Recent Update of Arctic Research and Products

Jia Wang
NOAA Great Lakes Environmental Research Laboratory (GLERL), Ann Arbor, Michigan; jia.wang@noaa.gov

Ayumi Fujisaki-Manome, Haoguo Hu, Dmitry Beletsky
Cooperative Institute for Great Lakes Research (CIGLR), University of Michigan, Ann Arbor, Michigan

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6. Summary and future efforts

1. Interannual and decadal variability in Arctic summer sea ice, 1850-2017

- Arctic amplification,
- teleconnections, and
- ice/ocean albedo feedback loop➔accelerating melting

Cai, Q., J. Wang, D. Beletsky, J.E. Overland, M. Ikeda, L. Wan, 2021, Accelerated Decline of Summer Arctic Sea Ice during 1850-2017 and the amplified Arctic warming during the recent decades, *Environ. Res. Lett.,* **16** (2021) 034015.

Cai, Q., D. Beletsky, J. Wang, and R. Lei, 2021. Interannual and decadal variability of Arctic summer sea ice associated with atmospheric teleconnection patterns during 1850-2017. *J. Climate,* DOI: https://doi.org/10.1175/JCLI-D-20-0330.1

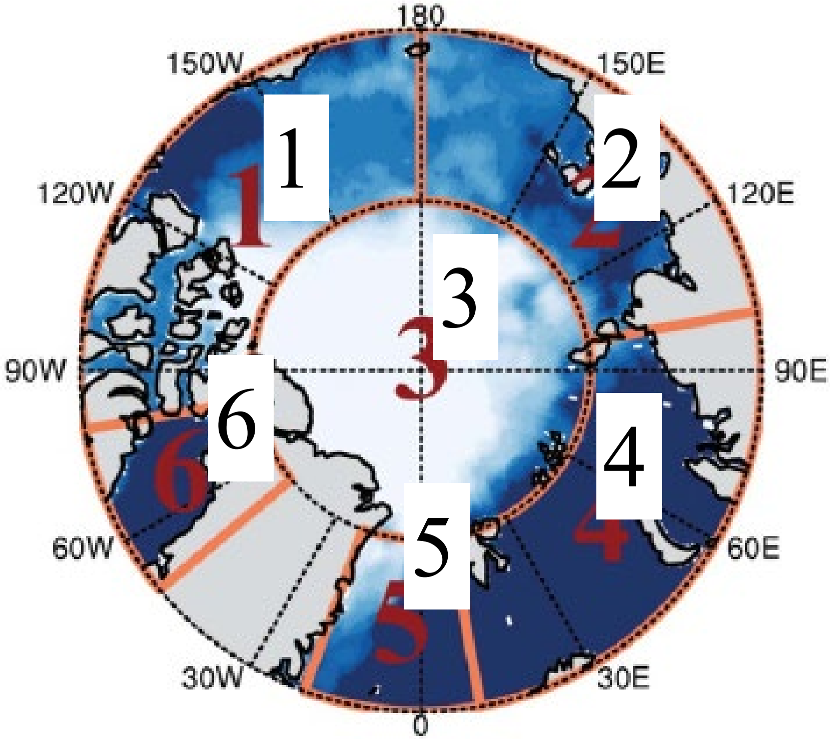
Lin, Y-C, A. Fujisaki-Manome, and J. Wang, 2022. Recently Amplified Interannual Variability of Great Lakes Ice Cover and its Connection to Sea Ice over the Bering and Chukchi Seas, *J. Climate*, 35, 2683-2700, DOI: 10.1175/JCLI-D-21-0448.1

Arctic Regions

7 Regions were considered

1. Chukchi/Beaufort/Canadian Archipelago
2. Laptev and Eastern Siberian Seas
3. Central Arctic
4. Barents and Kara Seas
5. Greenland Sea
6. Baffin Bay

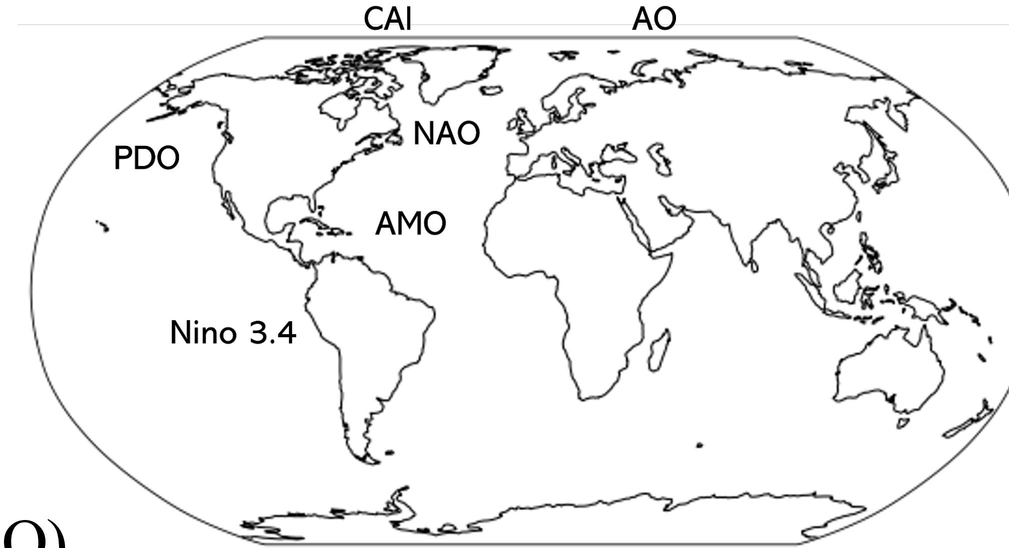
7. Whole Arctic (=1+2+3+4+5+6)



* Some regions are shortened for brevity

Image Courtesy of Q Cai et al (2021)

Teleconnection Patterns



Interannual Scale:

- Arctic Oscillation (AO)
- Arctic Dipole Anomaly (DA)
    - Referred to as Central Arctic Index (CAI)
- North Atlantic Oscillation (NAO)
- El Niño–Southern Oscillation (ENSO)
    - Used Nino 3.4

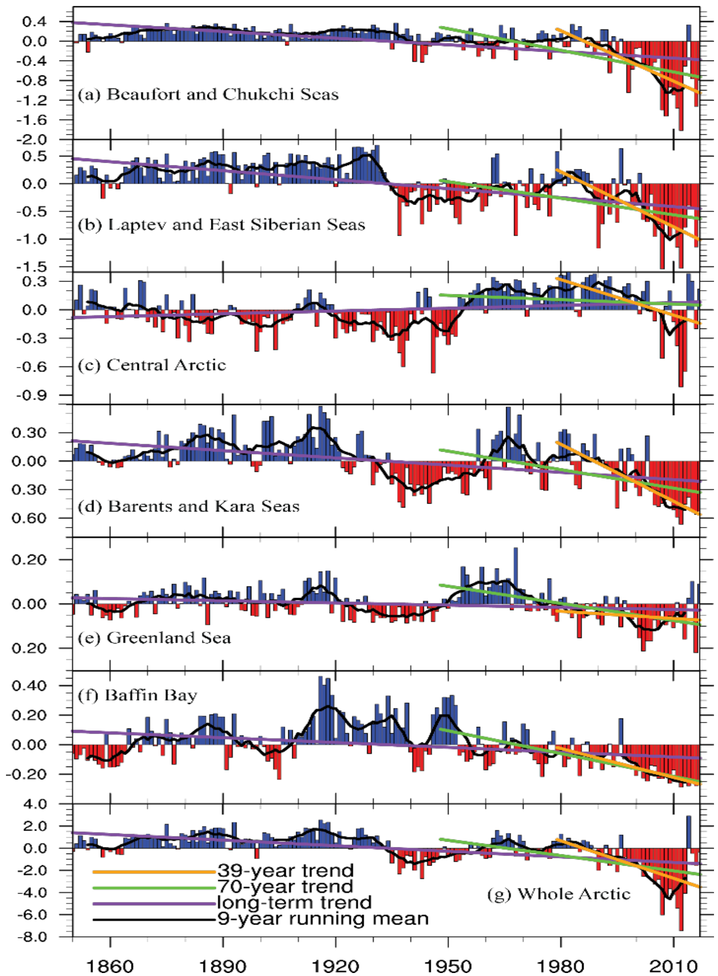
Decadal Scale:

- Atlantic Multidecadal Oscillation (AMO)
- Pacific Decadal Oscillation (PDO)

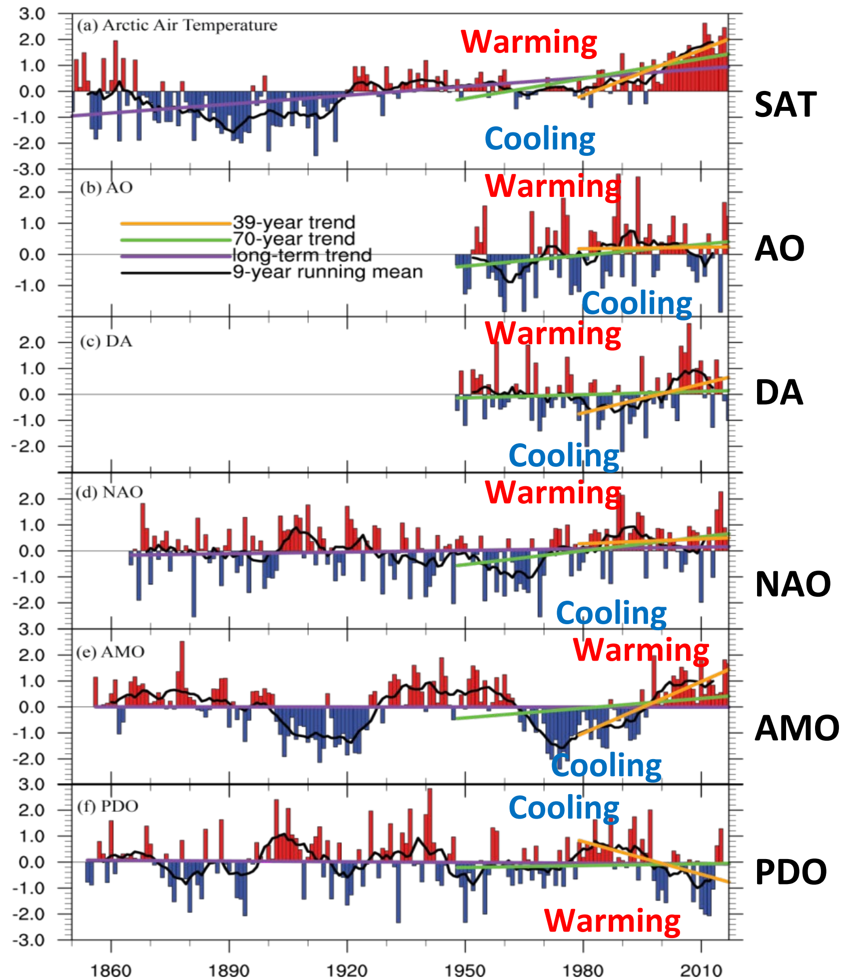
Image based on figure from Wang (2021)

Accelerated Summer Arctic Sea Ice Decline during 1850-2017 due to positive ice/ocean albedo feedback exerted by the amplified Arctic warming driven simultaneously by both global warming and the warming caused by teleconnection patterns during the recent decades (Cai et al. 2021a, ERL, 2021b, JC)

Sea ice areas anomalies



SAT &Teleconnection Anomalies

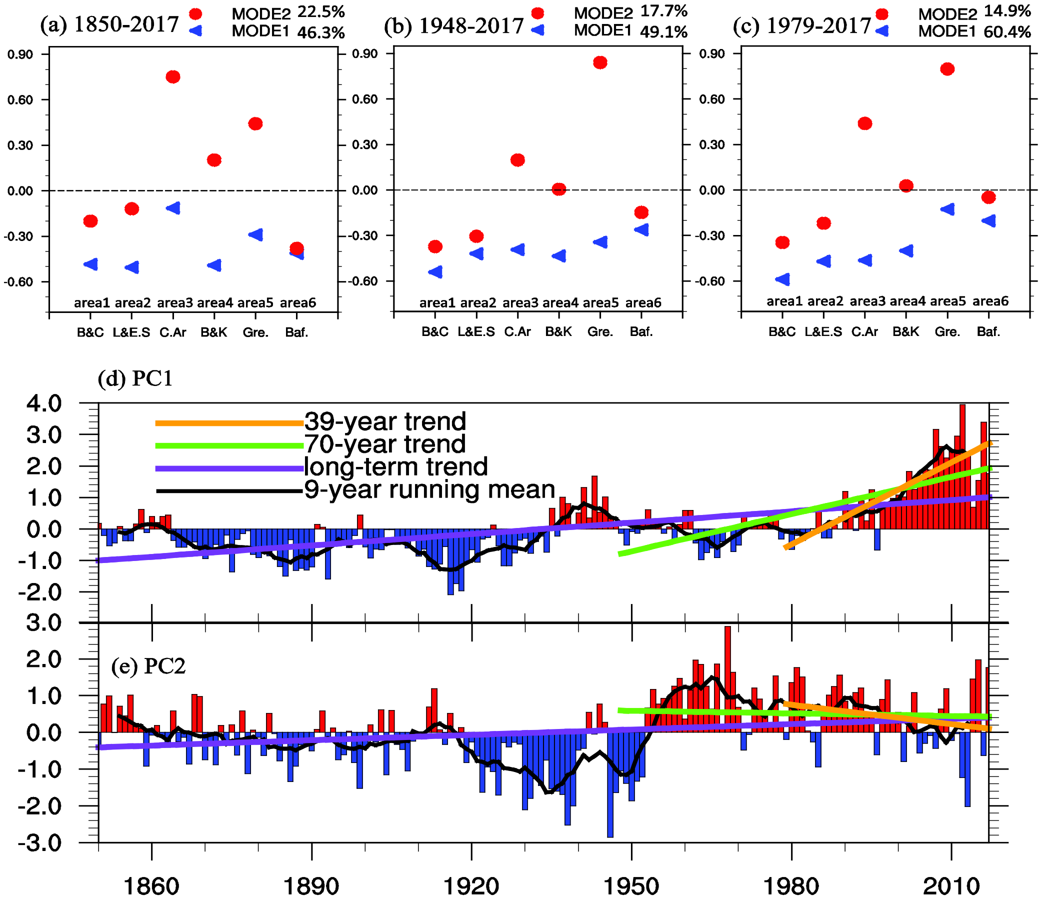


1850-2017

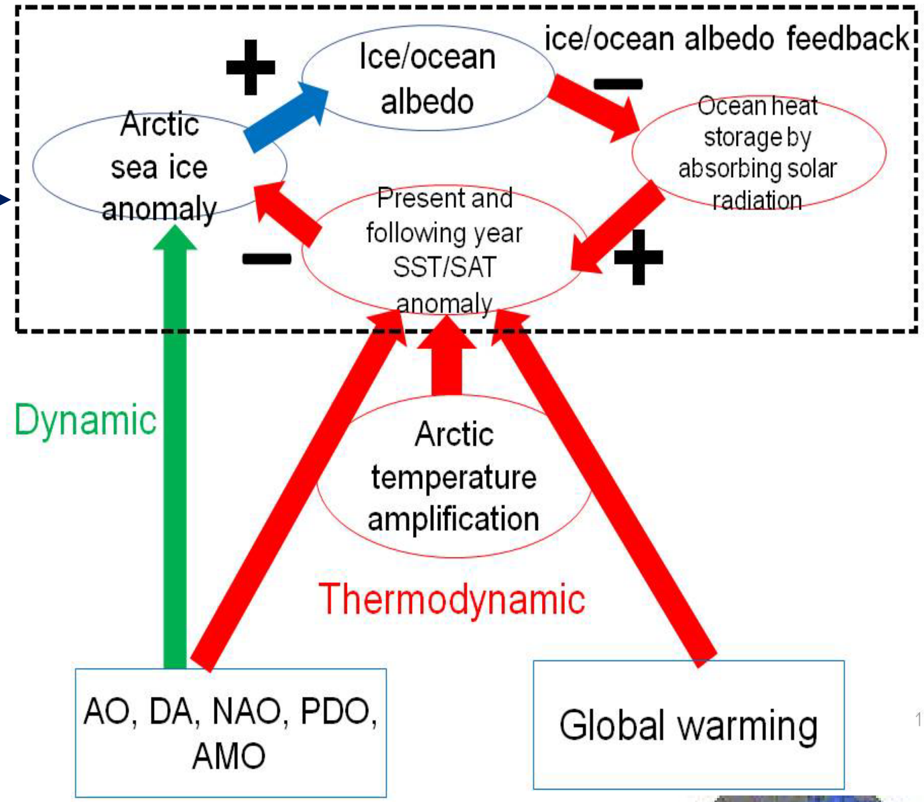
Principal Component (CP)/EOF Analysis of Sea Ice:

PC1: In-phase sea ice oscillation (up and down)➔Thermodynamics

PC2: Out-of-phase oscillation between Pacific and Atlantic Arctic➔Dynamics

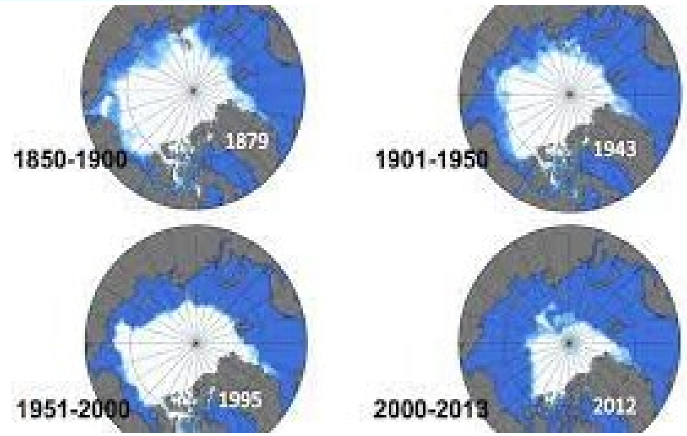


Ice/ocean albedo feedback loop



Thermodynamic (CP1): Global warming and telecon. warming ➔ Arctic amplification ➔**+ice/ocean ice albedo feedback** ➔ accelerating ice decline

Dynamic (CP2): DA, AMO➔ Meridional winds➔advect sea ice from Pacific Arctic (decrease) to Atlantic Arctic (increase)



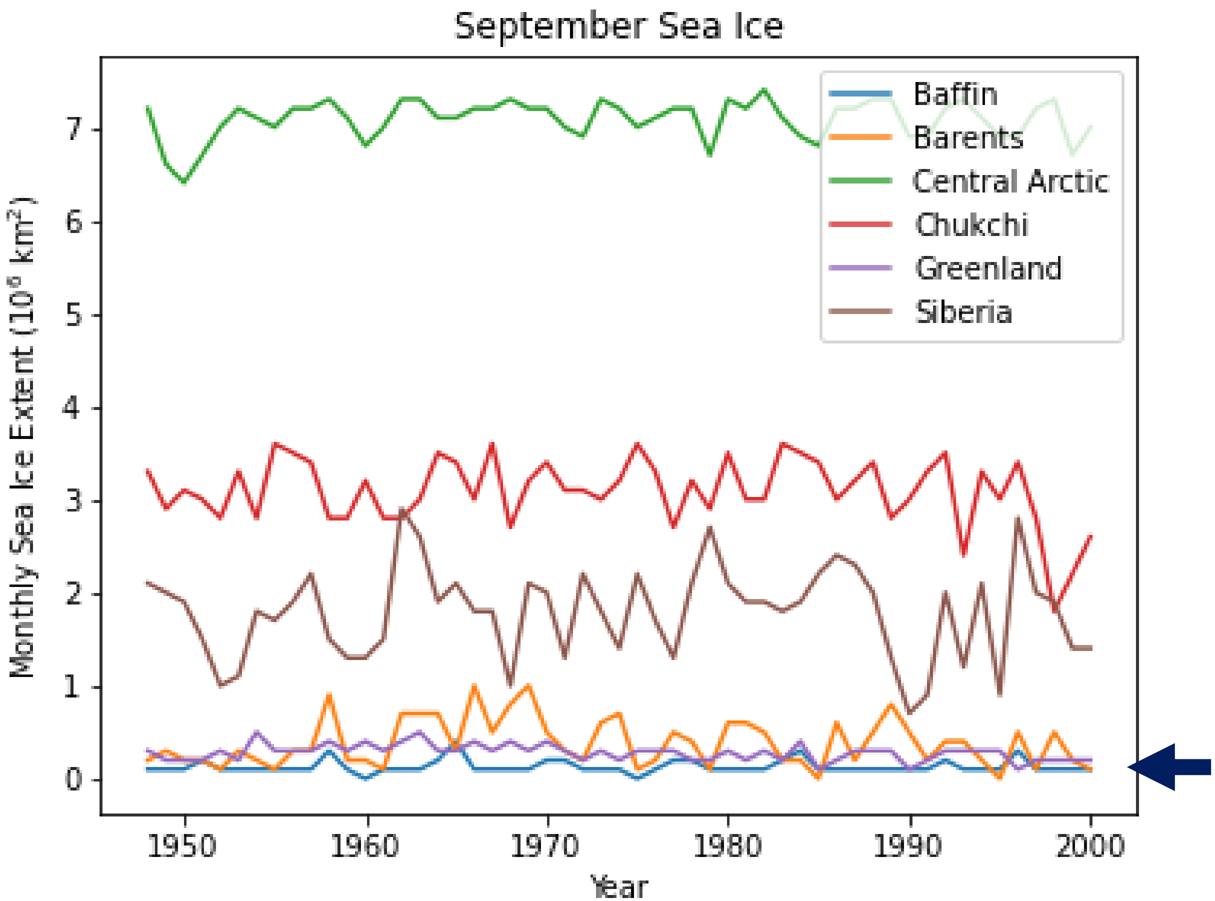
2. Hindcast of Arctic summer sea ice using regression models (potential for seasonal forecast)

Objectives

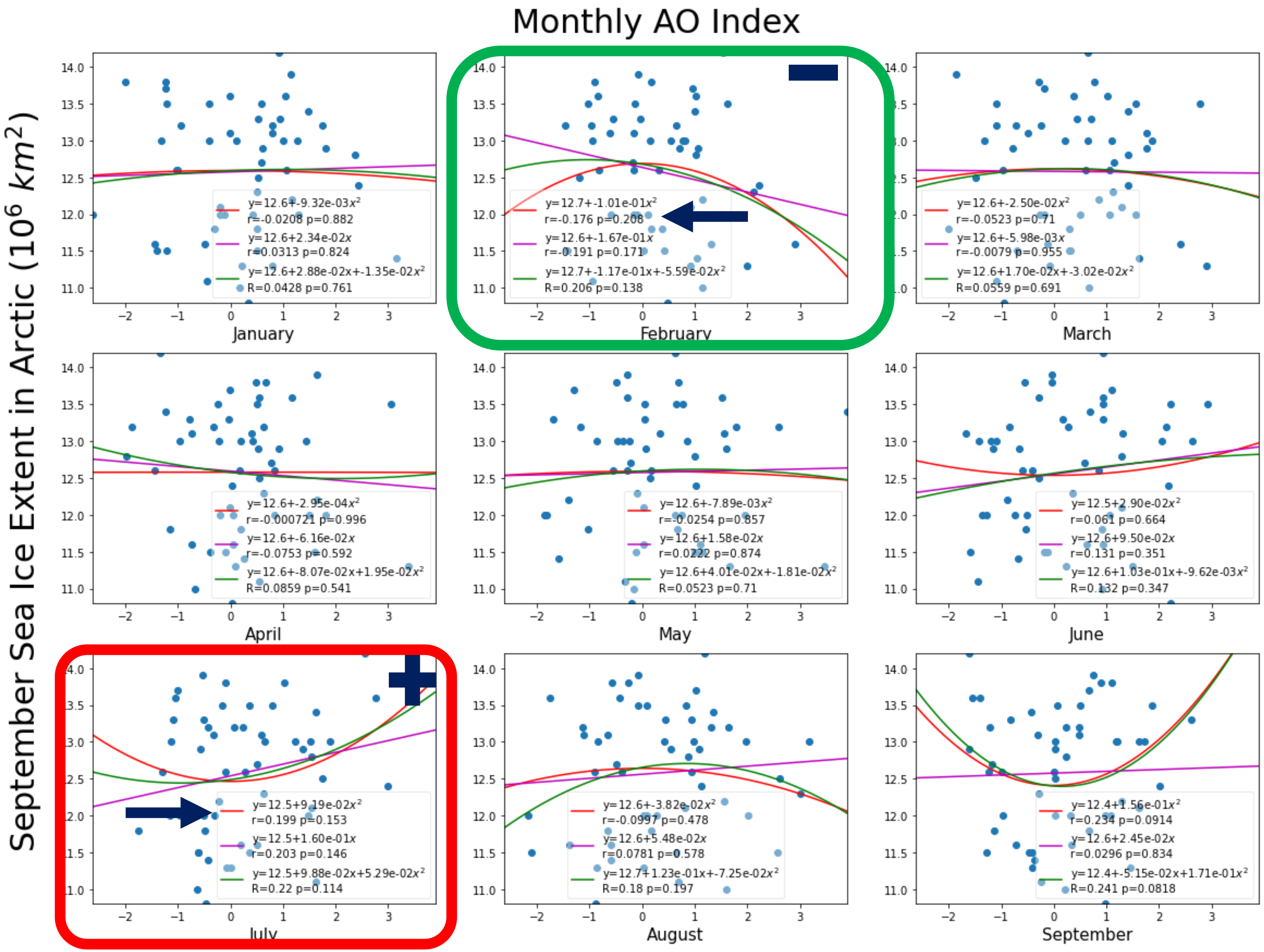
- Using monthly teleconnection pattern indices
- Hindcasting September Arctic sea ice extent using regression models
- Projecting Sep. minimum sea ice using teleconnection pattern indices observed before Sep.

Arctic Regions

- Greenland and Baffin were removed
  - Due to insufficient September sea ice quantities and variability
- Barents September sea ice was low but had sufficient variability



Methods: Step 1



Methods: Step 2

				r	p
Arctic	February	AO	Quadratic	-0.176	0.208
	February	AO	Linear	-0.191	0.171
	January	CAI	Linear	0.207	0.136
	May	NAO	Quadratic	0.136	0.332
	May	NAO	Linear	0.273	0.0481
	March	NINO 3.4	Linear	0.125	0.372
	August	AMO	Quadratic	-0.203	0.145
	August	AMO	Linear	-0.436	0.00111
	April	PDO	Quadratic	0.221	0.112
	April	PDO	Linear	0.164	0.241

Considerations:

- Significance
- Positive vs Negative
- Closer to September
- Skills for projection

Conception Model for All Regions

Methods: Step 3

September sea ice =	interannual (teleconnection forcing)	(1)
	+ interannual interactions	(2)
	+ decadal (teleconnection forcing)	(3)
	+ decadal-interannual interactions	(4)
	+ decadal interactions	(5)

Interannual teleconnections: AO, DA/CAI, Nino3.4, NAO

Decadal teleconnections: AMO, PDO

Arctic Example: Regression Model

Methods: Step 4

$$y = 12.521 - 0.401(AO_2) + 0.055(AO_2^2) + 0.234(CAI_1) + 0.104(NAO_5) \\ -0.006(NAO_5^2) + 0.079(NINO_3) \quad (1)$$

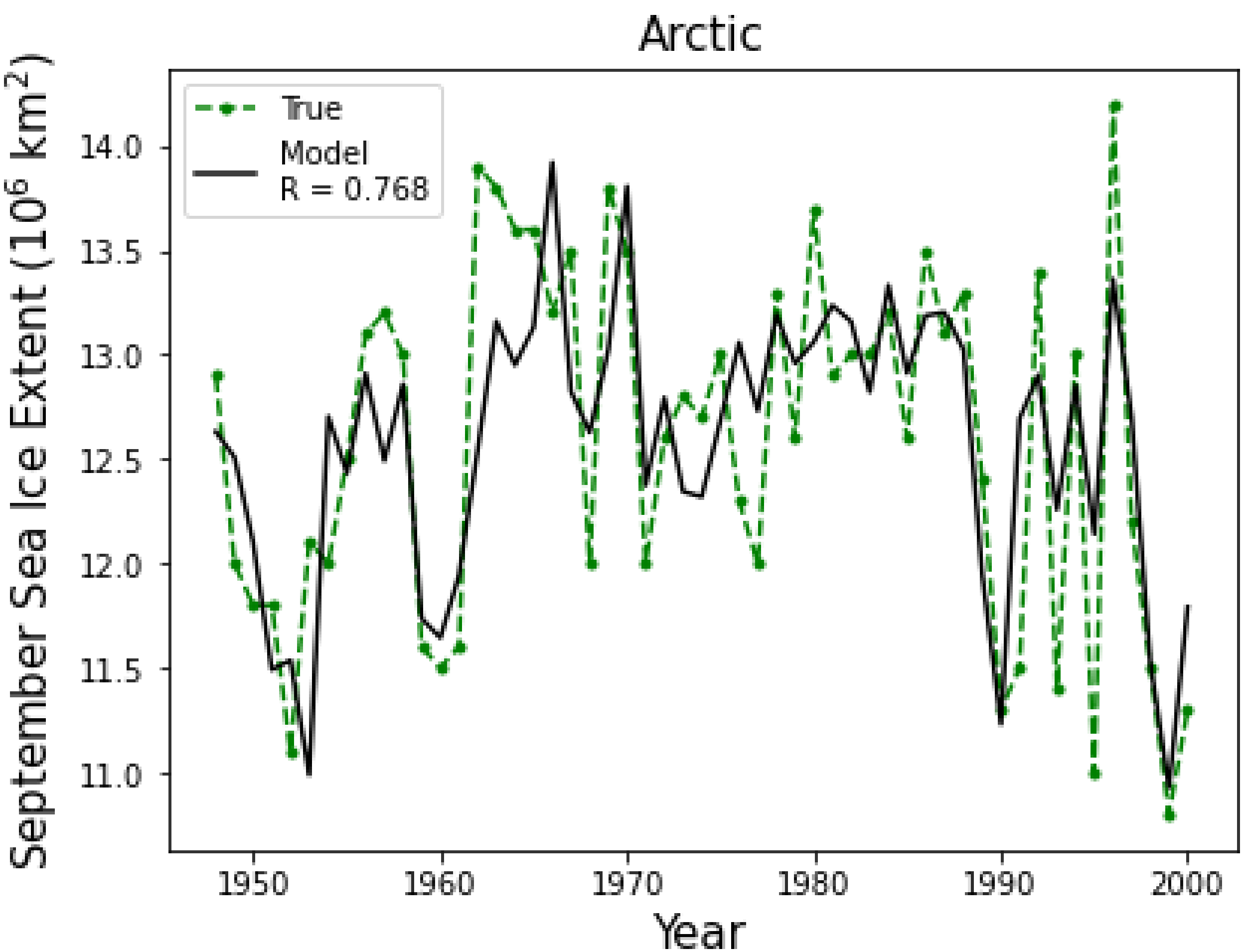
$$-0.040(AO_2 * CAI_1) - 0.104(NINO_3 * AO_2) \\ -0.032(NINO_3 * CAI_1) - 0.050(NAO_5 * AO_2) \\ -0.044(NAO_5 * CAI_1) \quad (2)$$

$$-2.934(AMO_8) - 3.349(AMO_8^2) + 0.141(PDO_4) + 0.100(PDO_4^2) \quad (3)$$

$$-0.240(AMO_8 * AO_2) + 0.209(AMO_8 * CAI_1) \\ -0.506(AMO_8 * NAO_5) + 0.299(PDO_4^2 * AO_2) \\ -0.048(PDO_4^2 * CAI_1) - 0.032(PDO_4^2 * NINO_3) \quad (4)$$

$$+1.305(PDO_4^2 * AMO_8) \quad (5)$$

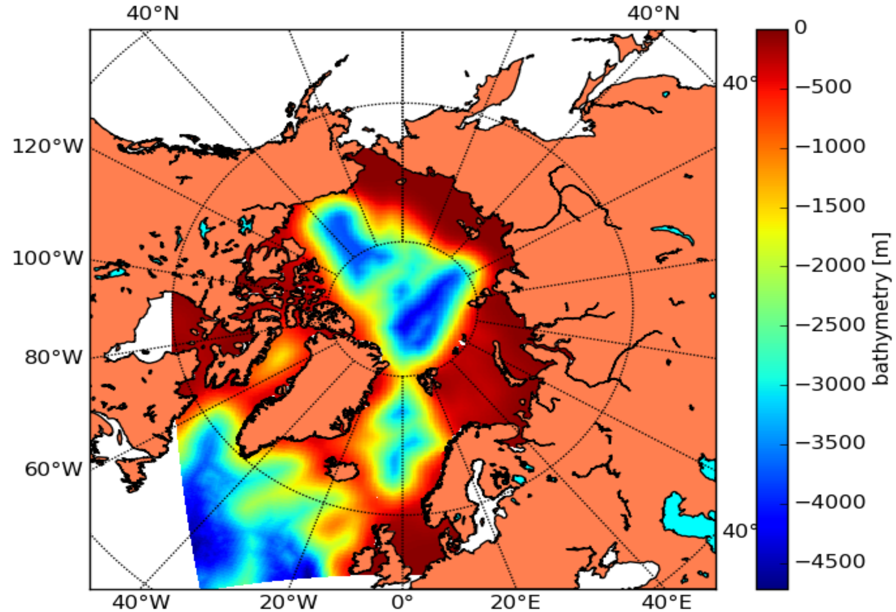
Results: Model vs Observation



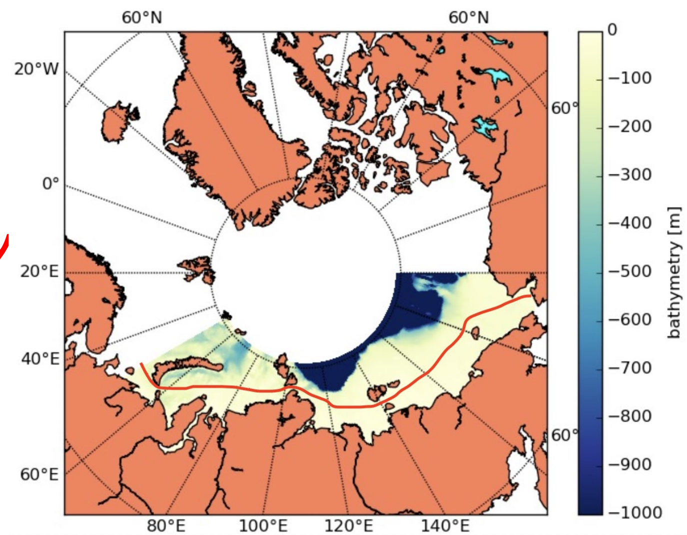
Region	R
Chukchi	0.78
Siberia	0.71
Central Arctic	0.76
Barents	0.62
Arctic	0.77

3) GLERL-CIGLR Arctic-Sea Routes Nowcast/Forecast System (GCAS) (5-day prediction)

- **5-day forecast for sea ice and ocean conditions**
- **Based on ICEPOM (parallelized version of Princeton Ocean Model coupled with an ice model)**
- **Higher-resolution model covering the Northern Sea Route is being developed. A real-time version is anticipated to become on live in June 2021.**

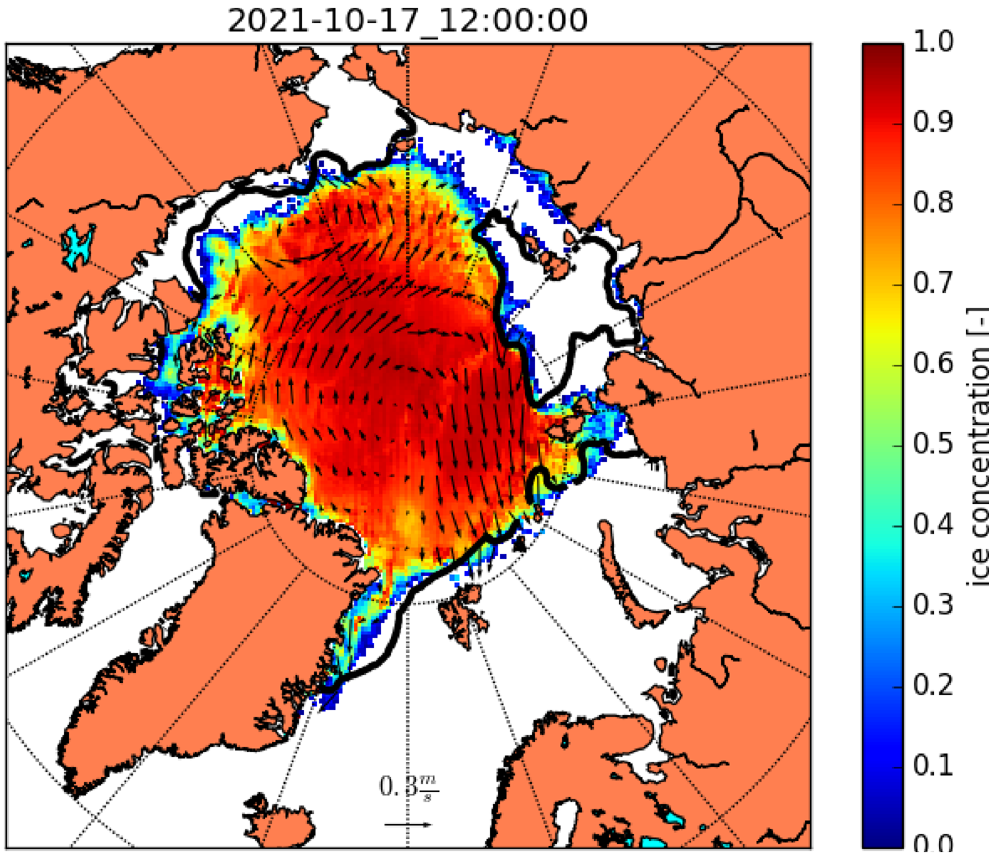


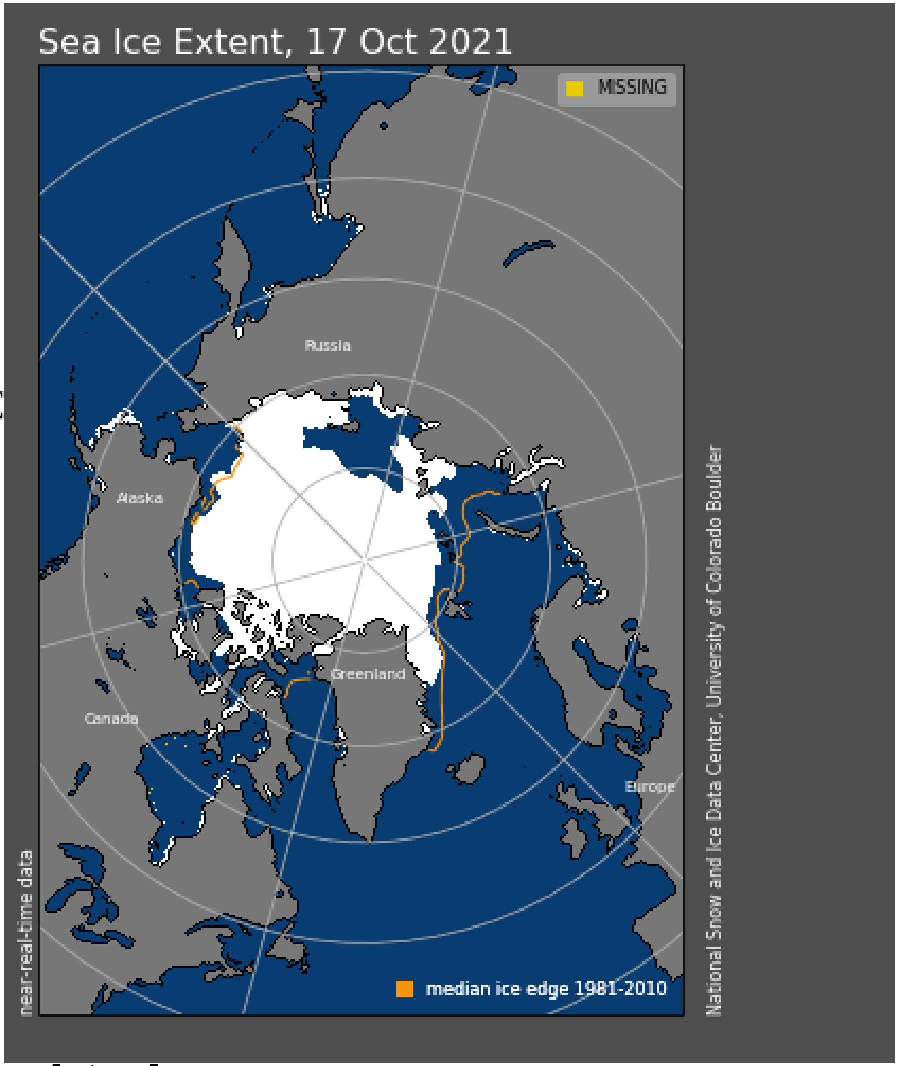
Nested domain (shaded by bathymetry) with the Northeast Passage (red line)



- Primitive equations (POM-based)
- Fully parallelized
- Ice dynamics with EVP rheology
- 0-layer ice thermodynamics with snow cover
- 25 km grids
- Climate Forecast Reanalysis (CFSR)
- 13 major river inputs from the discharge data of the Arctic Ocean Model Inter-comparison Project.

GCAS 25-km model's5-day prediction (Oct12-17, 2021)





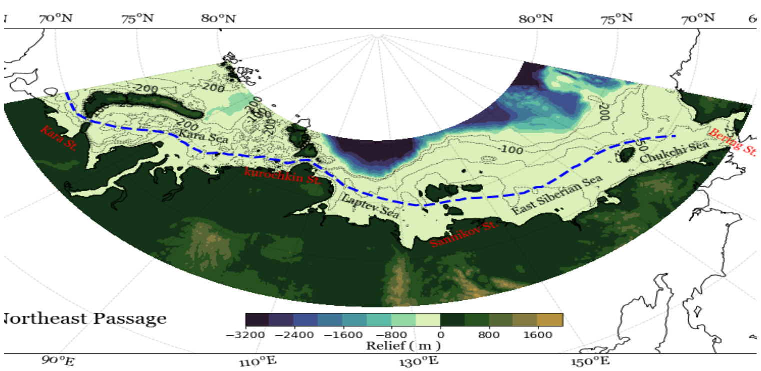
http://ww2/res/arctic_forecast/gcas/index.html

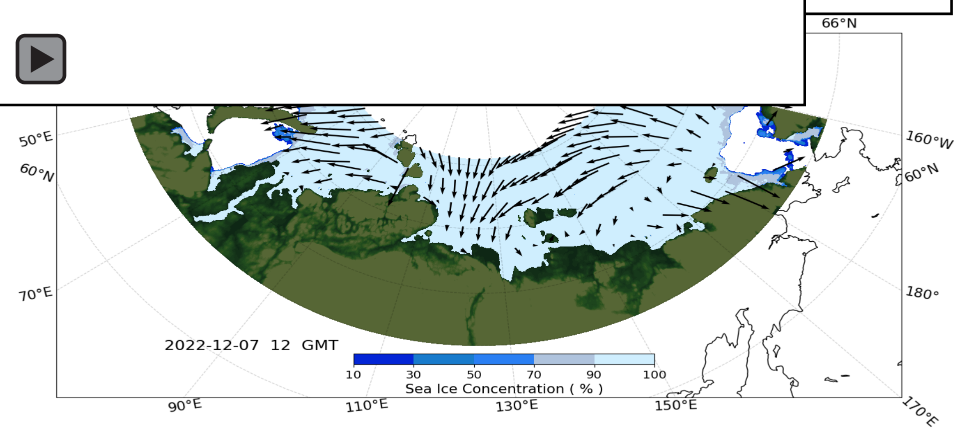
GLERL's GCAS 4-km model's 5-day (Dec 3-7, 2022) prediction:

ice concentration and temperature (animation)

ice thickness and salinity (animation)

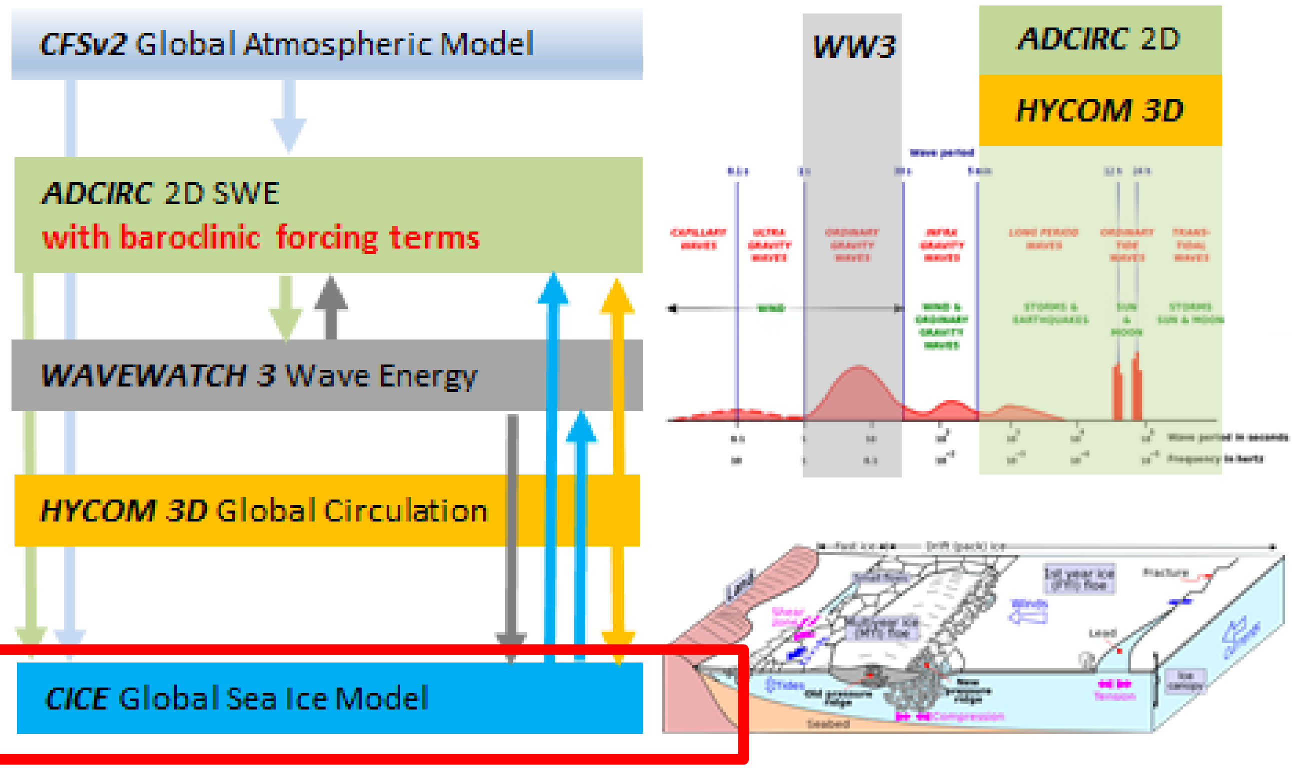
along Northeast Passage





4. ALaska Coastal Ocean Forecast System (ALCOFS) (PI: Johannes Westerink (Notre Dame)

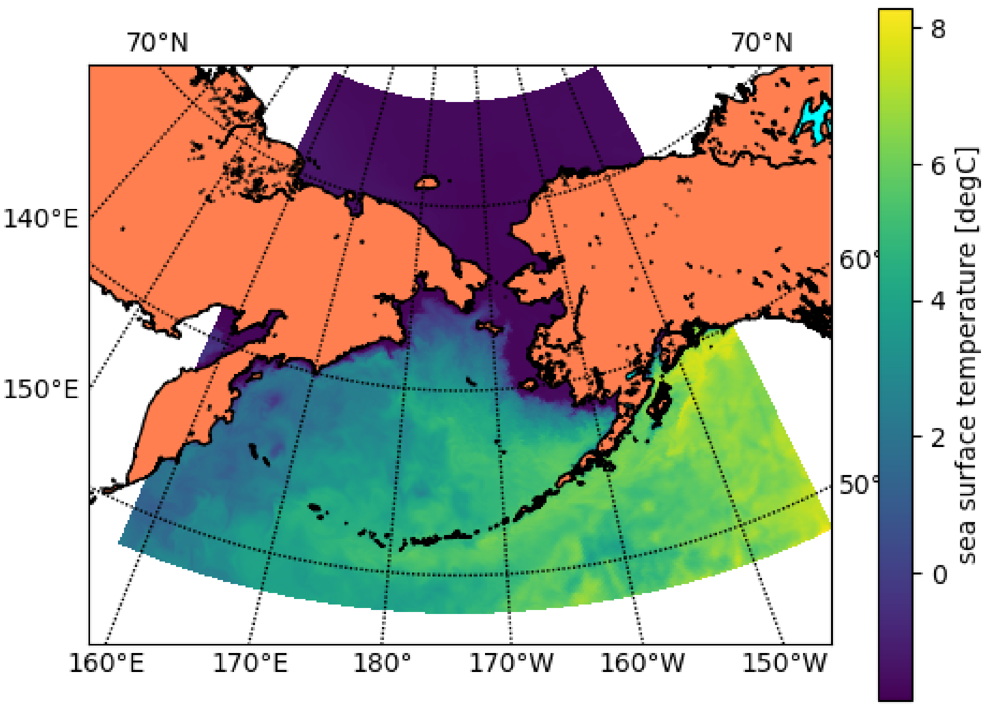
Alaska ADCIRC+WW3+HYCOM+CICE model



Our part

Coupling is conducted through the NOAA Environmental Modeling System (NEMS) and the Earth System Modeling Framework (ESMF)

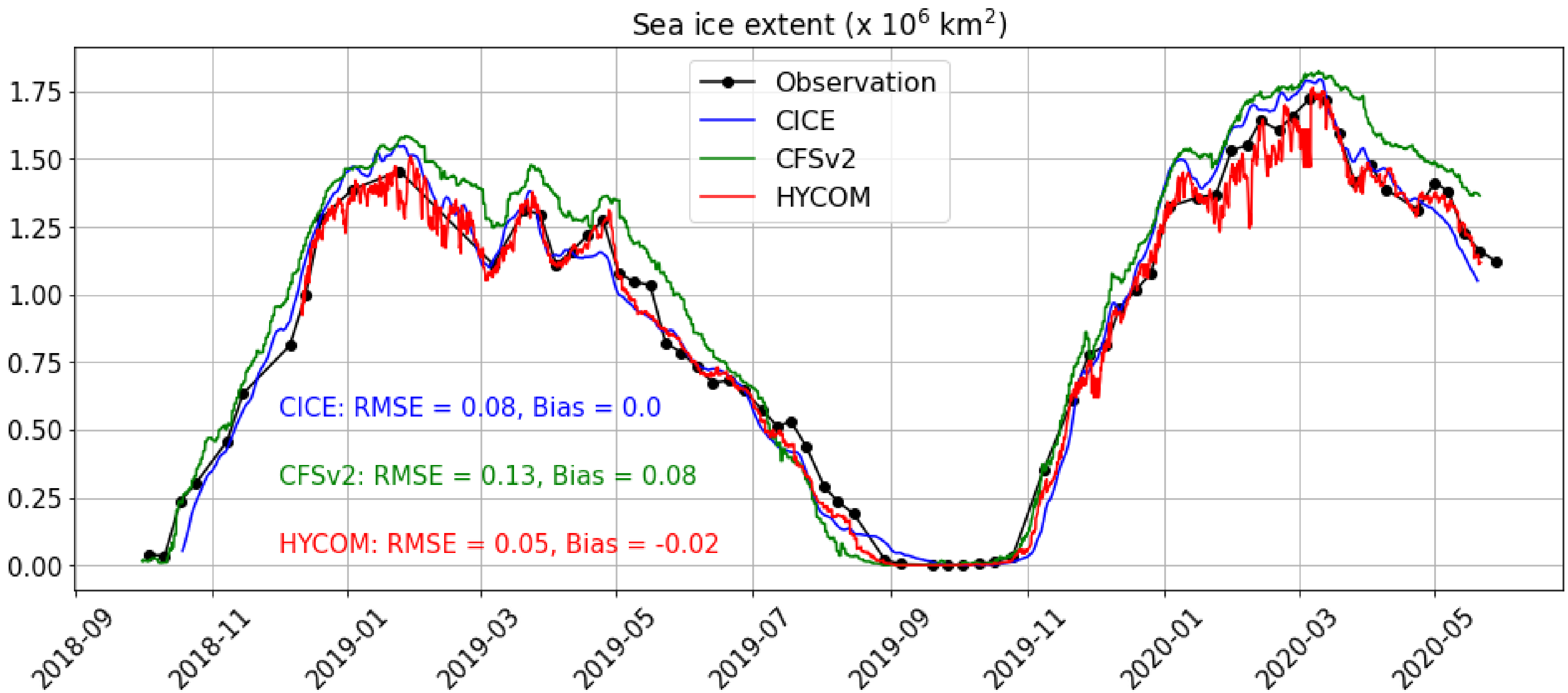
CICE standalone, regional configuration



Covered domain. Color contour is sea surface temperature from GOFS3.1 interpolated to the ice model grid.

- CICE Version 6
- Horizontal resolution 3 km
- Elastic-Viscous-Plastic rheology
- CFSv2 atmospheric forcing
- GOFS3.1 (HYCOM) ocean forcing (T, S, U, V)
- Slab ocean mixed layer model. Restored to GOFS's SST on 3 day time scale.
- Snow accumulation based on precipitation rate from CFSv2
- Continuous B.C. along the northern boundary.
- January – December 2011, October 2017- September 2019

Hindcast skill assessment, sea ice extent



5. Coupled FVCOM_ice_wave model

Ice cover dampen waves (done, Bai et al. 2020, ODyn). Waves break ice and generate mixing to the upper ocean (on-going)

6. Summary and Future Efforts

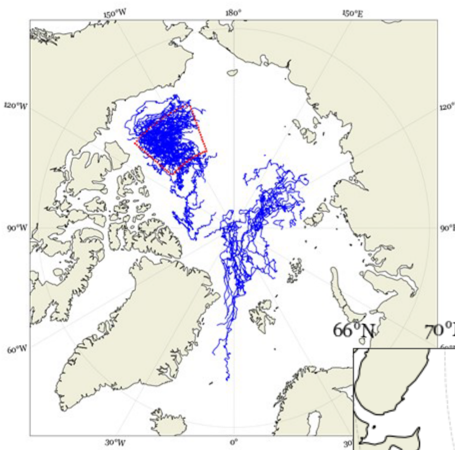
- Investigated sea ice variability on seasonal, interannual and decadal time scales
- Developed regression models for projecting seasonal summer/September sea ice using teleconnections (indices) only
- Developing GLERL-CIGLR Arctic sea route nowcast/forecast System (GCAS) (5-day forecast), publicized in FY23
- Implemented newest version, CICE6, for ALaska Coastal Ocean Forecast System (ALCOFS), led by U. Notre Dame, transitioned to NCEP
- Developing coupled FVCOM_ice_wave model:
  - Landfast ice module
  - Ice-wave feedback/interaction parameterization (module): ice dampens waves (done), waves break ice to smaller pieces (on going)
  - Wave mixing parameterization to the water column with no ice cover (module)

IcePOM simulates ice trajectories

Selected domain from the model

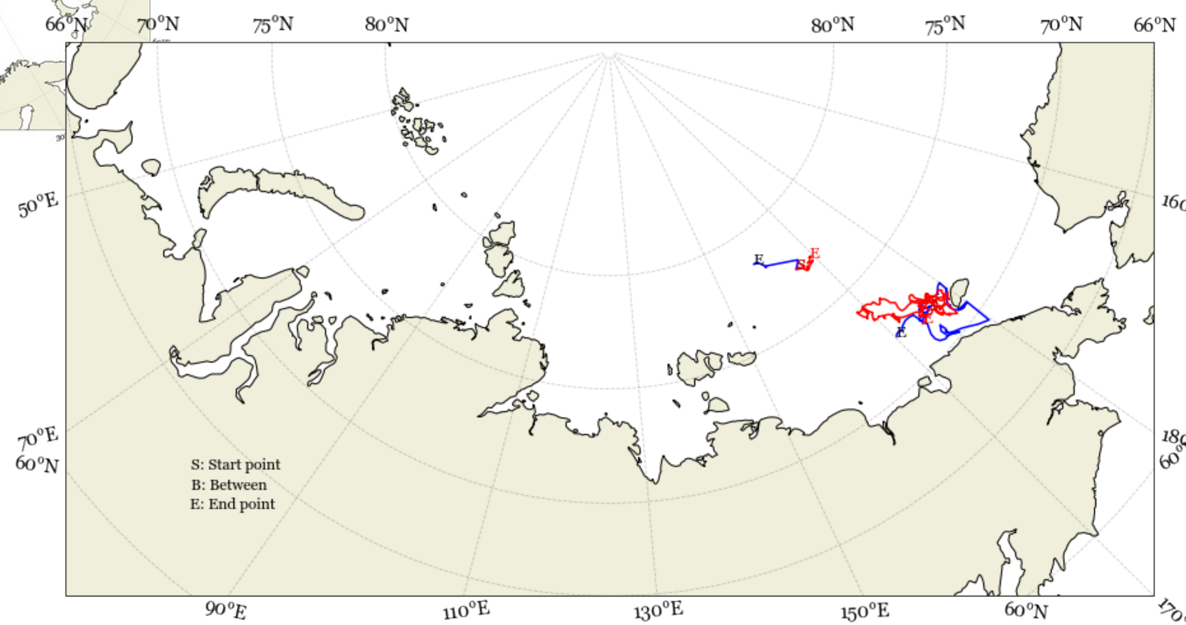
74 – 80 °N, 130-160 °W

from 2005 to 2017



Arctic buoys distribution. No buoys were found in the Northeast Passage region

Comparison between model and ITP buoys



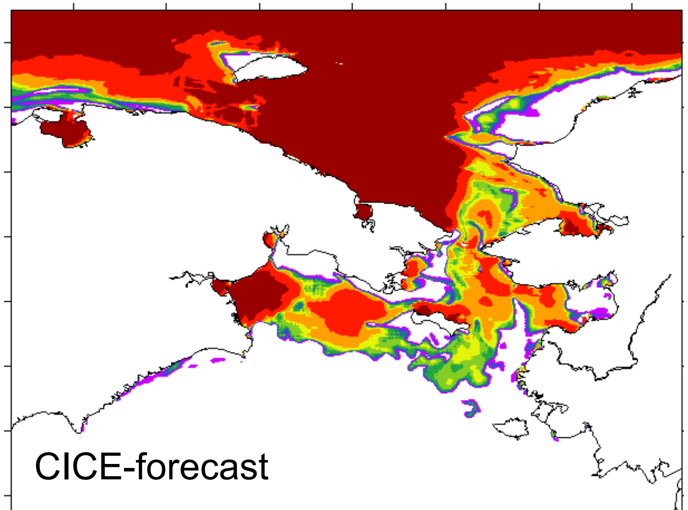
Numerical Experiments

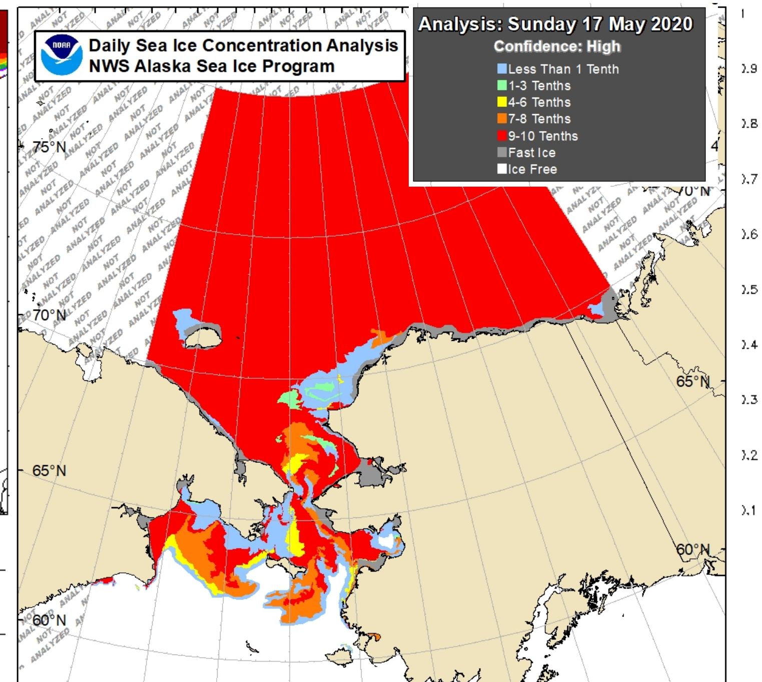
Perturbed process	
Air-ice drag coefficient	• Constant • Variable form drag by Tsamados et al. (2015, JPO)
Landfast ice	• None • Basal stress on. • Free parametesr k1, k2 are perturbed.
Snow properties	• Default snow density 330kg/m3, thermal conductivity 0.3W/K/m. • Reduced snow density 250kg/m3, thermal conductivity 0.17W/K/m.

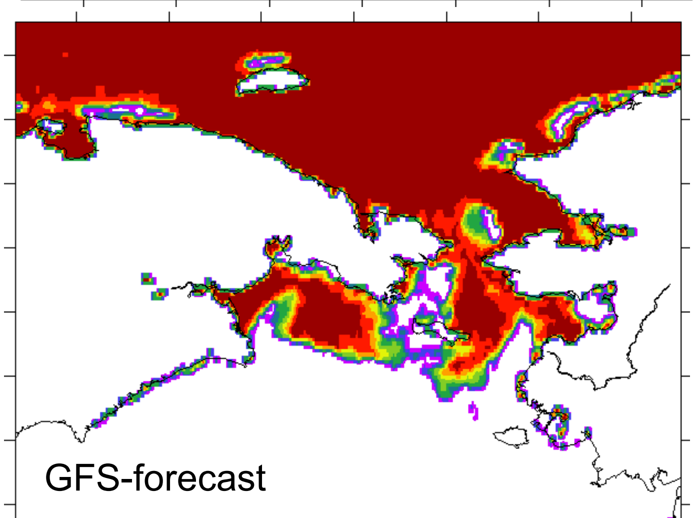
5 days forecast: ice distribution

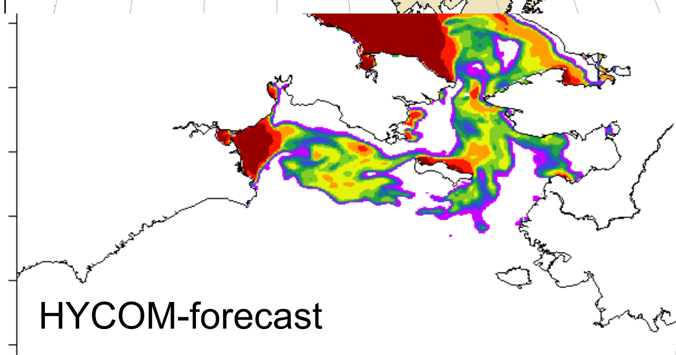
Model started on:
May 12

Result date:
May 17









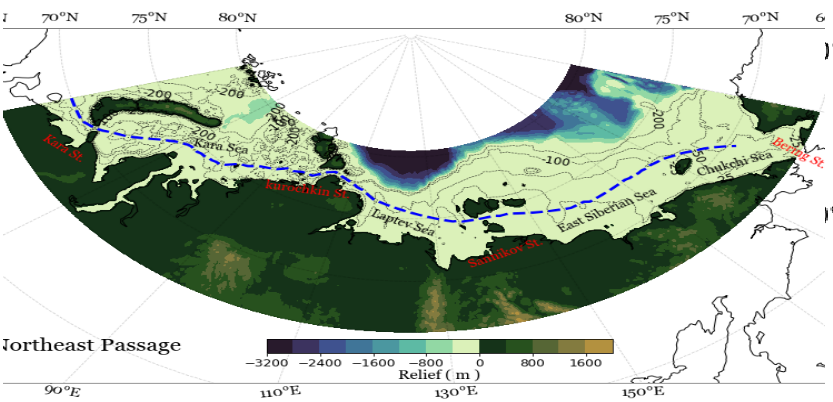
'HYCOM' is from Navy's global operational ocean forecast system (GOFS)

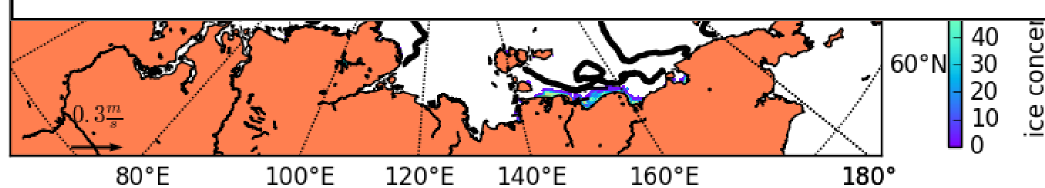
5-day (Oct 12-17, 2021) prediction:

ice concentration and temperature

ice thickness and salinity

along Northeast Passage

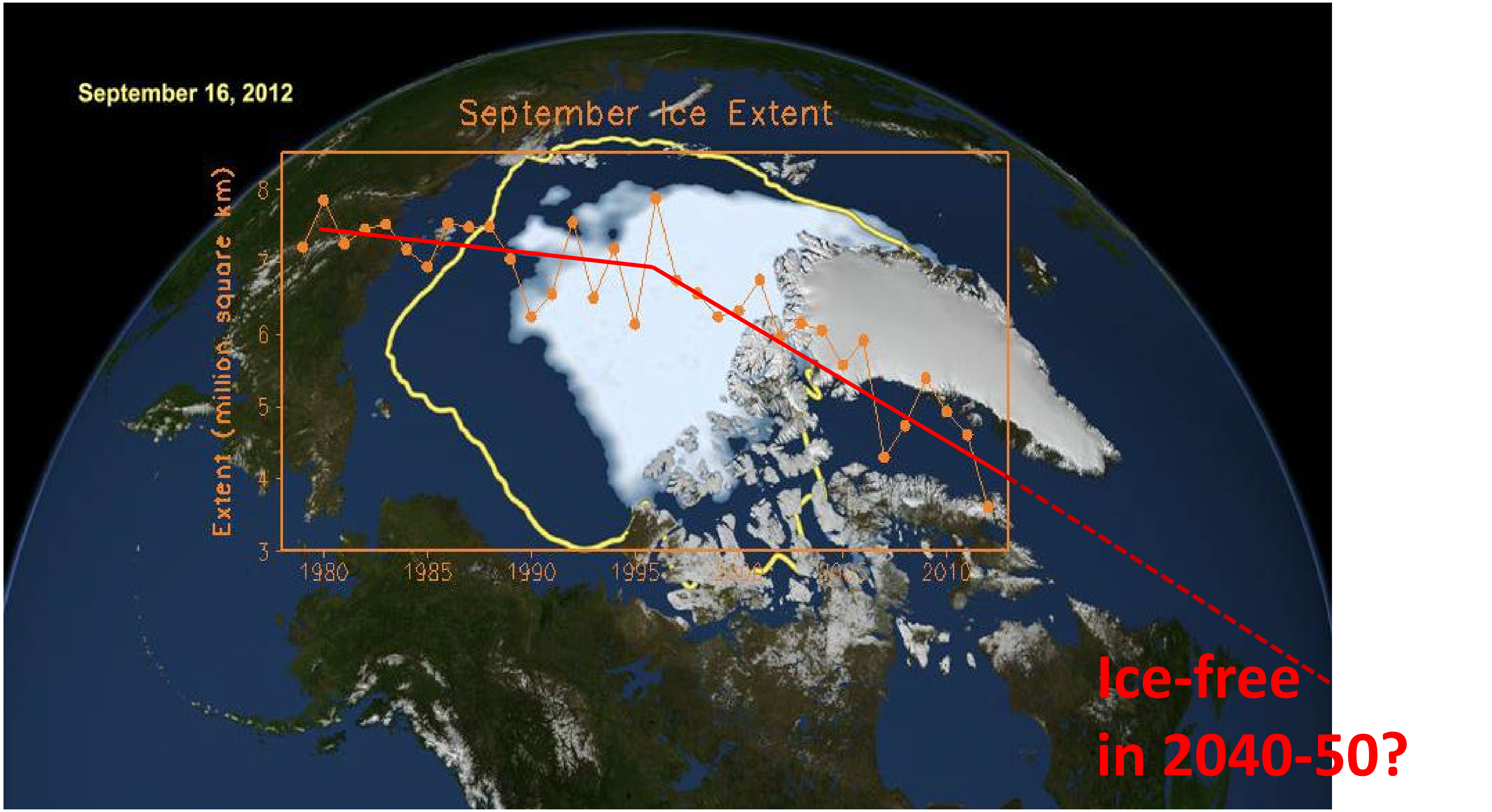




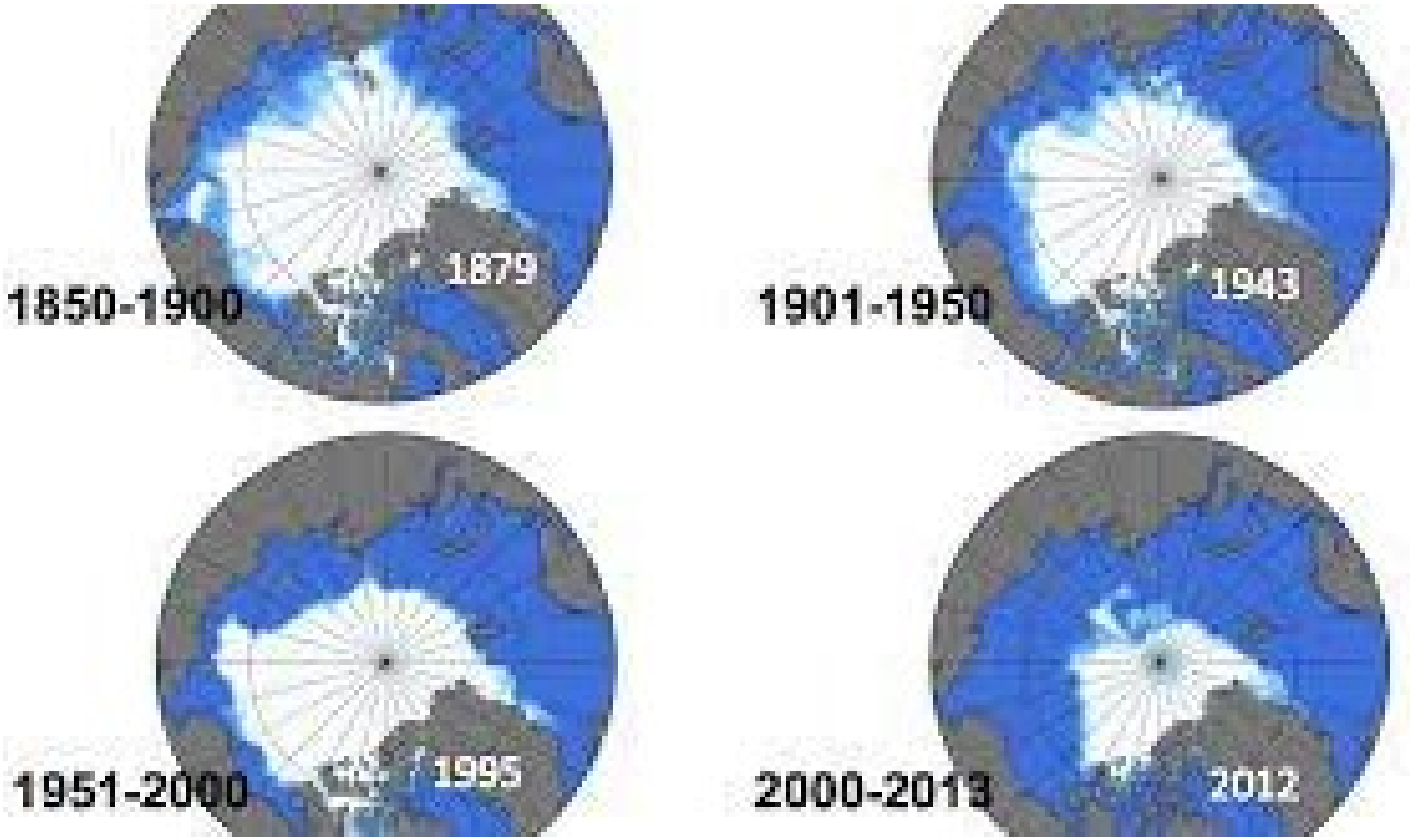
1. Motivation

Accelerating decline in Arctic summer sea ice

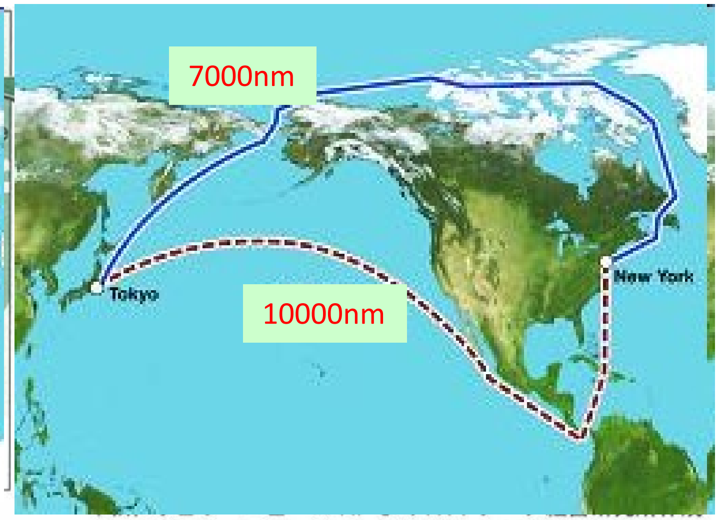
Impacts: Commercial and recreational shipping and ecosystem/fisheries



Climatological Spatial Distribution of Summer Sea Ice during Various Periods

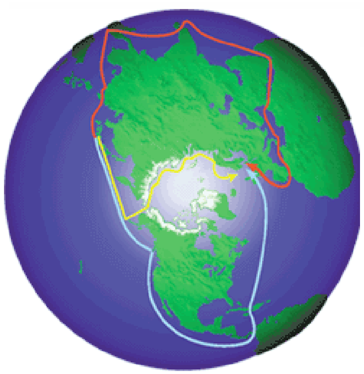


Impacts of diminishing summer sea ice on commercial shipping
(Lei, Wang, et al. 2015 CRST)



nm = Nautical Mile = 1.852 km

http://weathernews.com/jp/c/press/2008/080708.html



Arctic sea routes	
Northeast passage (NEP) Northern Sea Route (NSR)	Northwest passage (NWP)

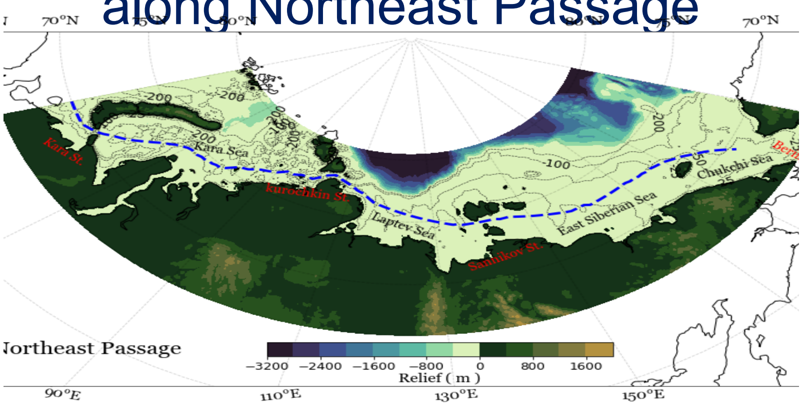
Exact definition of the Northern Sea Route is the route between the Kara Gate and the Bering Strait under the NSR Administration Agency.

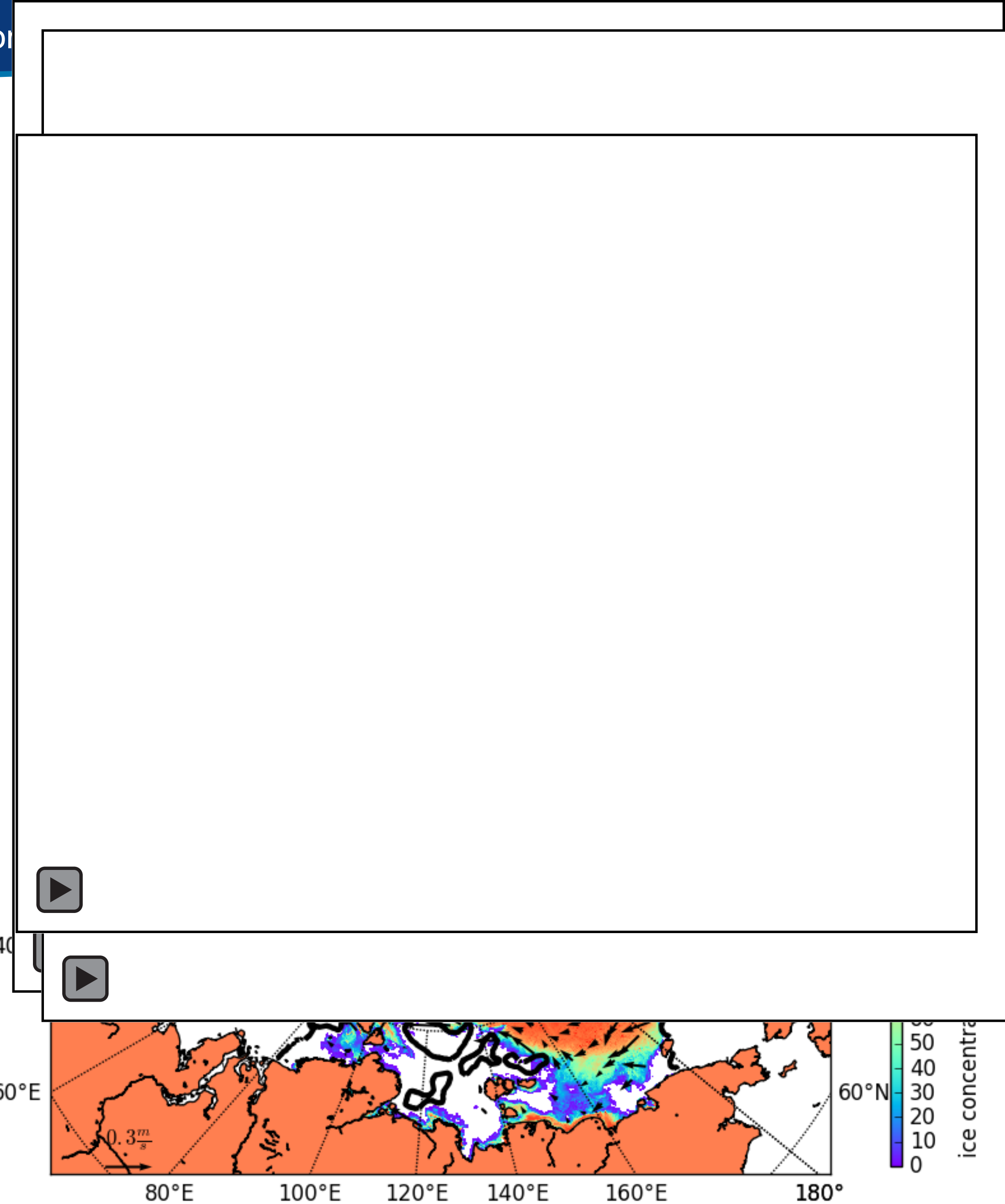
GCAS 4-km model's 5-day (Oct 22-26, 2021) prediction:

ice concentration and temperature

ice thickness and salinity

along Northeast Passage





Coupled model components

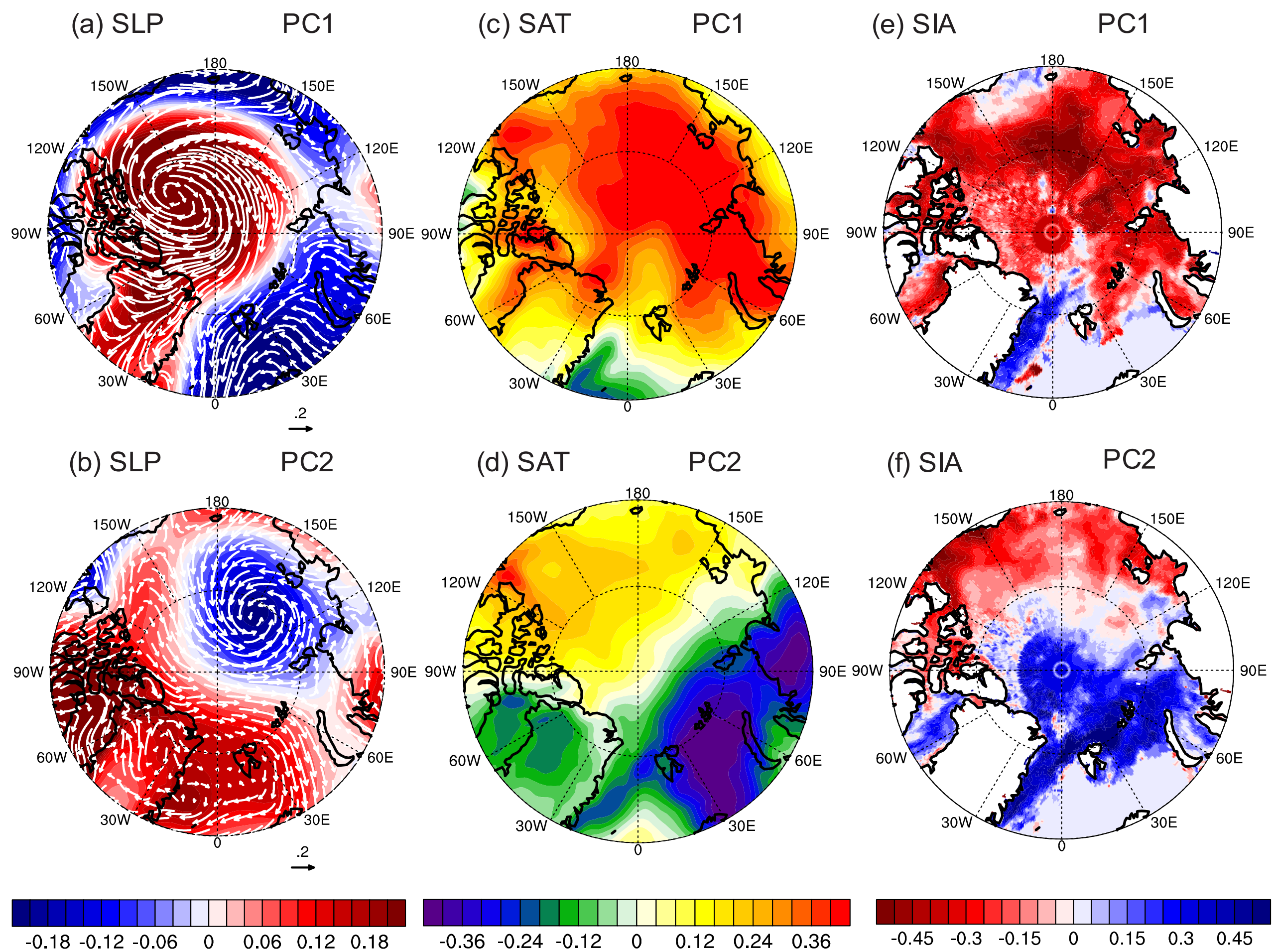
- Using NOAA Environmental Modeling System (NEMS) and Earth System Modeling Framework (ESMF).
- Flexible architecture that enables model coupling without changing source codes of each model.
- Well aligns with Coastal and Marine themes of the Unified Forecast System (UFS).
- But some undertaking to set up.
- Currently the team is setting up a coupled application for a small test case.

EOF Modes of Summer Sea Ice Regressed to SLP, SAT, and SIC

Anomalies: **SLP&Wind** **SAT** **SIC**

CP1:
Zonal Warming
In-phase ice decrease

CP2:
Meridional Warming/ Cooling
Out-of-phase ice seesaw



Composite Analysis (positive minus negative group):

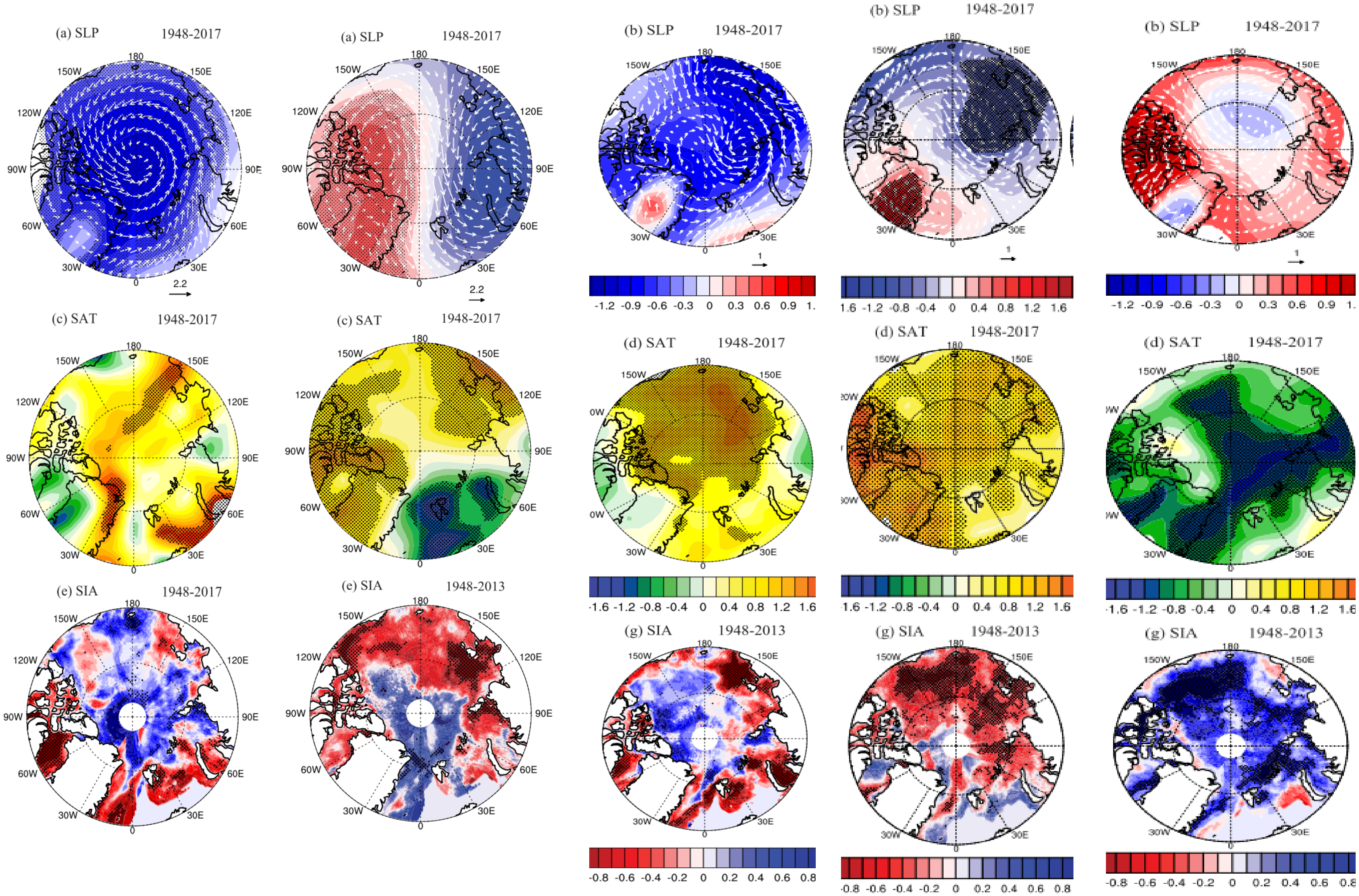
AO | **DA** | **NAO** | **AMO** | **PDO**

Anomalies:

SLP& Wind

SAT

SIC



Arctic Example: General Equation

Methods: Step 4

$$y = a + b_1(AO_2) + b_2(AO_2^2) + c_1(CAI_1) + d_1(NAO_5) + d_2(NAO_5^2) + e_1(NINO_3) \quad (1)$$

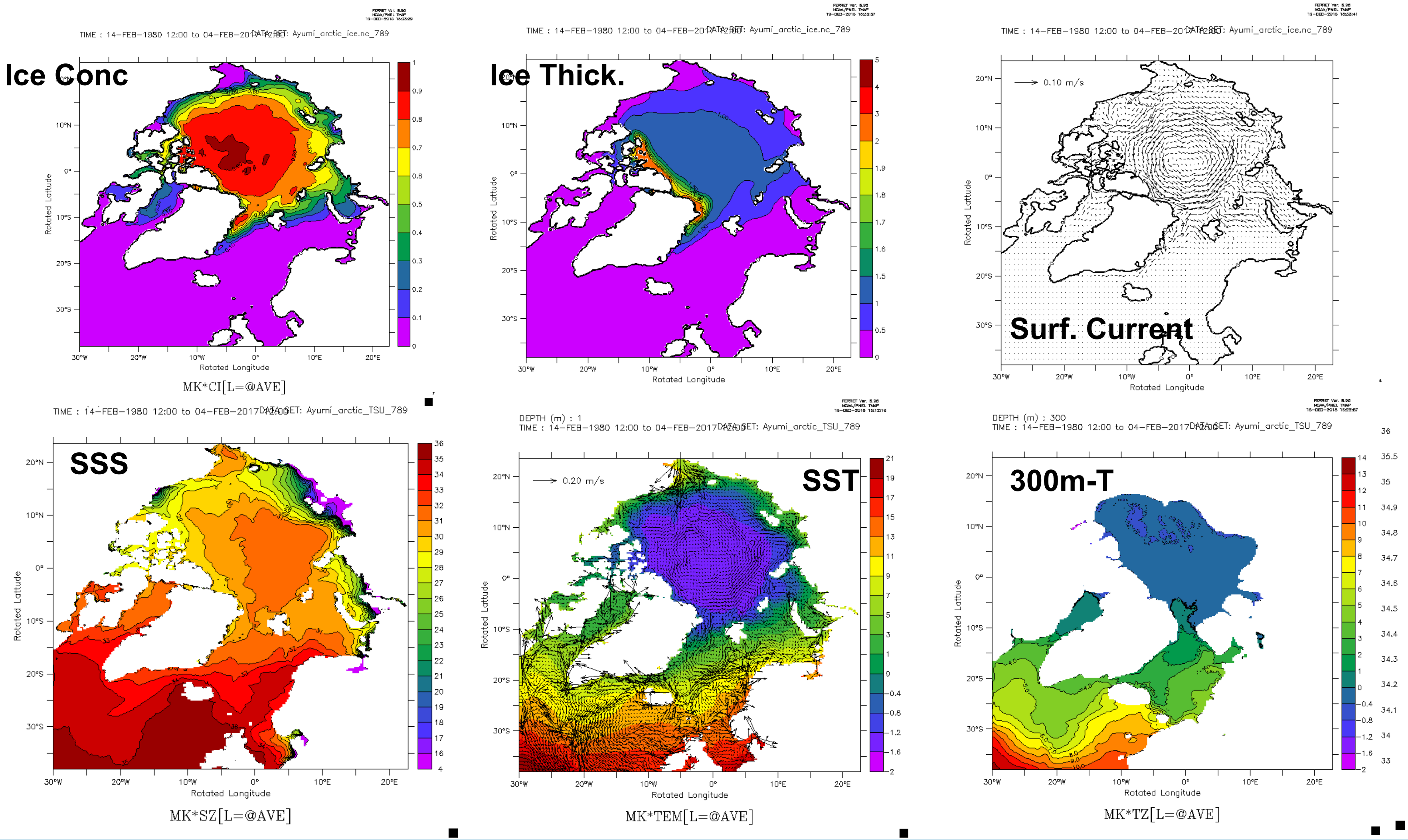
$$+f(AO_2 * CAI_1) + g_1(NINO_3 * AO_2) + g_2(NINO_3 * CAI_1) + h_1(NAO_5 * AO_2) + h_2(NAO_5 * CAI_1) \quad (2)$$

$$+i_1(AMO_8) + i_2(AMO_8^2) + j_1(PDO_4) + j_2(PDO_4^2) \quad (3)$$

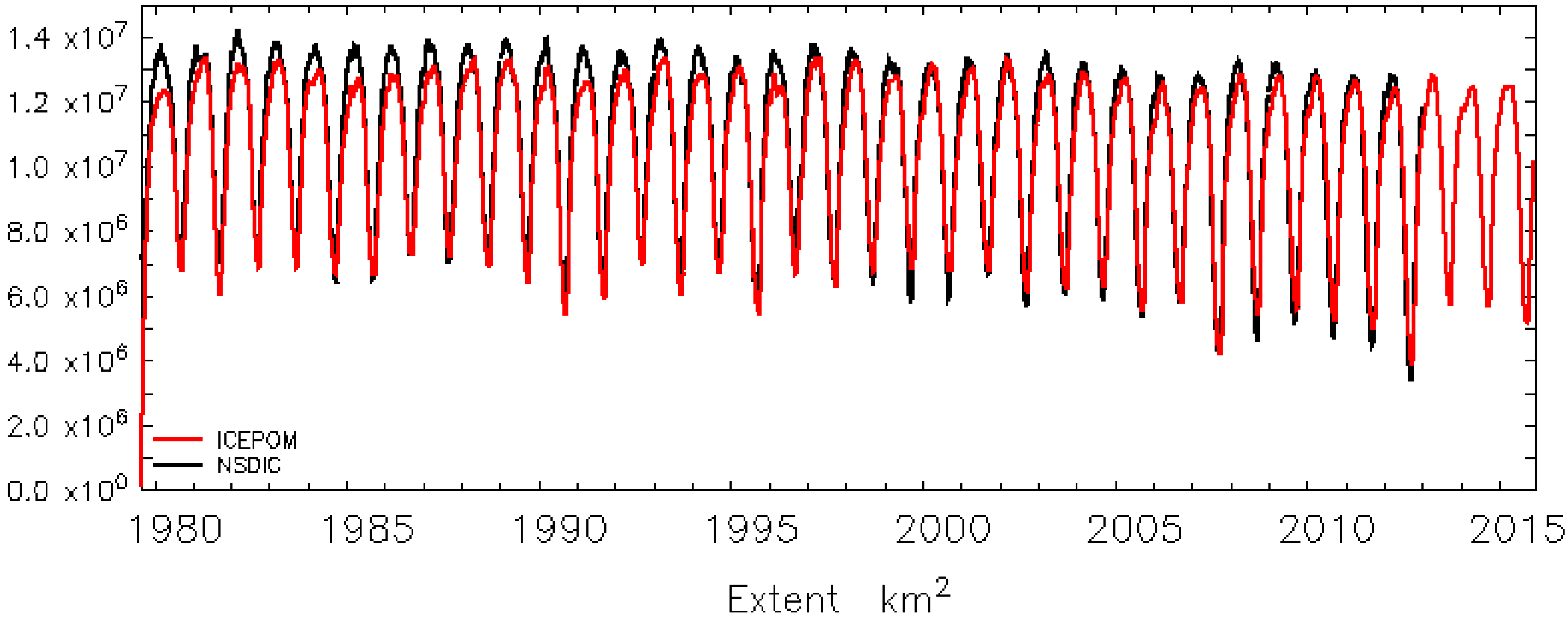
$$+k_1(AMO_8 * AO_2) + k_2(AMO_8 * CAI_1) + k_3(AMO_8 * NAO_5) + l_1(PDO_4^2 * AO_2) + l_2(PDO_4^2 * CAI_1) + l_3(PDO_4^2 * NINO_3) \quad (4)$$

$$+m(PDO_4^2 * AMO_8) \quad (5)$$

1979-2016 Climatology of ice concentration, thickness, velocity, surface S&T and 300-m T on Feb 14, 1980



25-km resolution Coupled Ice-Ocean Model (CIOM/IcePOM) for the period 1979-2016



5-day prediction (Oct. 12-17, 2021)