Prospects for Improved Regional Predictions of Arctic Sea Ice

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With contributions from:

SIPN2 Webinar
July 13, 2021
Observed Decline of September Arctic Sea Ice Extent (SIE)

Average Monthly Arctic Sea Ice Extent
September 1979 - 2020

[Graph showing the decline of September Arctic Sea Ice Extent from 1980 to 2020, with a decreasing trend line.]
Sea Ice Outlook: Predictions of September 2021 SIE

June 2021 SIO Arctic predictions by contributor (n = 38)

- University of Washington/APL
- UPenn Group 1 (FERL)
- PolArctic
- Wu, Tallapragada, and Grumbine
- Met Office (Blockley et al.)
- UCLouvain
- Simmons, Charles
- GP Regression (Cawley)
- KOPRI (Chi et al.)
- CNRM (Batté et al.)
- NCAR/CU-Boulder
- AWI Consortium (Kauker et al.)
- ARCUS Team (Wiggins et al.)
- CPOM
- ANSO IAP-LASG
- UPenn (VARCTIC)
- ASIC/NIPR
- Sun, Nico
- Climate Prediction Center
- FIO-ESM (Shu et al.)
- METNO-SPARSE-ST (Wang et al.)
- NSIDC Hivemind
- NSIDC (Horvath et al.)
- NMEC of China (Li and Li)
- APPLICATE Benchmark
- CPOM UCL (Gregory et al.)
- ECC-CanSIPSv2
- Vandevoorde, Pirlet, and Audoor
- UTokyo (Kimura et al.)
- BDAL Group
- SYSU/SML-MLM
- Kondrashv, Dmitri (UCLA)
- NSIDC (Meier)
- Lemont (Yuan and Li)
- RASM@NPS (Maslowski et al.)
- SYSU/SML-KNN
- Mihara Primary School (Ihoshii et al.)
- OSEIBOLA

Wang et al. (2021), Sea Ice Outlook June Report
Melia et al. (2016), GRL

Regional Predictions

ARCTIC SEA ICE – 05/04/2021

From Zack Labe

Shipping Routes

RCP2.6

Melia et al. (2016), GRL

Lincoln Sea Ice Arches

Moore et al. (2021), Nat. Comms.

North Greenland Polynya

Ludwig et al. (2019), Cryosphere

Ecosystem Prediction

George et al. (2020), Arctic Report Card

Fisheries Management

Outline for Today’s Talk:

• Introduce the FLOR and SPEAR_MED dynamical prediction systems
• Evaluate regional SIE prediction skill of these systems
• Understand mechanisms of regional SIE predictability
• Improve forecasts with sea ice data assimilation
• Skillful predictions of Arctic shipping routes
### GFDL Prediction Systems: Dynamical Models

<table>
<thead>
<tr>
<th></th>
<th><strong>FLOR</strong>¹</th>
<th><strong>SPEAR_MED</strong>²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>AM2.5; 0.5°, 32 vertical levels</td>
<td>AM4; 0.5°, 33 vertical levels</td>
</tr>
<tr>
<td>Land</td>
<td>LM3; 0.5°</td>
<td>LM4; 0.5°</td>
</tr>
<tr>
<td>Ocean</td>
<td>MOM5; 1.0°, 50 vertical levels</td>
<td>MOM6; 1.0°, 75 vertical levels</td>
</tr>
<tr>
<td>Sea Ice</td>
<td>SIS1; 1.0°, 5 category ITD</td>
<td>SIS2; 1.0°, 5 category ITD</td>
</tr>
</tbody>
</table>

**FLOR:** Forecast-oriented Low Ocean Resolution  
**SPEAR:** Seamless system for Prediction and Earth system Research

¹ Vecchi et al. 2014, *J. Climate*; ² Delworth et al. 2020, *JAMES*
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<th>FLOR(^1)</th>
<th>SPEAR_MED(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ocean Data</strong></td>
<td>Satellite SST, Argo, XBT, Moored Buoys, CTD, Seal Data, other WOD profiles; daily</td>
<td>Satellite SST, Argo, XBT, Moored Buoys; daily</td>
</tr>
<tr>
<td><strong>Atmospheric Data</strong></td>
<td>3-D Temp from NCEP2 Reanalysis; 6 hourly</td>
<td>3-D Temp, Winds, Humidity from CFSR; 6 hourly</td>
</tr>
<tr>
<td><strong>Sea Ice Data</strong></td>
<td>None</td>
<td>SIC used to adjust under-ice SST; daily</td>
</tr>
<tr>
<td><strong>Data assimilation method(s)</strong></td>
<td>Ensemble Kalman Filter (EnKF)(^1)</td>
<td>Ensemble Kalman Filter (ocean ICs); Nudged atmosphere/SST run (sea ice, atm, land ICs)(^2)</td>
</tr>
</tbody>
</table>

Note: No direct sea ice DA in these systems; will present SPEAR w/ sea ice DA ahead

1: Zhang et al. 2007 *Mon. Wea. Rev.*; 2: Lu et al. 2020 *JAMES*
## GFDL Prediction Systems: Retrospective Seasonal Predictions

<table>
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<tr>
<th></th>
<th>FLOR&lt;sup&gt;1&lt;/sup&gt;</th>
<th>SPEAR_MED&lt;sup&gt;2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initialization Dates</strong></td>
<td>First of the each month</td>
<td>First of the each month</td>
</tr>
<tr>
<td><strong>Prediction Length</strong></td>
<td>One year</td>
<td>One year</td>
</tr>
<tr>
<td><strong>Ensemble Size</strong></td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
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<sup>1</sup>Vecchi et al. 2014, *J. Climate*; 2: Delworth et al. 2020, *JAMES*
A first question:
How good are the sea ice initial conditions?
Sea Ice Concentration Climatological Biases (Model minus Obs)

- FLOR and SPEAR initial conditions (ICs) improve upon the model SIC biases from historical simulations (LE).

Bushuk et al. 2021, In prep.
Sea Ice Extent (SIE) Initial Conditions Interannual Variability

- SPEAR_MED has improved SIE initial conditions over FLOR in nearly all Arctic regions.
- Improvement is due to treatment of SST under sea ice, which provides a strong constraint on SIE.
Do FLOR and SPEAR have SIE prediction skill?
Skillful Predictions of Pan-Arctic September Sea Ice Extent (SIE)

(a) FLOR

(b) SPEAR_MED

ACC (detrend)
0.89 (0.63)
0.84 (0.47)
0.83 (0.43)
0.79 (0.33)

ACC (detrend)
0.94 (0.91)
0.87 (0.72)
0.86 (0.67)
0.83 (0.39)
A Cautionary Note: Systematic errors for real-time forecasts

Prediction made June 1, 2021

Pan–Arctic SIE Predictions Initialized Jun 1

Target: Jun, Lead 0

Target: Jul, Lead 1

Target: Aug, Lead 2

Target: Sep, Lead 3

Target: Oct, Lead 4

Target: Nov, Lead 5

Target: Dec, Lead 6

Target: Jan, Lead 7

Target: Feb, Lead 8

Target: Mar, Lead 9

Target: Apr, Lead 10

Target: May, Lead 11

Obs

SPEAR_MED Hindcasts

SPEAR_MED 2021 Prediction
A Cautionary Note: Systematic errors for real-time forecasts

Prediction made June 1, 2021

Pan–Arctic SIE Predictions Initialized Jun 1

- Real time forecasting necessitates the use of “preliminary” OISST data for the most recent two weeks
- Real-time SPEAR SIE forecasts at short leads currently have systematic high biases associated with these data.

Rerun June 1, 2021 prediction using “final” OISST data
Regional SIE Prediction Skill

Arctic Regions

1: Central Arctic
2: GIN Seas
3: Barents Sea
4: Kara Sea
5: Laptev Sea
6: East Siberian Sea
7: Chukchi Sea
8: Bering Sea
9: Sea of Okhotsk
10: Beaufort Sea
11: Canadian Archipelago
12: Hudson Bay
13: Baffin Bay
14: Labrador Sea
15: Open Ocean
Summer Regional Prediction Skill (Detrended ACC): Laptev and East Siberian

- Skill exceeds persistence
- Skill is significant, but lower than persistence
- SPEAR exceeds FLOR
- FLOR exceeds SPEAR
Summer Regional Prediction Skill (Detrended ACC): Beaufort and Chukchi

- Skill exceeds persistence
- Skill is significant, but lower than persistence
- SPEAR exceeds FLOR
- FLOR exceeds SPEAR
What are the key sources of predictability for summer SIE in these systems?
Sources of Summer (September) SIE Prediction Skill

- SIE/SIV predictors based on initial conditions used for forecasts
Sources of Summer (September) SIE Prediction Skill

• SIE/SIV predictors based on initial conditions used for forecasts
• Regional SIE persistence is the key source of summer prediction skill at short lead times (0-1 months)
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- Regional SIV persistence is the key source of summer prediction skill at longer lead times (2-4 months)
- Combination of SIE and SIV predictors provide a challenging skill benchmark for models to beat
Winter Regional Prediction Skill (Detrended ACC): Barents and Labrador Seas

- Skill exceeds persistence
- Skill is significant, but lower than persistence
- SPEAR exceeds FLOR
- FLOR exceeds SPEAR

[Maps of Barents and Labrador Seas with data plots showing skill levels over different lead months and target months.]
Winter Regional Prediction Skill (Detrended ACC): Bering and Okhotsk

- Skill exceeds persistence
- Skill is significant, but lower than persistence
- SPEAR exceeds FLOR
- FLOR exceeds SPEAR
What are the key sources of predictability for winter SIE in these systems?
Sources of Winter SIE Prediction Skill

- Regional SIE/OHC predictors based on initial conditions used for forecasts
Sources of Winter SIE Prediction Skill

- Regional SIE/OHC predictors based on initial conditions used for forecasts
- Regional SIE persistence is the key source of winter prediction skill at short lead times (0-2 months)
- Regional SIE shows a winter-to-winter reemergence of prediction skill
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- Regional SIE/OHC predictors based on initial conditions used for forecasts
- Regional SIE persistence is the key source of winter prediction skill at short lead times (0-2 months)
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- Regional OHC persistence is the key source of summer prediction skill at longer lead times (3-11 months)
Sources of Winter SIE Prediction Skill

- Regional SIE/OHC predictors based on initial conditions used for forecasts
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- Combination of SIE and OHC predictors provides a challenging skill benchmark
Connection to Large-Scale Modes of Variability: Labrador SIE - NAO

- Persistent correlations between winter Labrador SIE and earlier upper ocean temperature anomalies
- Spatial pattern is very similar to the NAO regression pattern
- Suggests that skillfully predicting the NAO could further improve Atlantic winter SIE predictions
Connection to Large-Scale Modes of Variability: Okhotsk SIE - NPGO

$r(\text{Sea of Okhotsk Feb SIE, Upper 200m Temp IC}_{\text{Feb-lead}})$
Revisiting Chukchi Sea Prediction Skill

- Skill exceeds persistence
- Skill is significant, but lower than persistence
- SPEAR exceeds FLOR
- FLOR exceeds SPEAR

- High skill for target months June, July, November
- Lower skill in intervening summer months
- Suggestive of a combination of different predictability regimes in this region.
Sources of Chukchi SIE Prediction Skill

Ocean-based predictability regime

- OHC predictor based on Chukchi and Bering Seas
Sources of Chukchi SIE Prediction Skill

- Ocean-based predictability regime
  - ACC
  - SIE predictor
  - SIV predictor
  - uOHC predictor

- Ice thickness-based predictability regime
  - OHC predictor based on Chukchi and Bering Seas
Sources of Chukchi SIE Prediction Skill

- **Ocean-based predictability regime**
  - OHC predictor based on Chukchi and Bering Seas
  - Findings consistent with Lenetsky et al. (2021), *J. Clim.*, who found that Bering Strait OHT skillfully predict Chukchi SIA in June, July, and November, but not the intervening summer months.
Why is there a trade off between ocean and thickness based predictability regimes?

- Ocean surface current speed (m/s) plotted in color
- Observed sea ice edges plotted in gray contours
- Inflowing ocean waters interact strongly with the sea ice edge in June and July.
- Interaction with inflowing ocean waters is lost in August, when the ice edge retreats.
- Ocean-based predictability returns in November when ice edge returns to inflow location
Can sea ice data assimilation improve prediction skill?

Work led by Yongfei Zhang
SIS2/MOM6 Sea Ice Data Assimilation System

• MOM6/SIS2 (SPEAR ice-ocean components) forced by the JRA-55do atmospheric reanalysis from 1982–2017
• SST is nudged to OISST (SST under sea ice is set to salinity-based freezing point)
• Perturbed physics ensemble (albedo and ice strength parameters)
• Sea ice concentration NSIDC Nasa Team observations assimilated using Data Assimilation Research Testbed (DART) and the Ensemble Adjustment Kalman Filter (EAKF)

SIC DA Improves Subseasonal (0-8 week) SIE Prediction Skill

ACC of Detrended SIE

Forecast Days

- Statistically significant, but relatively modest, improvements in regional SIE skill associated with SIC DA.
- Subseasonal predictions lose to persistence for first ~10 days, generally beat persistence beyond 10 days.

**SPEAR w/ SIC DA**
**SPEAR**
**SIE persistence**

SIC DA Improves Subseasonal Predictions of SIC

**ACC of Detrended SIC for Pan Arctic**

Solid: with ice DA  
Dashed: no ice DA

**SIC RMSE differences:** (IceDA minus No IceDA; 45 day lead)

(g) Jul  
(h) Aug  
(i) Sep

**SIC ACC differences:** (IceDA minus No IceDA; 45 day lead)

(g) Jul  
(h) Aug  
(i) Sep

Can shipping routes be skillfully predicted?

Work led by Mike Winton
Observed Minimum Ice Path is Highly Correlated with Regional SIE

Fig. 2. July-October average Northwest (top) and Northeast (bottom) MIPs and comparable total regional ice extents.

Skillful Predictions of Minimum Ice Path (MIP)

Figure 7. Averages of Fig. 6 SPEAR MIP forecast root mean squared errors (RMSEs) and ensemble spread compared to a heuristic forecast consisting of the anomaly persistence forecast for the first month and the 5-year trailing climatology thereafter.

- MIP predictions are slightly more skillful than persistence forecast.
- There is substantial room for improvement via bias correction (red vs magenta) and model/initialization improvement (red vs green).

5-year climatology plus anomaly persistence
SPEAR w/ SIC DA
SPEAR w/ SIC DA + trend bias correction
SPEAR ensemble standard deviation (upper limit of predictability)

Conclusions

• SPEAR and FLOR prediction systems skillfully predict Pan-Arctic and regional sea ice extent (SIE).

• SPEAR skill generally higher than FLOR due to improved SIE and sea ice volume (SIV) initial conditions.

• A combination of regional predictors (SIE, SIV, and upper ocean heat content) can match, or in some cases exceed, the skill of the dynamical models. We advocate using these three simple predictors as benchmark tests of Arctic seasonal prediction systems.

• Chukchi Sea exhibits a combined predictability regime, associated with interactions between the ice edge and inflowing ocean waters through Bering Strait.

• Sea ice concentration (SIC) data assimilation improves subseasonal predictions of SIE, SIC, ice free probability, and ice retreat date.

• SPEAR can skillfully predict “minimum ice path” through the Northeast and Northwest passages, and shows “room for improvement.”
References


Please contact me at Mitchell.Bushuk@noaa.gov for pdfs or preprints, and for questions!
Appendix Slides
Sea Ice Thickness and Drift Climatology

(a) FLOR IC
(b) SPEAR_MED IC
(c) Observations

(d) FLOR LE
(e) SPEAR_MED LE
Detrended regional SIV correlations with PIOMAS