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

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Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop
Seattle WA
June 27-29, 2022

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 → more solar absorption → warmer water
    - Wind-ice-ocean: less ice → more wind forcing → increased ocean heat flux
    - Ice-brine rejection: less ice → more brine rejection → 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).

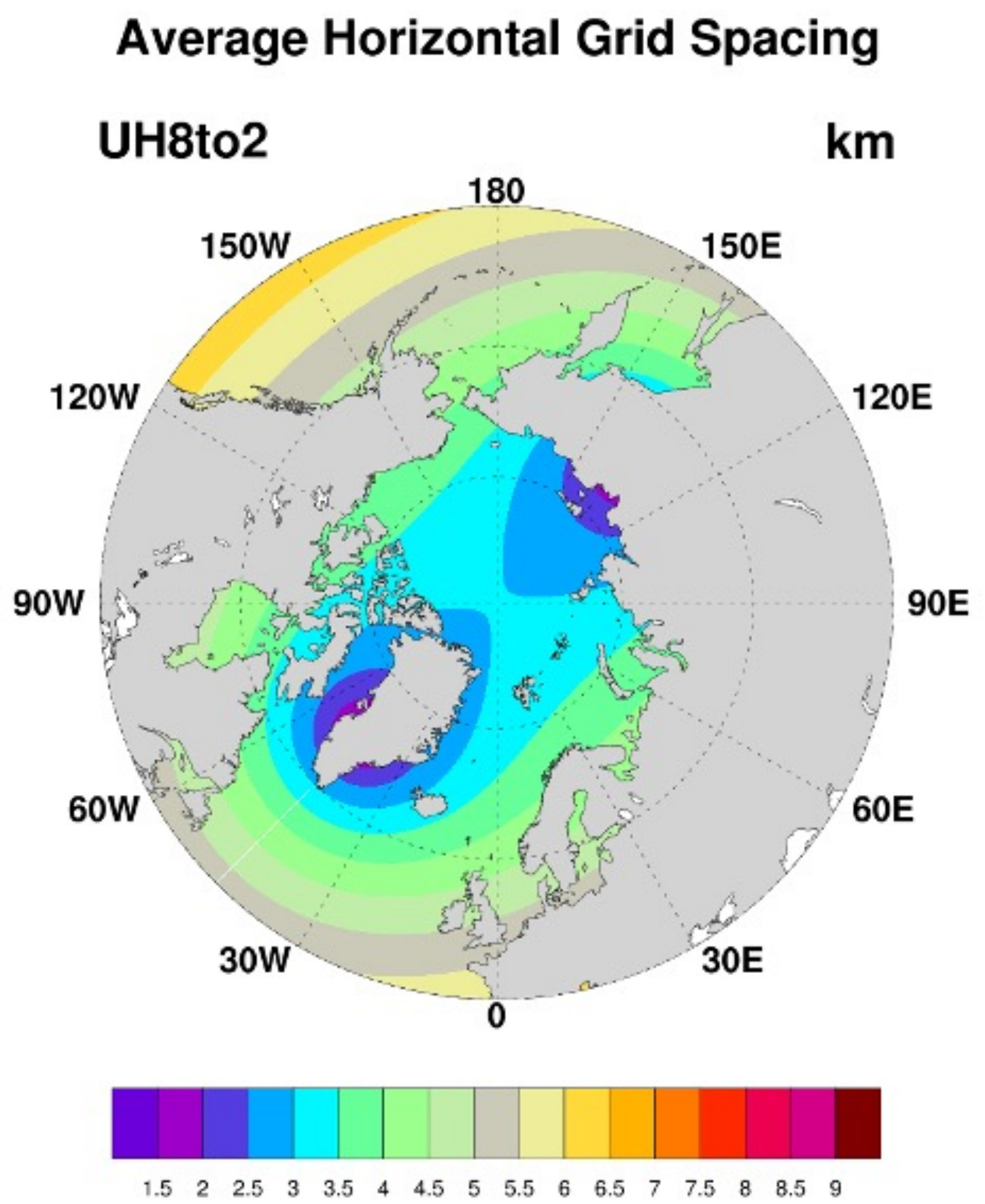
•New global tripole grid: NH poles in Greenland & Siberia

•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



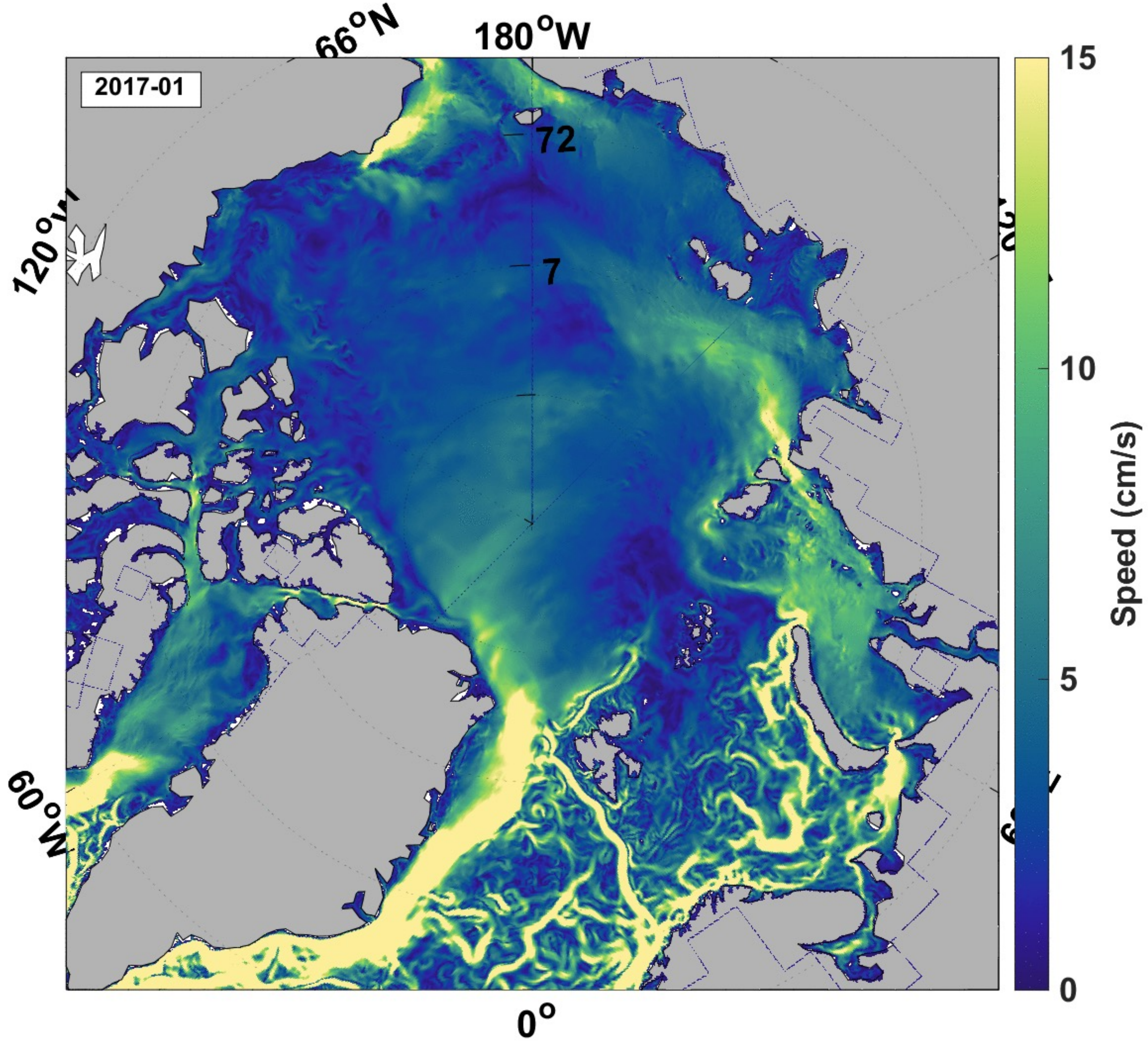
Mesh Resolution: Central Arctic: 2.5-3.5 km; Barents and Chukchi Seas: 3.5 km - 4 km

•Bathymetry: (GEBCO)_2014: 30-arc 2nd interval grid.

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

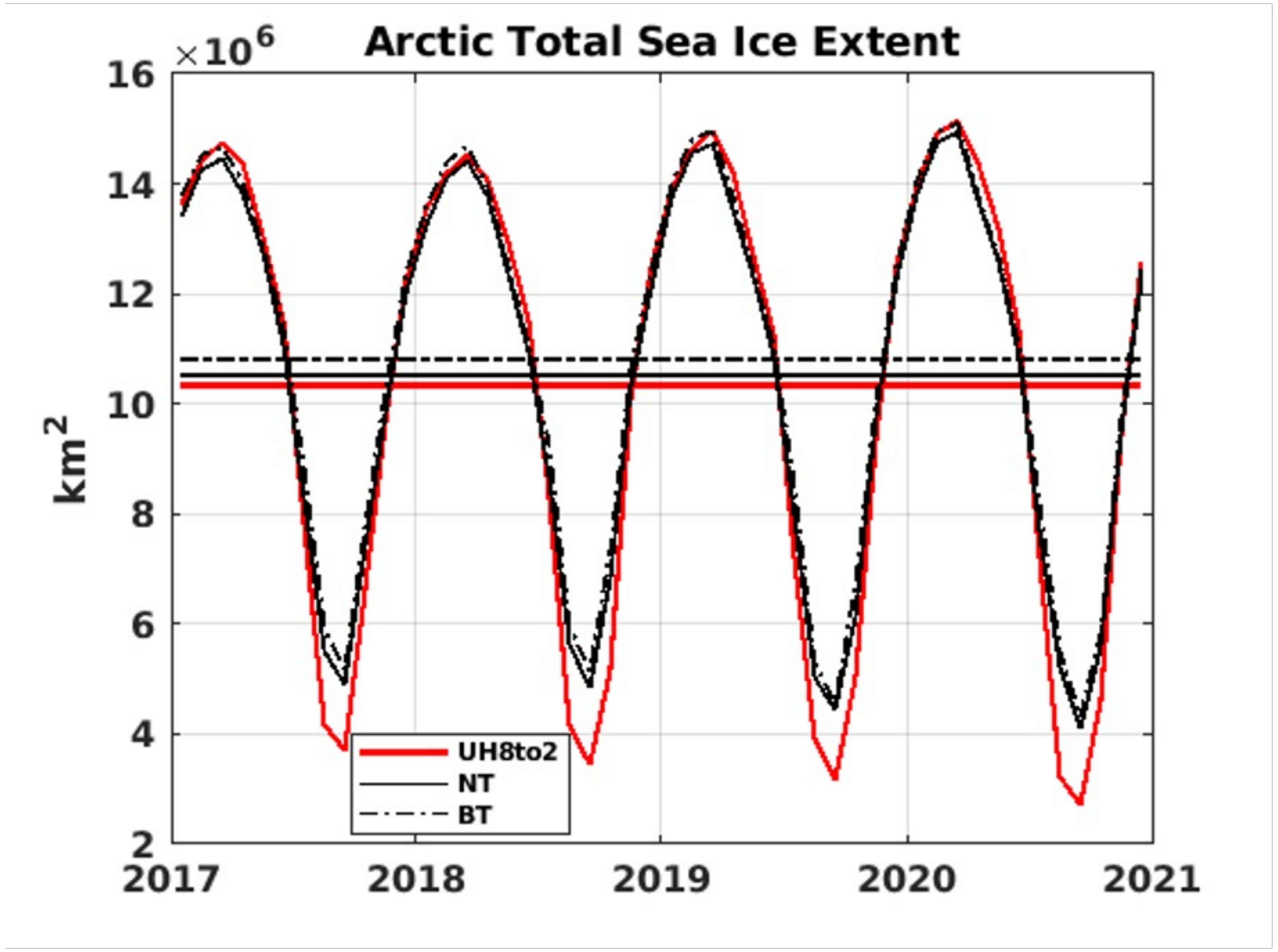
•vertical levels vary smoothly from 10 m over top 200m to 250m at max. depth of 5500m.

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

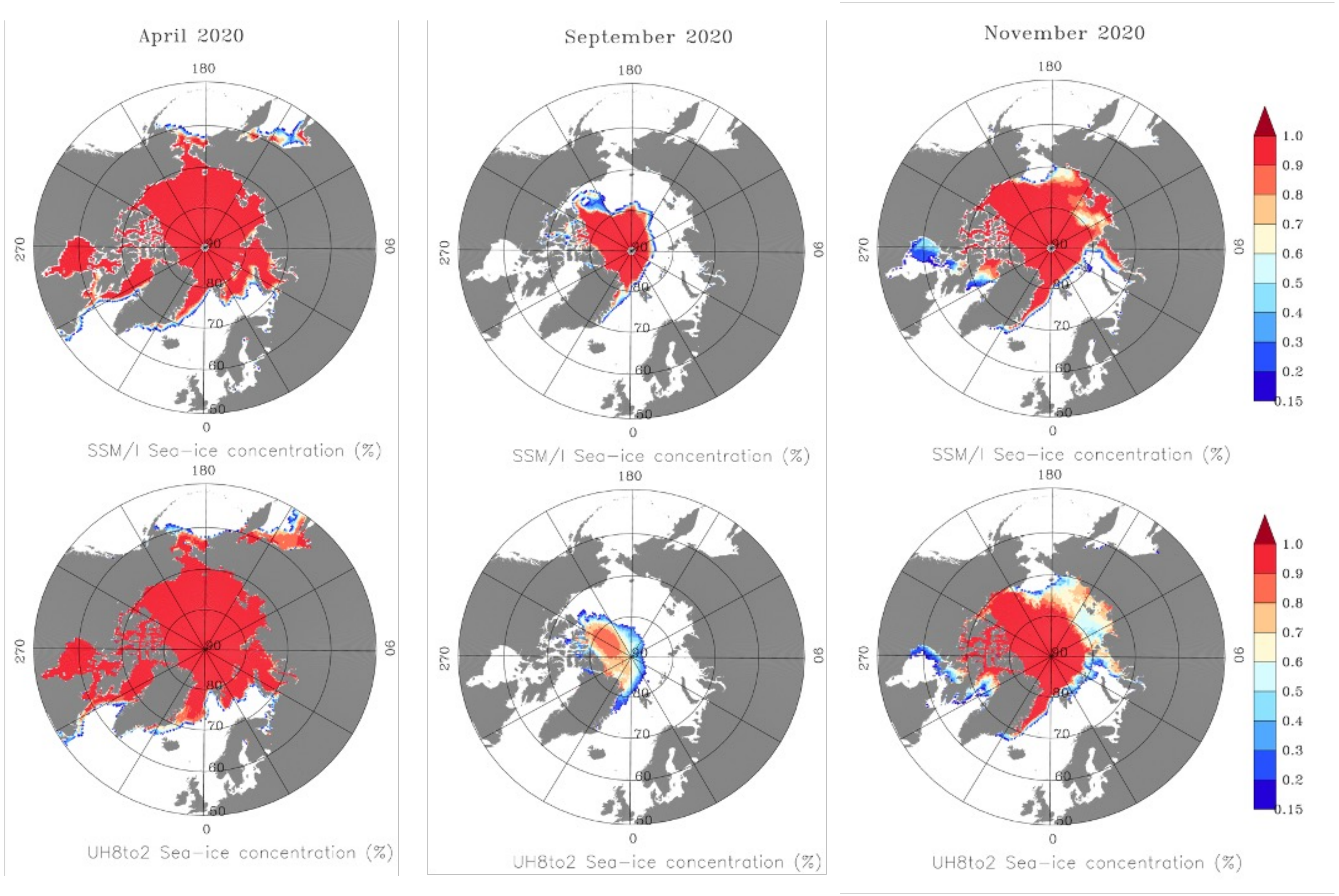


TSIE: sum of sea-ice area where sea-ice concentration ≥ 15%

NSDIC: NT: Nasa team algorithm data; **BT:** Bootstrap algorithm data

Model realism: Sea ice

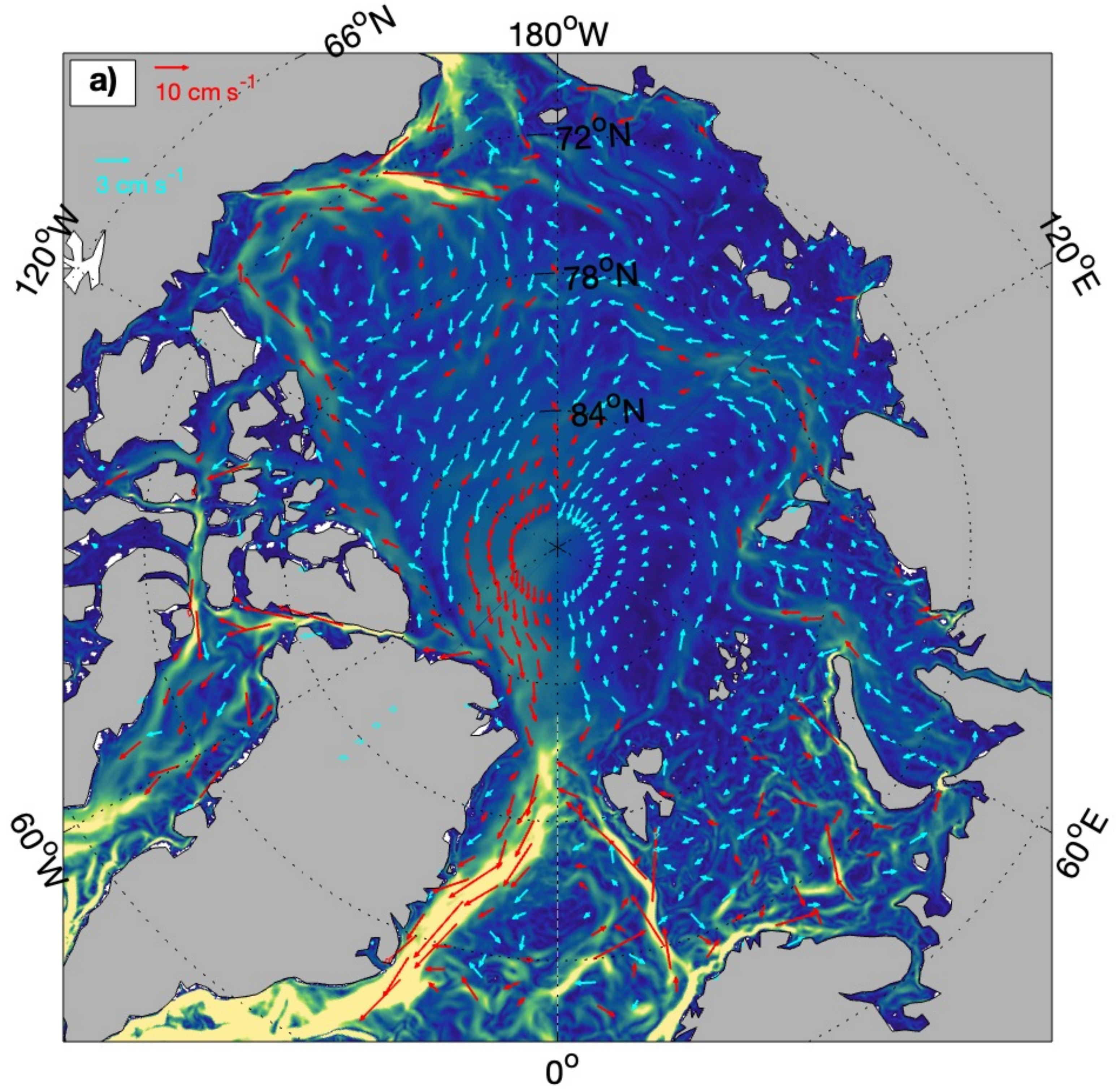
- Ice concentration close to observations in April
- In September UH8to2 ice concentration is low
- November freeze-up is slow, esp. in eastern Arctic



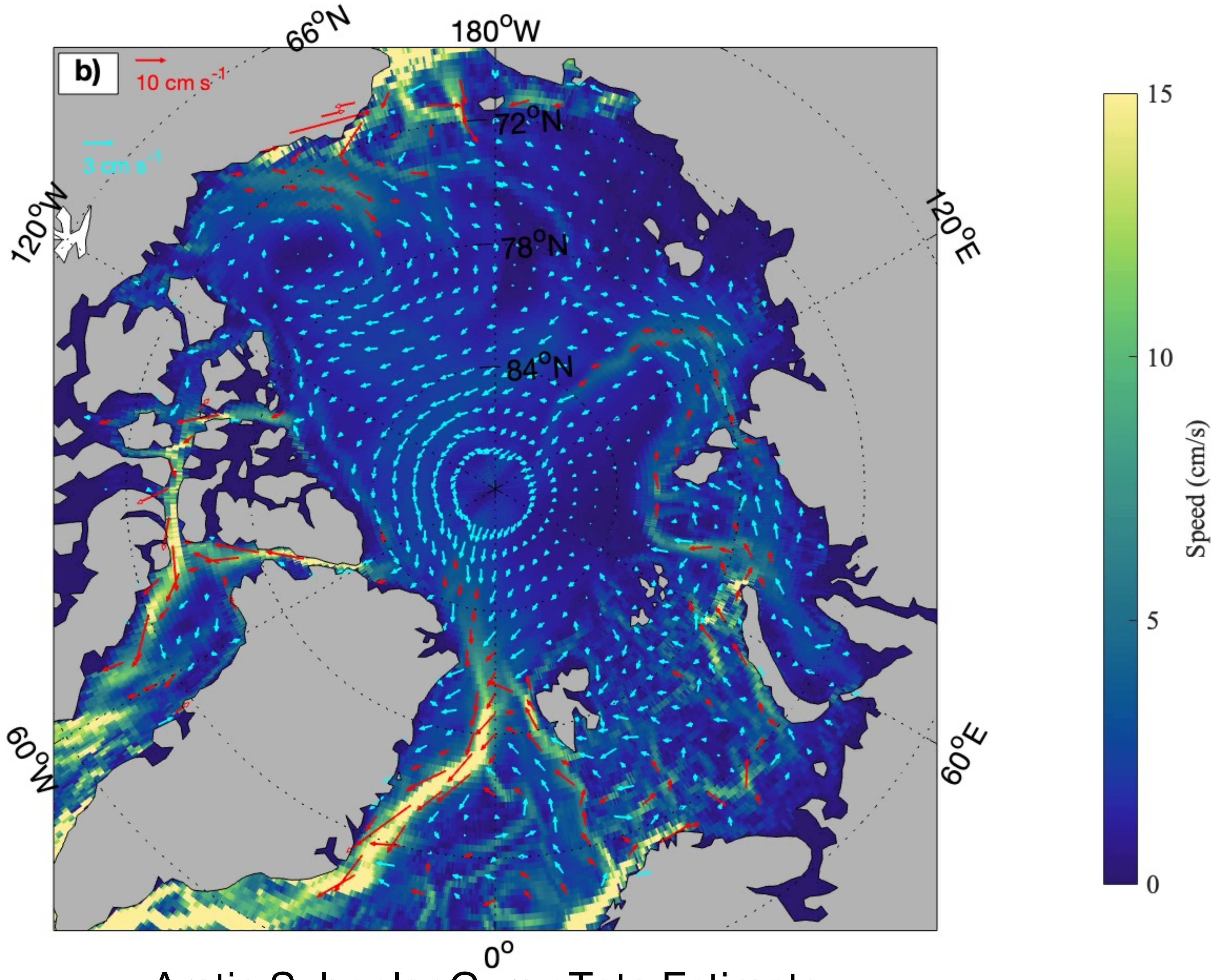
NOAA Polar Watch ERRDAP/NSIDC Climate Data Record

Model realism: Circulation

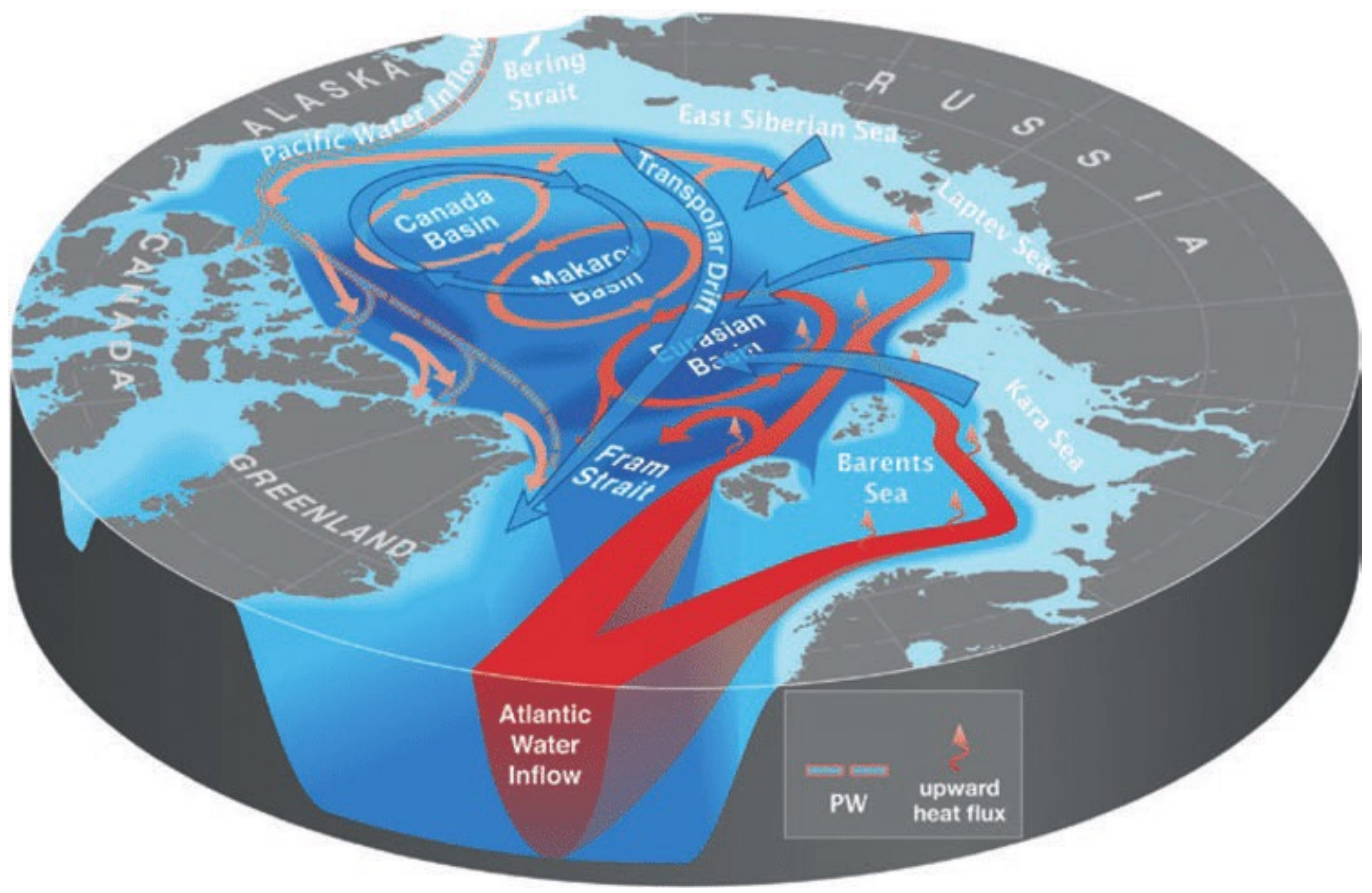
UH8to2 2017 Surface Velocities



ASTE 2017 Surface Velocities



Arctic Subpolar Gyre sTate Estimate
(Nguyen et al. 2021)



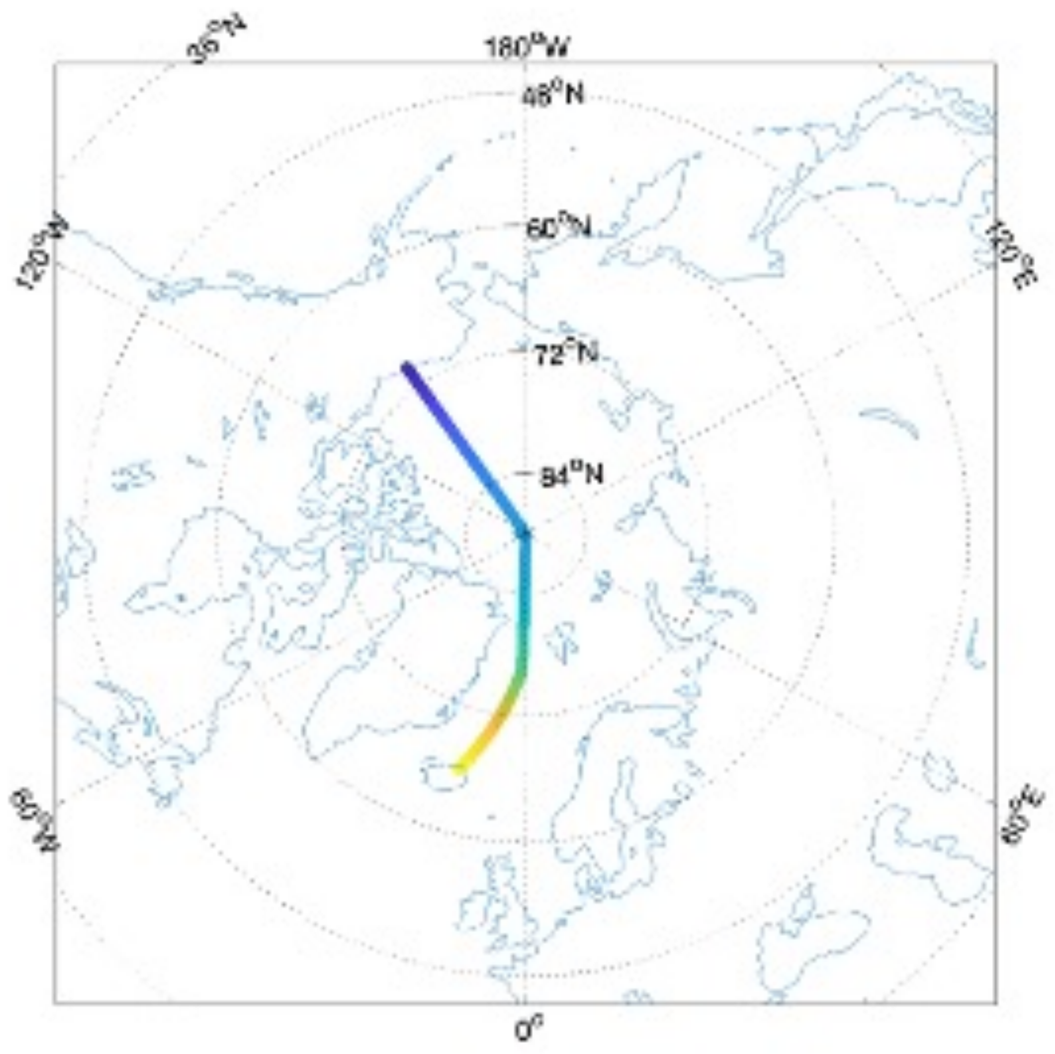
Carmack et al. 2015

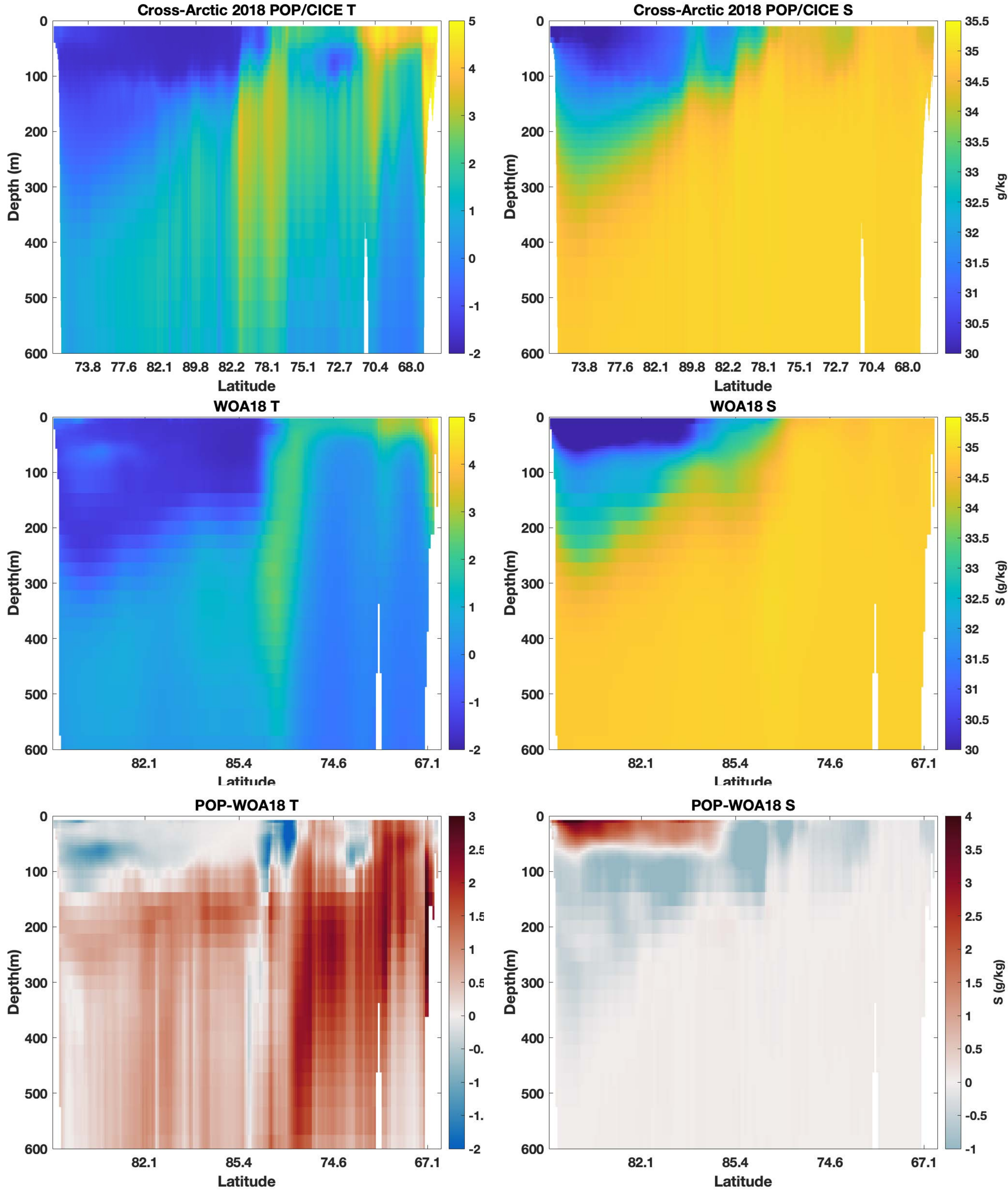
- Circulation outlines major Arctic currents: AW inflow and boundary current, Beaufort Gyre, Transpolar drift
- Velocity magnitudes larger than ASTE with more eddy variability (possibly expected at ultra-high resolution)

Model realism: Hydrography

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



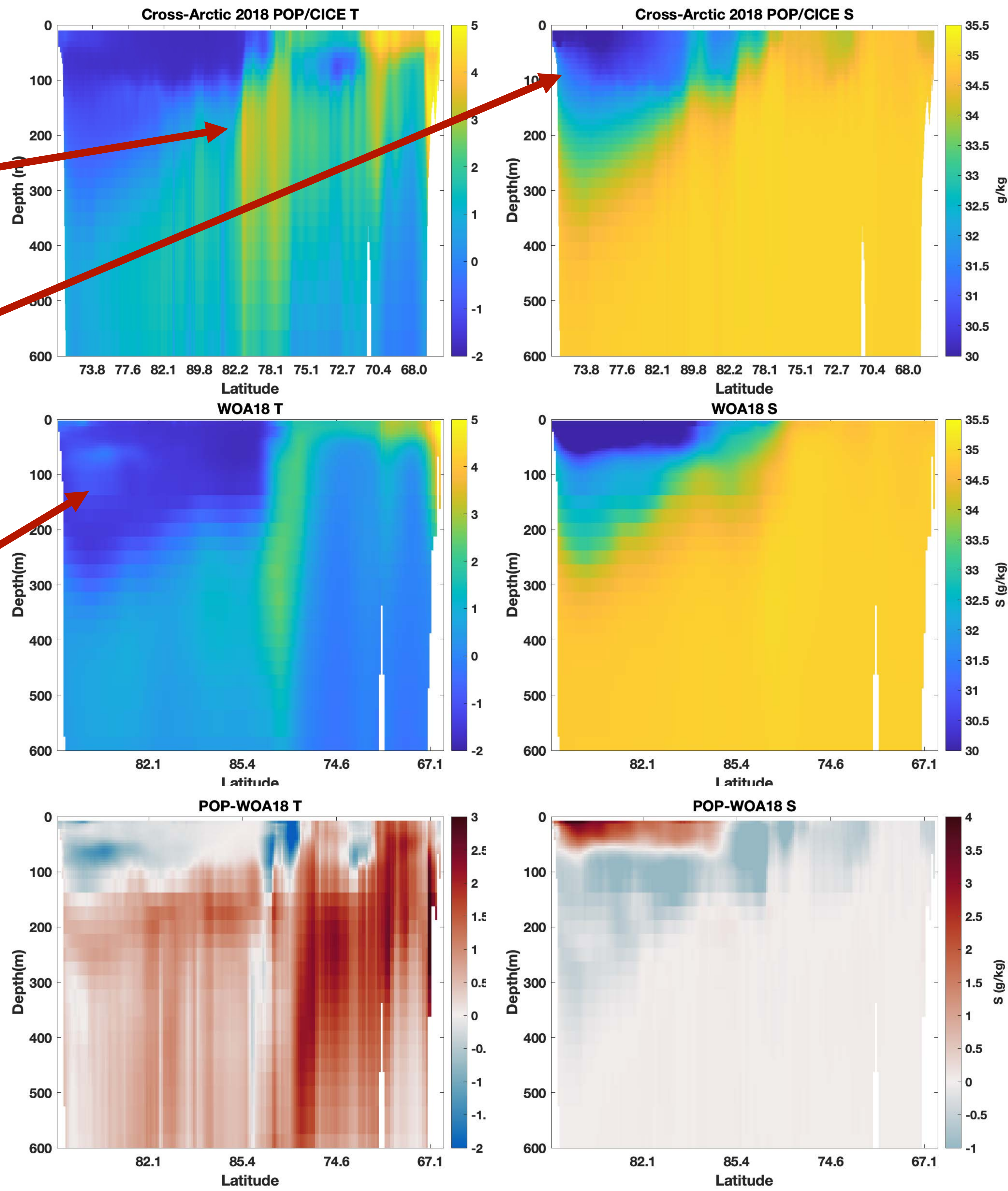


WOA18: https://www.ncei.noaa.gov/archive/accession/NCEI-WOA18

Model realism: Hydrography

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



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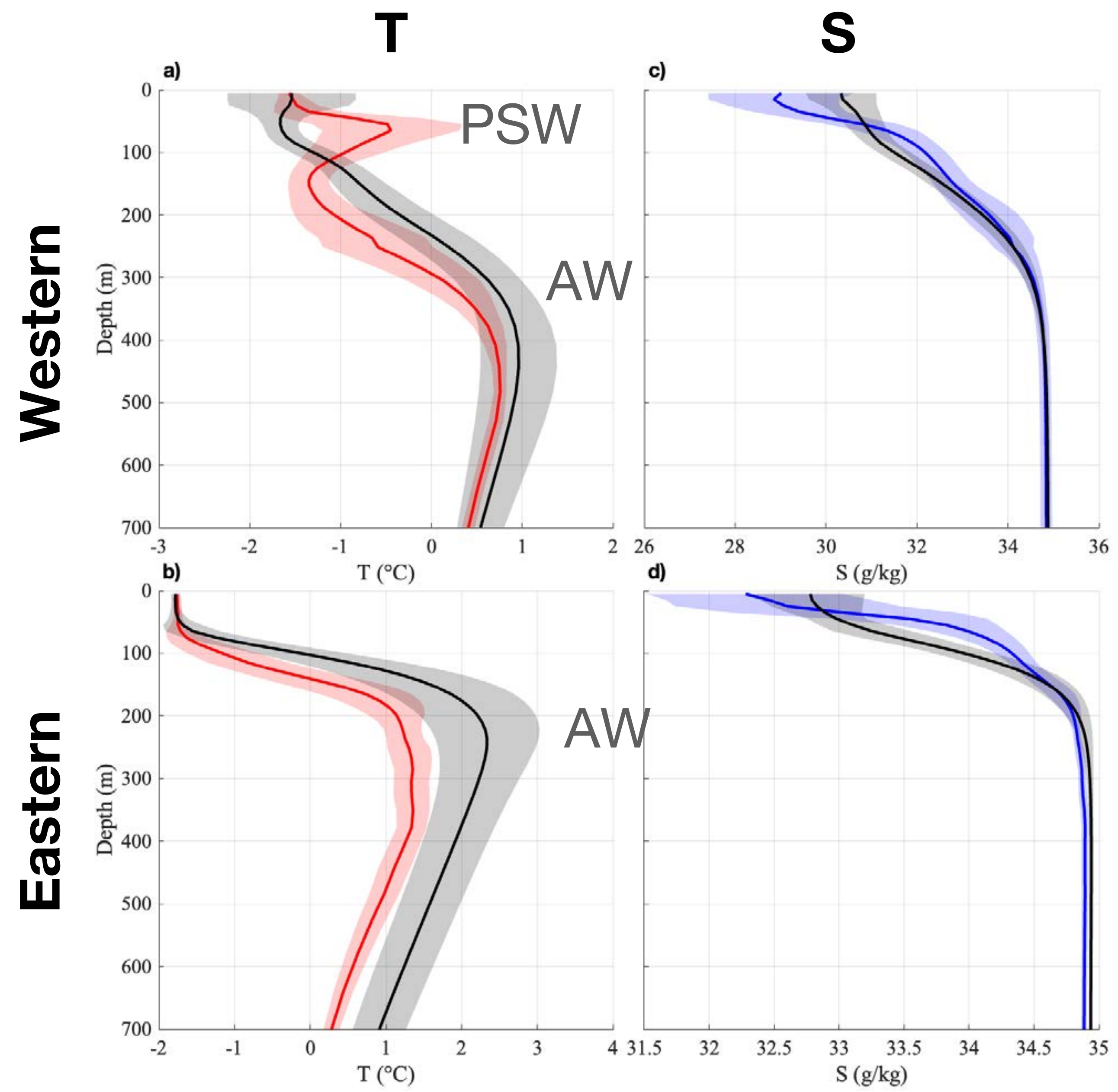
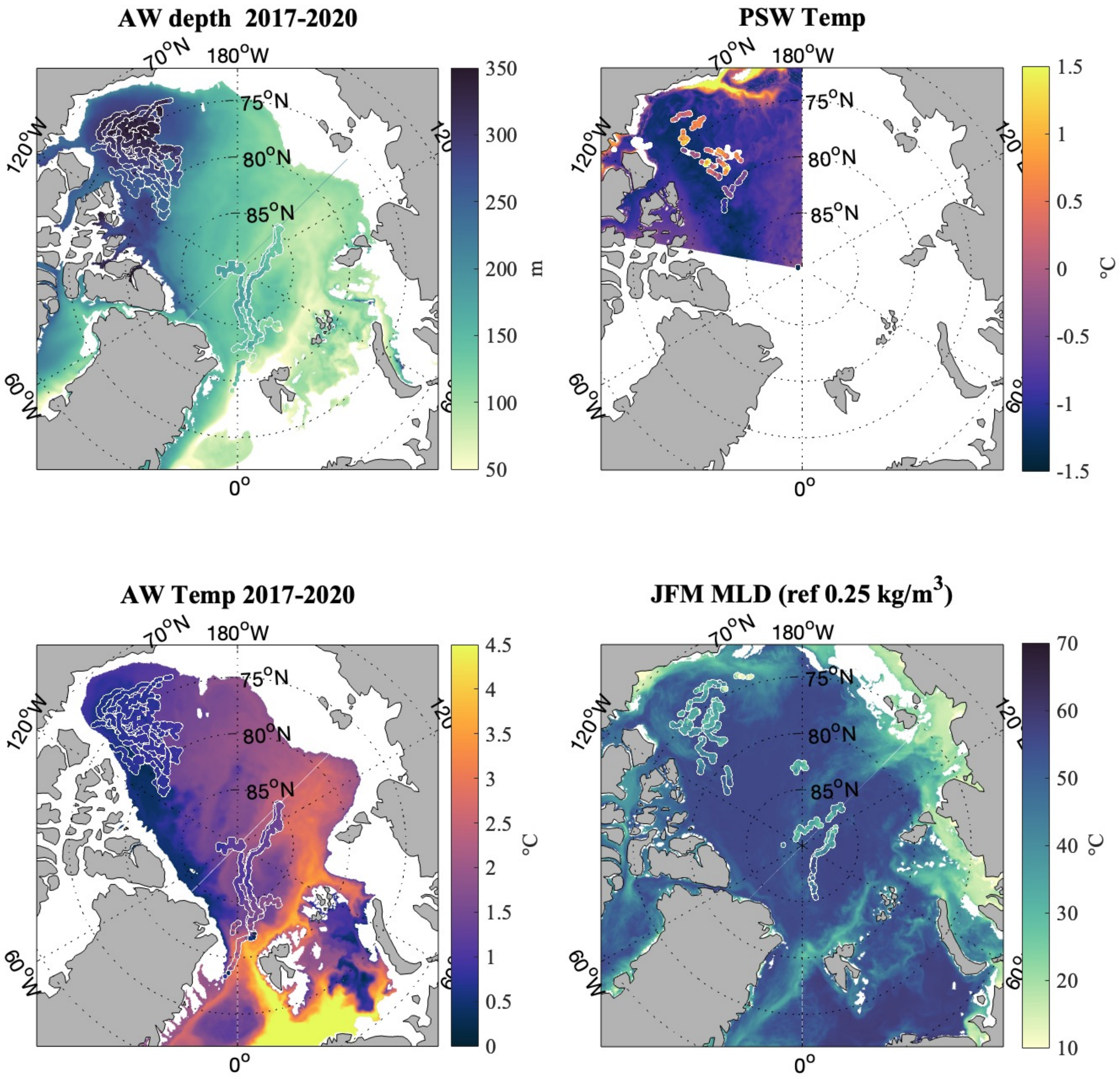
Model realism: Hydrography





Ice-tethered profiler observations show these are not simply problems with the climatology: synoptic observations find similar same model biases

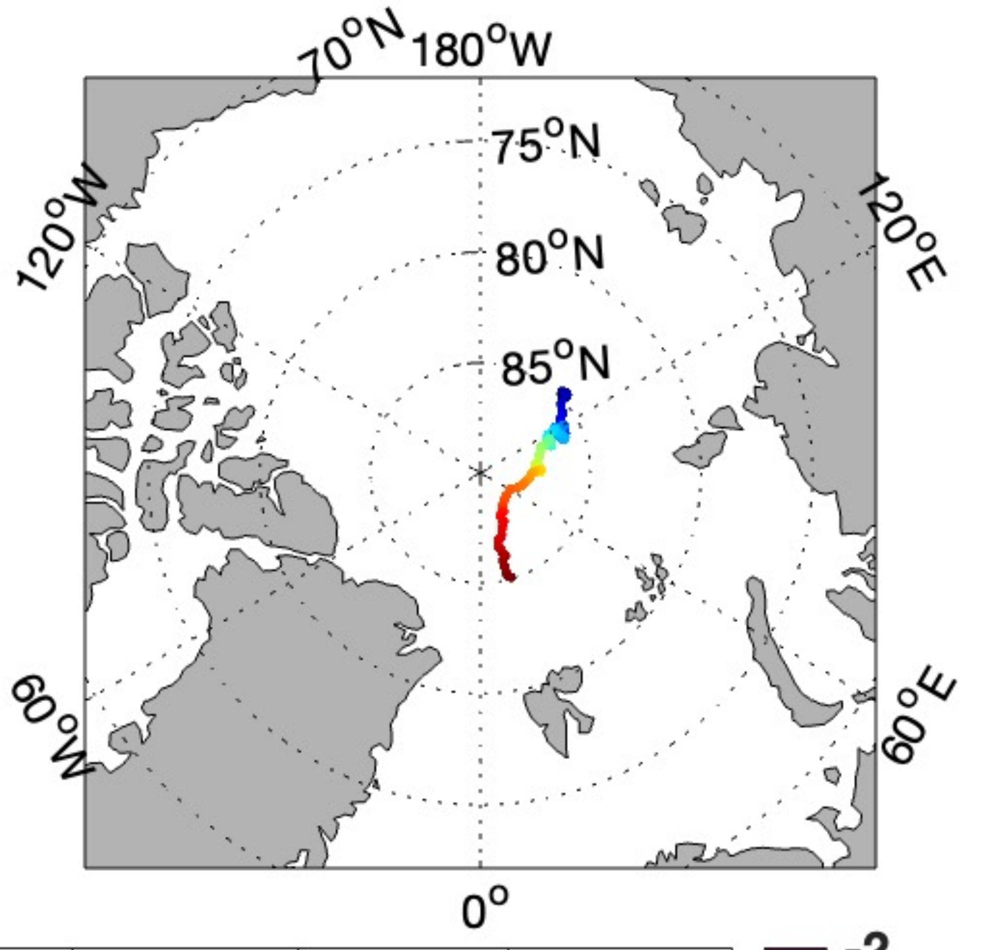
The Ice-Tethered Profiler data were collected and made available by the Ice-Tethered Profiler Program (Toole et al., 2011; Krishfield et al., 2008) based at the Woods Hole Oceanographic Institution (https://www.whoi.edu/itp).

Model realism: Summary

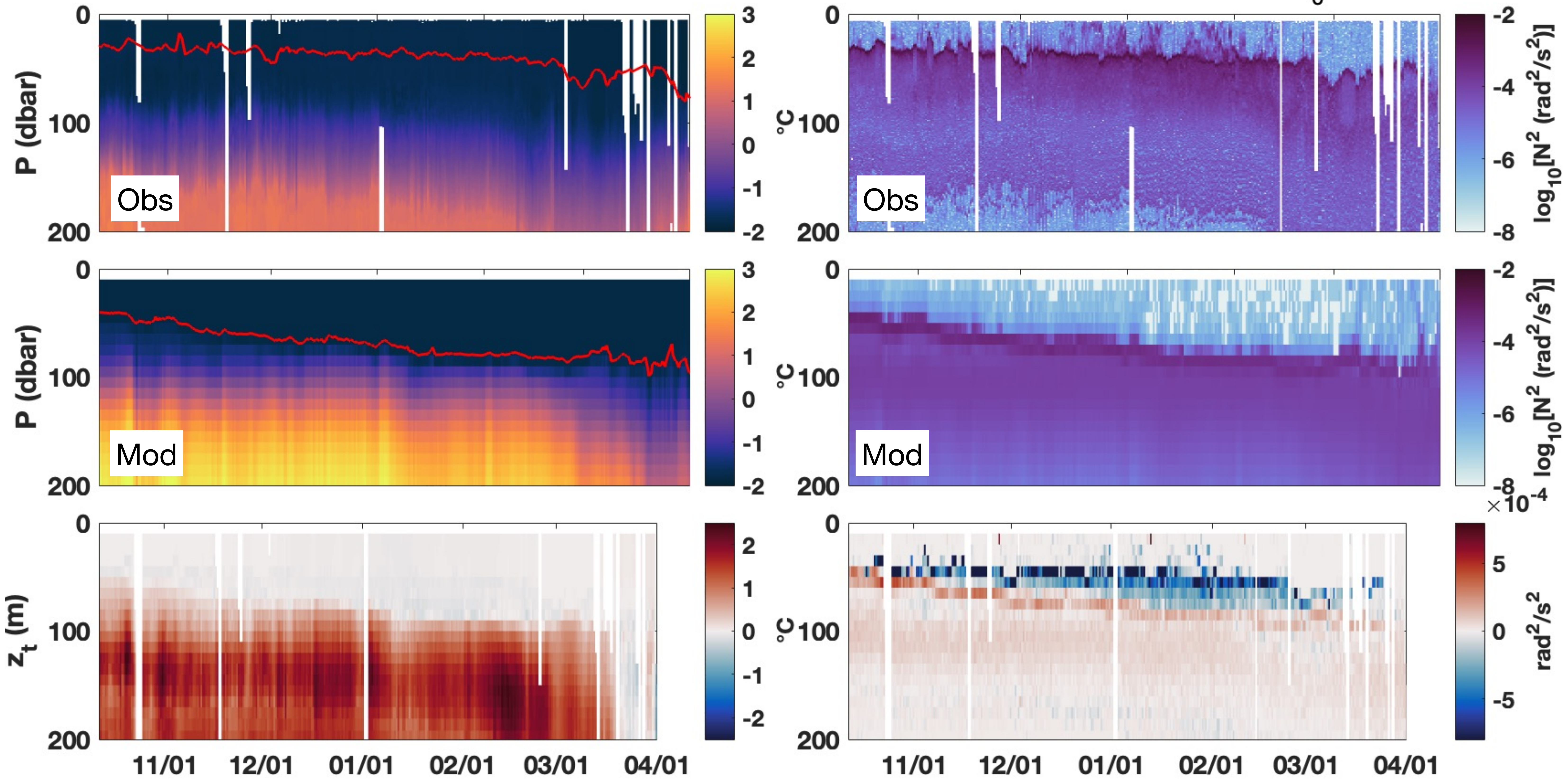
- UH8to2 sea ice generally agrees well with observations, with a bias towards low ice in the summer, particularly in the eastern Arctic
- Velocities reproduce known current pathways, and gateway fluxes are within observational bounds
- Water masses appear as expected, with a few discrepancies:
  - Atlantic 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

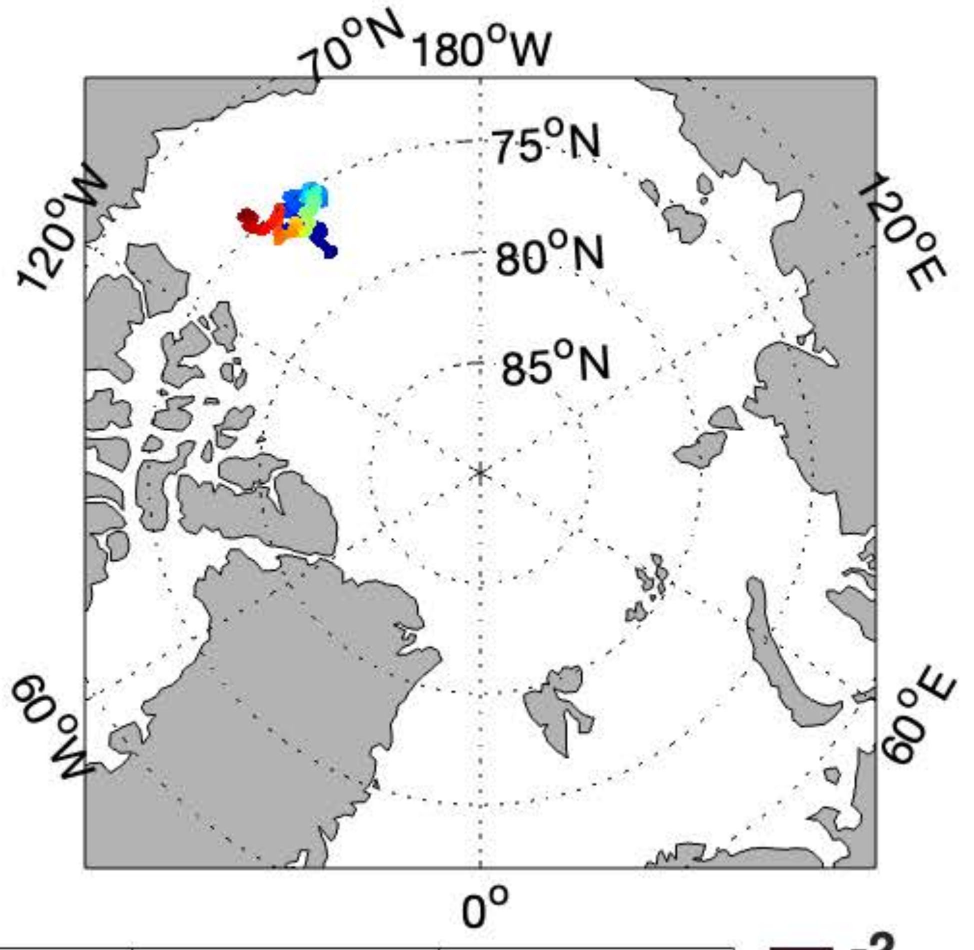


- In ITP observations, the deepening mixed layer is separated from the warm Atlantic water beneath by a cool halocline layer
- Model AW is warmer and closer to the surface, just below the (deeper) mixed layer
- Potential for excess entrainment of warm AW in model

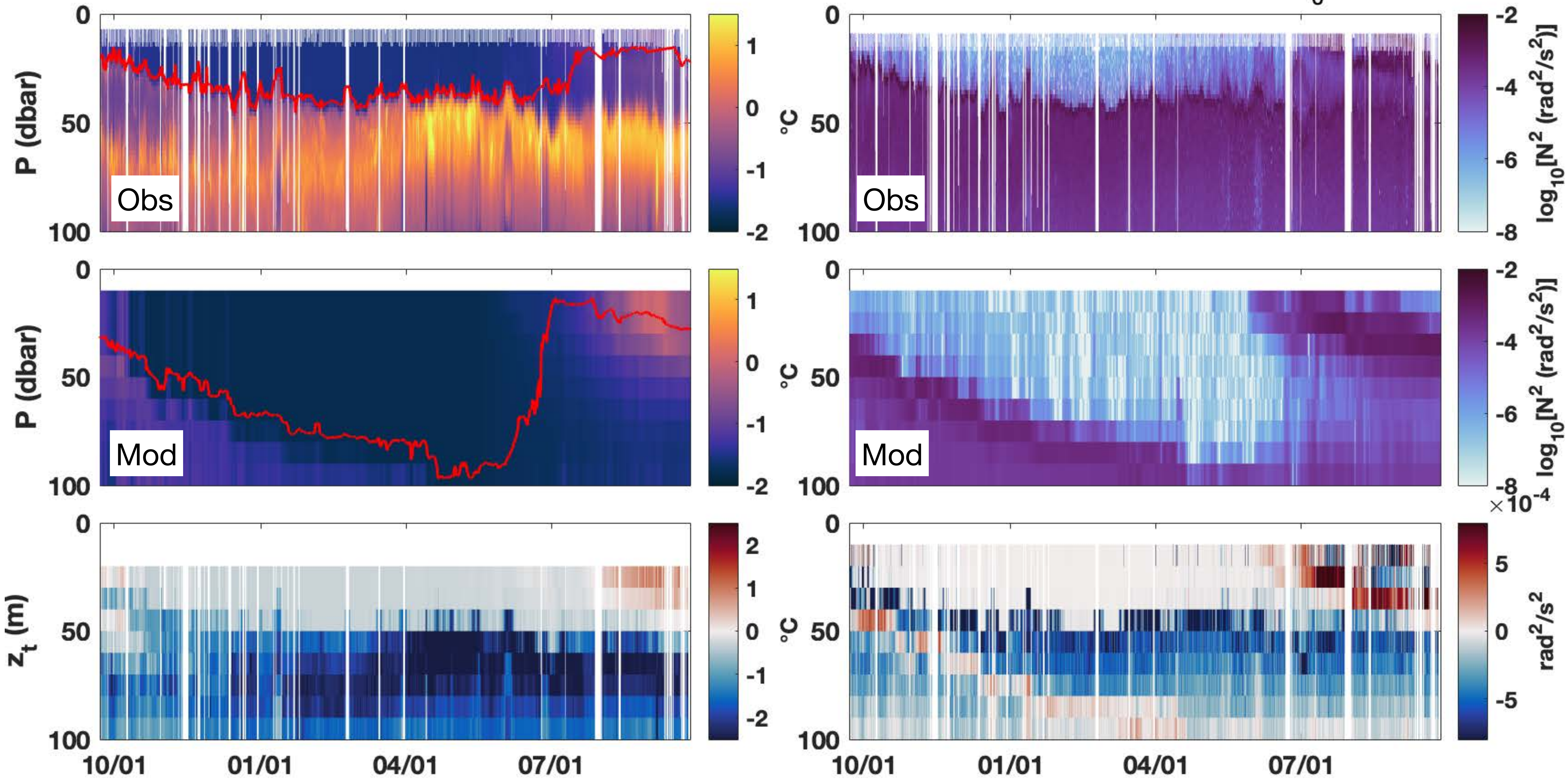


Potential sea ice impacts: Western Arctic

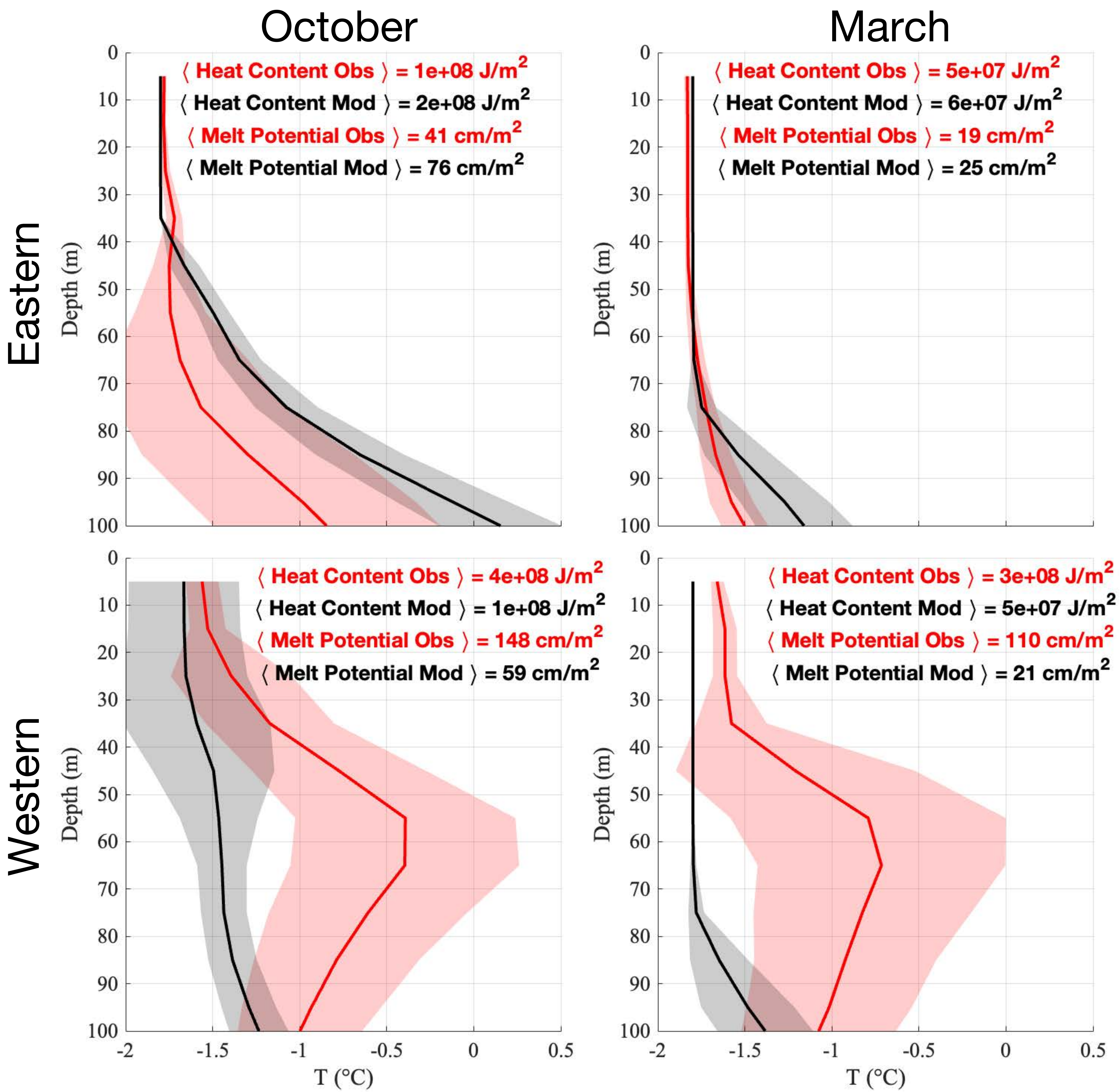
- ITP #114 drifted in western Arctic from 10/2019-8/2020
- This period includes the winter deepening of the mixed layer, and then summer restratification



- 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/m^2
  - Obs Δ potential ice melt = 22 cm/m^2
- 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/m^2
  - Obs Δ potential ice melt = 38 cm/m^2

Summary and discussion

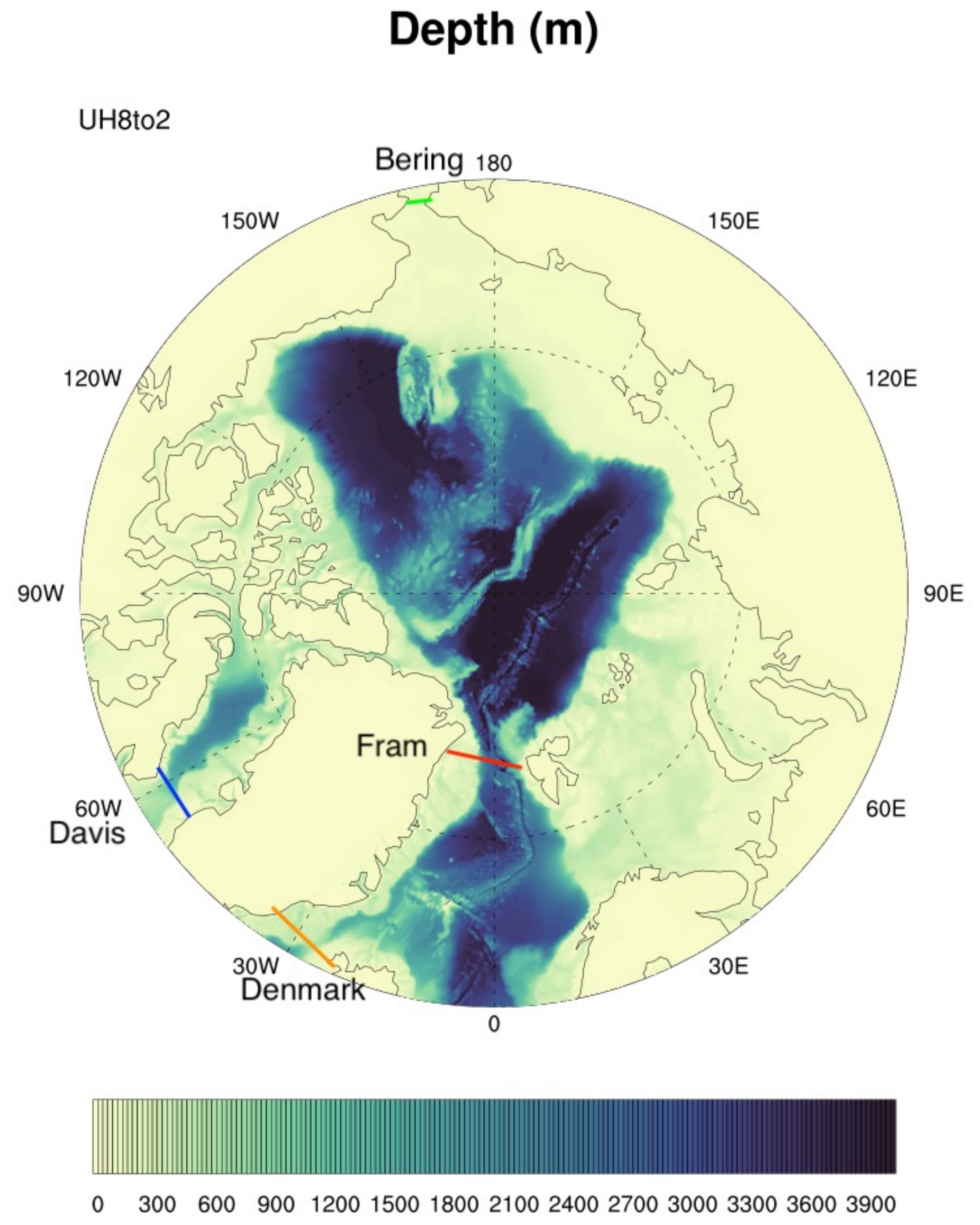
- Ultra-high resolution model largely reproduces Arctic circulation and water mass properties accurately, with some biases
  - Model biases are consistent with hypothesized climate feedbacks: weaker stratification and deeper mixed layers occur alongside reduced sea ice
- While model ice field agrees relatively well with observations, discrepancies in upper ocean (top 100 m) heat content are significant
  - 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

Model realism: Arctic gateway transports

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

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