Recent Update of Arctic Research and Products

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1. Interannual and decadal variability in Arctic summer sea ice, Arctic amplification, teleconnections, and ice/ocean albedo feedback loop

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

3. GLERL-CIGLR Arctic sea-route nowcast/forecast System (GCAS) (5-day prediction)

4. ALaska Coastal Ocean Forecast System (ALCOFS) (5-day prediction)

5. Great Lakes coupled FVCOM_ice_wave model

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., 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](https://doi.org/10.1175/JCLI-D-20-0330.1)

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)

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

![Graphs and charts illustrating PC1 and PC2 analysis of sea ice oscillations.](image)
**Ice/ocean albedo feedback loop**

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

**Dynamic (CP2):** DA, AMO $\rightarrow$ Meridional winds $\rightarrow$ 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

Great Lakes Environmental Research Laboratory’s Arctic Research and Applications

Monthly AO Index

September Sea Ice Extent in Arctic (10⁶ km²)

January

February

March

April

May

June

July

August

September


data points and regression lines with equations and R² values.
### Methods: Step 2

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

**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

\[
y = 12.521 - 0.401(AO_2) + 0.055(AO_2^2) + 0.234(CAI_1) + 0.104(NAO_5) - 0.036(NAO_5^2) + 0.079(NINO_3)
\]

(1)

\[
-0.040(AO_2 \times CAI_1) - 0.104(NINO_3 \times AO_2)
-0.032(NINO_3 \times CAI_1) - 0.050(NAO_5 \times AO_2)
-0.044(NAO_5 \times CAI_1)
\]

(2)

\[
-2.934(AMO_8) - 3.349(AMO_8^2) + 0.141(PDO_4) + 0.100(PDO_4^2)
\]

(3)

\[
-0.240(AMO_8 \times AO_2) + 0.209(AMO_8 \times CAI_1)
-0.506(AMO_8 \times NAO_5) + 0.299(PDO_4^2 \times AO_2)
-0.048(PDO_4^2 \times CAI_1) - 0.032(PDO_4^2 \times NINO_3)
\]

(4)

\[
+1.305(PDO_4^2 \times AMO_8)
\]

(5)
Results: Model vs Observation

<table>
<thead>
<tr>
<th>Region</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chukchi</td>
<td>0.78</td>
</tr>
<tr>
<td>Siberia</td>
<td>0.71</td>
</tr>
<tr>
<td>Central Arctic</td>
<td>0.76</td>
</tr>
<tr>
<td>Barents</td>
<td>0.62</td>
</tr>
<tr>
<td>Arctic</td>
<td>0.77</td>
</tr>
</tbody>
</table>
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.

- 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’s 5-day prediction (Oct12-17, 2021)

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))

Coupling is conducted through the NOAA Environmental Modeling System (NEMS) and the Earth System Modeling Framework (ESMF).
CICE standalone, regional configuration

• 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

Covered domain. Color contour is sea surface temperature from GOFS3.1 interpolated to the ice model grid.
Hindcast skill assessment, sea ice extent

Sea ice extent (x $10^6$ km$^2$)

- Observation
- CICE
- CFSv2
- HYCOM

CICE: RMSE = 0.08, Bias = 0.0
CFSv2: RMSE = 0.13, Bias = 0.08
HYCOM: RMSE = 0.05, Bias = -0.02
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

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

Ice-free in 2040-50?
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)

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:

CP1:
Zonal Warming
In-phase ice decrease

CP2:
Meridional Warming/
Cooling
Out-of-phase ice seesaw
Composite Analysis (positive minus negative group):

Anomalies:

SLP & Wind

SAT

SIC

AO

DA

NAO

AMO

PDO
Arctic Example: General Equation

\[ y = a + b_1(AO_2) + b_2(AO_2^2) + c_1(CAI_1) + d_1(NAO_5) + d_2(NAO_5^2) + e_1(NINO_3) \]  

(1)

\[ + f(AO_2 \ast CAI_1) + g_1(NINO_3 \ast AO_2) + g_2(NINO_3 \ast CAI_1) + h_1(NAO_5 \ast AO_2) + h_2(NAO_5 \ast CAI_1) \]  

(2)

\[ + i_1(AMO_8) + i_2(AMO_8^2) + j_1(PDO_4) + j_2(PDO_4^2) \]  

(3)

\[ + k_1(AMO_8 \ast AO_2) + k_2(AMO_8 \ast CAI_1) + k_3(AMO_8 \ast NAO_5) + l_1(PDO_4^2 \ast AO_2) + l_2(PDO_4^2 \ast CAI_1) + l_3(PDO_4^2 \ast NINO_3) \]  

(4)

\[ + m(PDO_4^2 \ast AMO_8) \]  

(5)
1979-2016 Climatology of ice concentration, thickness, velocity, surface S&T and 300-m T on Feb 14, 1980

Great Lakes Environmental Research Laboratory’s Arctic Research and Applications
25-km resolution Coupled Ice-Ocean Model (CIOM/IcePOM) for the period 1979-2016
5-day prediction (Oct. 12-17, 2021)