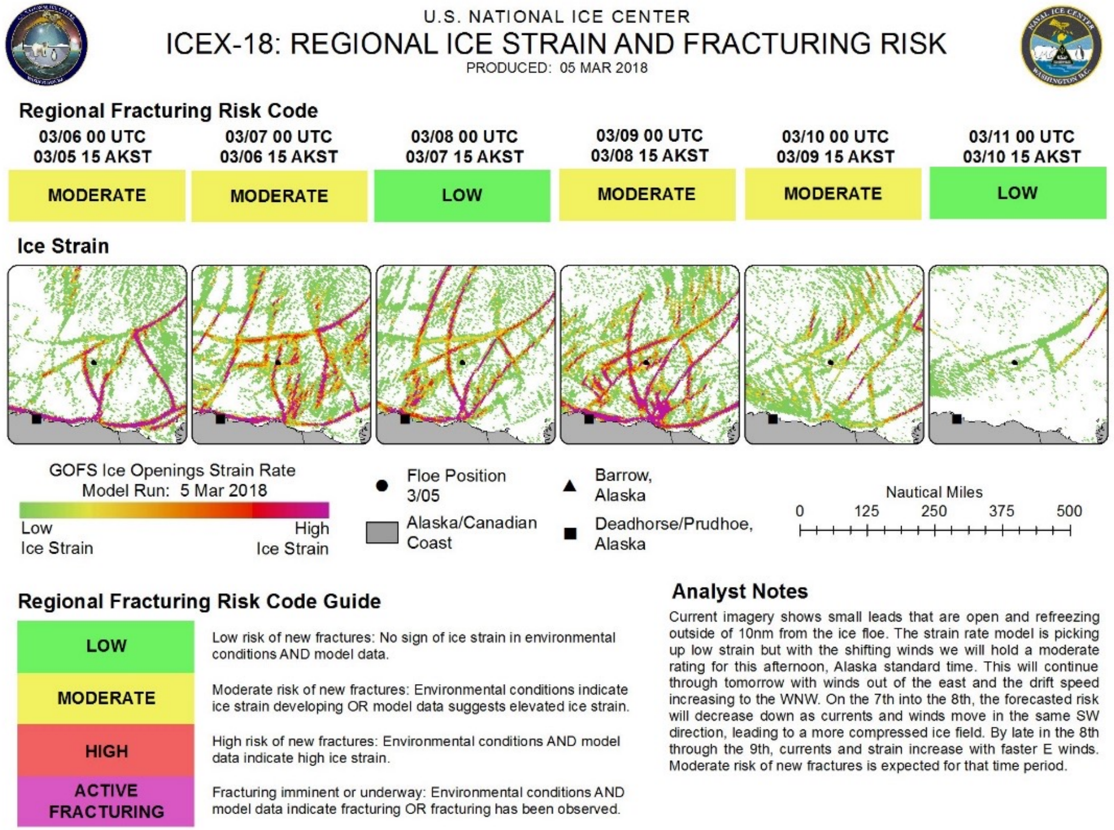
GOFS 3.1 Support for ICEX 2018



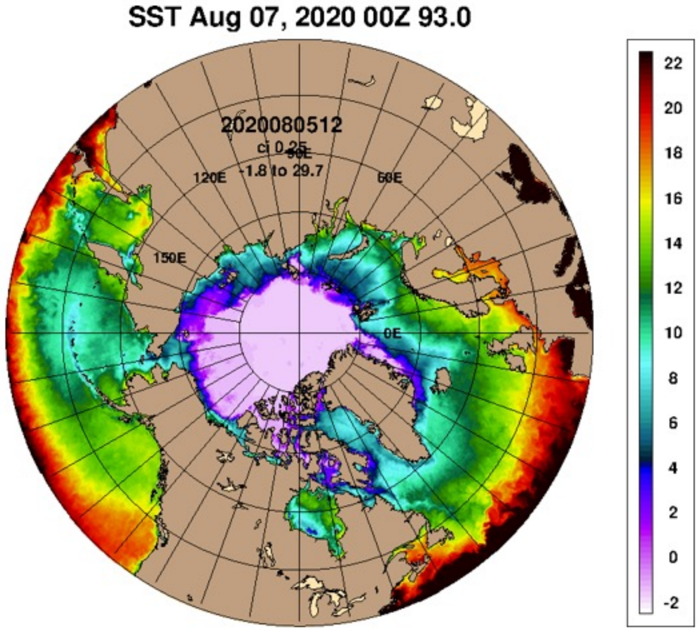
GOFS 3.1 (green arrows) used to forecast ice camp (red polygon) drift



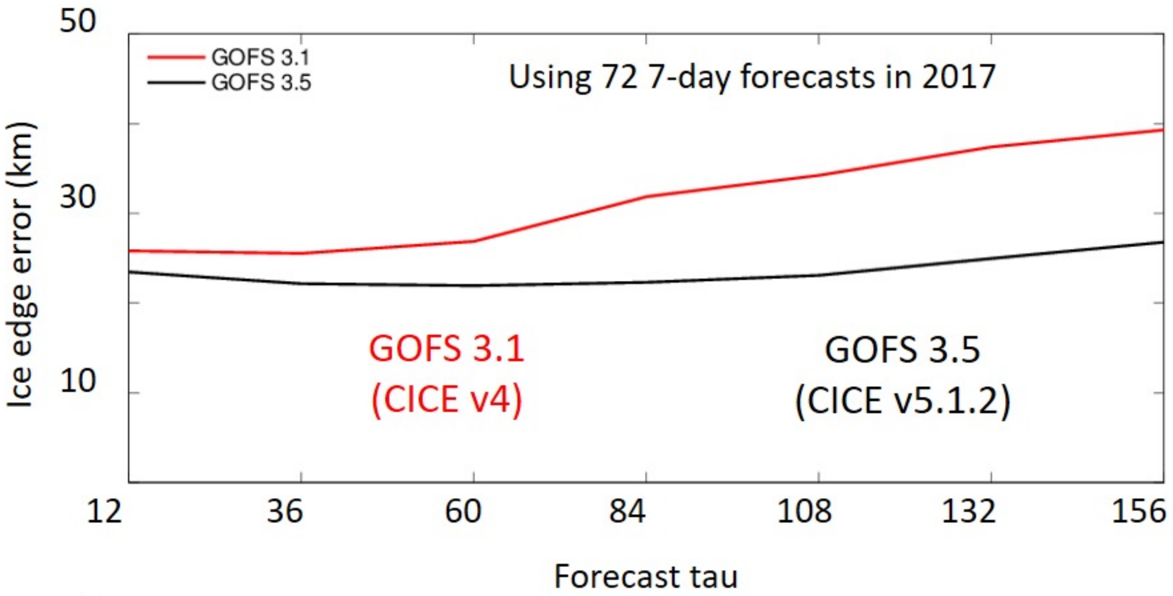
GOFS 3.1 forecasts used in the ice fracturing analysis produced at NIC

Global Ocean Forecast System (GOFS 3.5)

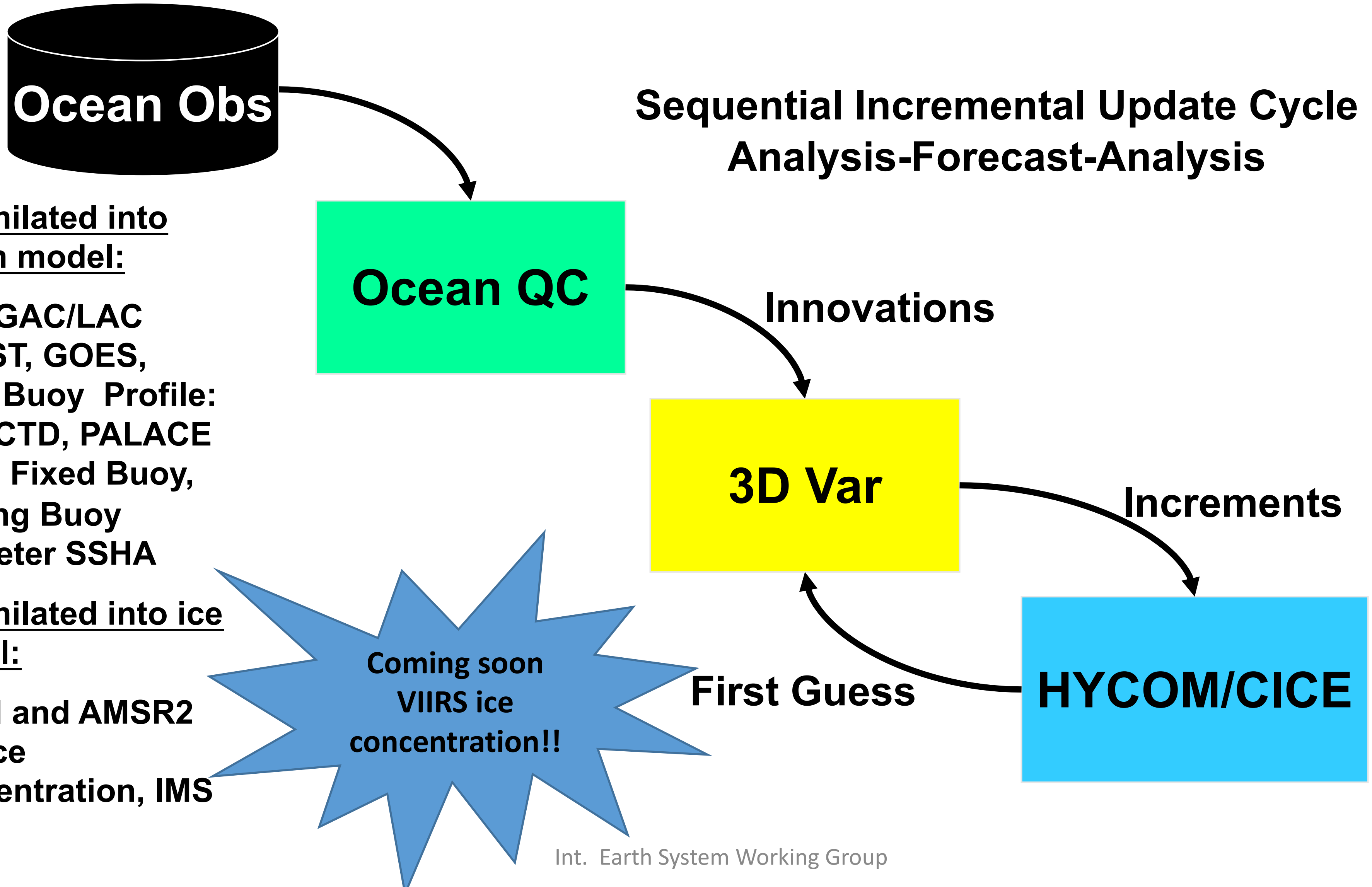
- Global Ocean Forecast System (GOFS) 3.5 scheduled for transition in next few months.
  - Will replace GOFS 3.1
- Resolution increase from 1/12° to 1/25° (1.75 km at North Pole)
- Inclusion of tides in HYCOM → internal waves at tidal frequencies
- Coupled HYCOM – CICE (v5.1.2)



Sea ice edge error (km) as a function of forecast length vs. the independent NIC ice edge: Pan-Arctic domain



Navy Coupled Ocean Data Assimilation (NCODA)



Assimilated into ocean model:

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

Assimilated into ice model:

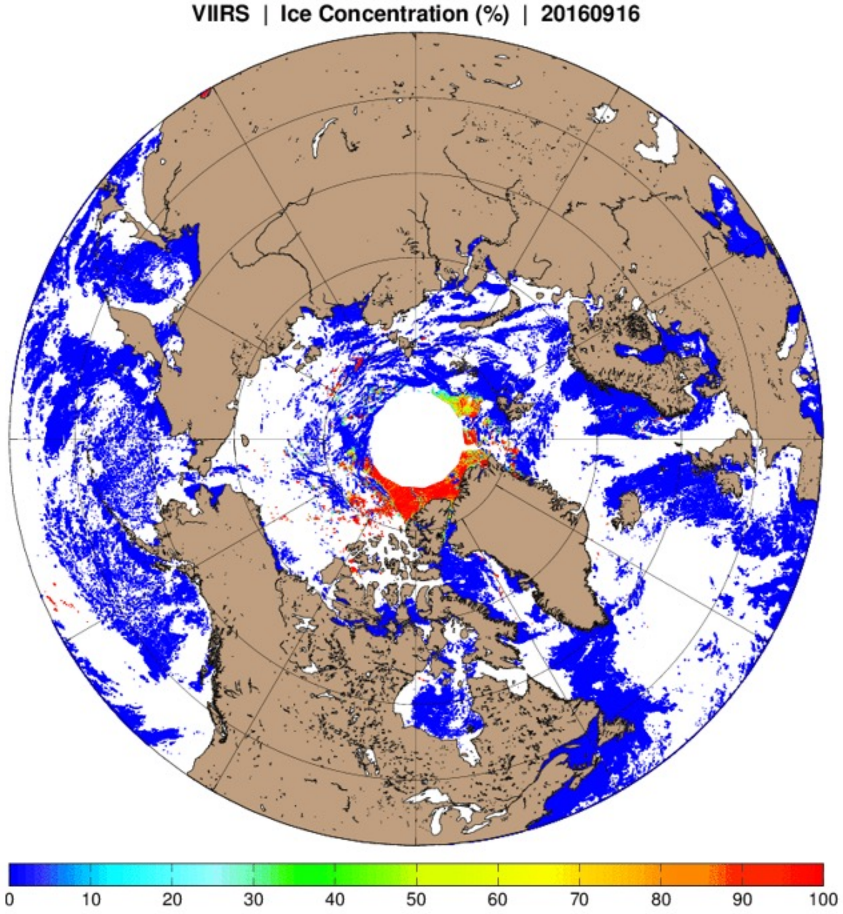
SSM/I and AMSR2 Sea Ice Concentration, IMS

VISIBLE INFRARED IMAGING RADIOMETER SUITE (VIIRS)

New data source: VIIRS

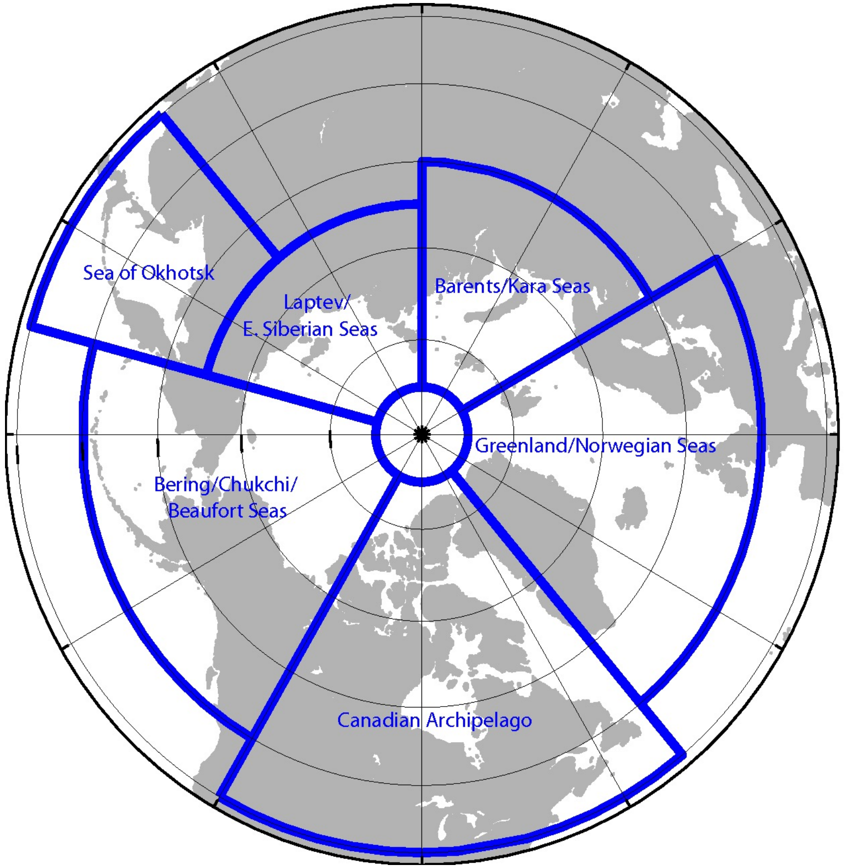
- High resolution (375-750m) vs AMSR2 (10km), SSMI (25km)
- Does not see through clouds
- Ice concentration data available during visible light periods (spring, summer, autumn)
- Does not misclassify melt ponds as open water (passive microwave issue). Most problematic in melt season (spring/summer).
- VIIRS provides observations during melt seasons which help overcome meltpond issue

NAVOCEANO in-house VIIRS
Ice Concentration

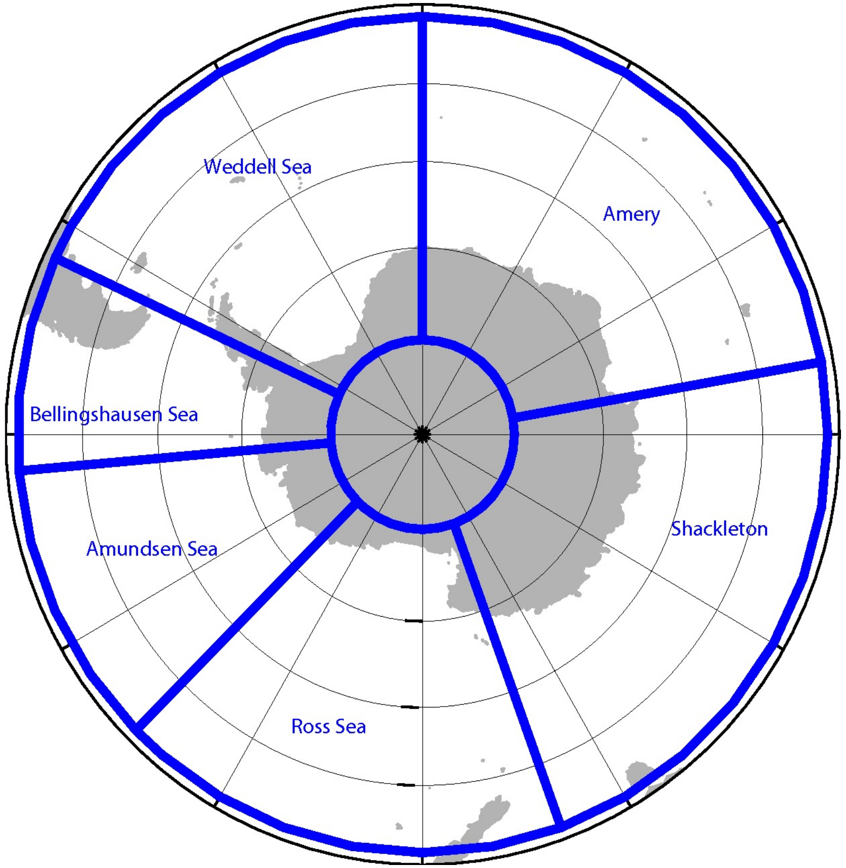


Ice Concentration (%)

Defined regions for ice edge error analysis



Arctic



Antarctic

Mean ice edge errors (km) between the observed ice edge and 12-hr GOFS 3.1 for the time period of Nov 2016 – Oct 2017

Arctic	GOFS 3.1 SSMI/AMSR2	GOFS 3.1 SSMI/AMSR2/VIIRS	Total improvement over pre-operational GOFS 3.1
Greenland	31 km	21 km	31%
Barents	24 km	22 km	8%
Laptev	28 km	23 km	16%
Sea of Okhotsk	20 km	18 km	8%
Bering/Beaufort/Chukchi	24 km	22 km	9%
Canadian Archipelago	31 km	25 km	21%
Pan-Arctic	27 km	22 km	**19%**

Pan-Arctic improvement of 19% over current operational capability adding in NAVOCEANO in-house AMSR2 and VIIRS data.

Mean ice edge errors (km) between the observed ice edge and 12-hr GOFS 3.1 for the time period of Nov 2016 – Oct 2017

Antarctic	GOFS 3.1 SSMI/AMSR2	GOFS 3.1 SSMI/AMSR2/VIIRS	Total improvement over pre-operational GOFS 3.1
Amery	39 km	33 km	15%
Shackleton	32 km	29 km	8%
Ross	42 km	38 km	9%
Amundsen	37 km	34 km	9%
Bellingshausen	28 km	25 km	9%
Weddell	46 km	41 km	12%
Pan-Antarctic	38 km	34 km	**11%**

Pan-Antarctic improvement of 11% over current operational capability adding in NAVOCEANO in-house AMSR2 and VIIRS data.

Mean ice edge errors (km) between the observed ice edge and GOFS 3.1+VIIRS for the time period of Nov 2016 – Oct 2017

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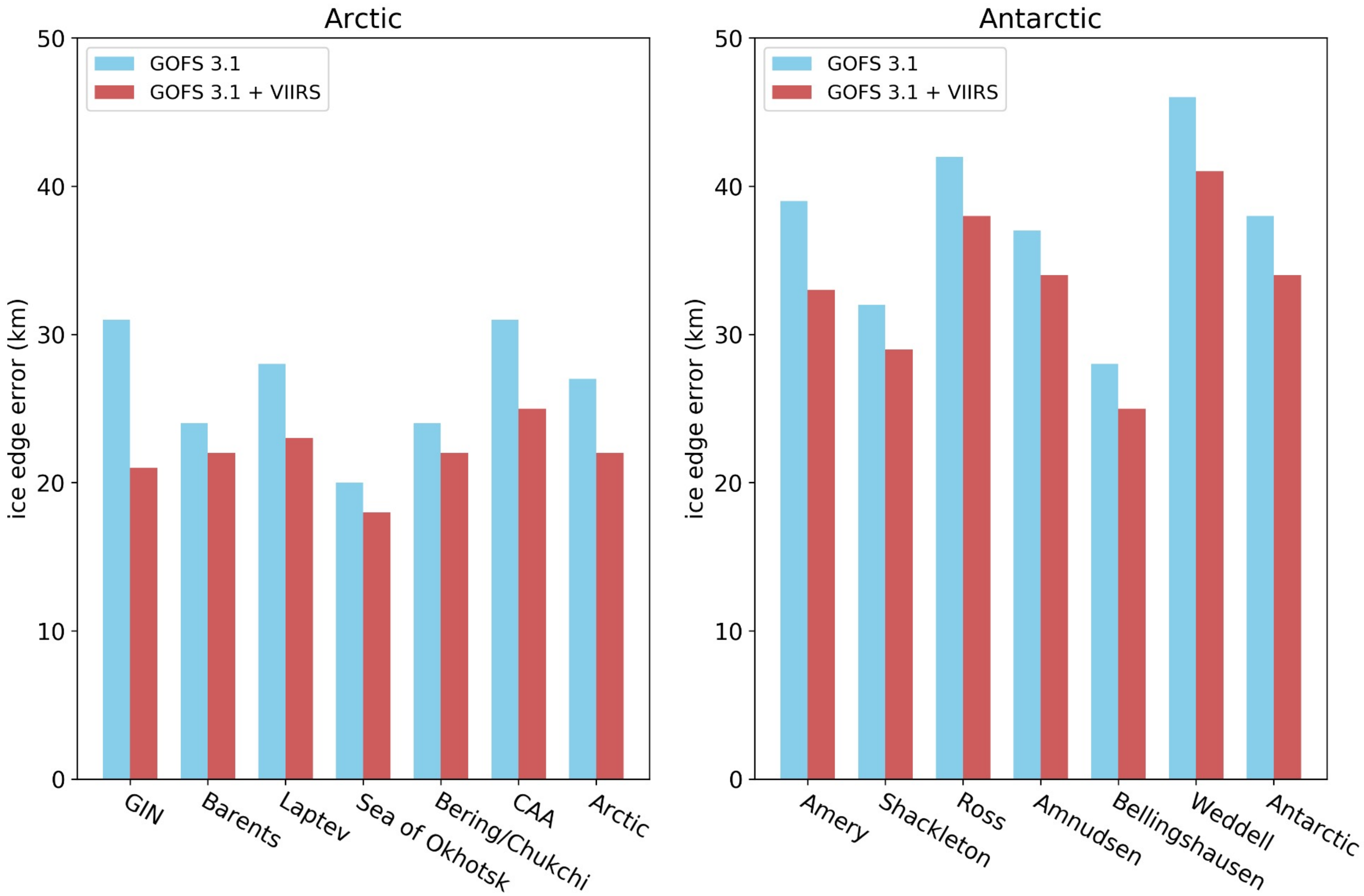


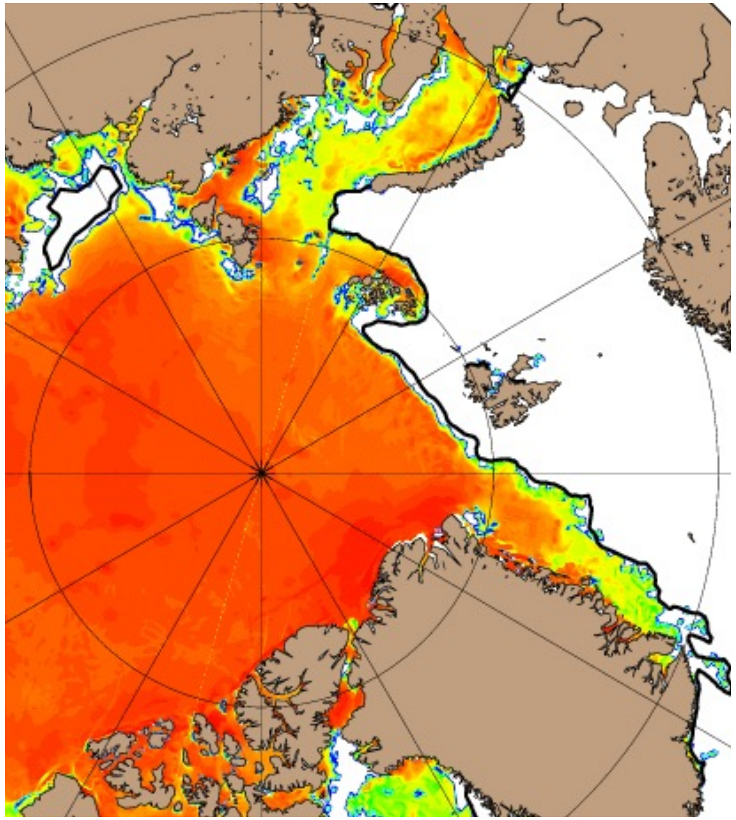
PanArctic error reduction 19%

PanAntarctic error reduction 11%

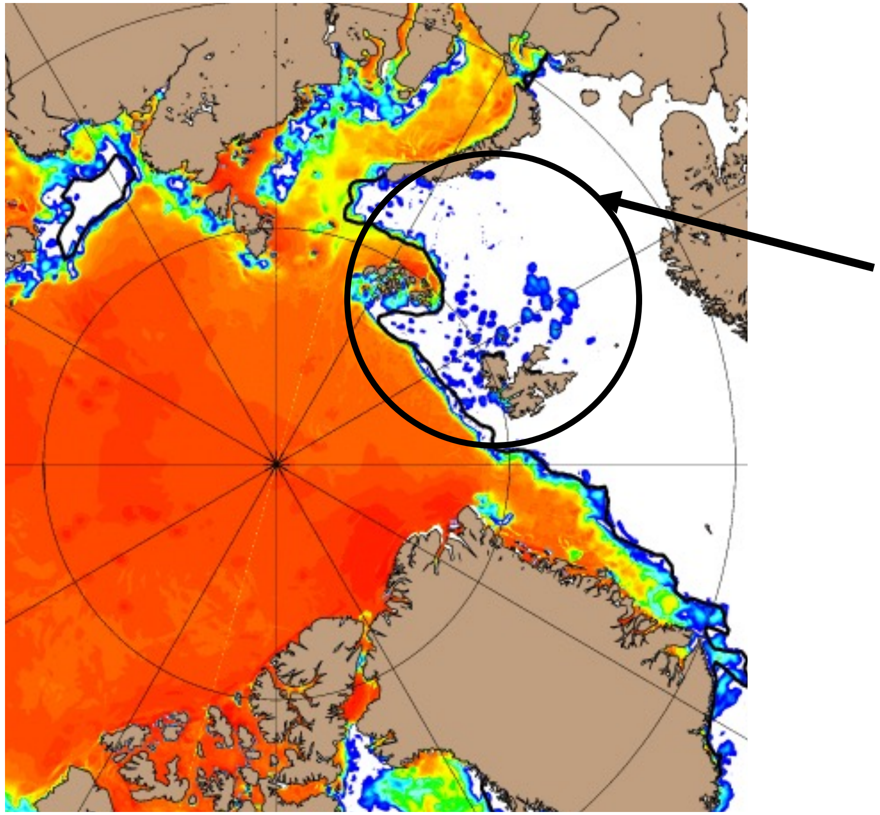
Same as above previous slides but in graphical form

Cloud Contamination in VIIRS

Operational GOFS 3.1:
-AMSR2, SSMI, No VIIRS,
-IMS applied to NCODA analysis



Test GOFS 3.1:
AMSR2, SSMI, +VIIRS,
+IMS in NCODA as QC flag



Clouds misidentified as ice.

This is being addressed in work by Dr. Li at NRL-DC

Interactive Multisensor Snow and Ice Mapping System (IMS)

Toward Next-Gen Earth System Prediction ESPC

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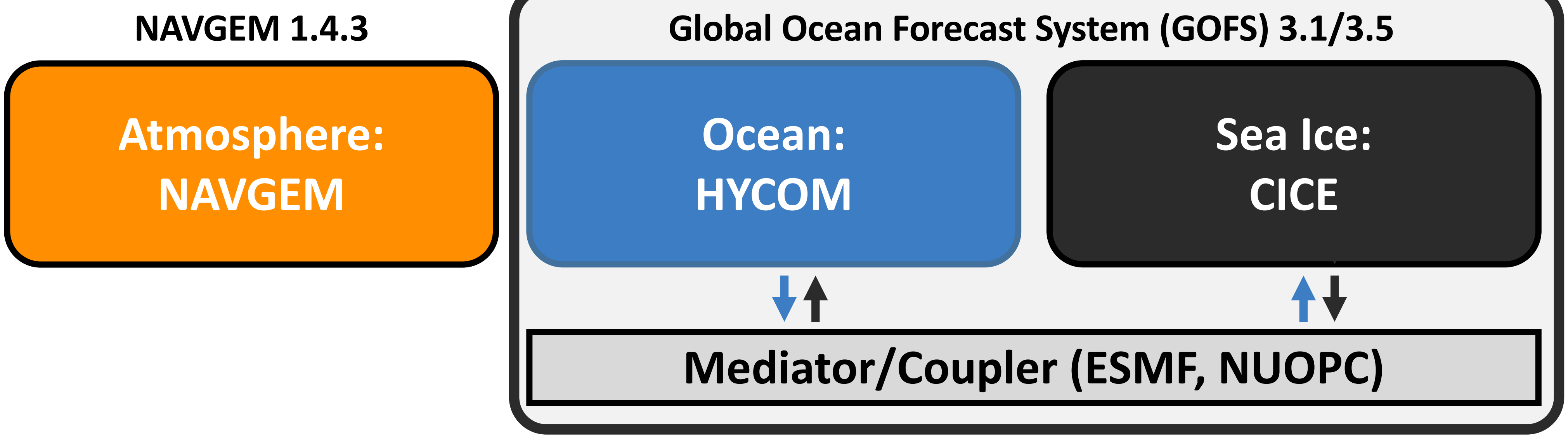
Current Operational Global Atmosphere Model

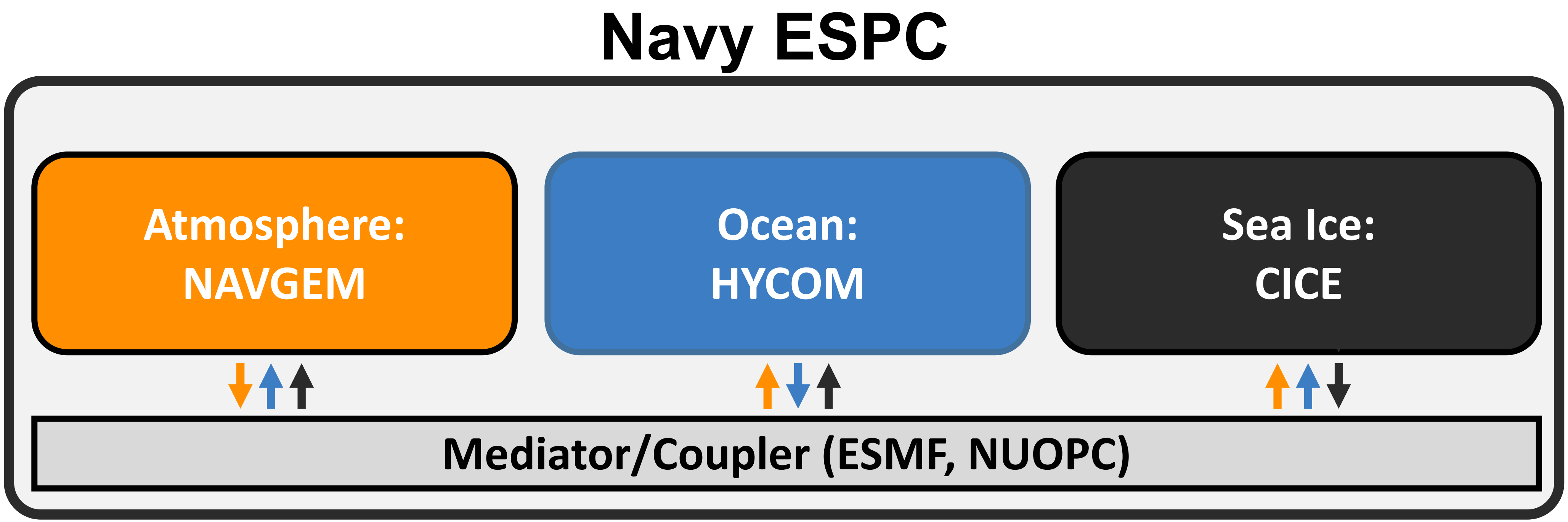
Current Operational Global Ocean/Sea Ice Models



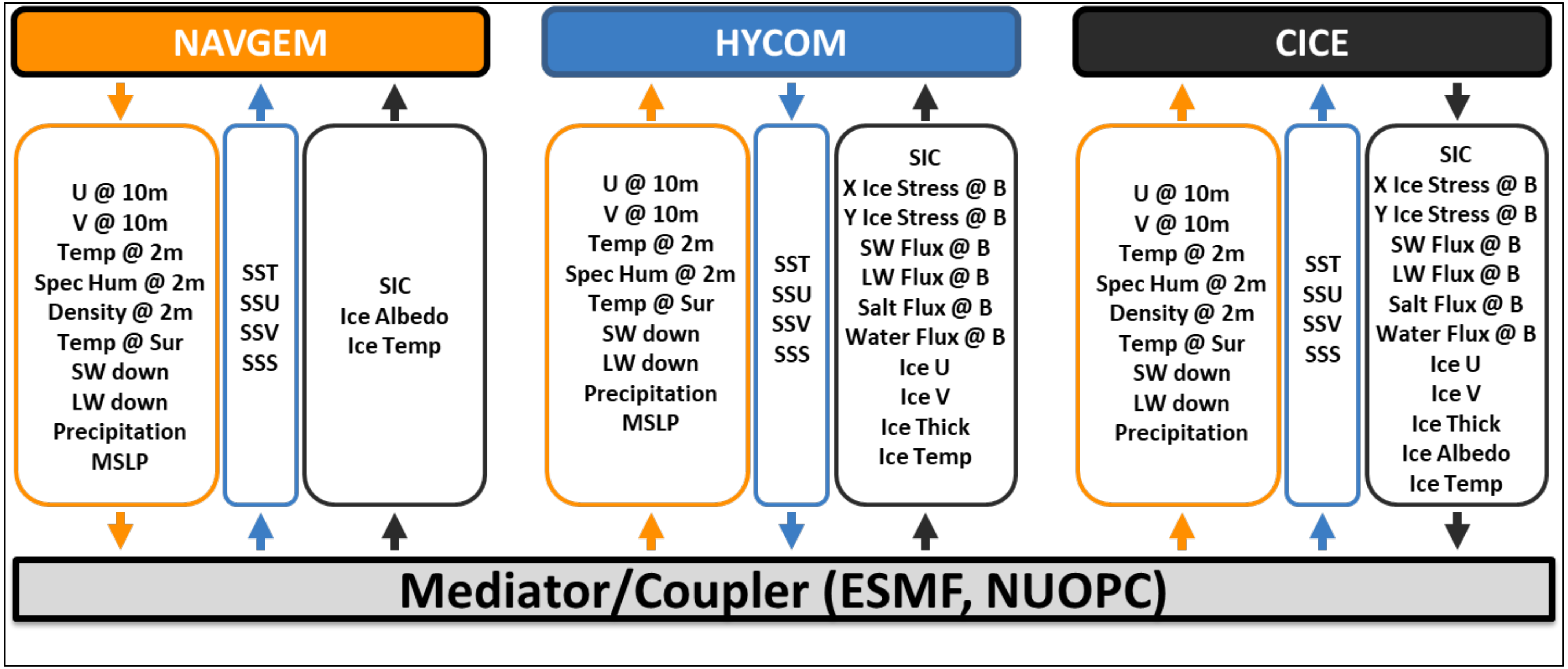
NAVGEM = NAVy Global Environmental Model
HYCOM = HYbrid Coordinate Ocean Model
CICE = Community Ice CodE

Toward Next-Gen Earth System Prediction ESPC

The Navy's Global Coupled System Based on Current Operational Systems



ESPC Overview



Navy ESPC Overview

Ensemble ESPC: V1 vs V2

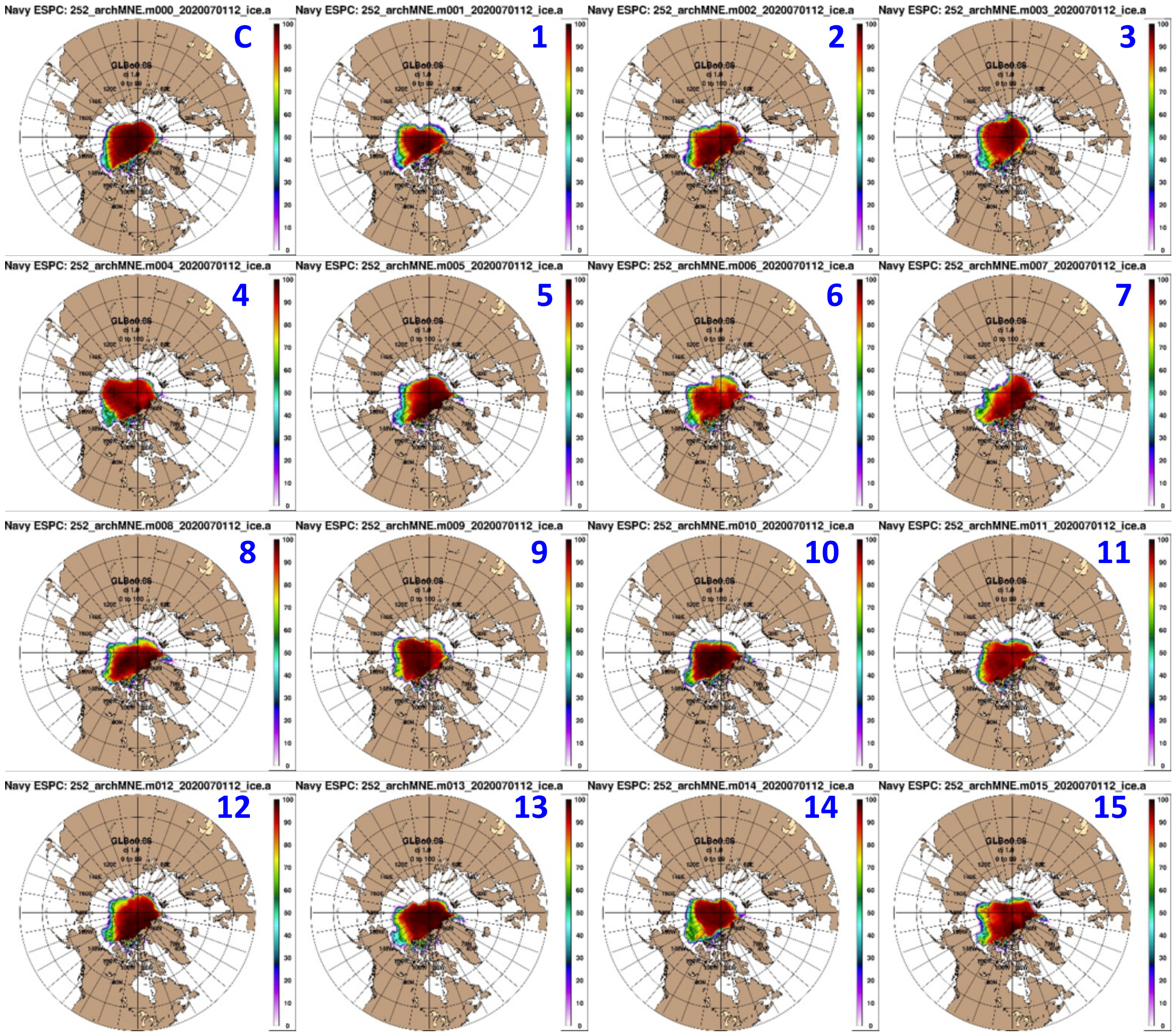
ESPC Version Number	Time Scale, Frequency	Atmosphere NAVGEM	Ocean HYCOM	Sea Ice CICE	Waves[1] WW3	Land Surface LSM	Aerosol[2]
V1	0-45 days weekly 16 members	T359L60 (37 km) 60 levels	1/12° (9 km)[3] 41 layers	1/12° (3.5 km)[4] CICE V4		Module within NAVGEM	
V2	0-45 days (2x) weekly 16 members[5]	T681L100 (19 km) L143 HA	1/12° (9 km)[3] 41 layers Tides	1/12° (3.5 km)[4] CICE V6	1/4° (28 km)	Module within NAVGEM	Module within NAVGEM

[1] One-way coupling to waves only.
[2] Atmosphere-aerosol coupling only.
[3] Horizontal resolution at the equator.
[4] Horizontal resolution at the North Pole.
[5] The exact configuration determined by operational resources available.

Navy ESPC V1 Description: Barton, N., et al. 2020: The Navy's Earth System Prediction Capability. Earth and Space Science. e2020EA001199. doi.org/10.1029/2020EA001199

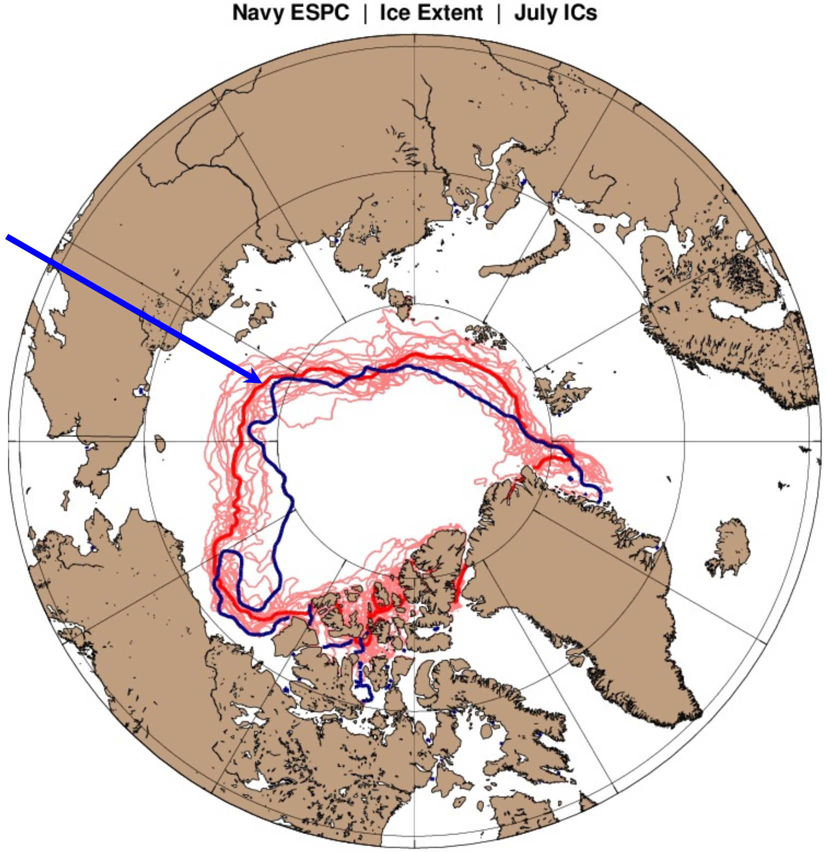
August Report Initialized 1 July 2020 (SIPN2)

Navy ESPC used to predict Sept sea ice minimum extent



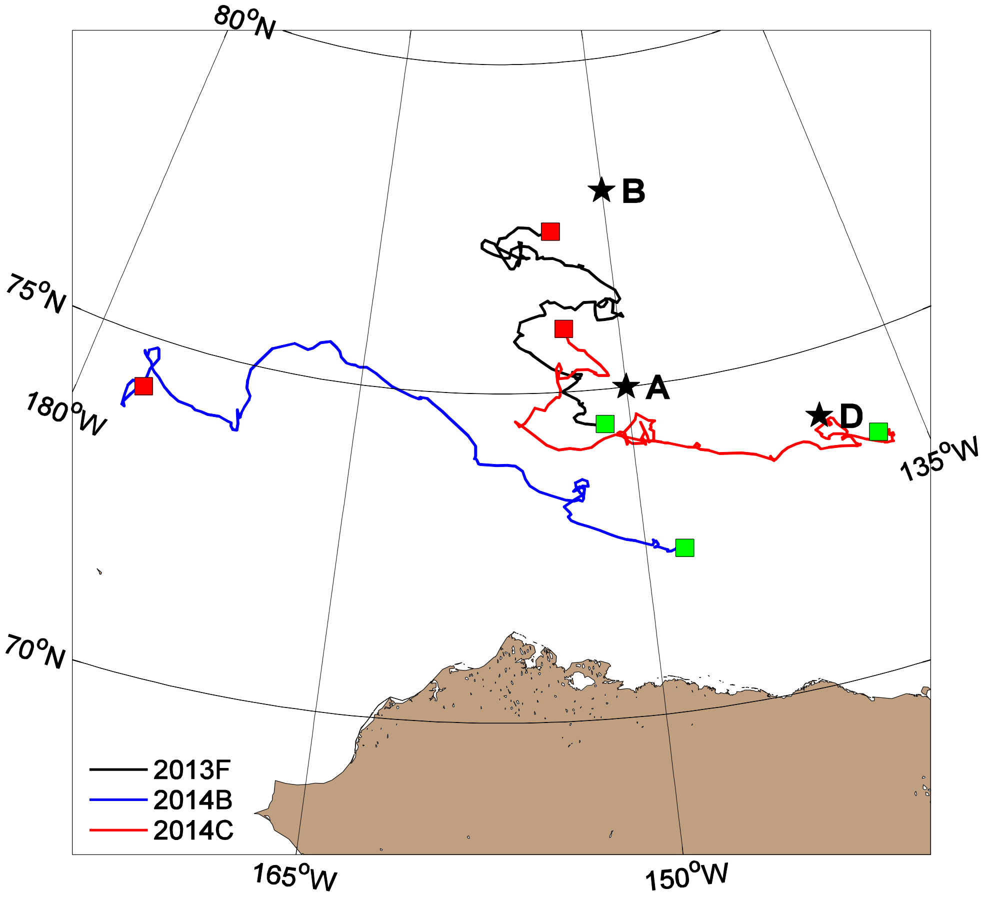
Predicted September Minimum Sea Ice Extent Initialized 1 July 2020

NSIDC minimum extent for 13 Sep shown in blue

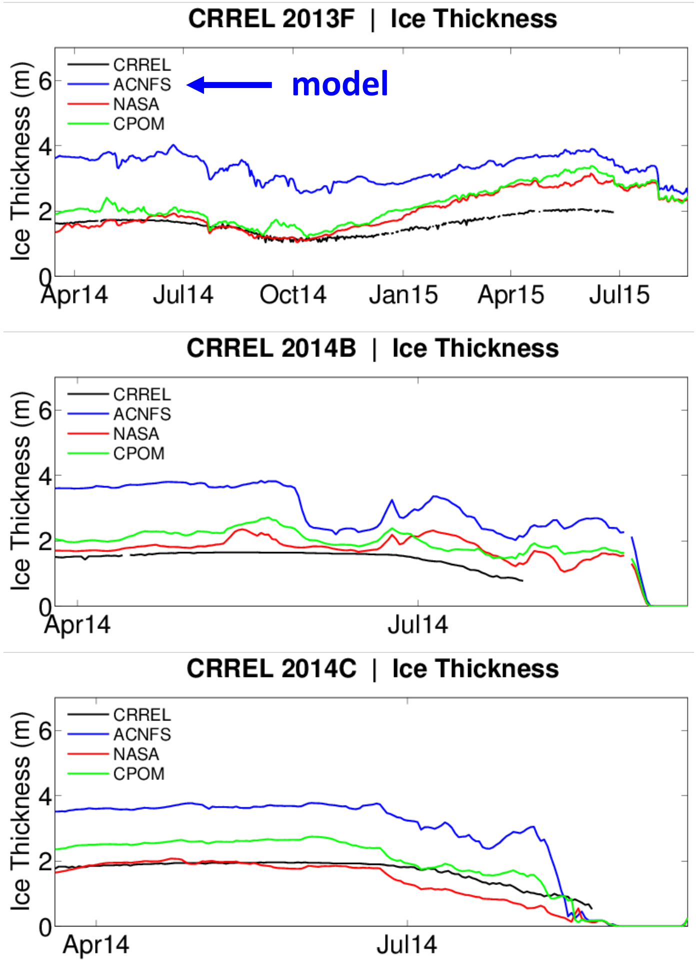


16 Ensemble members shown in red

Motivation: Hindcast Study With CS2 Initialization

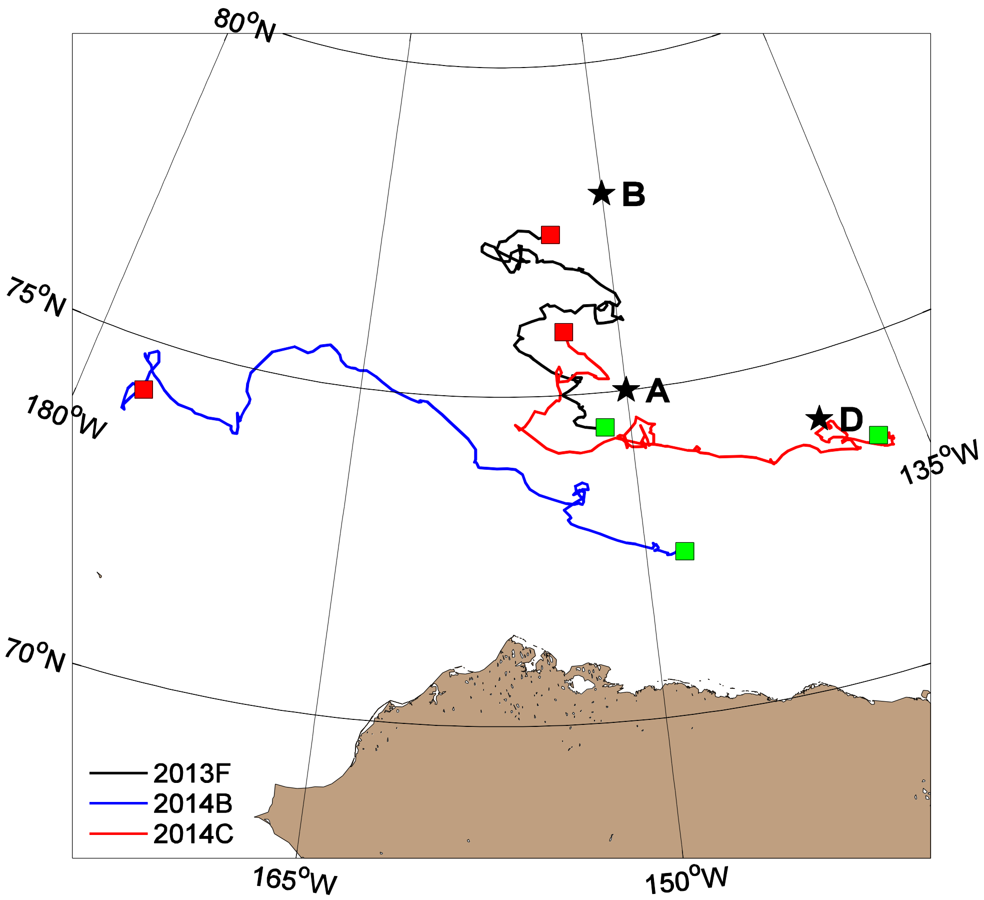


Significant reduction in ice thickness bias in ice-ocean modeling system when reinitializing with CyoSat-2 ice thickness data.



Allard, R. A., Farrell, S. L., Hebert, D. A., Johnston, W. F., Li, L., Kurtz, N. T., Phelps, M. W., Posey, P. G., Tilling, R., Ridout, A., and Wallcraft, A. J. Utilizing CryoSat-2 sea ice thickness to initialize a coupled ice–ocean modeling system, Adv. Space Res., 62, 1265–1280, https://doi.org/10.1016/j.asr.2017.12.030, 2018.

Motivation: Hindcast Study With CS2 Initialization



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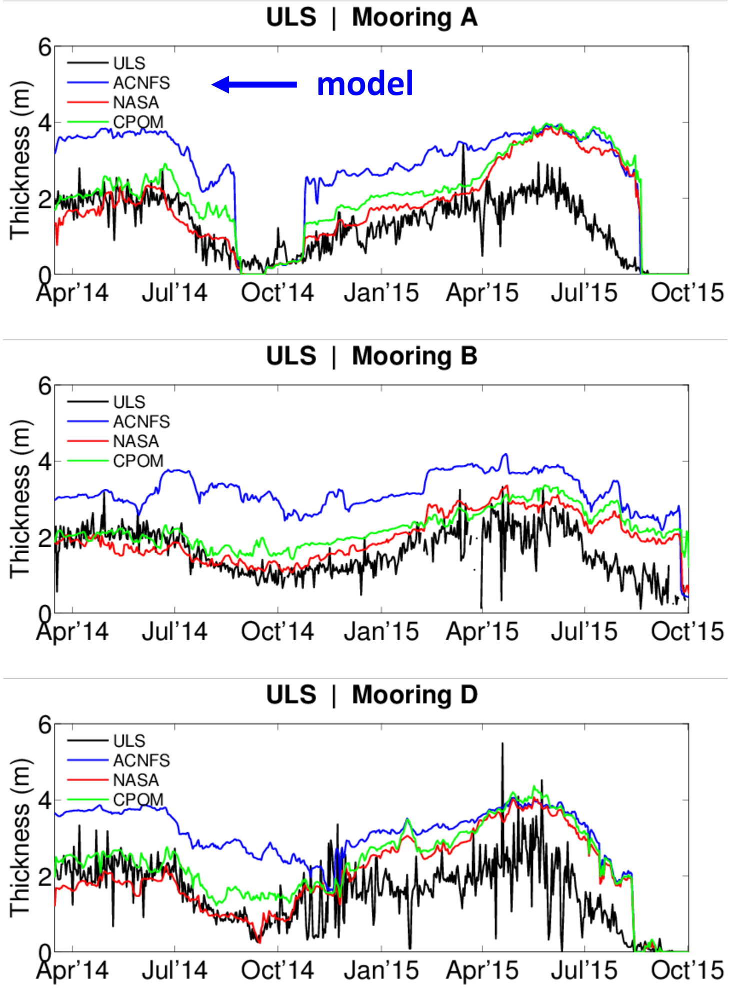
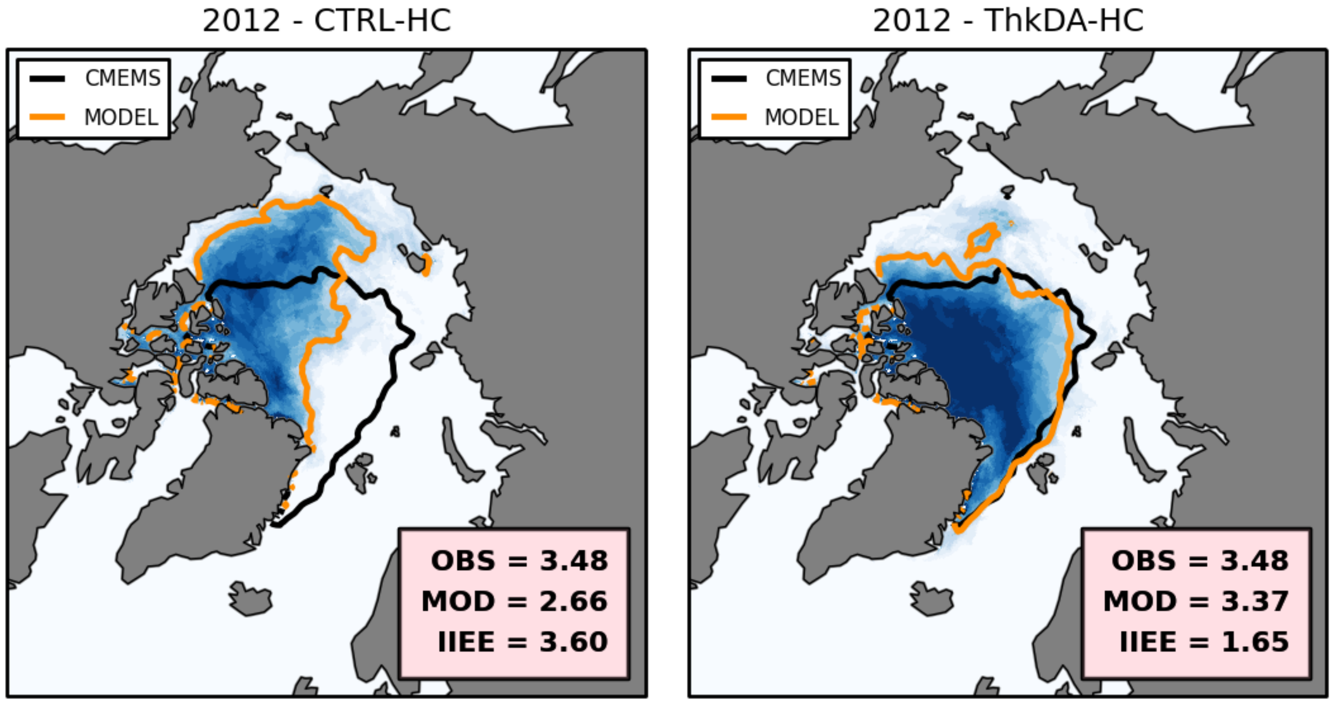


Allard, R. A., Farrell, S. L., Hebert, D. A., Johnston, W. F., Li, L., Kurtz, N. T., Phelps, M. W., Posey, P. G., Tilling, R., Ridout, A., and Wallcraft, A. J.: Utilizing CryoSat-2 sea ice thickness to initialize a coupled ice–ocean modeling system, Adv. Space Res., 62, 1265–1280, https://doi.org/10.1016/j.asr.2017.12.030, 2018.

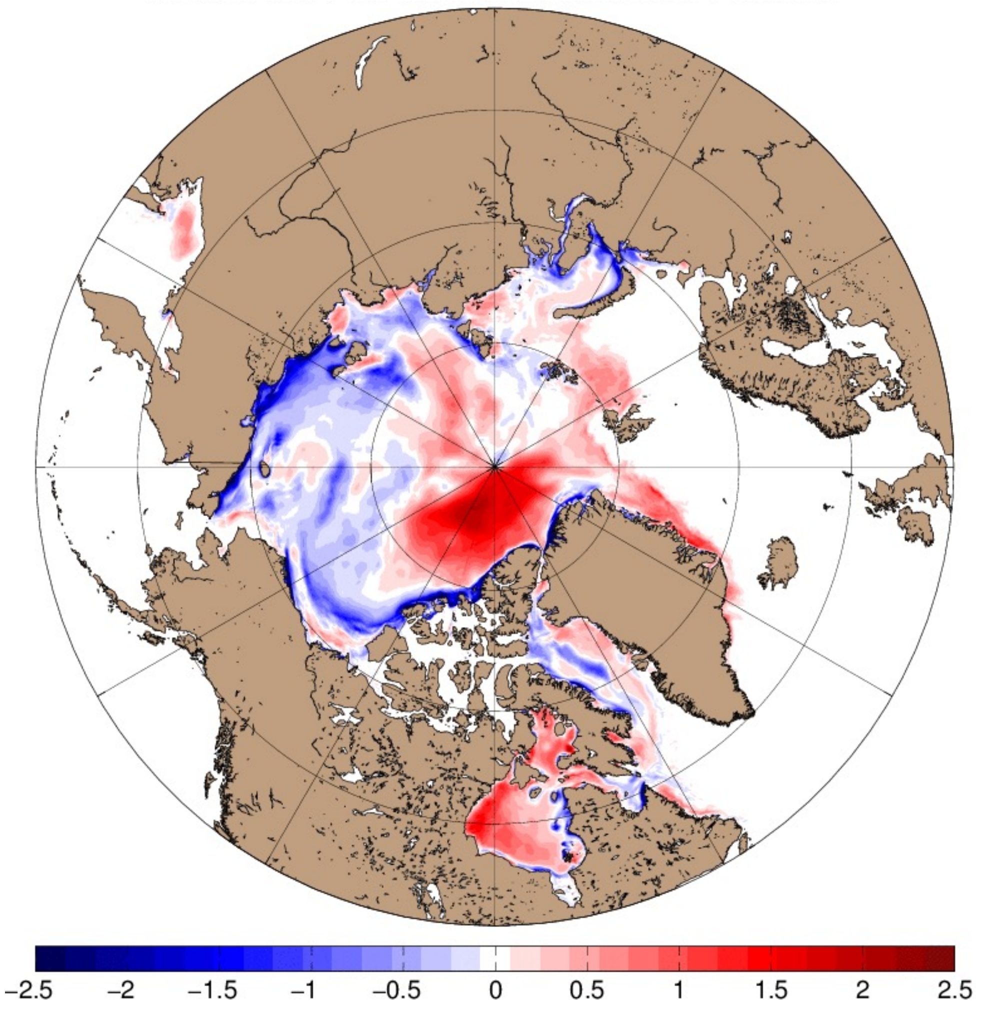
Motivation: Seasonal Prediction Using Coupled Modeling System Initialized with CS2



Significant improvement in September forecast probability of ice (conc > 15%) when running seasonal fully coupled forecast system with CS2.

Blockley, E. W. and Peterson, K. A.: Improving Met Office seasonal predictions of Arctic sea ice using assimilation of CryoSat-2 thickness, The Cryosphere, 12, 3419-3438, https://doi.org/10.5194/tc-12-3419-2018, 2018.

Ensemble Ice Thickness Difference (m) for May 15, 2018 (CS2 – Control)

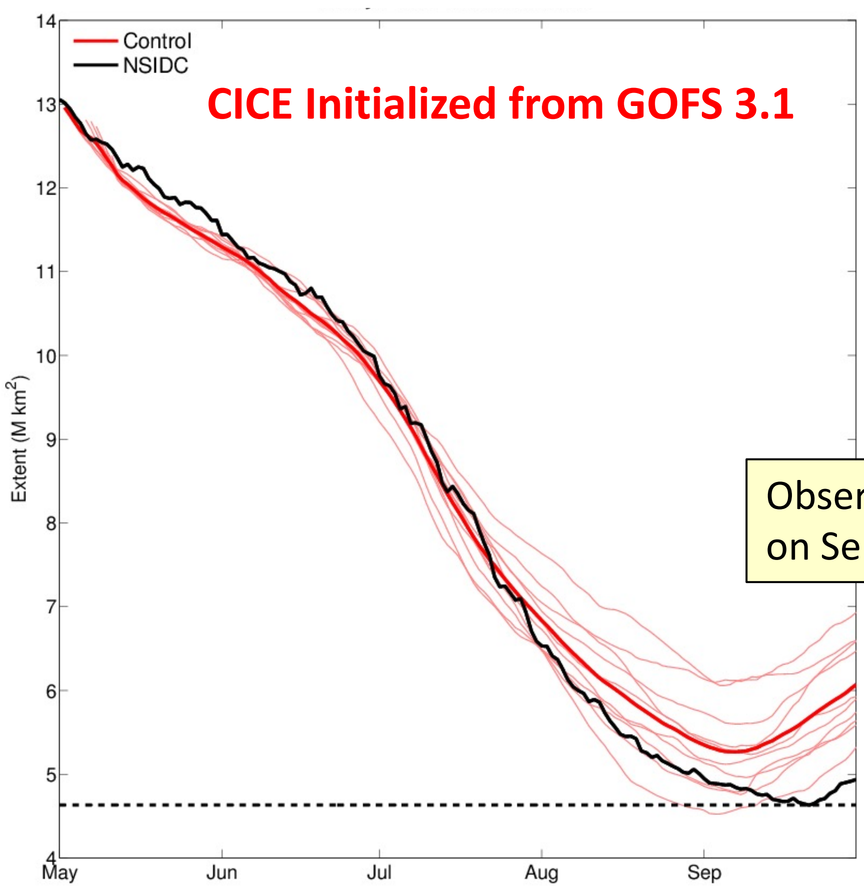


- Blue regions indicate CS2 initialization results in thinner ice than GOFS 3.1-based initialization.
- Red regions indicate thicker ice with CS2 initialization.

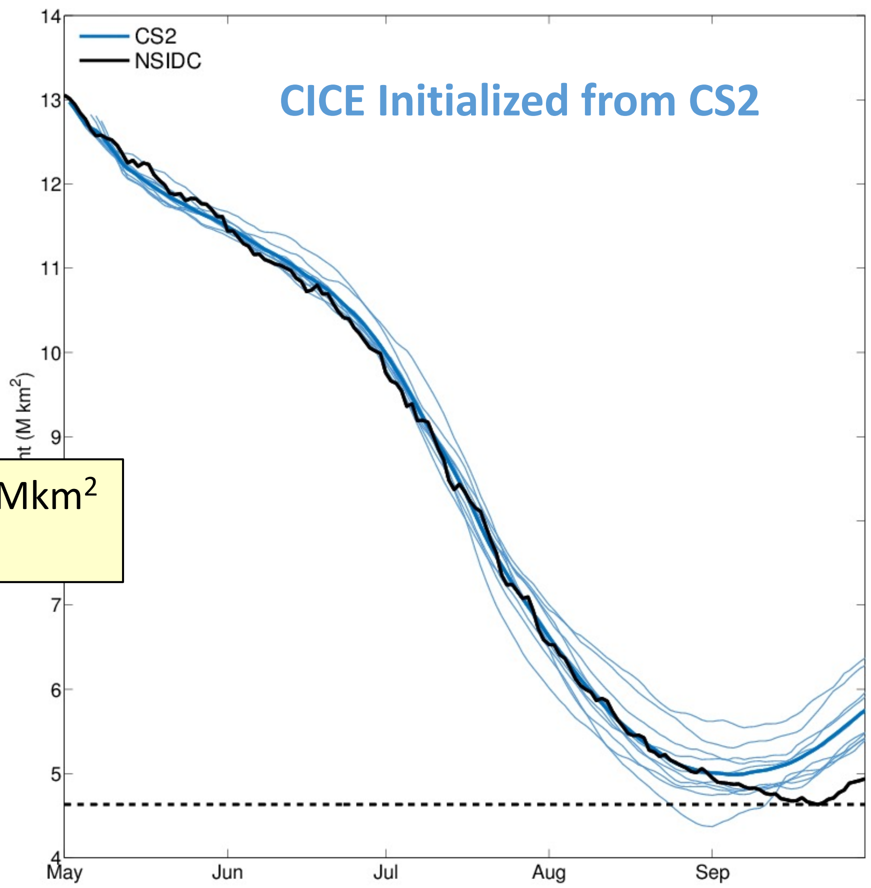
Global Ocean Forecast System (GOFS 3.1); Navy's operational HYCOM/CICE modeling system

Allard, R., Metzger, E., Barton, N., Li, L., Kurtz, N., Phelps, M., Posey, P. (2020). Analyzing the impact of CryoSat-2 ice thickness initialization on seasonal Arctic Sea Ice prediction. *Annals of Glaciology, 61*(82), 78-85. doi:10.1017/aog.2020.15

2018 Arctic Sea Ice Extent

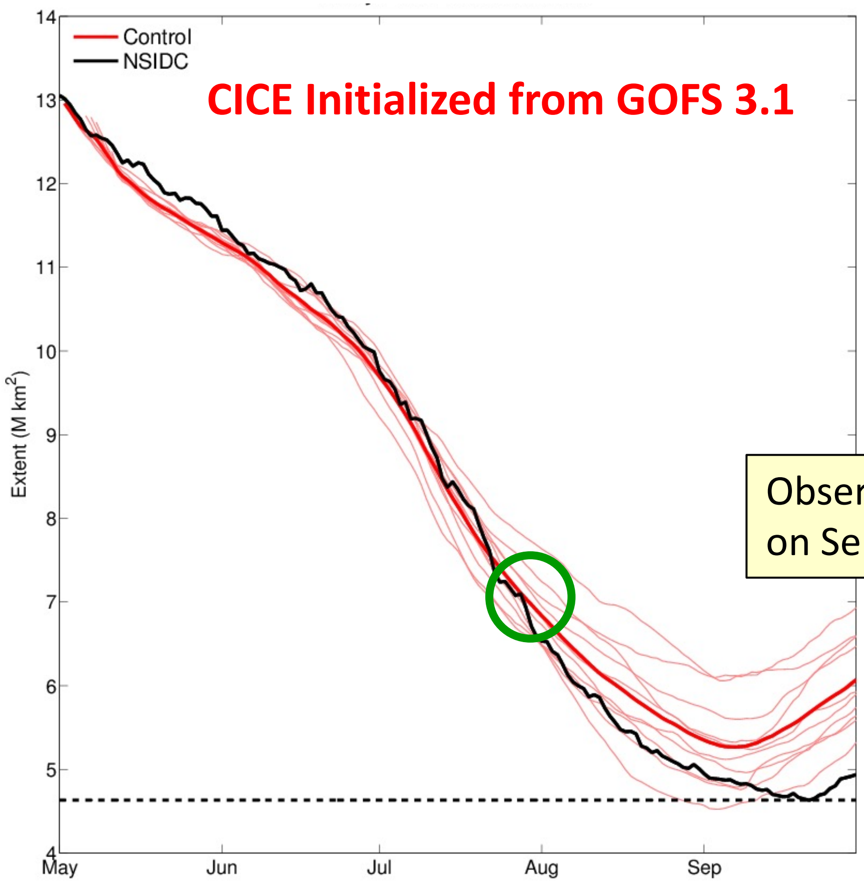


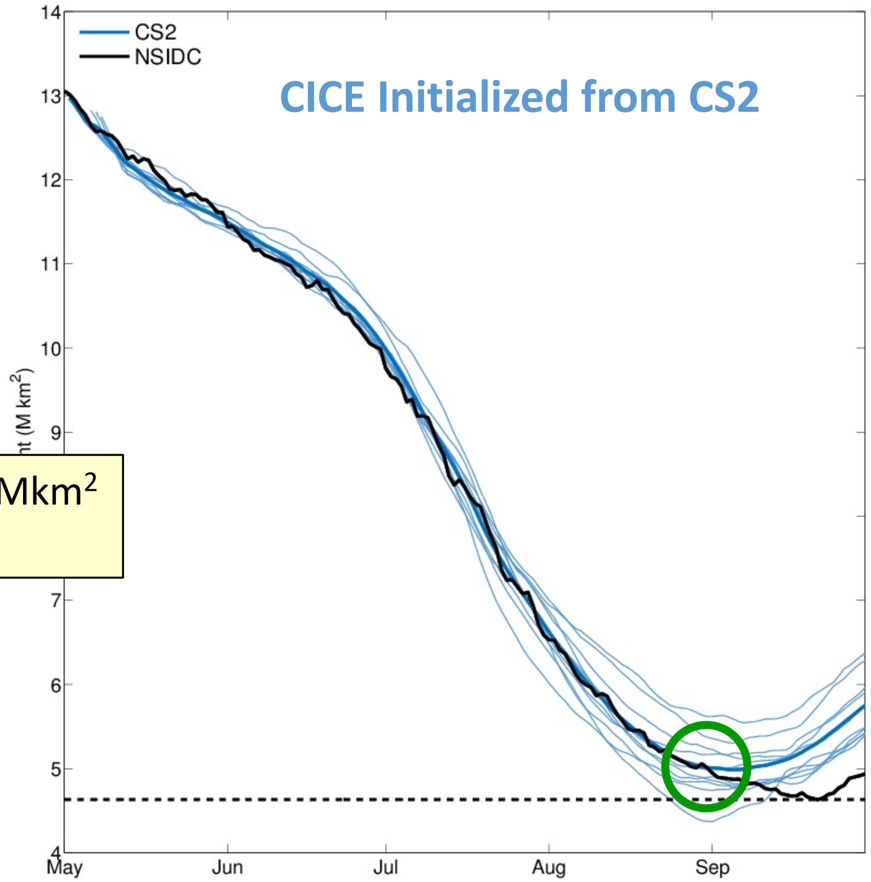
Observed minimum of 4.63 Mkm^2 on September 23



Navy ESPC ensemble mean September 2018 minimum sea ice extent initialized with GOFS 3.1 ice thickness was over-predicted by 0.64 M km^2 (5.27 M km^2) versus the ensemble set of runs initialized with CS2 ice thickness which had an error of 0.36 M km^2 (4.99 M km^2), a 56% reduction in error.

2018 Arctic Sea Ice Extent

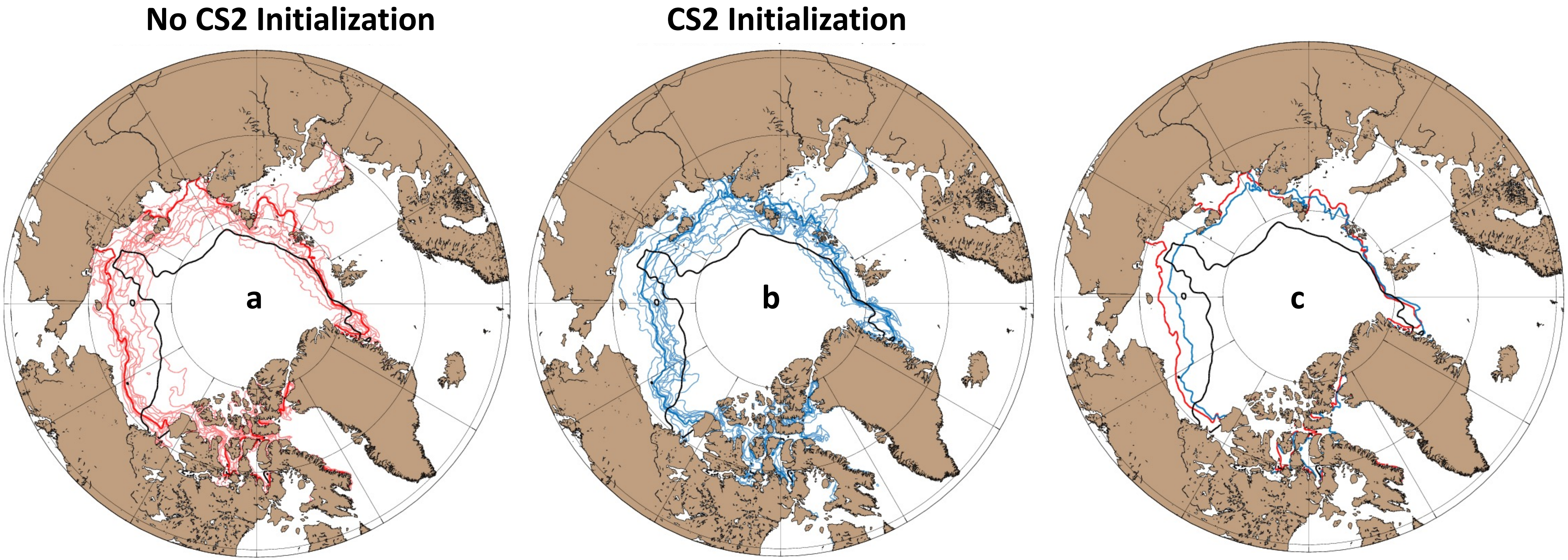




Observed minimum of 4.63 Mkm^2 on September 23

In control forecasts, ensemble mean separates from NSIDC extent on July 29; in CS2 forecasts, separation occurs on Aug 31, **an improvement of 33 days**.

September, 2018 Sea Ice Extent



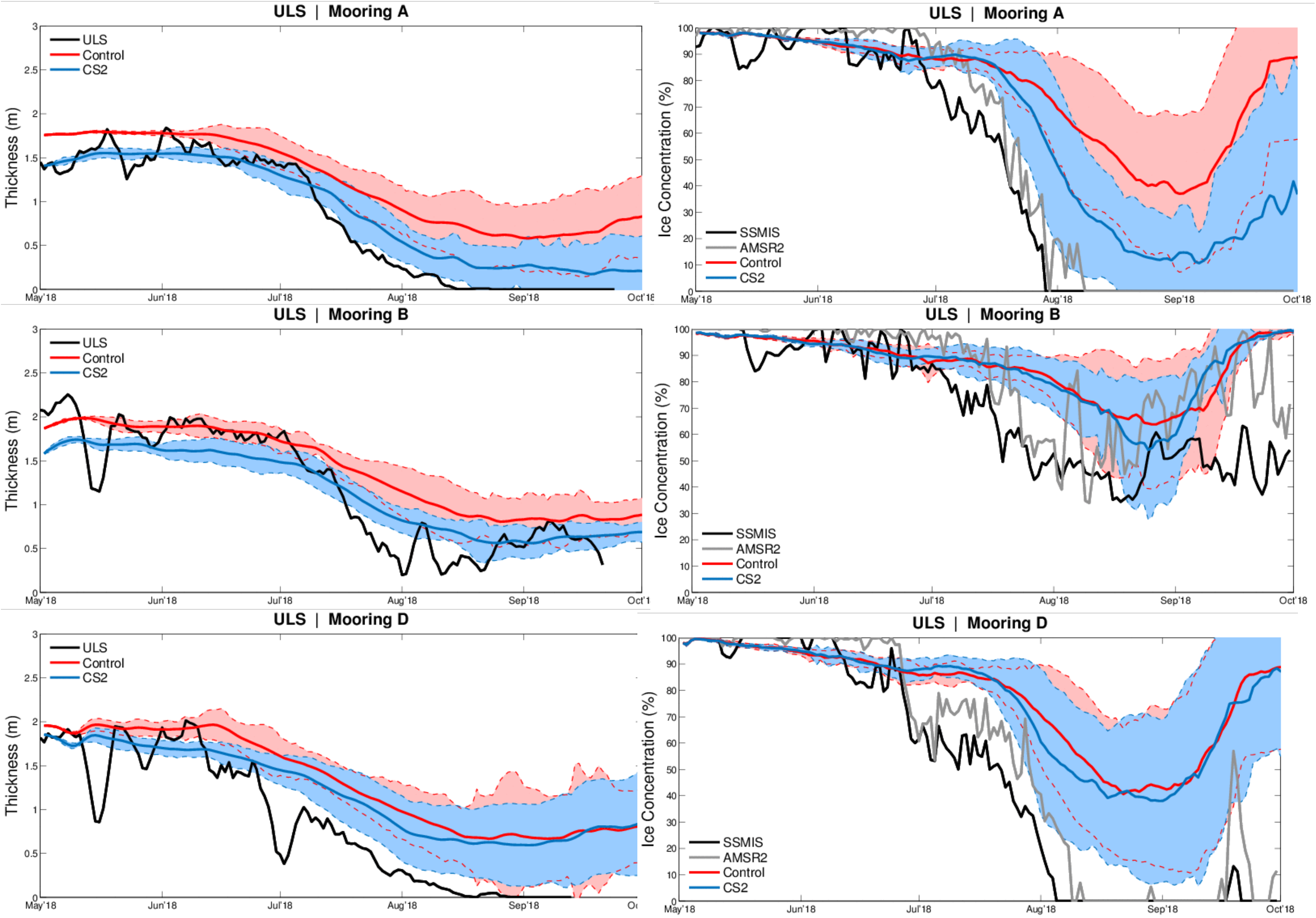
(a) September mean sea ice extent prediction for 10 ensemble members from control run; **dark red line** denotes ensemble mean. (b) Same as (a) but based on CS2 initialization; **dark blue line** represents ensemble mean. (c) Ensemble mean for control (red) and CS2 (blue). **Black lines** denote NSIDC observed mean September extent.

Ensemble mean ice thickness, concentration from models versus observations (black)

Mooring A

Mooring B

Mooring C



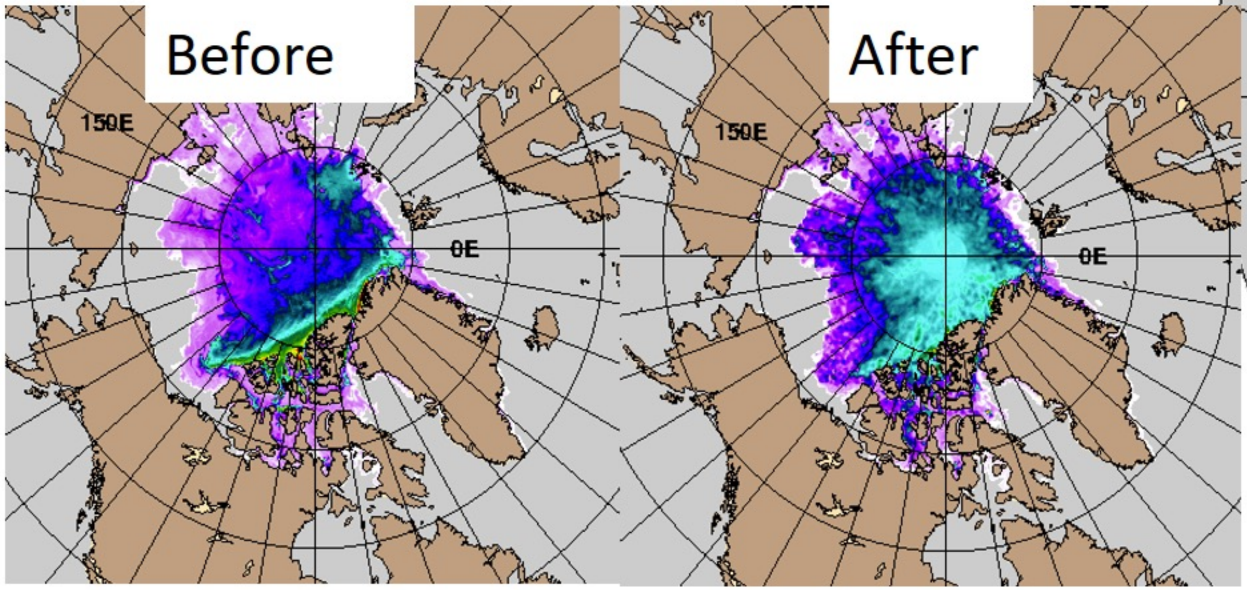
Ice Thickness

Ice Concentration

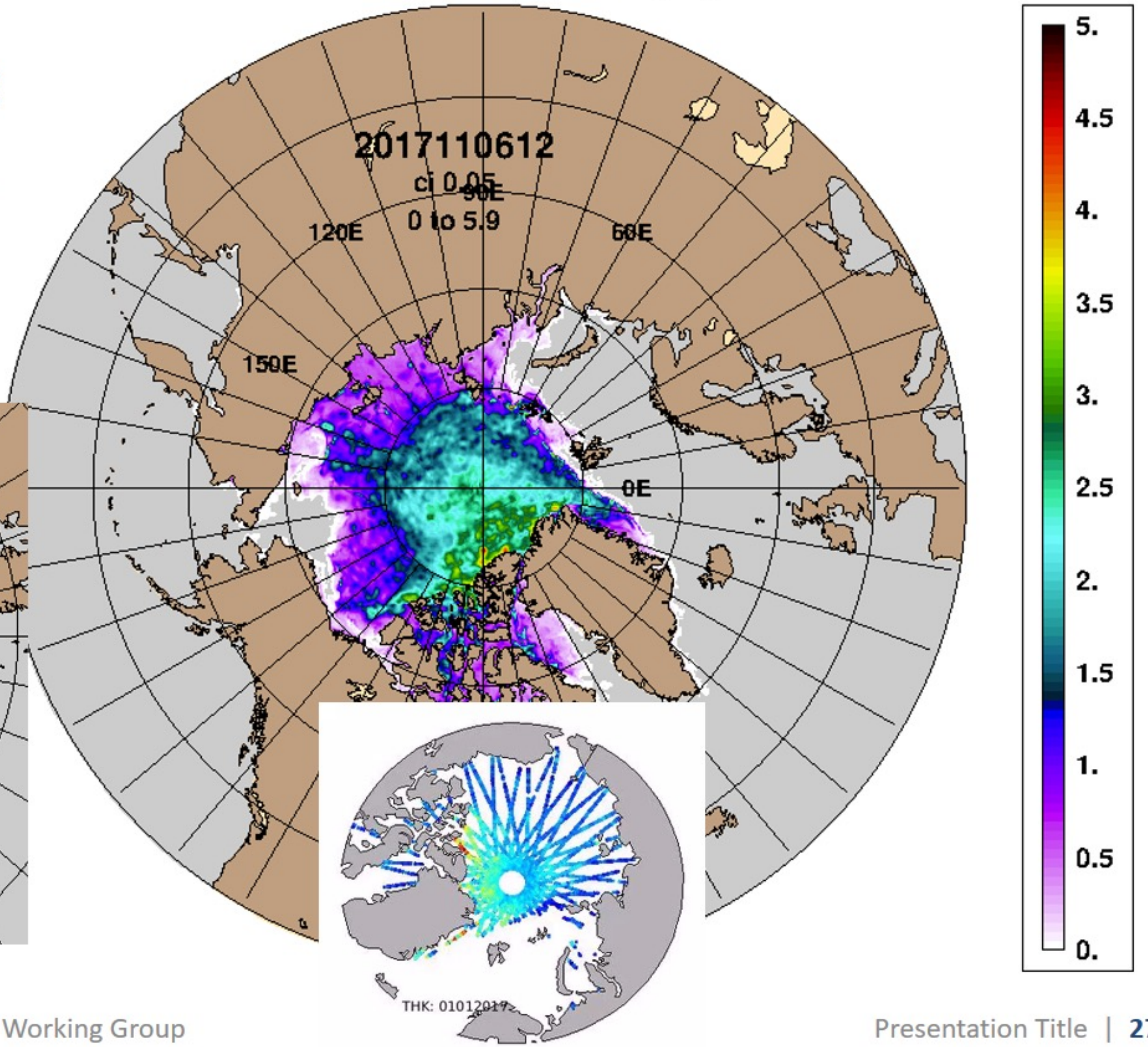
Initialization with CryoSat-2 shows improvement over control run, especially at Mooring A in this 5-month forecast.

Operationally implementing satellite-derived ice products within the Navy's ice forecast systems: Assimilate CryoSat-2 2-day tracks.

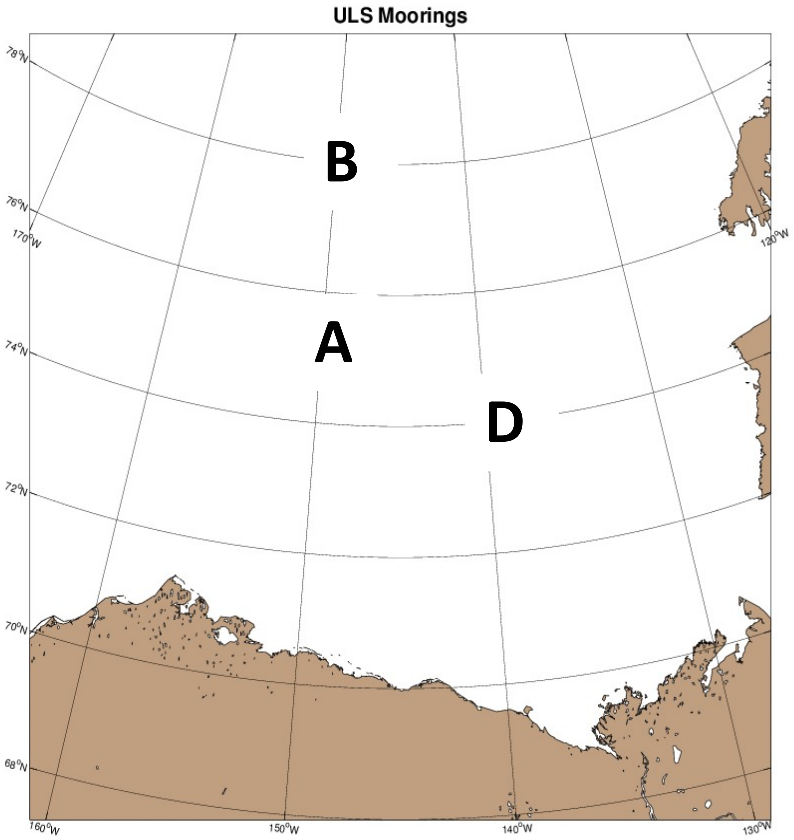
- Ice thickness type added to NCODA.
- Started from GOFS 3.5, but reinitialized with CryoSat-2 2 Day data 15 OCT 2017
  - Reduce large difference when starting to assimilate tracks.
  - Here we assimilate CPOM 2-day along-track data

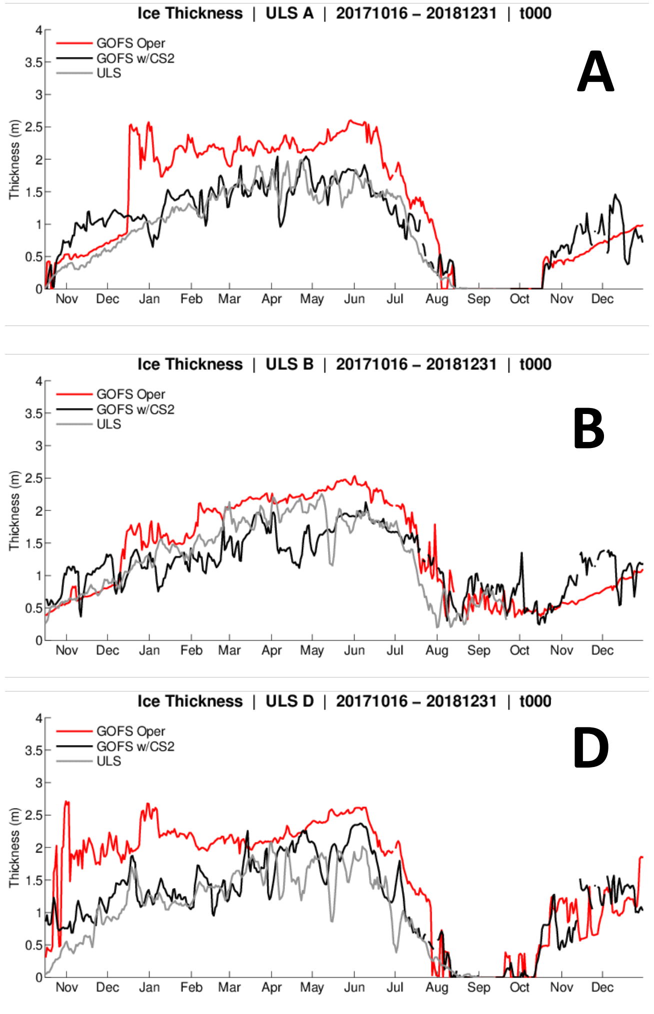


GLBc0.04-30.2 Ice Thickness (m): 20171107



Comparison of GOFS 3.5 Ice thickness versus ULS Mooring Data

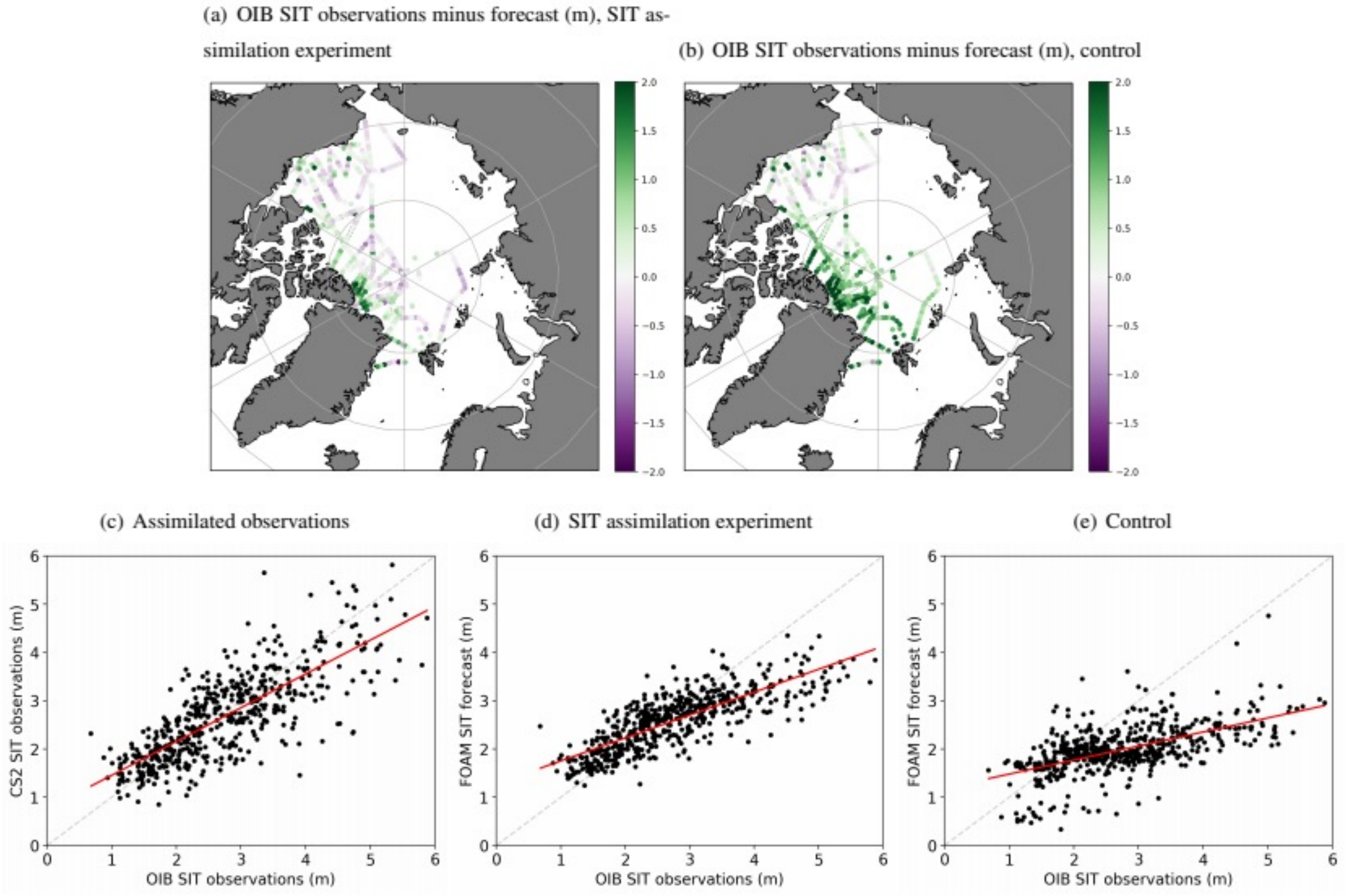




Significant reduction in RMSE and bias when CS2 along-track data (**grey**) is assimilated versus unassimilated GOFS 3.5 (**red**)

Hebert et al., in preparation.

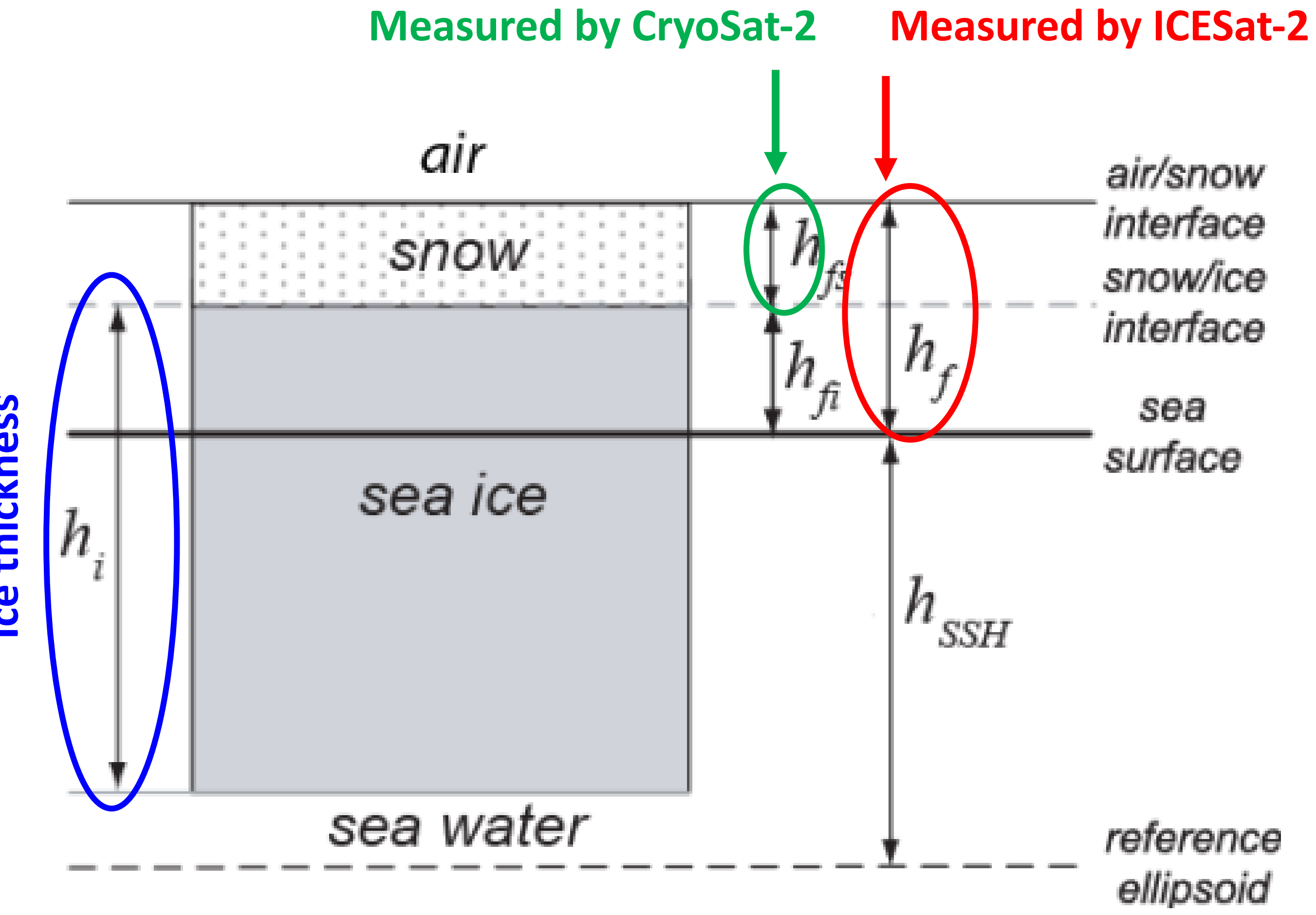
Related Research



Fiedler, E. K., Martin, M., Blockley, E., Mignac, D., Fournier, N., Ridout, A., Shepherd, A., and Tilling, R.: Assimilation of sea ice thickness derived from CryoSat-2 along-track freeboard measurements into the Met Office's Forecast Ocean Assimilation Model (FOAM), The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2021-127, in review, 2021.

CPOM CS2 along-track ice freeboard data is assimilated into FOAM. CS2 freeboard is converted to ice thickness using model's snow depth.

Determining Ice thickness from freeboard (IceSat-2)



Kwok, R., Kacimi, S., Webster, M. A., Kurtz, N. T., & Petty, A. A. (2020). Arctic snow depth and sea ice thickness from ICESat2 an d CryoSat2 freeboards: A first examination. Journal of Geophysical Research: Oceans, 125, e2019JC016008. https://doi.org/10.1029/2019JC016008

$$h_i = \left(\frac{\rho_w}{\rho_w - \rho_i}\right) \boldsymbol{h_f} - \left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i}\right) h_{fs}$$

New research uses both CryoSat-2 and IceSat-2 to determine Arctic snow depth; then that snow depth can be used to produce ice thickness (as opposed to using climatology).

NSIDC should be making IceSat-2 freeboard data (ATL07) with **3-day latency** available soon.

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Summary

- Navy modeling systems have been assimilating ice concentration for many years using SSMIS, AMSR and more recently AMSR2. The addition of VIIRS will complement the existing ice concentration data and should improve our forecast skill.
- Initialization of derived ice thickness from CryoSat-2 has demonstrated improved ice thickness predictions in our coupled HYCOM/CICE and ESPC modeling systems.
- Testing of the assimilation of 2-day along-track CryoSat-2 ice thickness for a 15-month period has shown reduced errors and bias in the system. Recent paper (in review) by UKMO shows improved results when assimilating ice freeboard in their FOAM modeling system.
- Further testing of assimilation of ice thickness/freeboard data in *fully coupled systems* could show improved ice drift predictions.
- NASA's IceSat-2 ice freeboard data should be available through NSIDC with a 3-day latency, paving the way for future gains in forecast skill.