Arctic Ocean circulation and water mass properties in an ultra-high resolution global model

Effie C. Fine¹, Julie L. McClean¹, Anthony Craig⁴, Eric Chassignet³, Alan Wallcraft³, Mathew E. Maltrud², & Detelina P. Ivanova⁵

Other Contributors: John Richie¹ (retired), Elizabeth Hunke²
¹SIO/UCSD, ²LANL, ³FSU, ⁴SIO/UCSD contractor, ⁵now at Climformatics

Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop
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Motivation

• Arctic climate is rapidly changing
  • Declining sea ice
  • Warming ocean
• Climate system is sensitive to Arctic changes
  • Potential feedback loops:
    • Ice-albedo: less ice $\rightarrow$ more solar absorption $\rightarrow$ warmer water
    • Wind-ice-ocean: less ice $\rightarrow$ more wind forcing $\rightarrow$ increased ocean heat flux
    • Ice-brine rejection: less ice $\rightarrow$ more brine rejection $\rightarrow$ increased ocean heat flux
• "Nature run" model developed for use in collaboration with FSU and NRL to optimize Arctic observational sampling strategies
  • Ultra-high resolution to capture mesoscale dynamics
Outline

• Model set up
• Model Realism
  • Sea ice
  • Arctic Circulation
  • Arctic Hydrography
• Implications for understanding ocean-ice system
  • Upper ocean heat content and stratification
  • Possible sea ice effects
Model set up

• **Ultra-high UH8to2**: 8 km at equator reducing to 2 km at poles. Higher horizontal resolution than 0.1° grid.

• **Parallel Ocean Program2 (POP2)/CICE5 (sea-ice) run in “HiLat” (E3SMv0/CESM) framework (partially coupled via model SST, surface velocity & ice drift in bulk formulae).**

• **New global tripole grid**: NH poles in Greenland & Siberia

• **Model set-up** from DOE-funded interannual CORE-II forced UH8to2 running at NERSC for 1975-2009 (CORE-II ends 2009).

• **Forcing**: 55-year Japanese Atmospheric Reanalysis (JRA-55), includes representation of GrIS and AIS melt. July 2016 - December 2020. (NCAR provided JRA-55 in CESM ingestion format)

• **Initial Conditions**: Data assimilative GOFS3.5 (HYCOM/CICE5) from 01/07/2017. GOFS3.5 from multidecadal HYCOM/CICE4.

• **Spin-up**: 07/2016-12/2016; **Production**: 2017-2020

• **Bathymetry**: (GEBCO).2014: 30-arc 2nd interval grid.

• **Global Grid size**: 5148x4400x60; needs cdf5 for ocean output.

• **Vertical levels**: vary smoothly from 10 m over top 200 m to 250 m at max. depth of 5500 m.
Model set up
Model realism: Sea ice

• Total sea ice extent agrees well with observations in winter

• In summer, ice extent is lower in UH8to2 than observed

**Arctic Total Sea Ice Extent**

![Graph showing Arctic Total Sea Ice Extent from 2017 to 2021](image)

**TSIE:** sum of sea-ice area where sea-ice concentration ≥ 15%

**NSDIC:** NT: Nasa team algorithm data; BT: Bootstrap algorithm data
Model realism: Sea ice

- Ice concentration close to observations in April
- In September UH8to2 ice concentration is low
- November freeze-up is slow, esp. in eastern Arctic

NOAA Polar Watch ERRDAP/NSIDC Climate Data Record
Circulation outlines major Arctic currents: AW inflow and boundary current, Beaufort Gyre, Transpolar drift

Velocity magnitudes larger than ASTE with more eddy variability (possibly expected at ultra-high resolution)
Comparing a cross-Arctic section we see structure that matches climatology:

- **Salinity-dominated stratification**: Surface waters cooler than deep
- **Warm Atlantic-origin Water**: Shallower on the eastern edge of the basin deeper and cooler on the west
- **Cool and fresh western halocline**: Beaufort Gyre accumulates freshwater

Model realism: Hydrography

WOA18: https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18
However there are also some differences:

- Modeled Atlantic water **warmer** than climatology
- **Weaker** salinity (and therefore stratification) gradient in Western Arctic
- Missing Pacific Summer Water temperature maximum

WOA18: https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18
Ice-tethered profiler observations show these are not simply problems with the climatology: synoptic observations find similar same model biases.
Model realism: Summary

- UH8to2 sea ice generally agrees well with observations, with a bias towards low ice in the summer, particularly in the eastern Arctic.

- Velocities reproduce known current pathways, and gateway fluxes are within observational bounds.

- Water masses appear as expected, with a few discrepancies:
  - Atlantic Water is warm and shallow.
  - Pacific Summer Water is cool and largely absent.
  - Winter mixed layers are overly deep.
Potential sea ice impacts: Eastern Arctic

• ITP #111 drifted in eastern Arctic from 10/2019-4/2020

• This period includes the winter deepening of the mixed layer

• In ITP observations, the deepening mixed layer is separated from the warm Atlantic water beneath by a cool halocline layer

• Model AW is warmer and closer to the surface, just below the (deeper) mixed layer

• Potential for excess entrainment of warm AW in model
Potential sea ice impacts: Western Arctic

• ITP #114 drifted in western Arctic from 10/2019-8/2020

• This period includes the winter deepening of the mixed layer, and then summer restratification

• In ITP observations, the deepening winter ML lies just above warm Pacific Summer Water, resulting in potential entrainment

• Model ML is so deep that all heat below 50 m is entrained

• Net impact on sea ice—unclear!
Potential sea ice impacts

- In eastern Arctic, there is more model heat stored beneath the summer ML:
  - In winter, excess model heat may be entrained.
  - Model Δ potential ice melt = 51 cm/m²
  - Obs Δ potential ice melt = 22 cm/m²

- In western Arctic, there is less model heat stored beneath summer ML:
  - Similar heat available for entrainment due to shallower observed mixed layer.
  - Model Δ potential ice melt = 38 cm/m²
  - Obs Δ potential ice melt = 38 cm/m²
Summary and discussion

• Ultra-high resolution model largely reproduces Arctic circulation and water mass properties accurately, with some biases
  o Model biases are consistent with hypothesized climate feedbacks: weaker stratification and deeper mixed layers occur alongside reduced sea ice

• While model ice field agrees relatively well with observations, discrepancies in upper ocean (top 100 m) heat content are significant
  o Poses challenges for some applications
    • understanding dynamics of Pacific Summer Water
    • projections for sea ice under climate change
Outstanding questions

• Ultimate cause of overly warm Atlantic Water in model
  • Warm anomaly appears in north Atlantic in 2017 (in both model and observations; Desbruyeres et al. 2021)
  • Warming Atlantic Water 2017-2020 not seen to same degree in observations
    • Model discrepancies in lateral and vertical mixing?
    • Observational bias?
      • Few observations in region where warm anomaly first occurs in model
  • Net effects of feedbacks?
    • Single model realization doesn’t allow for controlled studies
Validation question: Are inflowing currents represented approximately correctly in the model?

- **Volume**: Generally yes, transport within the range of observations
- **Freshwater**: Yes, but with high variability
- **Heat**: fewer observations, but generally good agreement with model

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Gateway</th>
<th>UH8to2</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (Sv)</td>
<td>Bering Strait</td>
<td>1.2 ± 1.1</td>
<td>1.2 ±1 (Woodgate 2018)</td>
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<tr>
<td></td>
<td>Davis Strait</td>
<td>-2.1 ± 0.8</td>
<td>-1.6 ± 0.5 (Curry et al. 2014)</td>
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<tr>
<td></td>
<td>Fram Strait</td>
<td>-1.6 ± 2.3</td>
<td>-2 ± 2.7 (De Steur et al., 2018)</td>
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<tr>
<td></td>
<td>Denmark Strait</td>
<td>-5.3 ± 2.7</td>
<td>-3.4 (Vage et al. 2013)</td>
</tr>
<tr>
<td>Heat (TW, ref - 1.9 °C)</td>
<td>Bering Strait</td>
<td>17.9 ± 25.7</td>
<td>13 (Woodgate 2012)</td>
</tr>
<tr>
<td>Heat (TW, ref - 0.1 °C)</td>
<td>Fram Strait</td>
<td>39.1 ± 19.0</td>
<td>28 ± 5 to 46 ± 5 (Schauer et al. 2004)</td>
</tr>
<tr>
<td>Heat (TW, ref 0 °C)</td>
<td>Davis Strait</td>
<td>13.1 ± 18.0</td>
<td>20 ± 9 (Curry et al., 2014)</td>
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