Arctic Observing System Simulation Experiments within the Navy Global Ocean Forecasting System GOFS3.5

Large-scale and mesoscale ocean circulation in a high-resolution HYCOM2.3-CICE5 simulation

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Arctic Observing System Simulation Experiments (OSSEs)

OSSE basic principle: (a) assimilate synthetic observations subsampled from realistic high-resolution free-runs ("the **nature runs**") to:

- Assess benefits from expansions of the existing observing systems
- Identify / develop methodologies to incorporate data types not previously assimilated
  - ✓ Sea ice thickness
  - ✓ Snow cover
- Evaluate sensitivity of the operational forecasts to proposed new instrumentation designed for persistent robotic observing systems in the Arctic (e.g., Arctic Mobile Observing System)
  - ✓ Argo-like instruments under the ice (deep ocean)
  - ✓ Tethered under-ice measurements
  - ✓ Multiple unmanned platforms (under-ice navigating autonomous platforms)
  - ✓ Surface drifters in ocean and ice

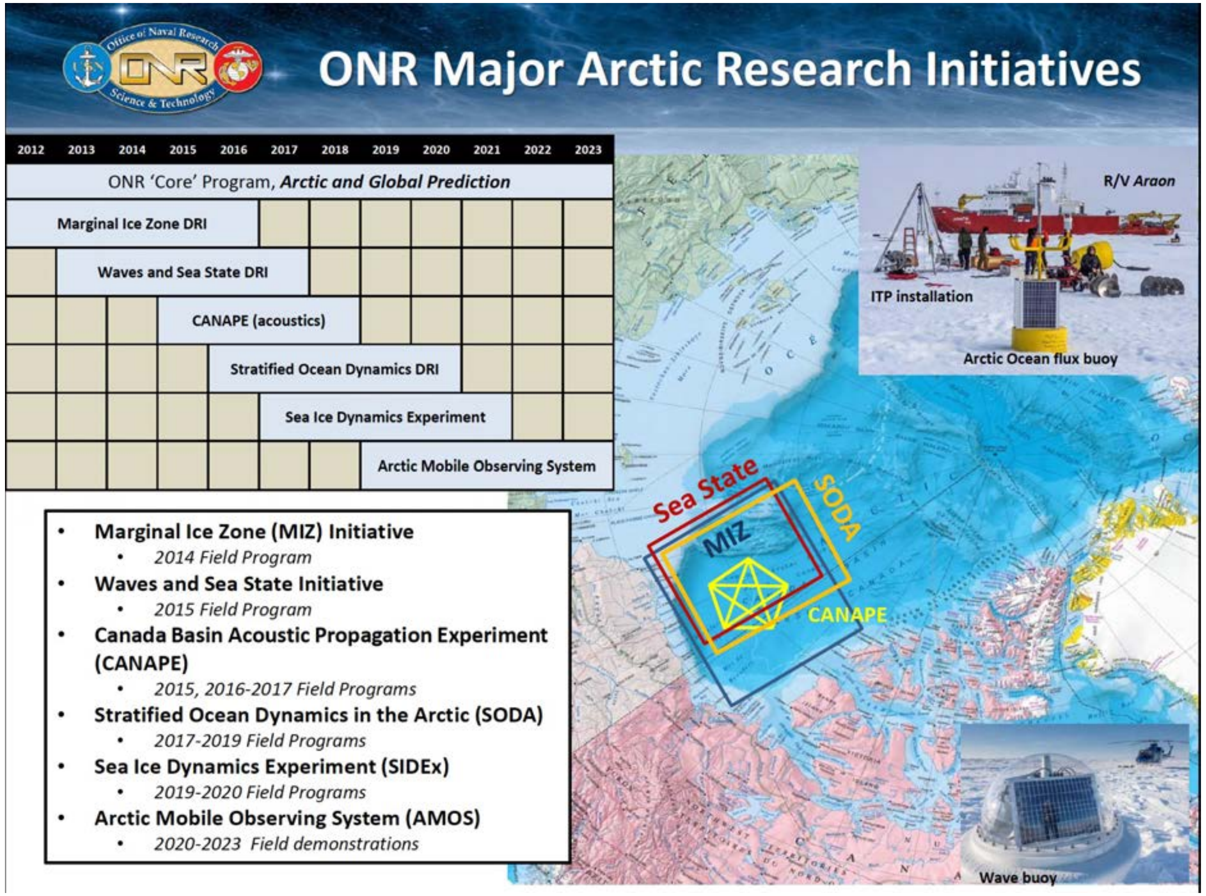
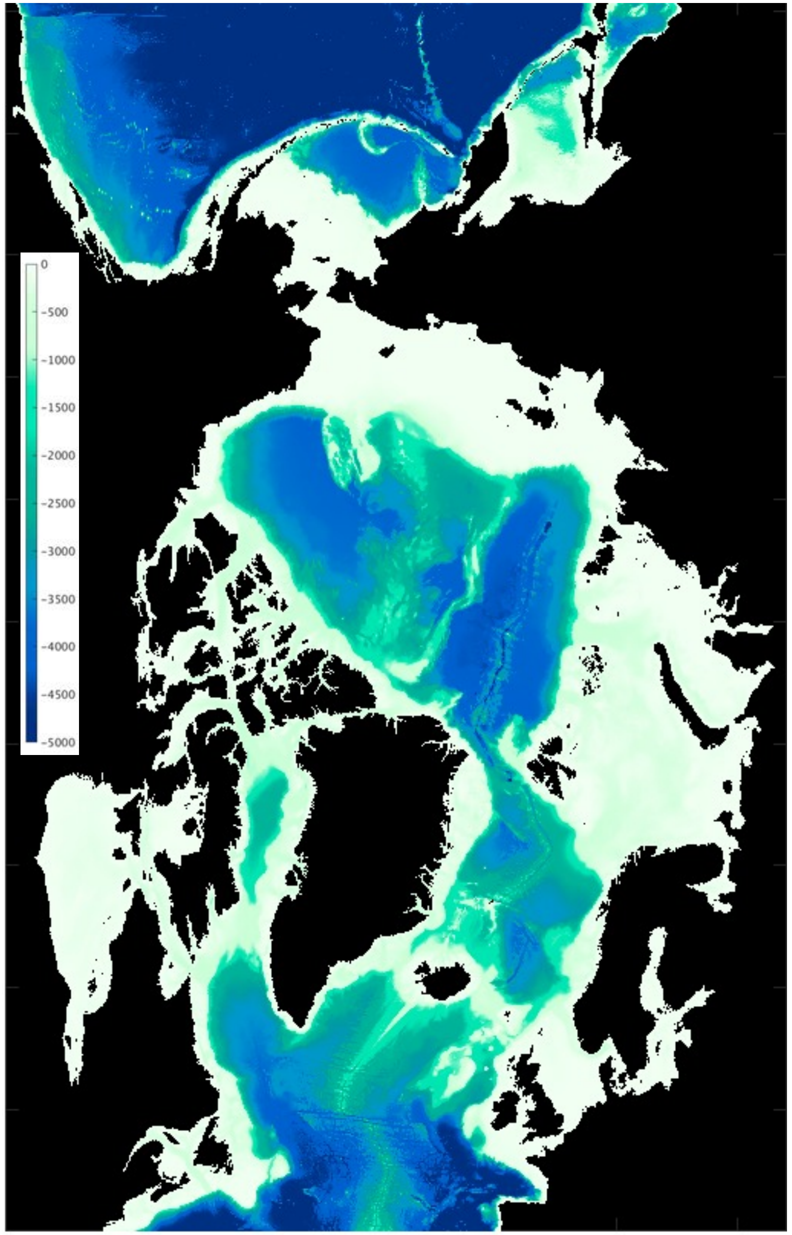


Figure courtesy of Scott Harper (ONR)

OSSE basic principle: (b) the nature run becomes the "truth" that we are trying to reproduce => the nature run needs to be close to the observations

Regional Arctic Ocean 0.04° HYCOM-CICEv5

Model Bathymetry

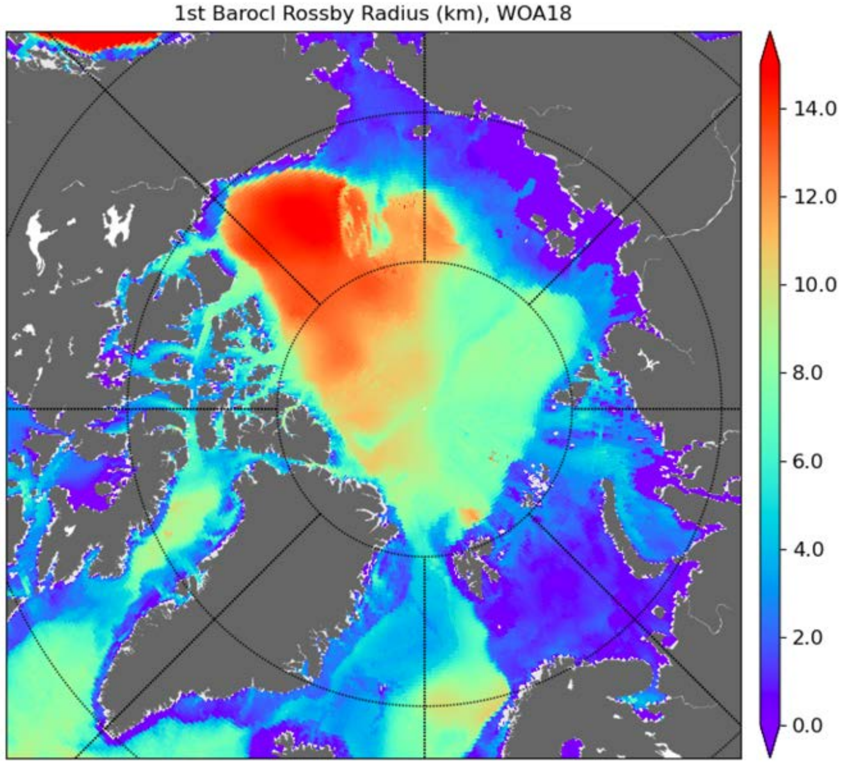


- **Ocean Model:** Hybrid Coordinate Ocean Model (HYCOM) v2.2.99/2.3
- **Sea Ice Model:** LANL Sea ice code (CICEv5)
- **Vertical Grid:** 41 hybrid layers
- **Horizontal Grid:** 0.04º (<2 km in the Arctic Ocean)
- **Initial fields:** 0.04° Global GOFS3.5 analysis
- **CICE:** 5 ice categories, 4 ice layers, 1 snow layer
- **Atmospheric forcing:** (1) CFSR/CF 2 fields
  (2) JRA55
- **Lateral OBs:** GOFS3.5 0.04° Global HYCOM+NCODA
- **Greenland Runoff:** Monthly data of *Bamber* (2018)
  >200 freshwater sources
- **Rivers:** Monthly runoff UCAR/NCAR data set; 2016 is used for 2016–2020

Bathymetry:
GEBCO: 30-arc second interval grid

Regional Arctic Ocean 0.04° HYCOM-CICEv5

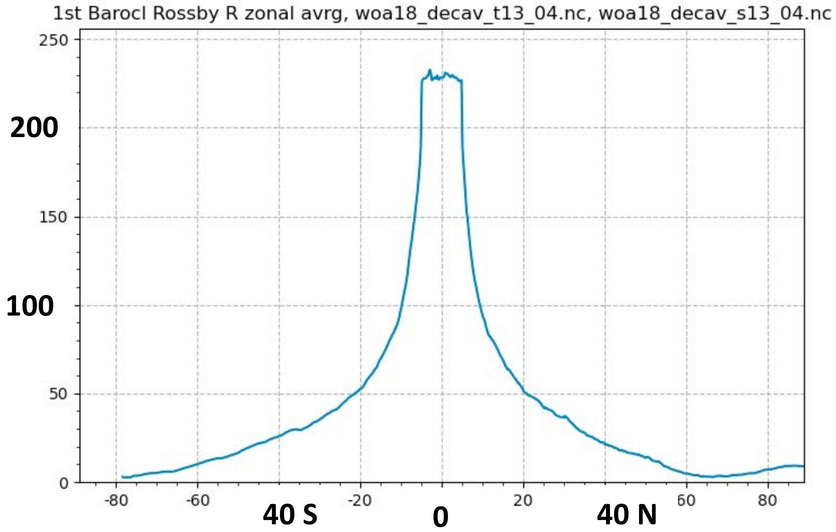
The 1st Baroclinic Rossby Radius of Deformation (km) computed from the 0.25° NOAA NCEI WOA18 (winter)



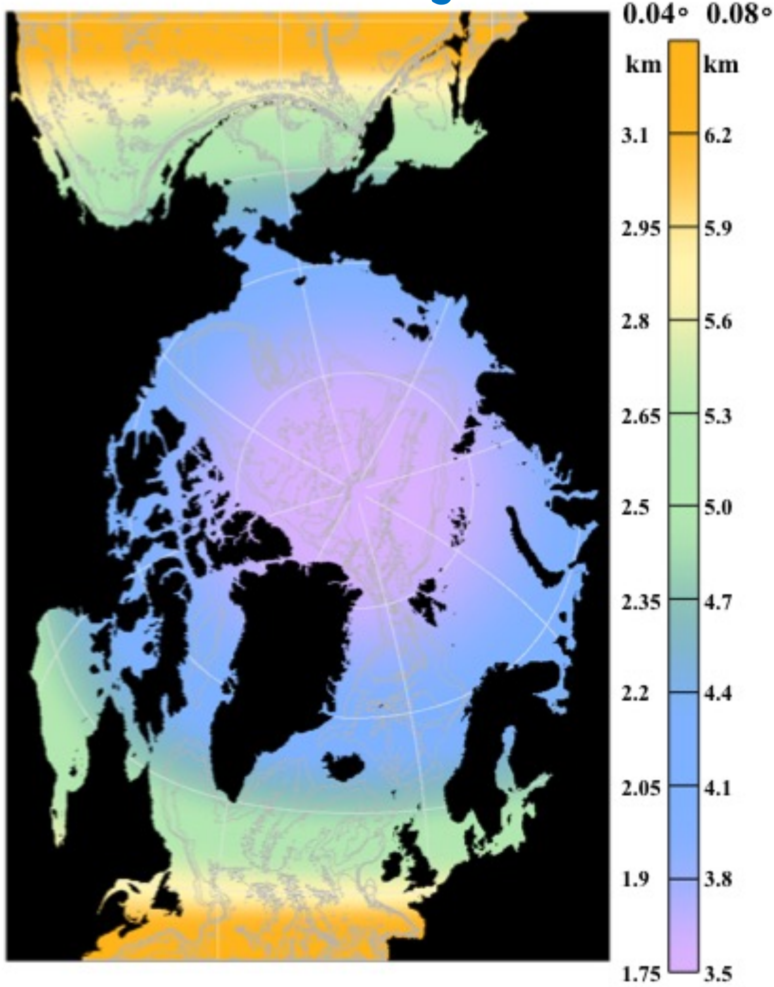
/home/ddmitry/codes/PYTHON/rossby/plot_rrossby_topo.py

- "Eddy-resolving" grid: model horizontal grid spacing should be at least two grid points per Rossby radius of deformation and the grid spacing is measured as the grid-diagonal distance (Hallberg, 2013).
- Eddy-resolving model for the Arctic Ocean:
  ~2.5 km in the deep Nordic Seas
  ~4-5 km in the deep Arctic Ocean
  ~4-5 km in the SPNA

The global zonally averaged 1st baroclinic Rossby radius (km)

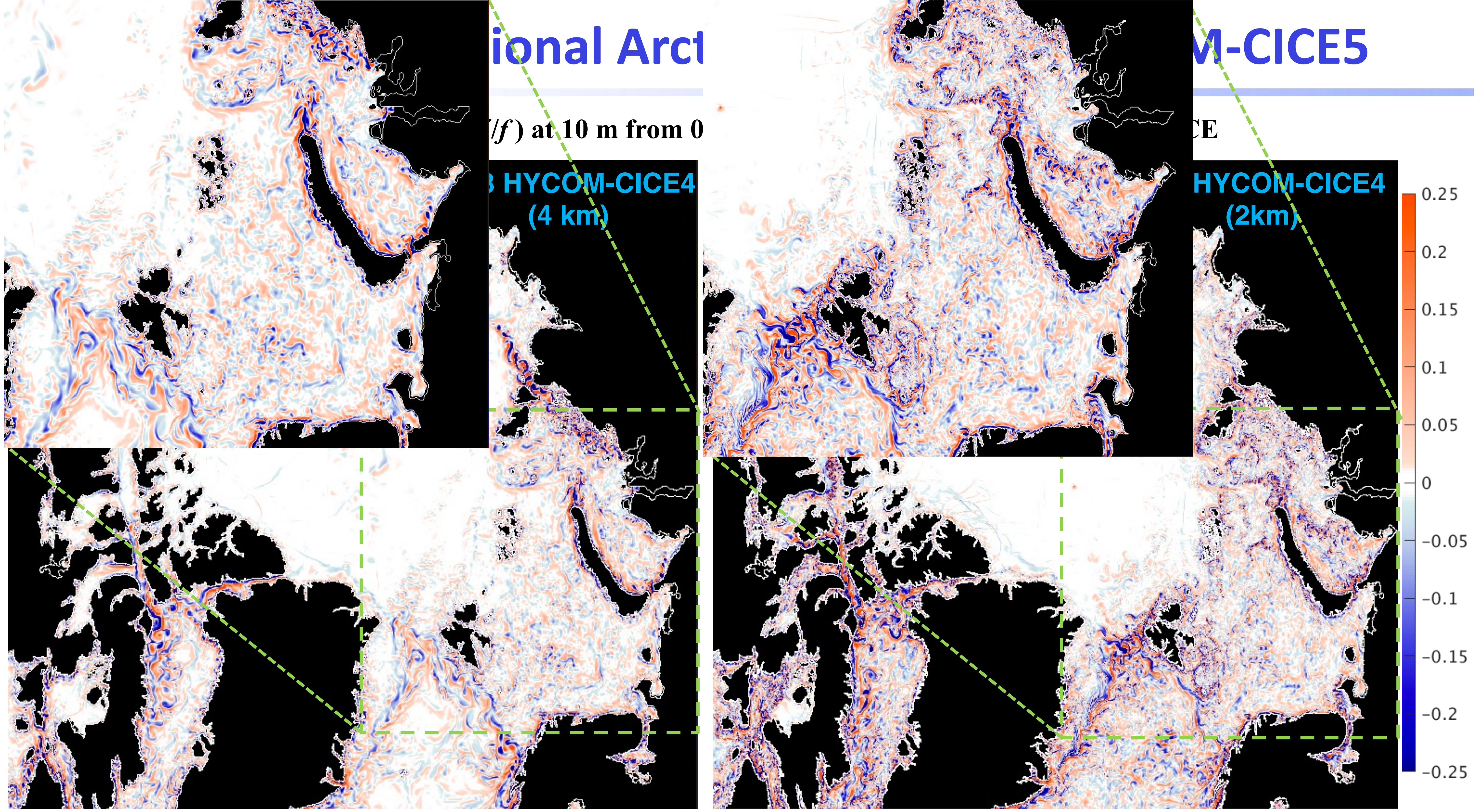


Grid spacing for 0.08° and 0.04° configurations



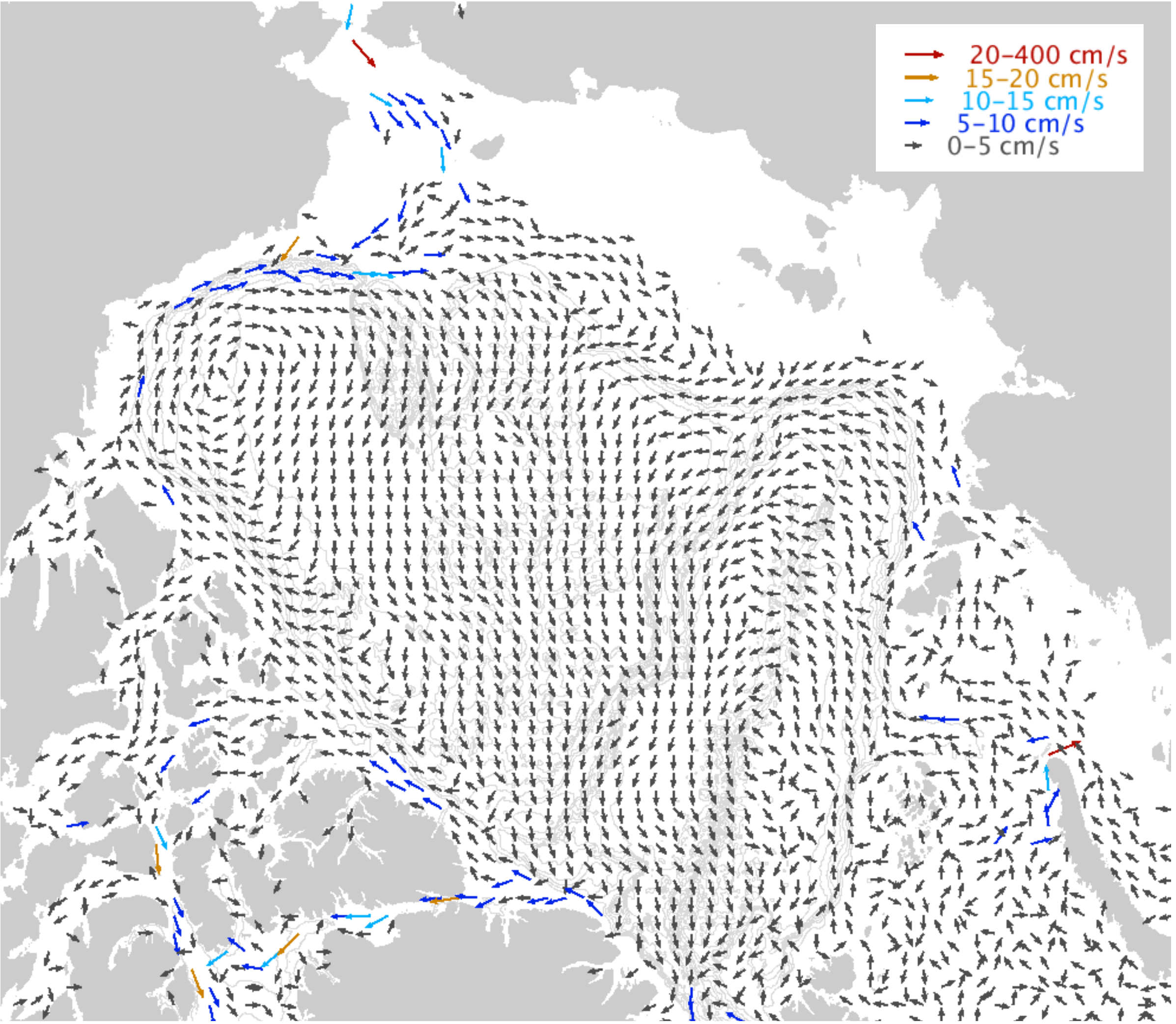
0.04 Grid Resolution:

Central Arctic:	~1.8 km
Subpolar Seas:	2.2–2.4 km

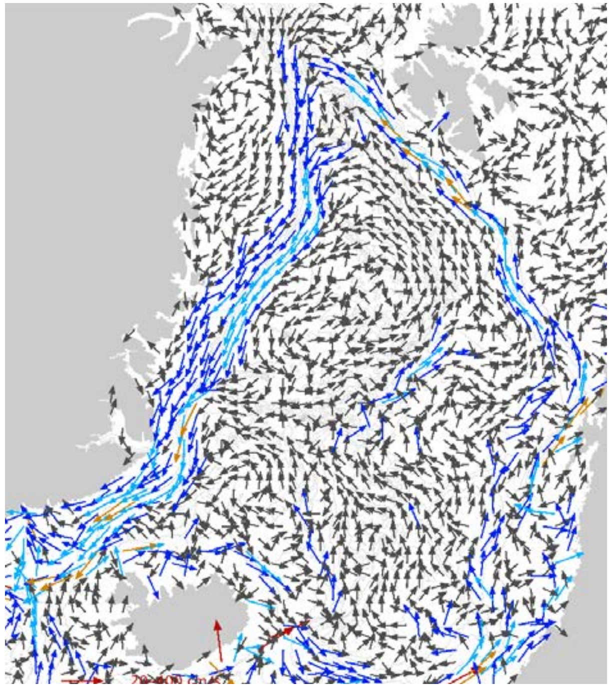

ional Arct
M-CICE5
/f) at 10 m from 0
CE
HYCOM-CICE4
(4 km)
HYCOM-CICE4
(2km)
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25

Mean surface (50 m) velocity vectors (2018-2020) in HYCOM2.3-CICE5

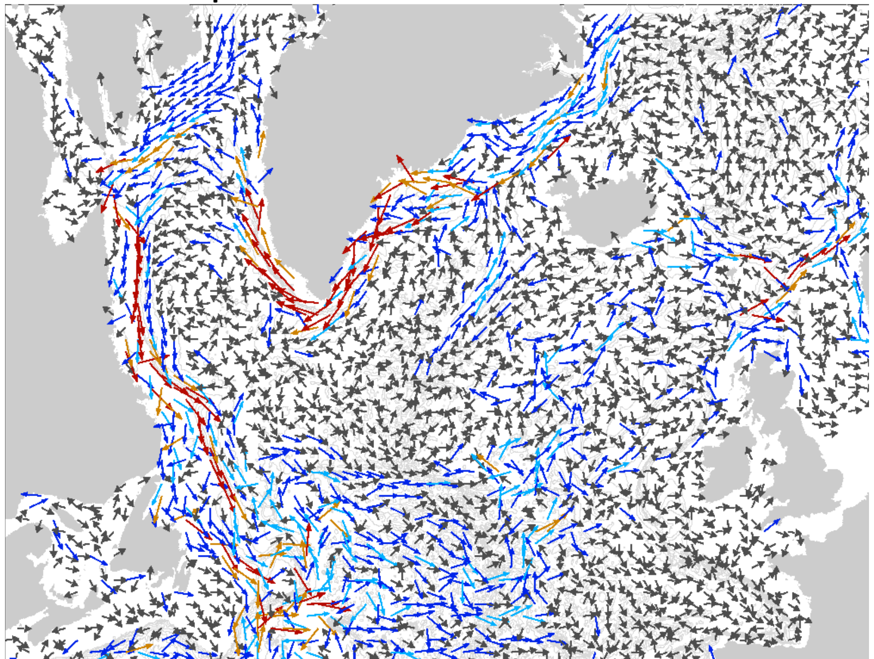
Arctic Ocean



Nordic Seas

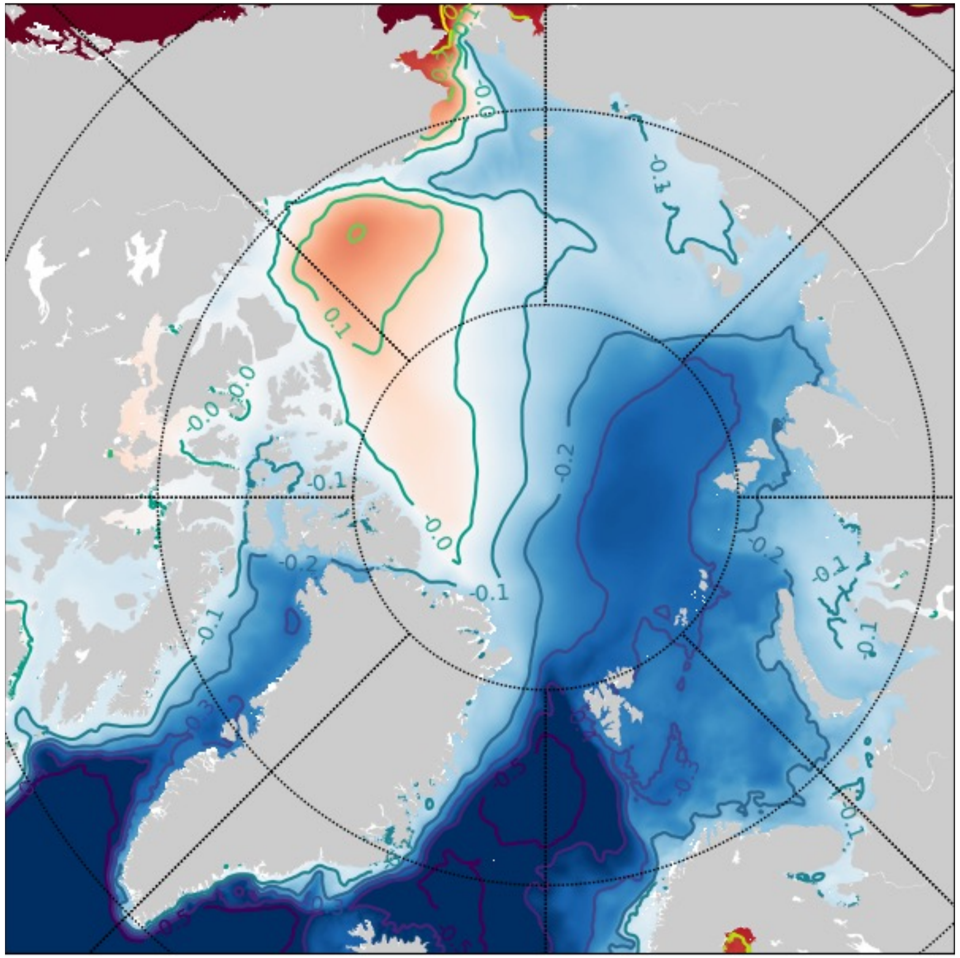


Subpolar North Atlantic

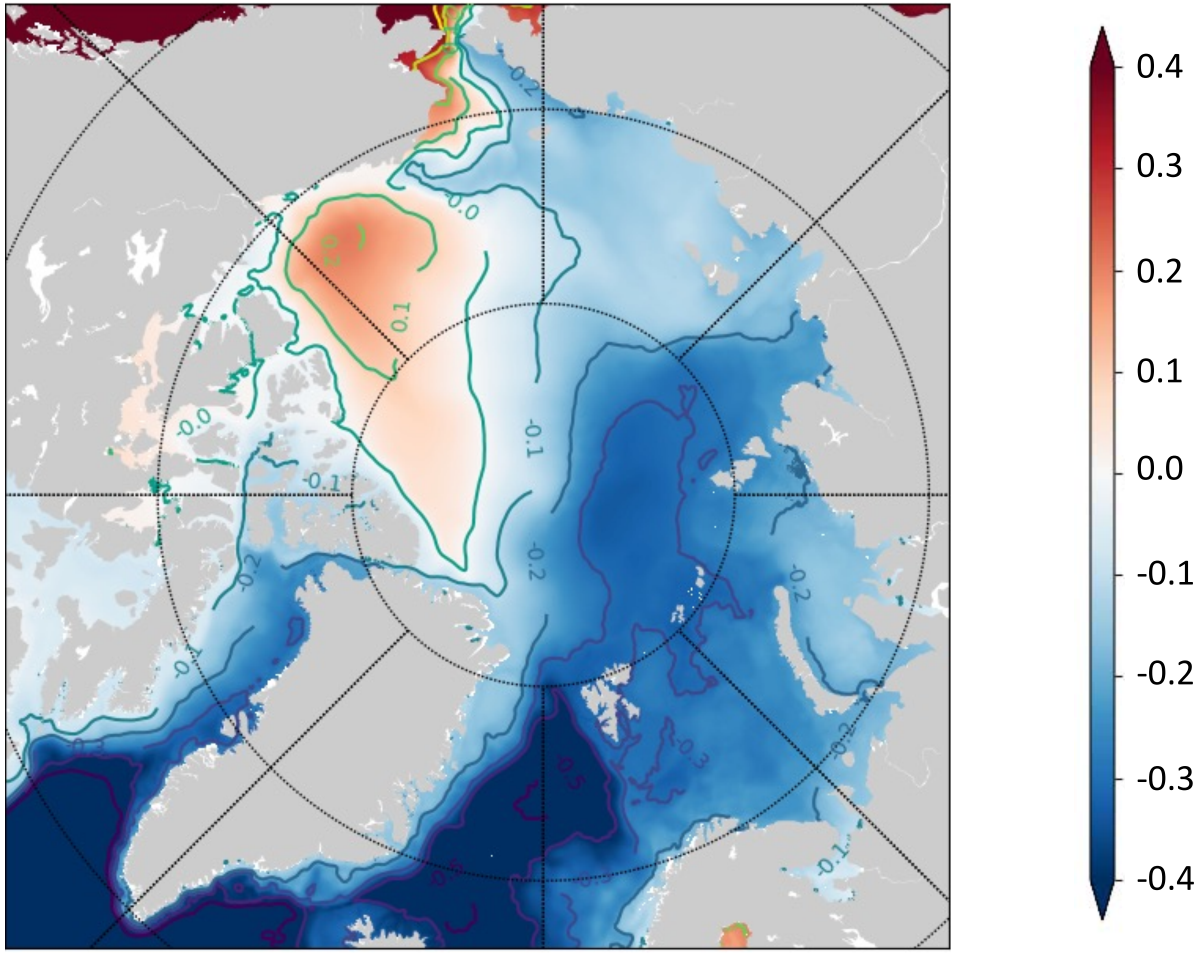


Mean sea surface height in HYCOM-CICE5

Winter SSH
2017-2020



Summer SSH
2017-2020

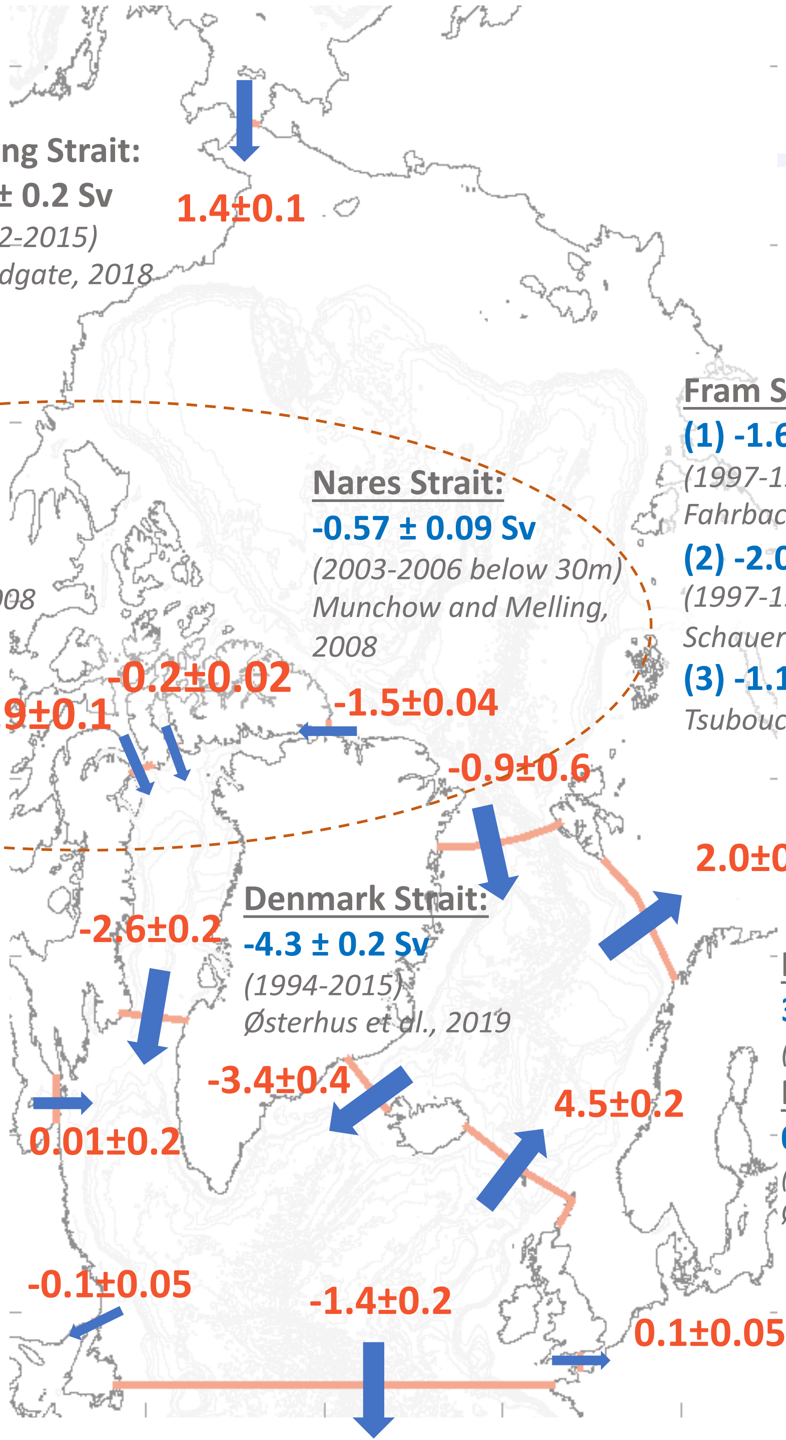


Volume Transport Estimates from the HYCOM-CICE5 (2017-2020)

Ratio of volume fluxes through CAA

Observations
(Peterson et al., 2012):
LS=0.35
JS=0.23
NS=0.43

HYCOM-CICE:
LS=0.35
JS=0.08
NS=0.57



Bering Strait:
1.0 ± 0.2 Sv
(2002-2015)
Woodgate, 2018

Jones Sound:
-0.3 ± 0.09 Sv
Melling et al., 2008

Nares Strait:
-0.57 ± 0.09 Sv
(2003-2006 below 30m)
Munchow and Melling, 2008

Lancaster Sound:
-0.46 ± 0.09 Sv
(1998-2011)
Peterson et al., 2012

Fram Strait:
(1) -1.6 ± 2.7 Sv
(1997-1999)
Fahrbach et al., 2001
(2) -2.0 ± 2 Sv
(1997-1999)
Schauer et al., 2004
(3) -1.1 ± 1.2 Sv
Tsubouchi et al., 2018

Barents Sea Opening:
2.3 ± 1.2 Sv
(2005-2006)
Tsubouchi et al., 2018

Davis Strait:
-1.6 ± 0.5 Sv
(2004-2010)
Curry et al., 2014

Denmark Strait:
-4.3 ± 0.2 Sv
(1994-2015)
Østerhus et al., 2019

Iceland-Faroe:
3.4 ± 0.6 Sv
(1993-2015)

Faroe-Shetland:
0.5 ± 0.6 Sv
(2006-2013)
Østerhus et al., 2019

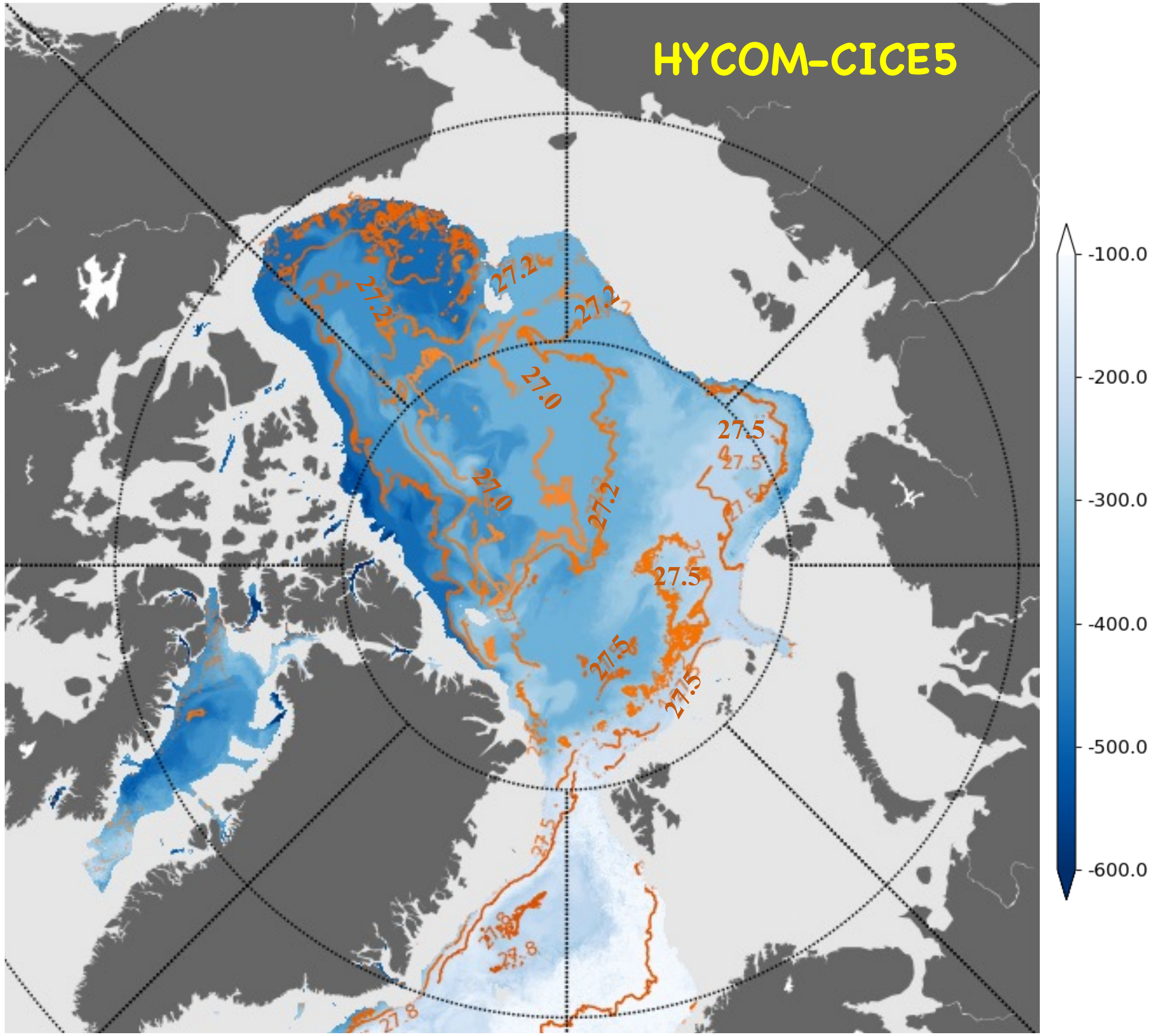
Hudson Strait:
0.11 ± 0.24 Sv
(08/1982-10/1982)
Drinkwater, 1988

Strait of Belle Isle
-0.13 Sv
(Jul-Oct 1980)
Petrie et al., 1988

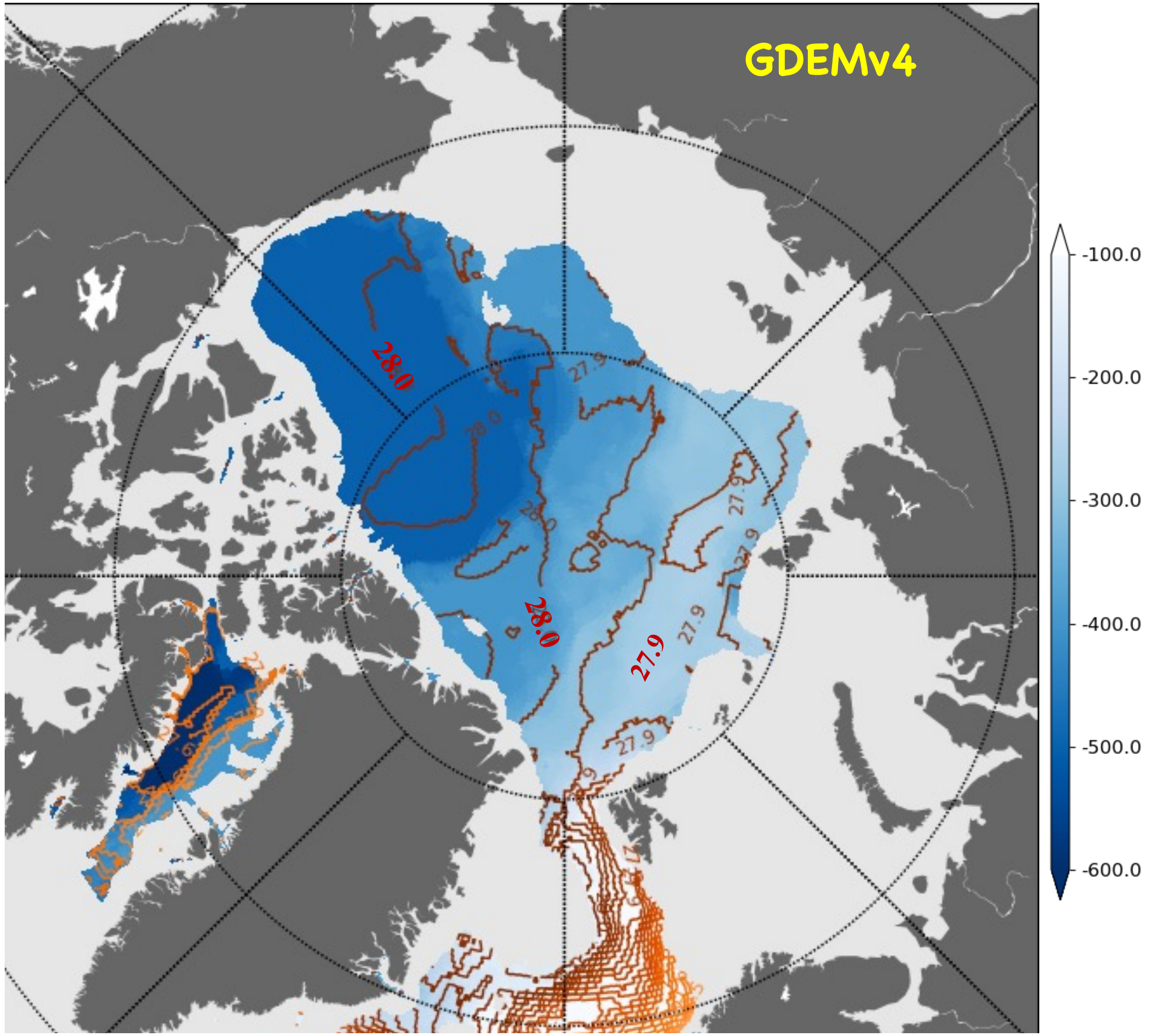
Shetland-Scotland and La Manche:
0.6 ±0 .6 Sv
(1993-2015)

Atlantic Layer

Depth of t_{max} (m)
Contours: $\sigma_0(z_{t_{max}})$ (kg/m³)

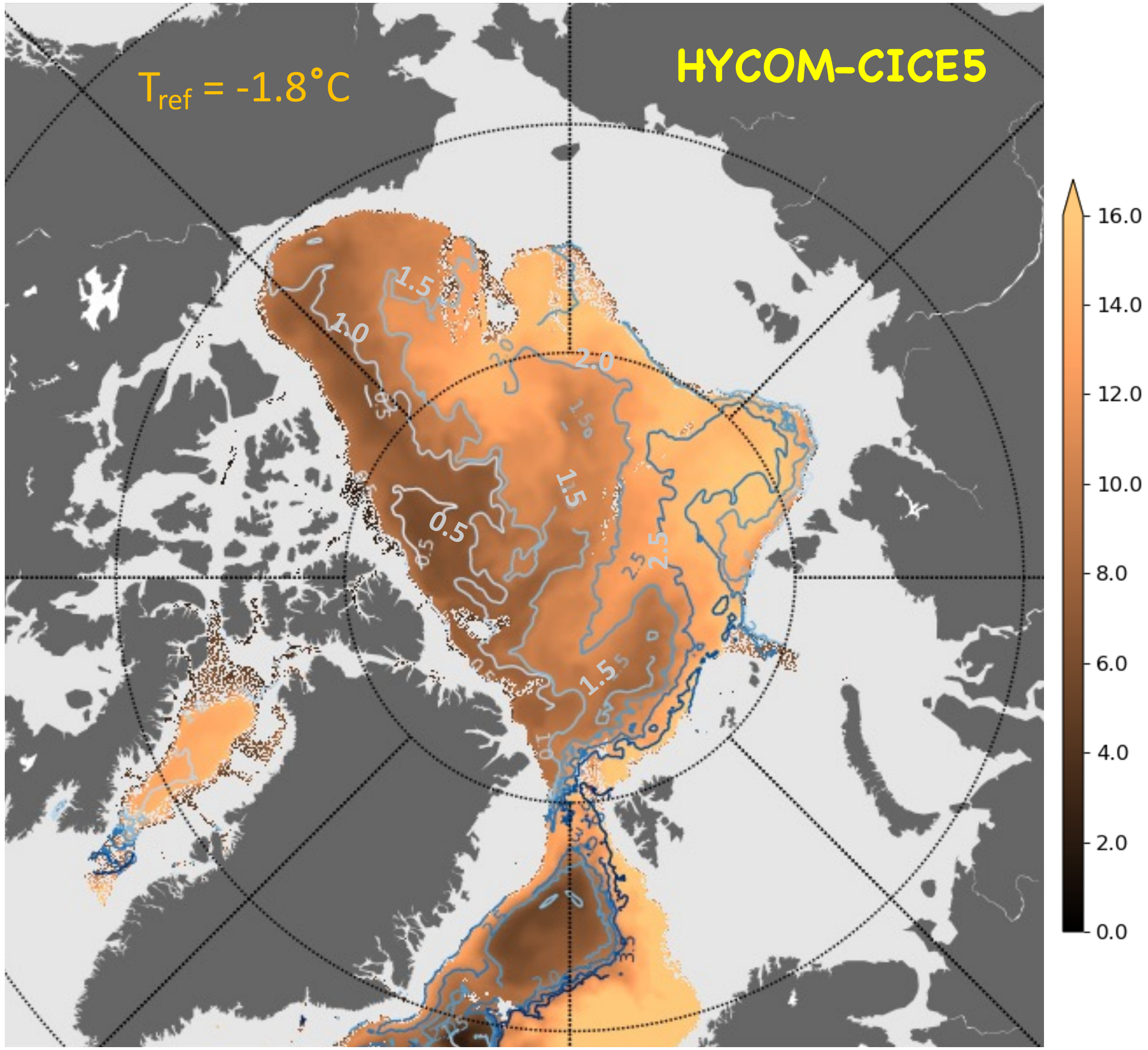


Depth of t_{max} (m)
Contours: $\sigma_0(z_{t_{max}})$ (kg/m³)

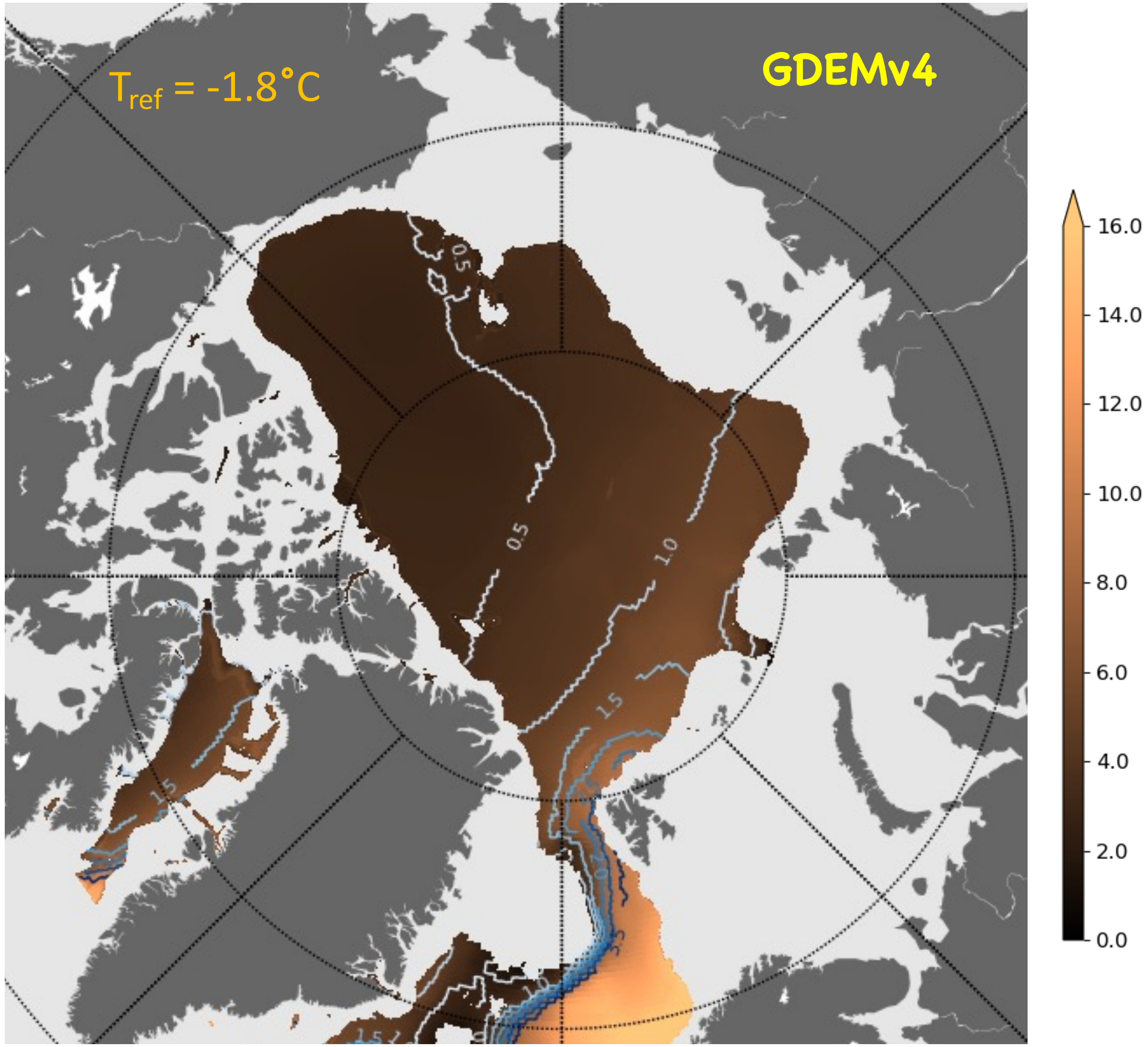


Atlantic Layer

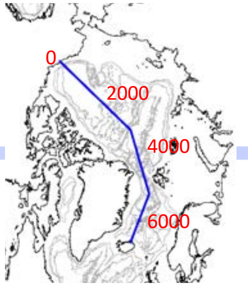
Atlantic Layer Heat Content Density (GJ/m^2)
Contours: t_{max} (°C)

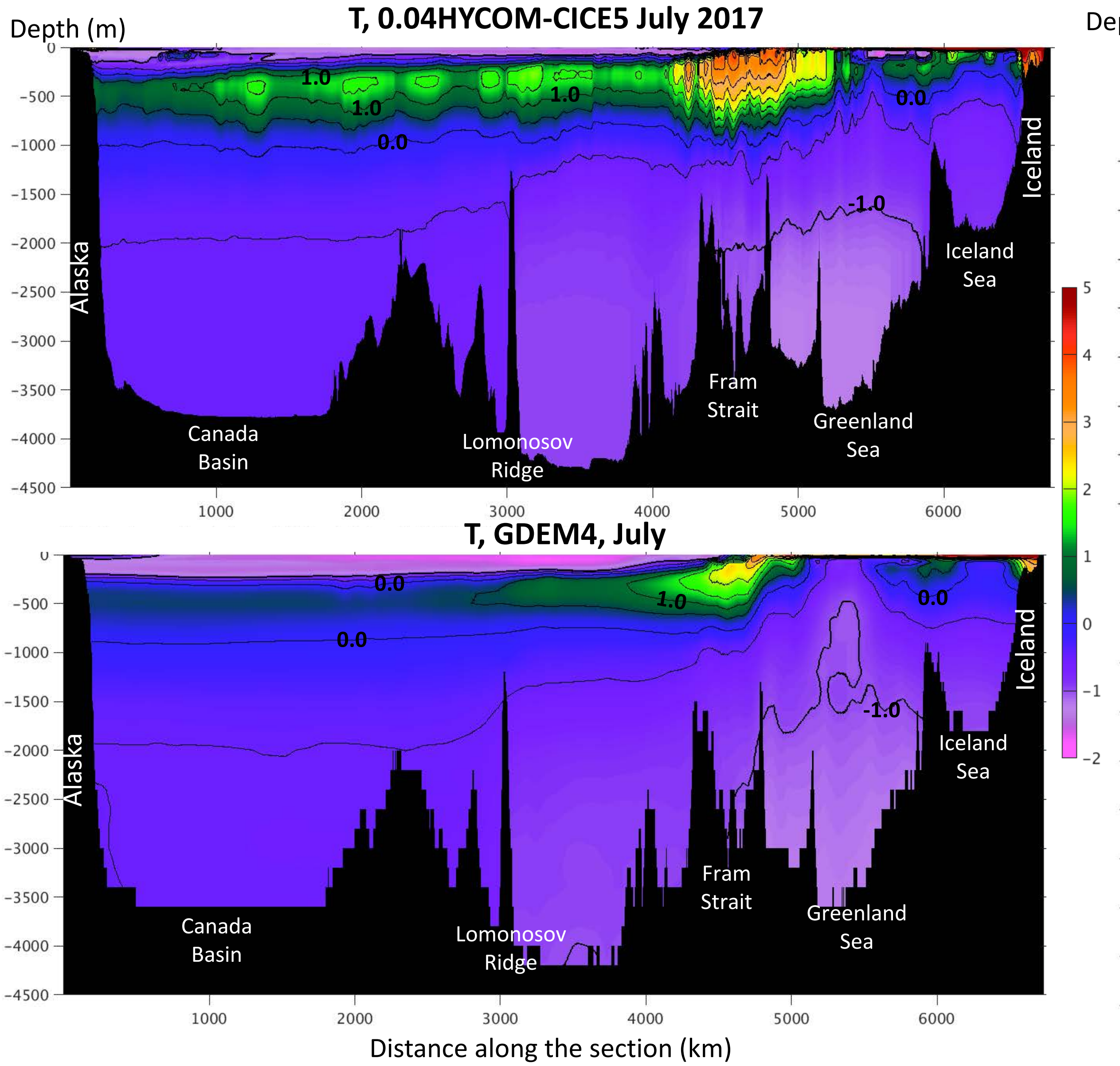


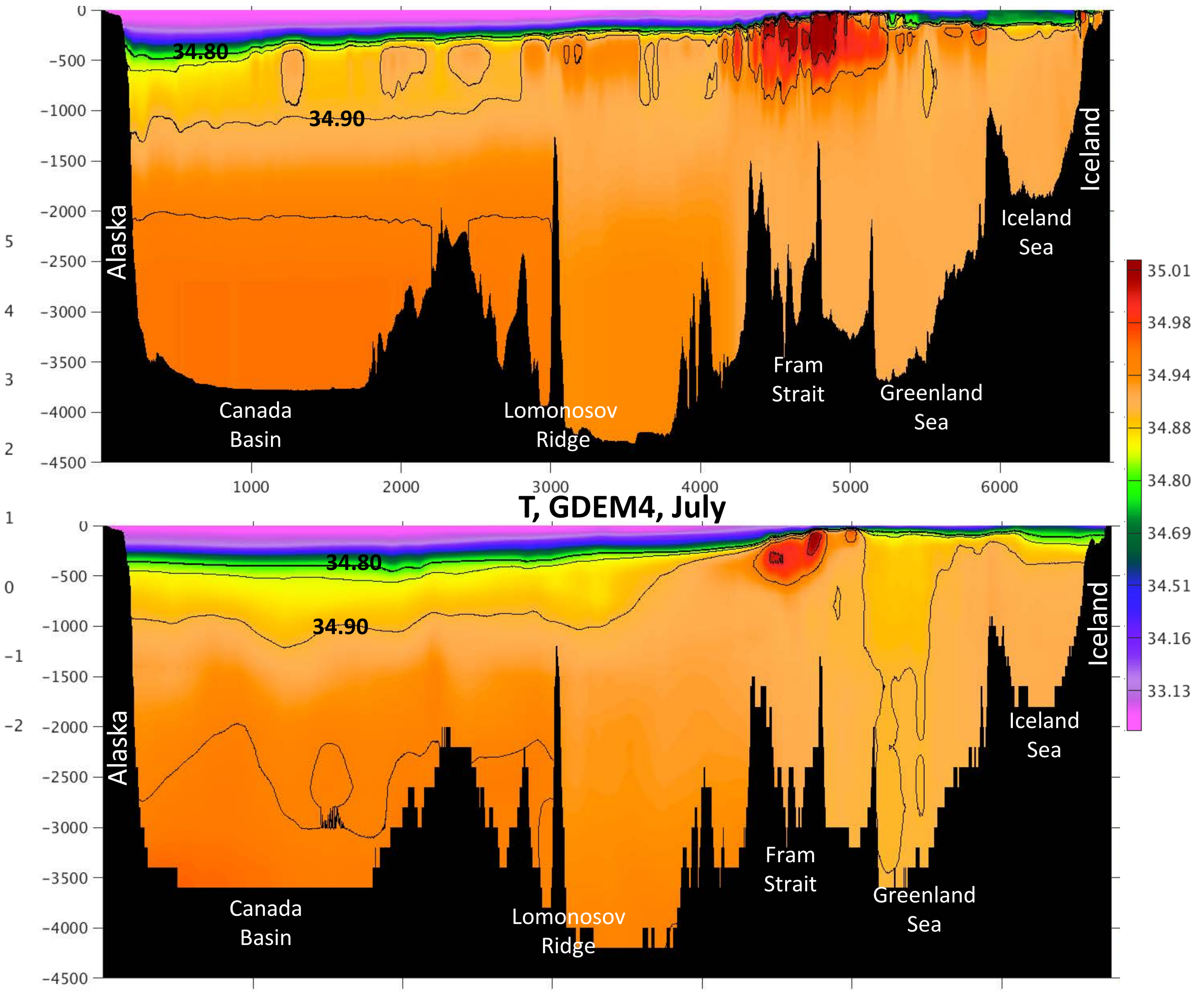
Atlantic Layer Heat Content Density (GJ/m^2)
Contours: t_{max} (°C)



T and S vertical sections: Bering Strait – North Pole – Iceland

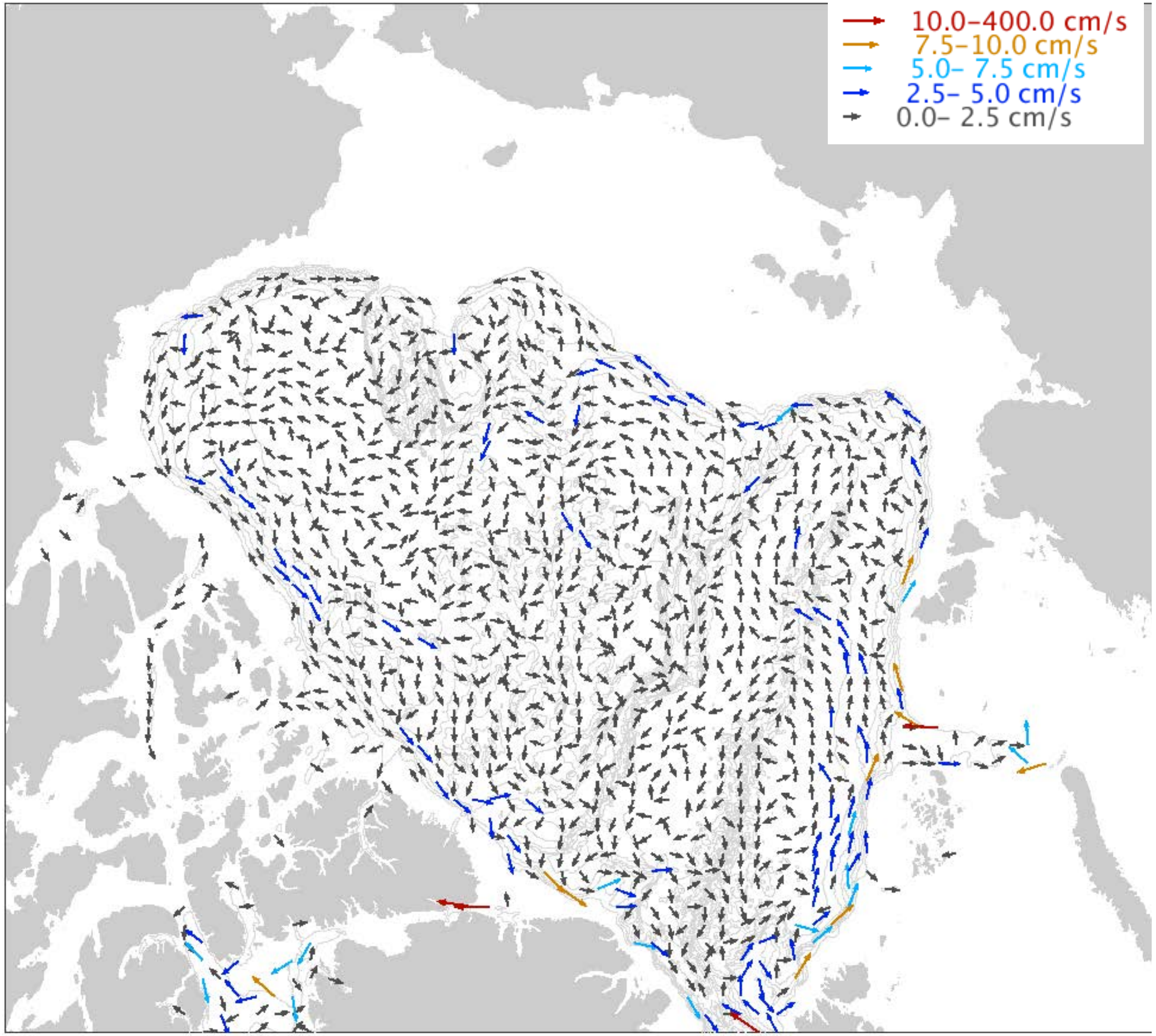






Mean Circulation of Atlantic Water

HYCOM-CICE5
2017-2020



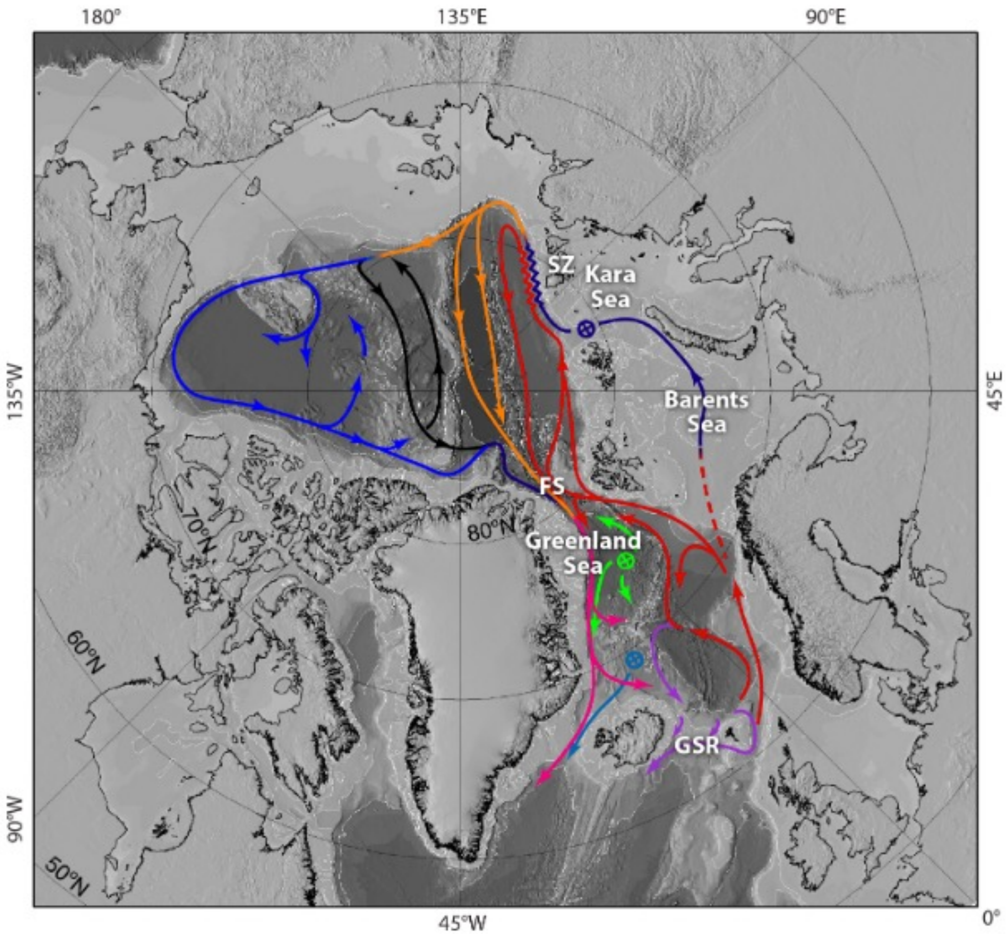


FIGURE 4. Schematic showing the circulation in the subsurface Atlantic Ocean and intermediate layers in the Arctic Ocean and the Nordic Seas. The interactions between the Barents Sea and the Fram Strait (FS) inflow branches north of the Kara Sea and Severnaya Zemlya (SZ) are indicated. The colors of the different loops show the gradual cooling of the Atlantic layer. The recirculation in Fram Strait and the intermediate water formation in the Greenland Sea are shown as well as the overflows across the Greenland-Scotland Ridge (GSR). *From Rudels et al. (2012).* > High res figure

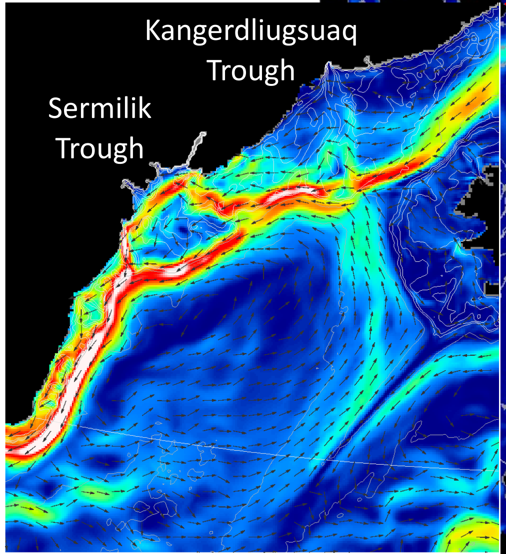
Mean Surface Currents from 0.08° & 0.04° HYCOM-CICE

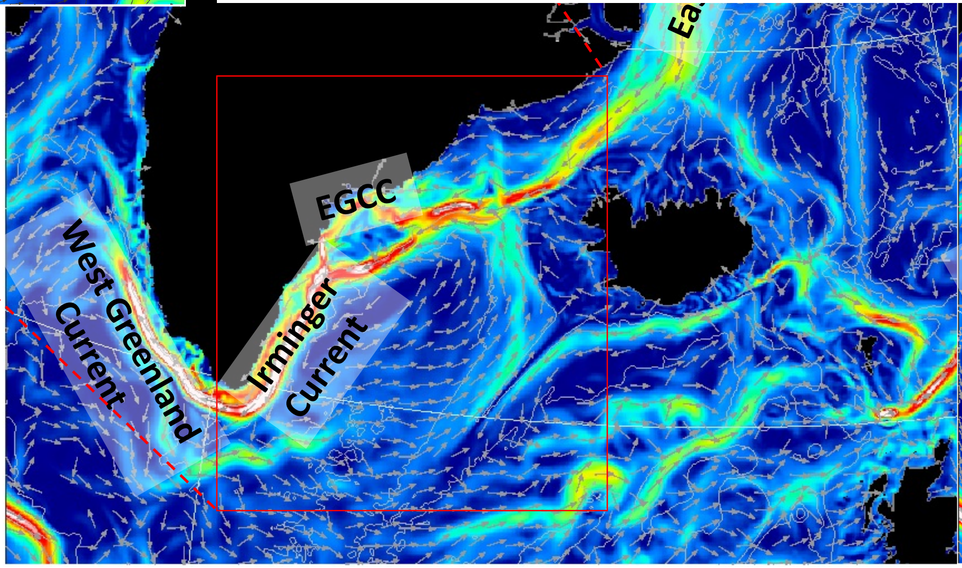
0.08 HYCOM-CICE (~4.5 km)

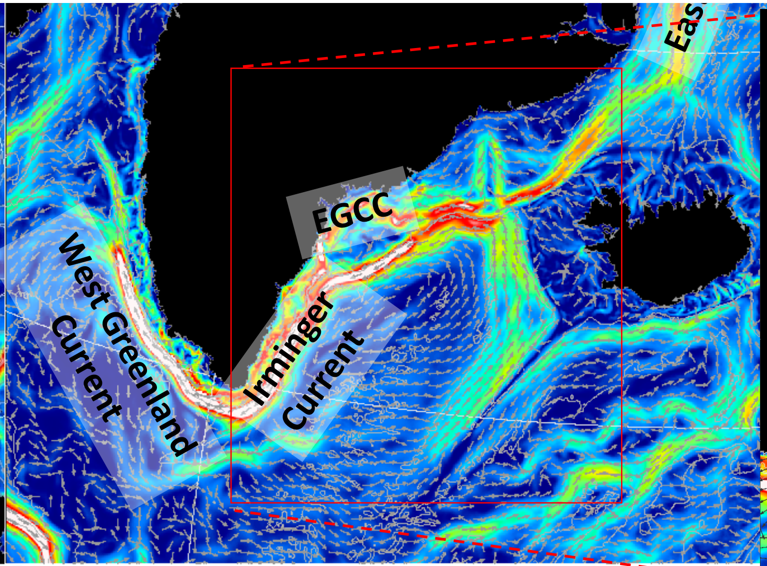
0.04 HYCOM-CICE (~2.0 km)

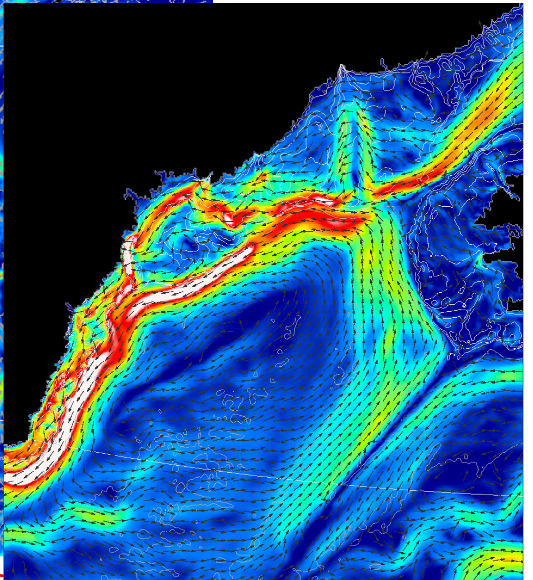
East Greenland Coastal Current:

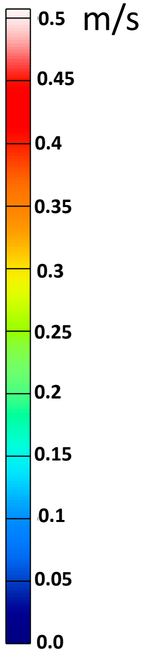
- First observed in the summer of 1997 as a "southward-flowing jet" and named East Greenland Coastal Current (EGCC; Bacon et al., 2002)
- EGCC is a low-salinity, high-velocity jet with a wedge-shaped hydrographic structure characteristic of other surface buoyancy-driven currents (Sutherland & Pickart, 2008).
- Strong seasonal variability, volume transport ~2Sv (Pickart et al., 2005)
- Spatial scale is O(10km)



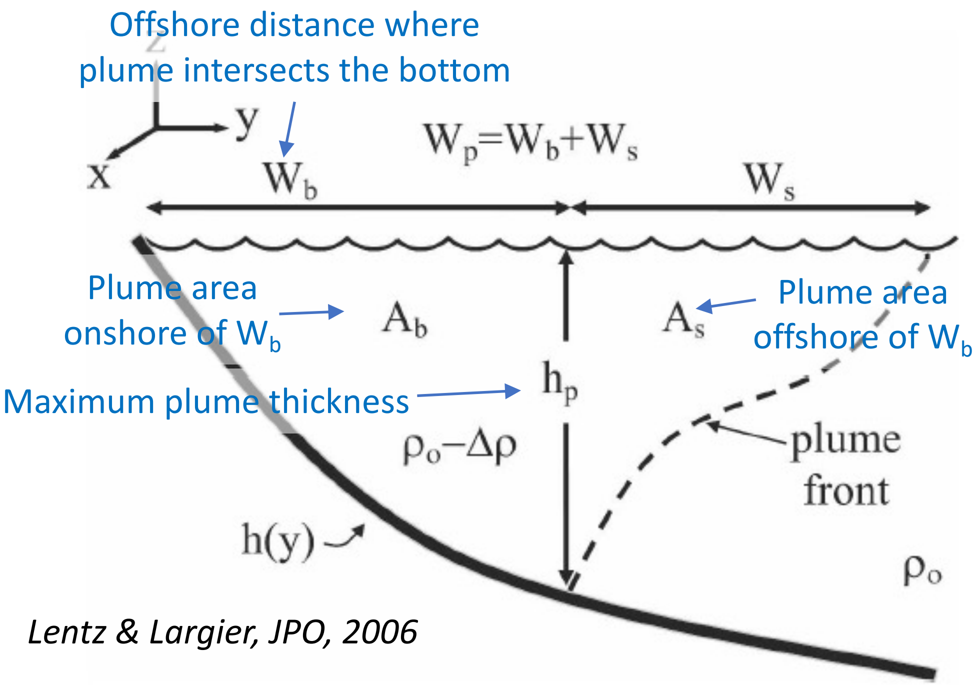








Buoyant Plume on a Shelf



Lentz & Largier, JPO, 2006

The depth of the foot of the front (h_p) is a function of the along-isobath wind stress (τ_x):

$$h_p \approx \left(\frac{2Qf}{g'}\right)^{1/2}$$

Plume transport:

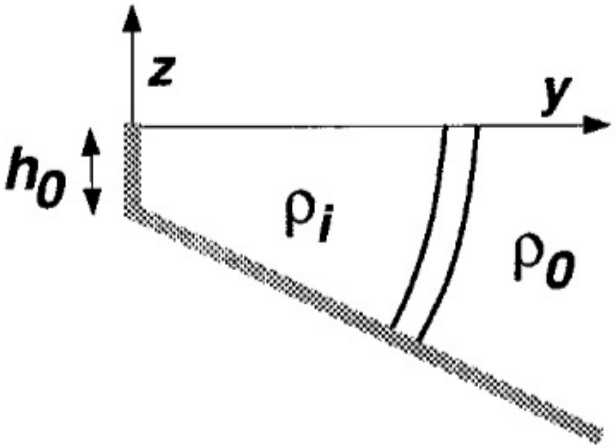
$$Q = Q_w + Q_g$$

Wind-driven transport: $Q_w = u_w A_p$

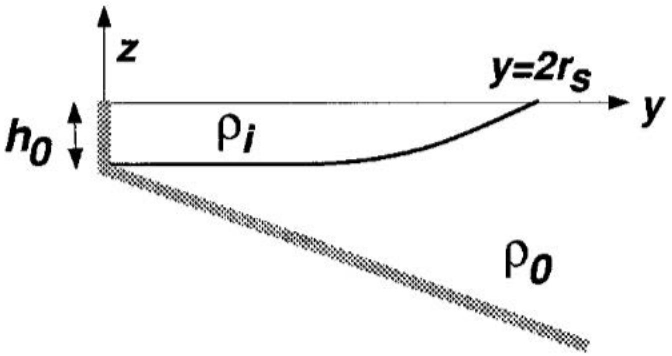
$$u_w = \tau_x / \rho_w r$$

ρ_w - water density
r - bottom stress

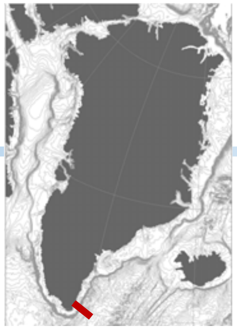
$A_b/A_s > 1$: Bottom-advected plume



$A_b/A_s < 1$: Surface-advected plume

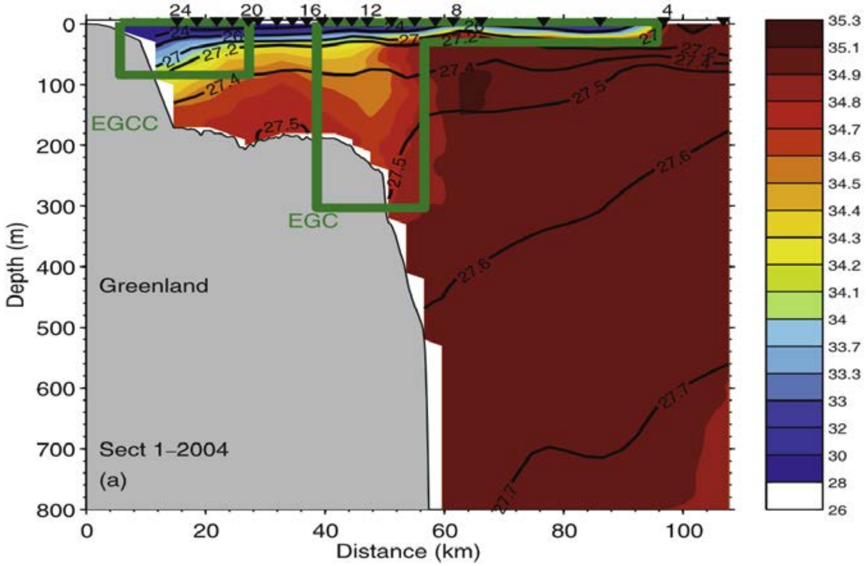


(Yankovsky and Chapman, 1997)

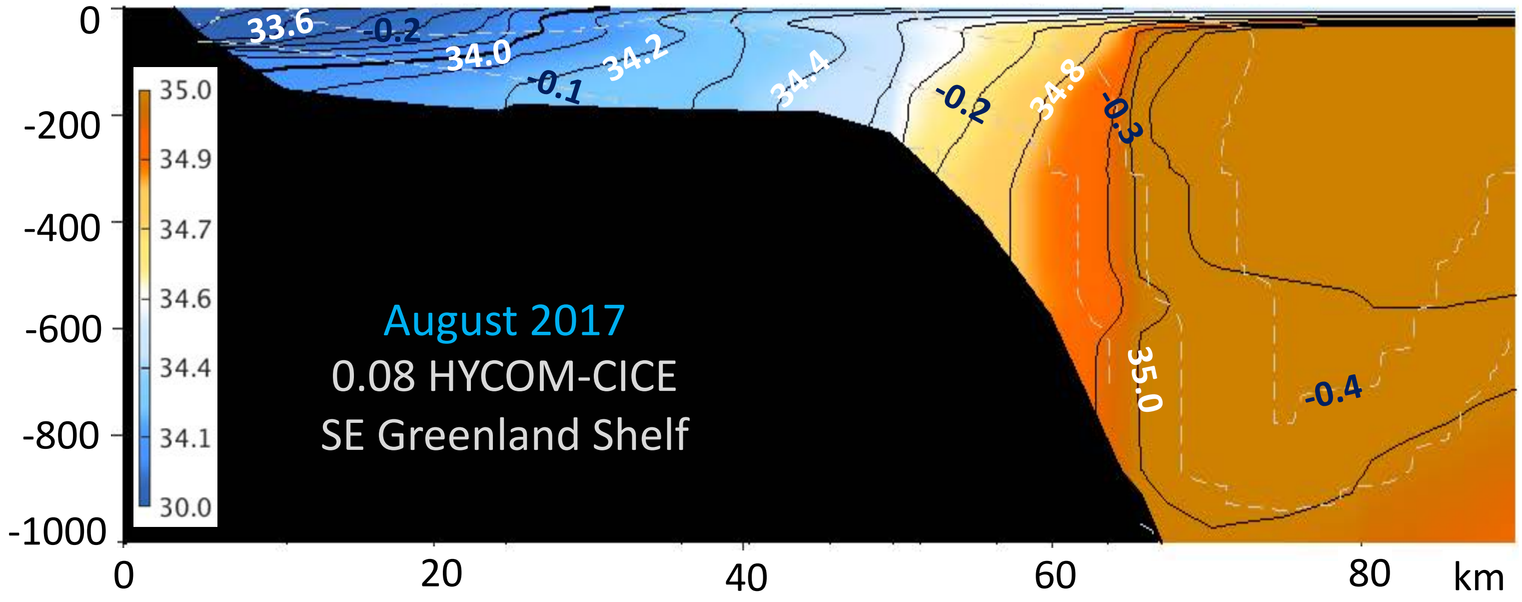


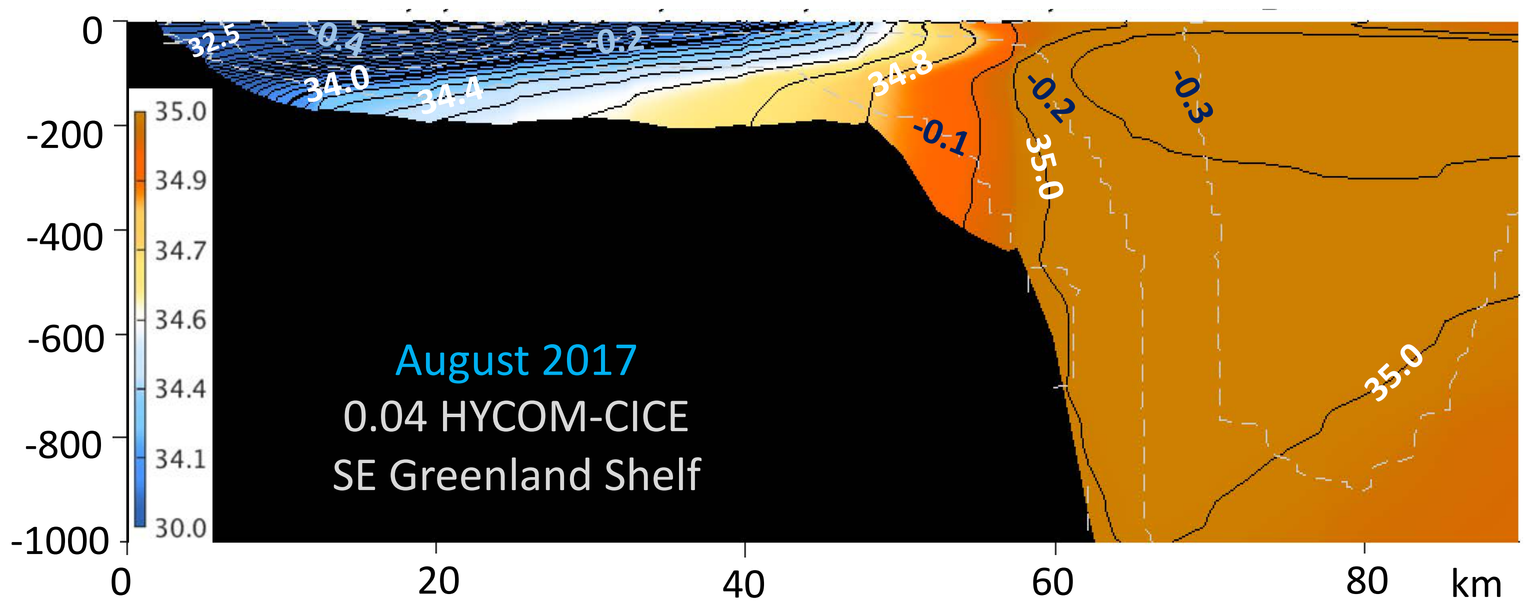
Buoyant Plume on the Southeastern Greenland Shelf, August 2017
0.08° HYCOM2.2-CICE4 and 0.04° HYCOM2.3-CICE5

Salinity field from 2004 hydrographic section 1 near Cape Farewell (60°N)



Sutherland & Pickart, 2008

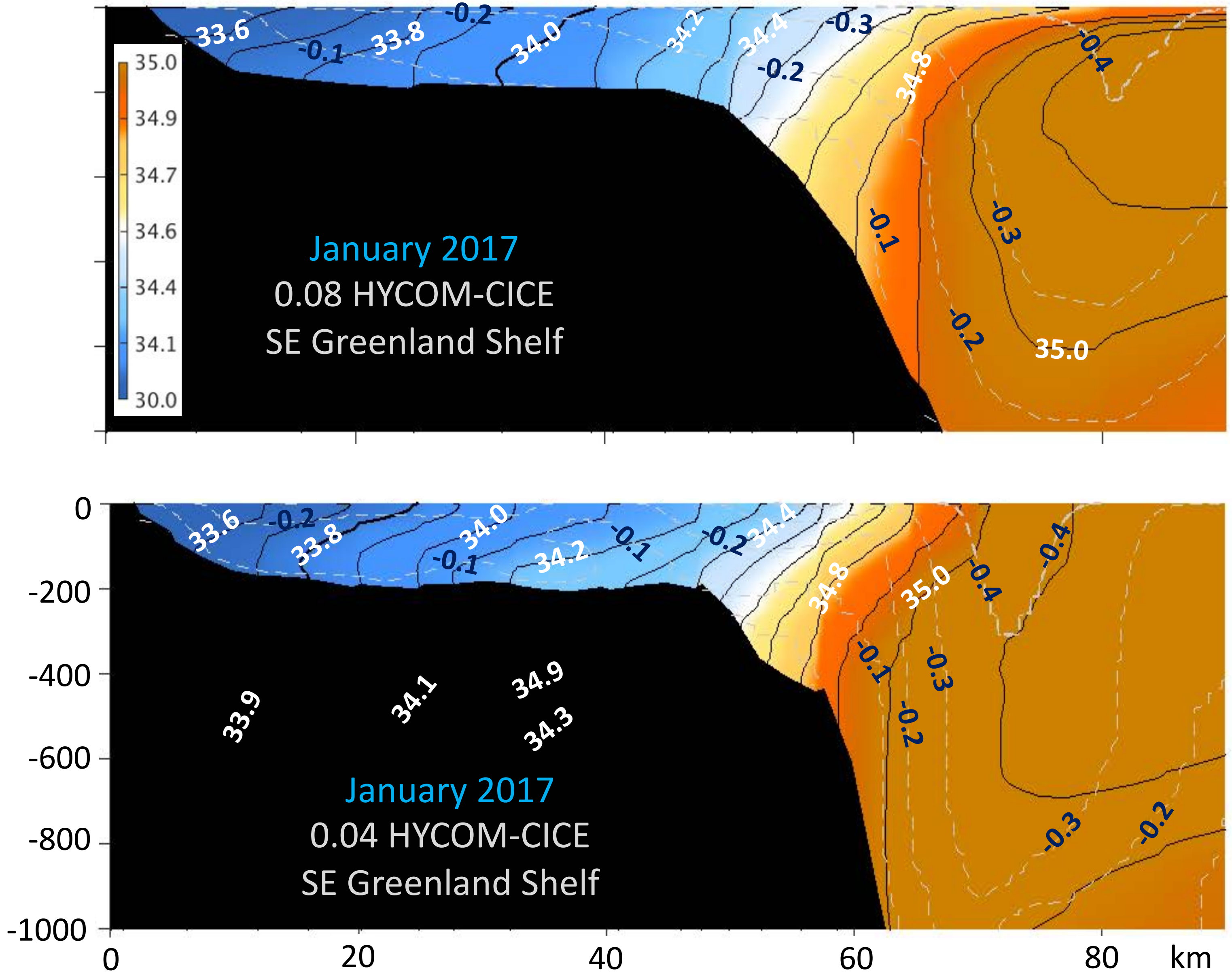


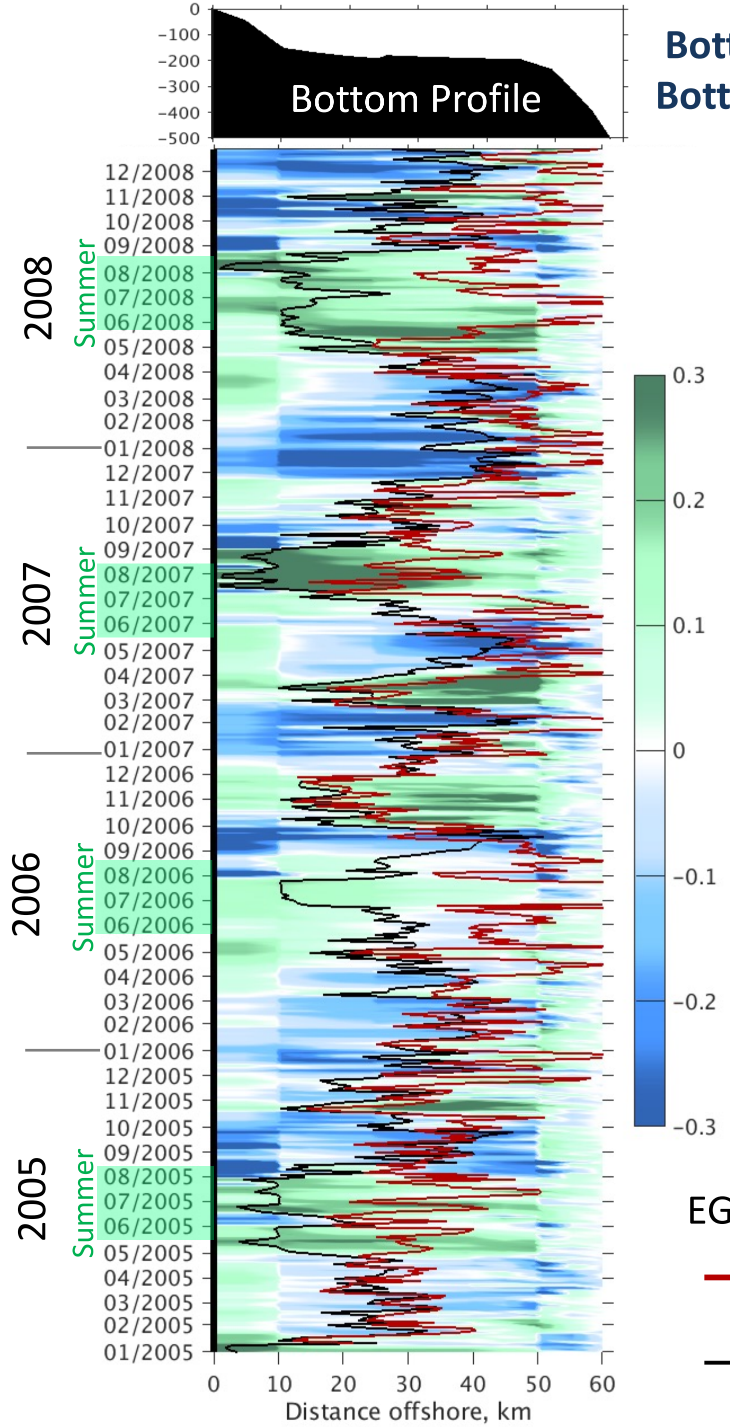


- EGCC is weakly pronounced in 0.08 HYCOM-CICE
- Stronger S gradients in 0.04 HYCOM-CICE
- In 0.04 HYCOM-CICE, the EGCC structure and S values are closer to the hydrographic section in 2004 (Sutherland & Pickart, 2008)

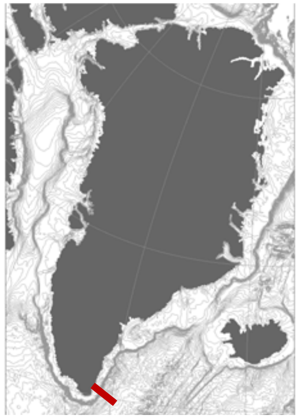
Buoyant Plume on the Southeastern Greenland Shelf, January 2017
0.08° HYCOM2.2-CICE4 and 0.04° HYCOM2.3-CICE5

- In both simulations, freshwater is mixed through the entire water column
- Similar offshore S gradients in 0.08 and 0.04 HYCOM-CICE
- The EGCC is absent in 0.08 HYCOM-CICE
- The southward flowing coastal jet is weak but noticeable (0.2 m/s) in the 0.04 HYCOM-CICE





Bottom Salinity Anomalies and Bottom/Surface Front Locations 0.08 HYCOM-CICE



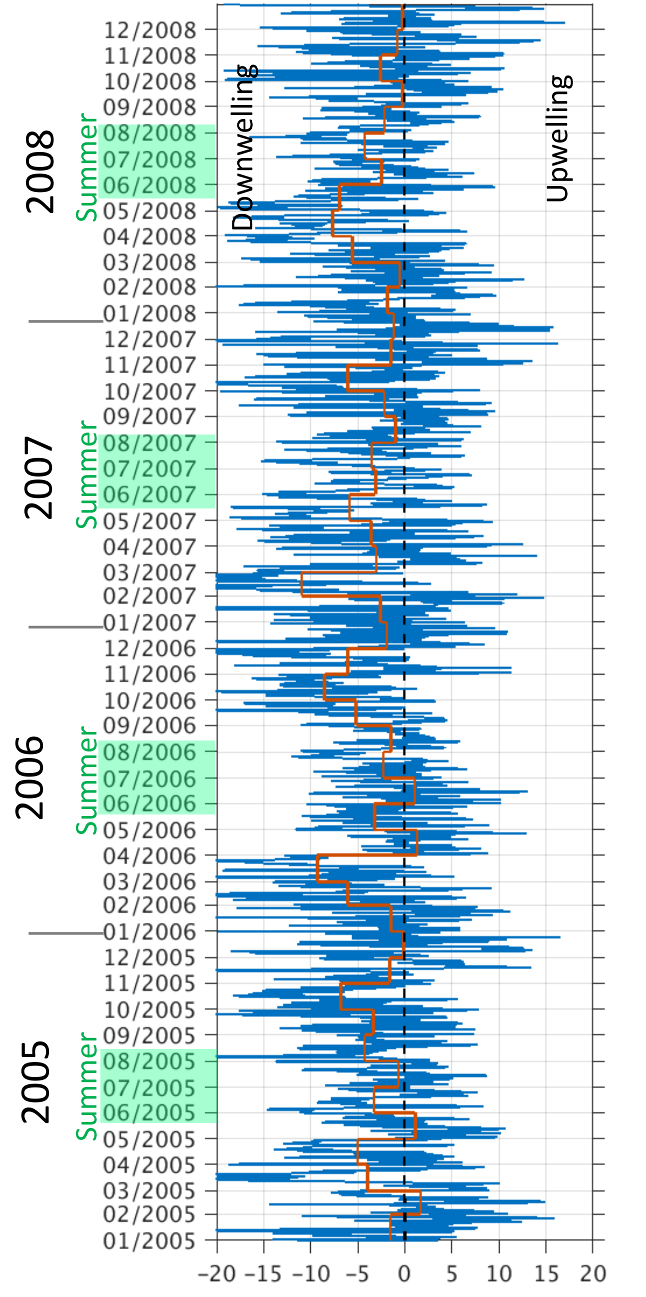
- Bottom salinity anomalies correlate with wind vectors: Strong downwelling-favorable winds pump fresh water into the deep layers during winter
- FWC on the outer shelf is minimum during summer and maximum during early winter when strong wind mix the fresh water downard
- Majority of hydrographic observations on the Greenland shelf are conducted during summer months

EGCC front (S=33.8)

— 33.80 surf

— 33.80 bottom

Wind Vector Projected onto the Along-Shore Direction



Summary

- A new setup of the Arctic Ocean HYCOM-CICE model on a 0.04-degree (~2km) computational grid has been prepared and integrated for 2017-2020 to produce "Nature runs" for the OSSEs with the Arctic Cap HYCOM-CICE5 + NCODA nested in GOFS3.5

- Compared to the coarser 0.08-degree (~4.5 km) configuration:

  = *both configurations provide realistic mesoscale circulation with major dynamic features*

  = *major water masses and hydrographic structure are represented in both resolutions, however several water mass characteristics disagree with the climatology fields (e.g., Atlantic water T)*

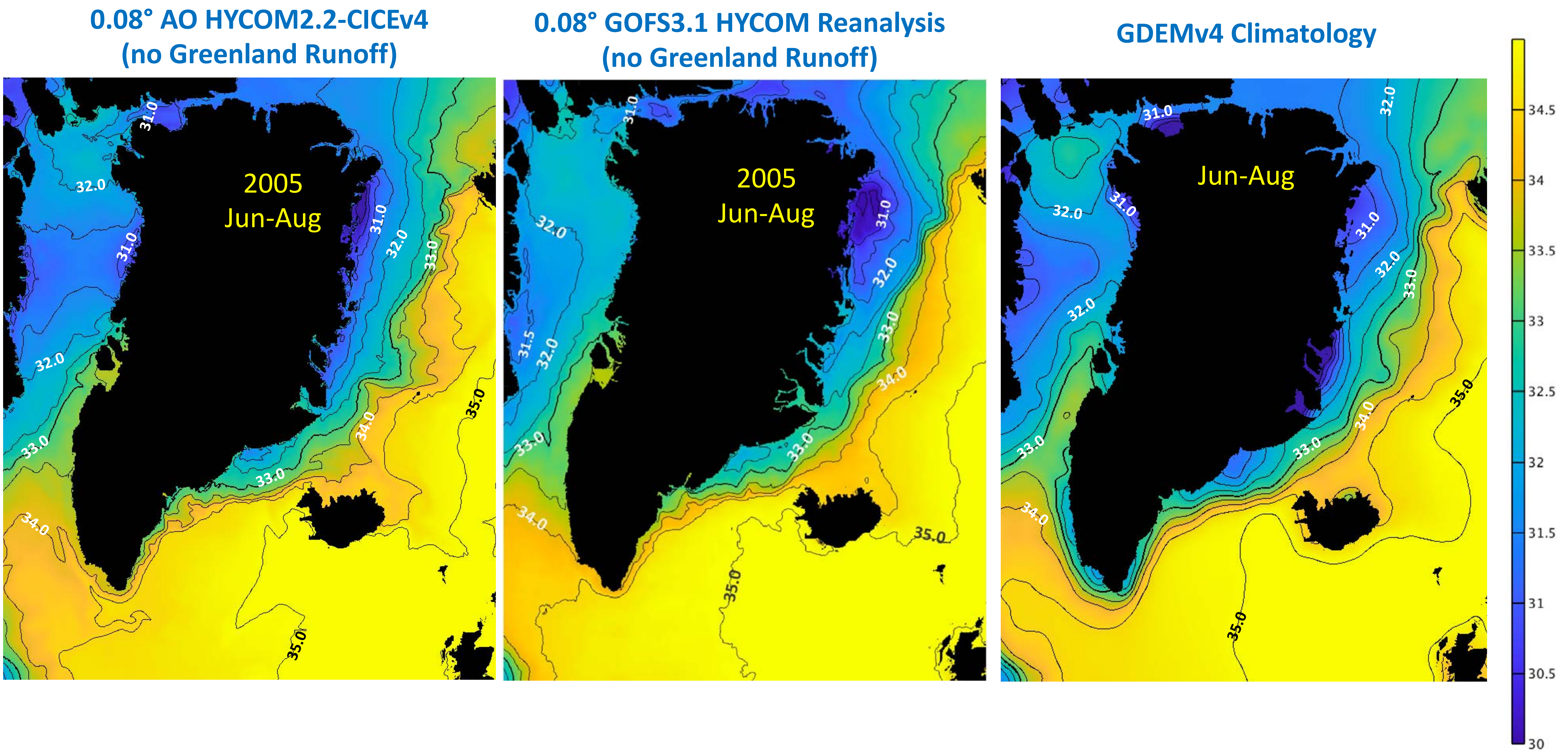
- 0.04 HYCOM-CICE has a more realistic representation of coastal currents and shelf dynamics

- Major challenges in the HYCOM2.3-CICE5:

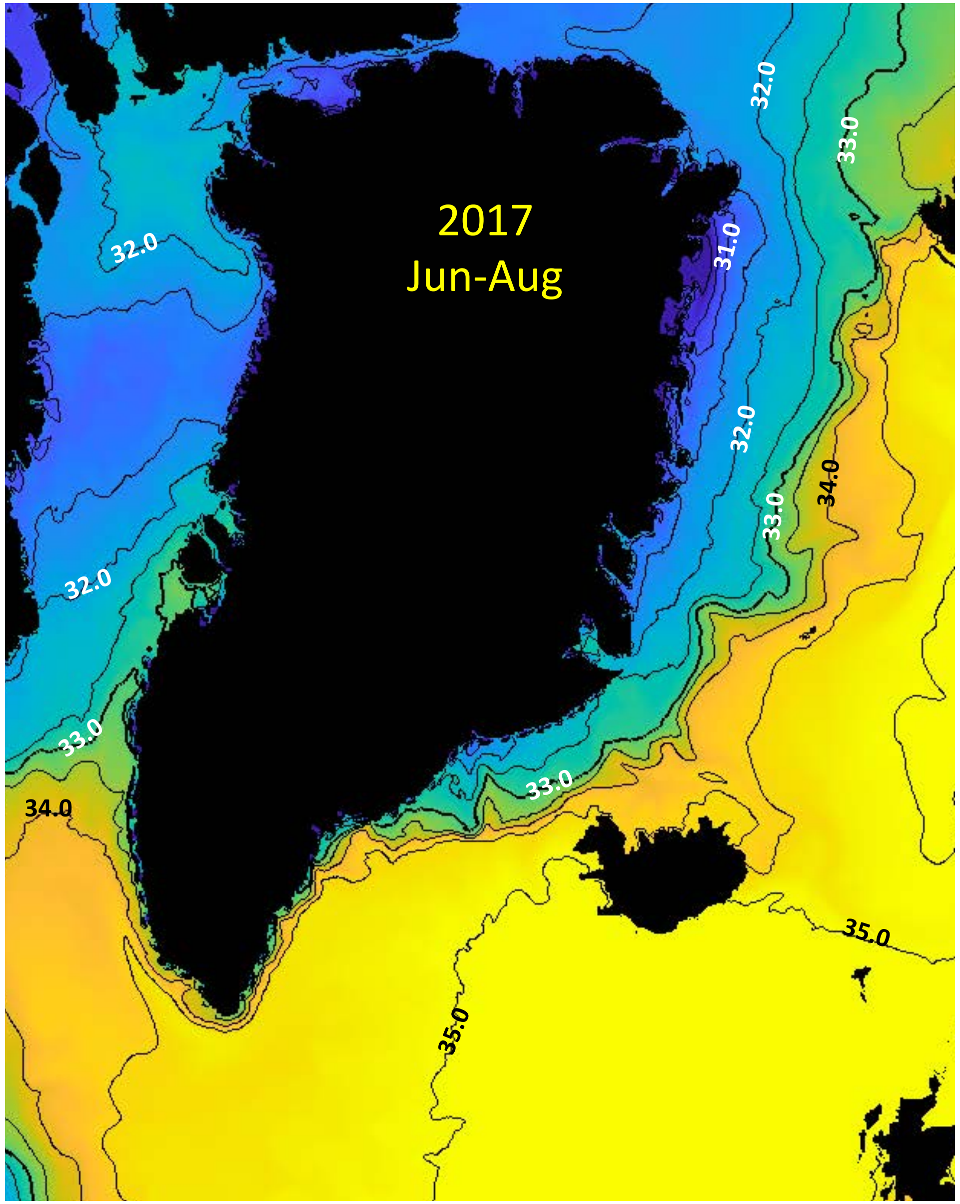
  = Flow structure in the narrow straits and channels (Bering Strait, CAA)

  = Sea ice during melt season (excessive ice melt in the central Arctic)

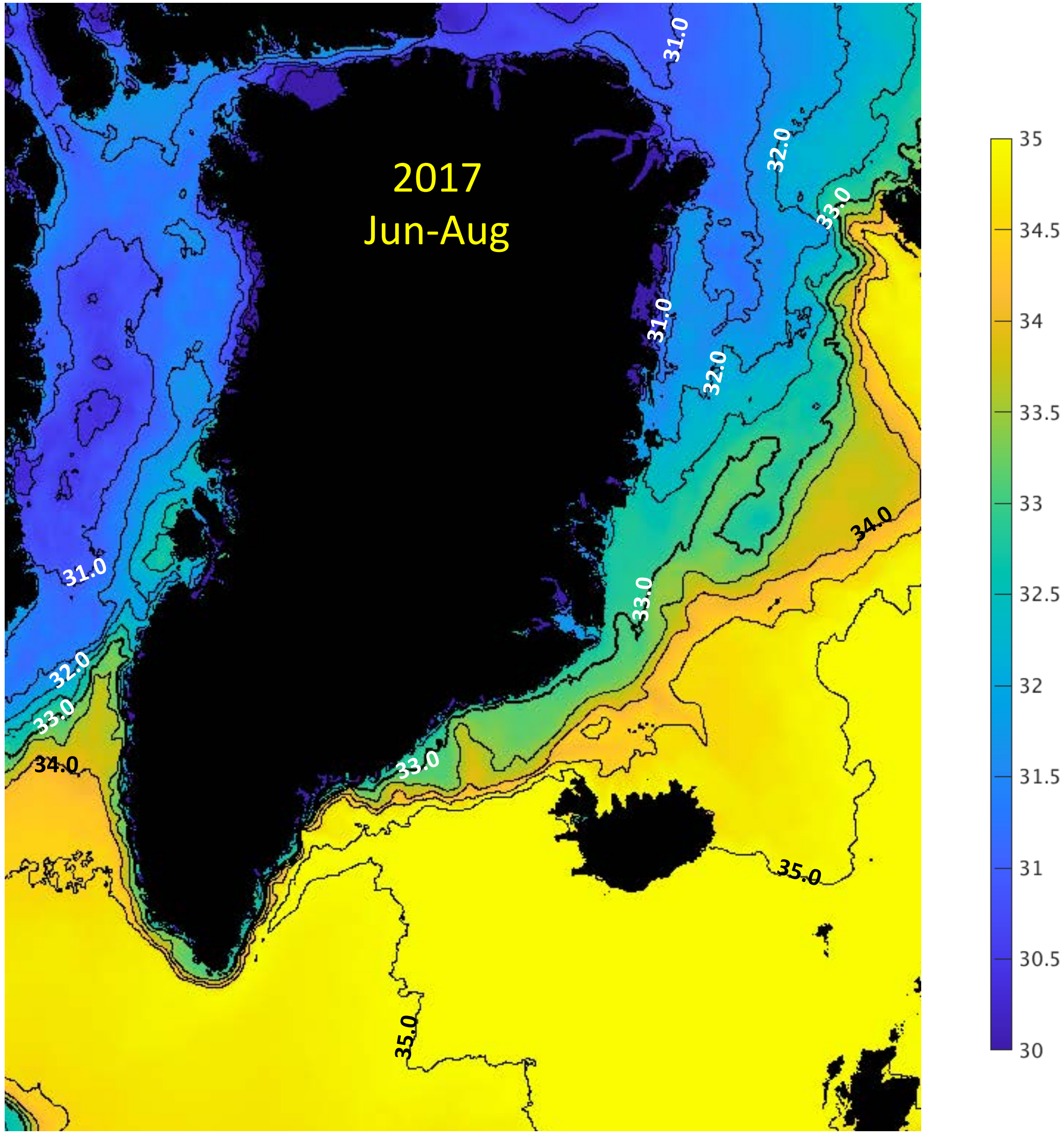
Summer (JJA) Surface Salinity



0.08° AO HYCOM2.2-CICEv4 (Greenland Runoff is on)



0.04° AO HYCOM2.3-CICEv5 (Greenland Runoff is on)



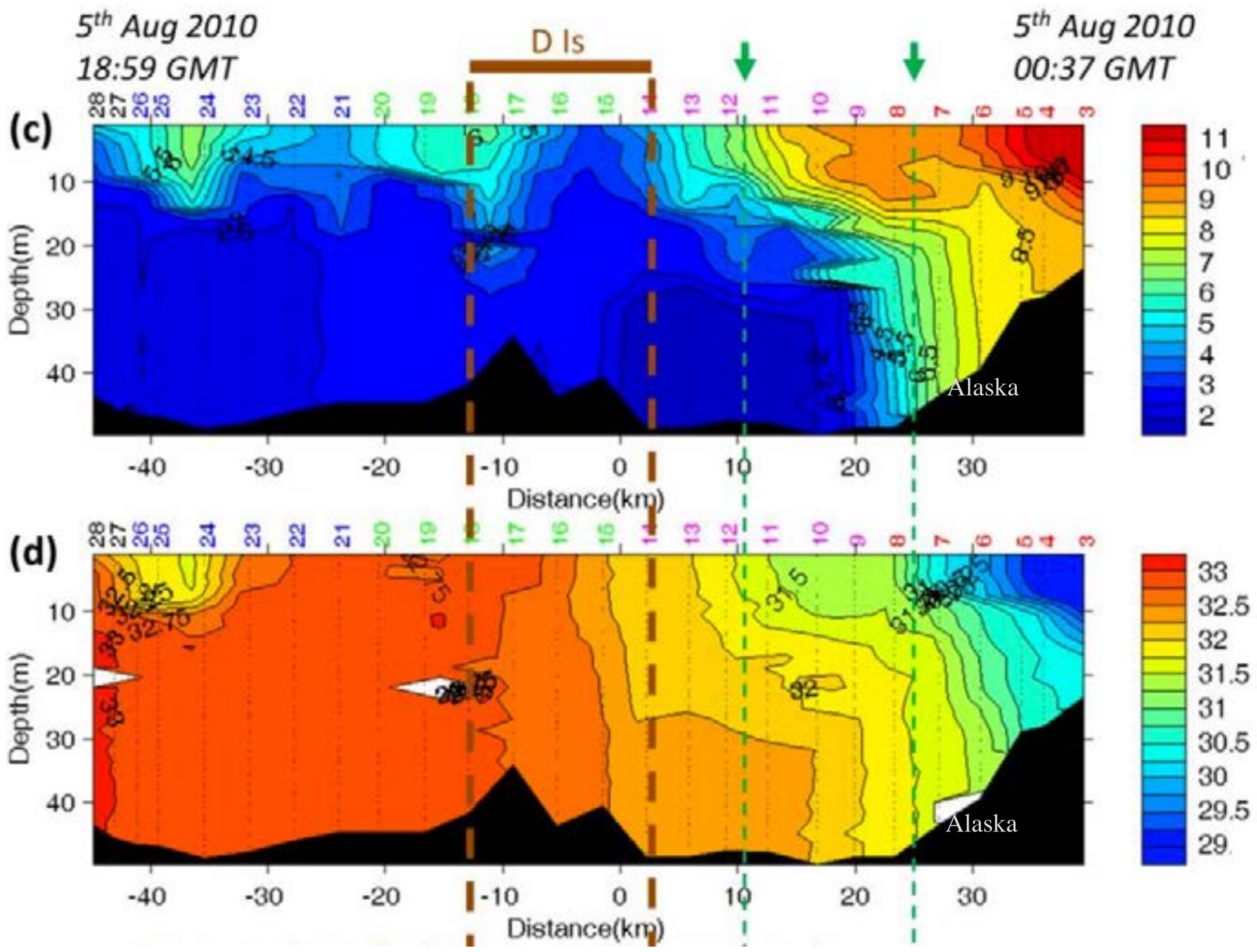
Sensitivity Experiments with 0.04 & 0.08 HYCOM-CICE5

Configuration	Forcing	Thermo dynamics	Thermal Conductivity	Rheology	Ice Freeze Potential	Sh/wave Radiative Transfer	Nest
0.04HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt = Tfrz	BL99	GOFS3.5–73.7
0.04HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt > Tfrz	deltaEdd	GOFS3.5–73.7
0.04HYCOM- CICE5	CFSv2	mushy	bubbly	EAP	Tmlt > Tfrz	deltaEdd	GOFS3.5–73.7
0.04HYCOM- CICE5	JRA-55	mushy	bubbly	EAP	Tmlt > Tfrz	deltaEdd	GOFS3.5–73.7
0.08HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt = Tfrz	BL99	GOFS3.5–73.7
0.08HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt > Tfrz	BL99	GOFS3.5–73.7
0.08HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt = Tfrz	deltaEdd	GOFS3.5–73.7
0.08HYCOM- CICE5	CFSv2	mushy	bubbly	EVP	Tmlt > Tfrz	deltaEdd	GOFS3.5–73.7
0.08HYCOM- CICE5	JRA-55	mushy	bubbly	EAP	Tmlt > Tfrz	deltaEdd	GOFS3.5–73.7
0.04HYCOM-CICE4	CFSv2	BL99	MU71	EVP	Tmlt = Tfrz	BL99	GOFS3.1–53.X

0.72º Arctic Ocean HYCOM-CICE

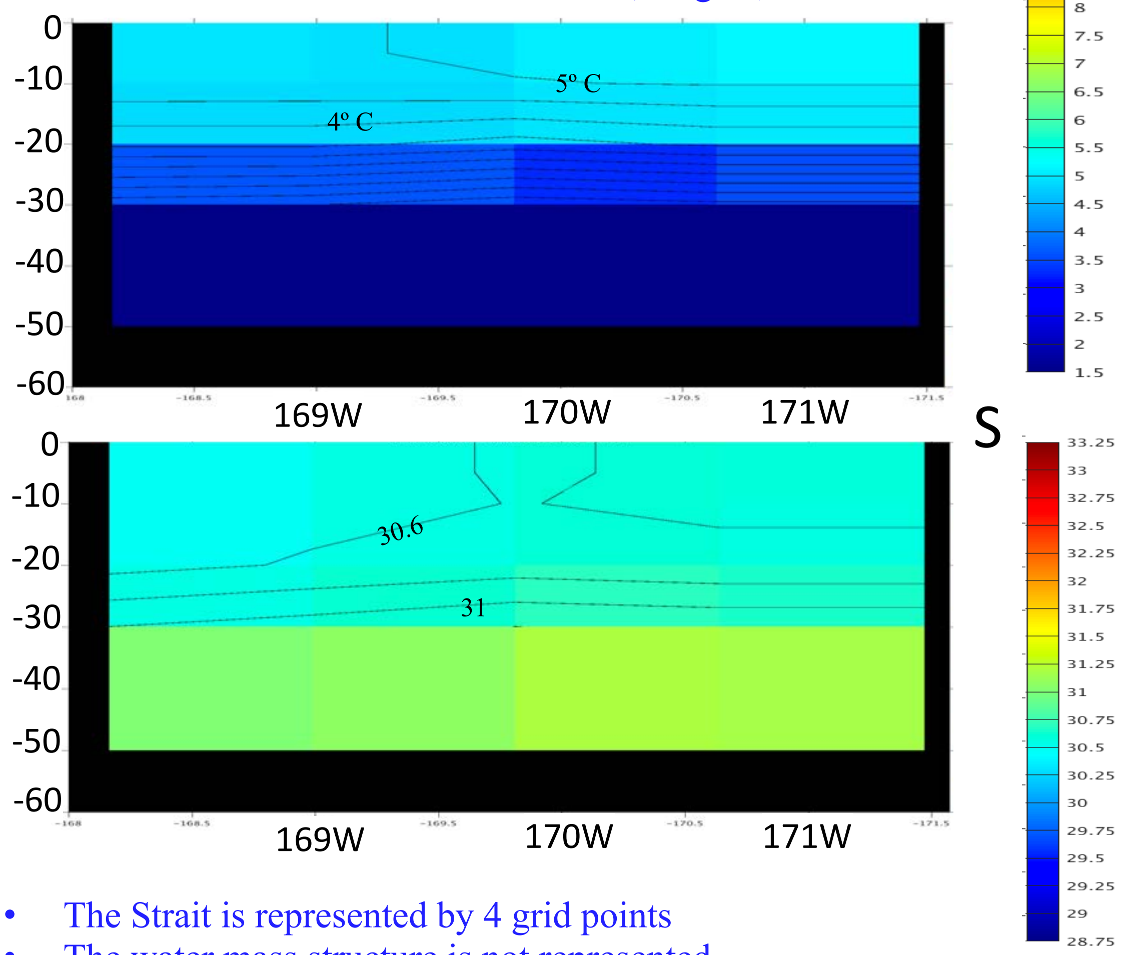
T & S Vertical Section in the Bering Strait in August 2010

T & S from CTD observations, August 5, 2010



Woodgate, R. A., and K. Aagaard (2005)

T & S 0.72 HYCOM-CICE, August, 2010

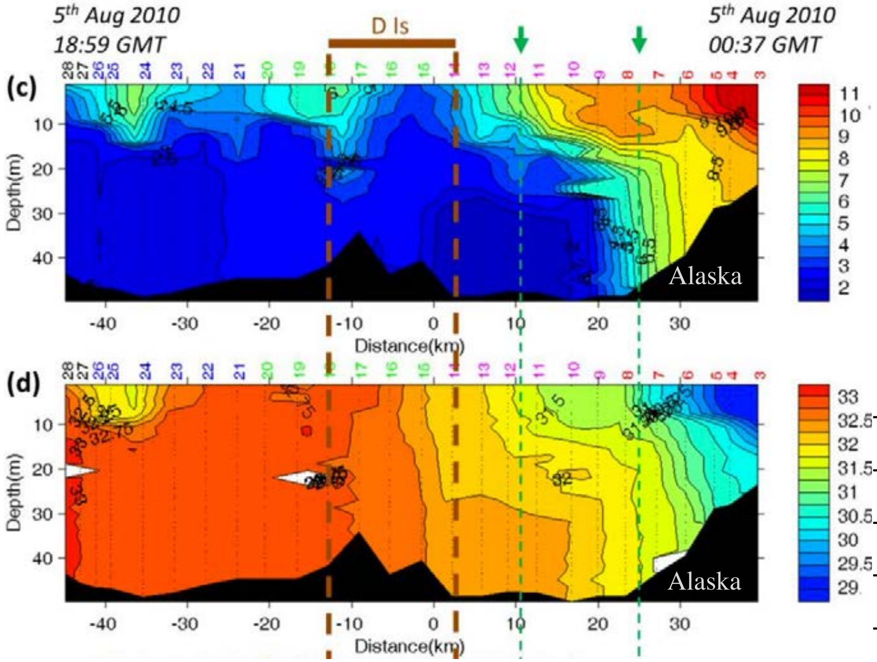


- The Strait is represented by 4 grid points
- The water mass structure is not represented
- Flow structure is not represented

0.08º Arctic Ocean HYCOM-CICE, Experiment 11.0

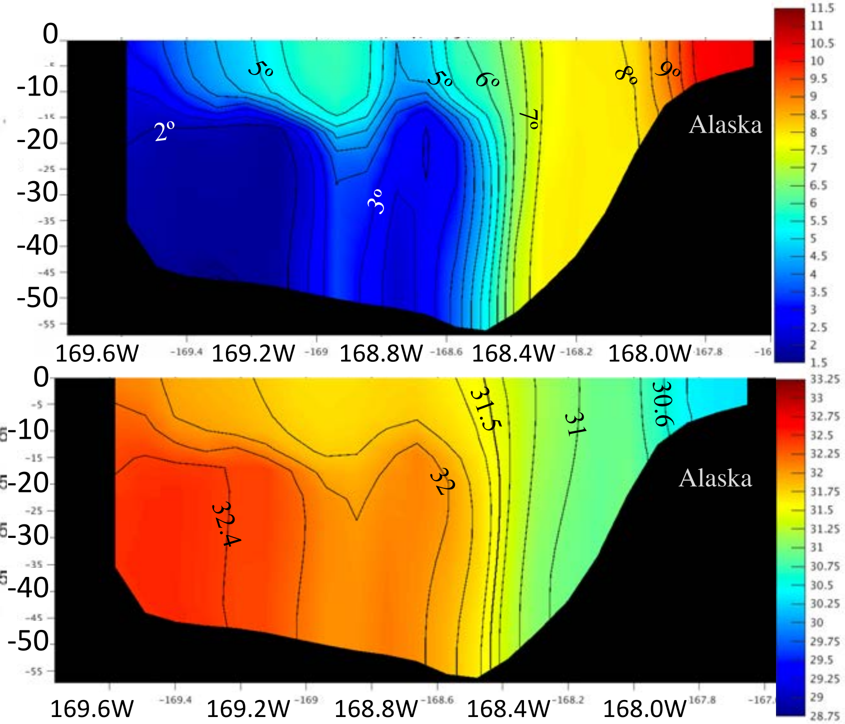
T & S Vertical Section in the Bering Strait in August 2010

T & S from CTD observations, August 5, 2010

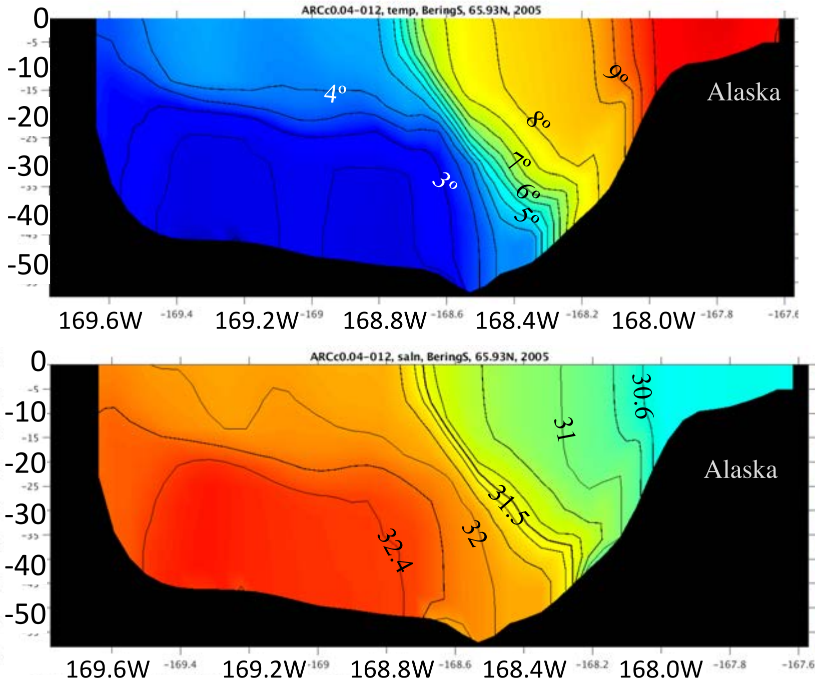


Woodgate, R. A., and K. Aagaard (2005)

T & S 0.08 HYCOM-CICE, August 29, 2005



T & S 0.04 HYCOM-CICE, August 29, 2005



- The Strait is represented by 22 grid points
- The model reproduces major features of the water mass structure in the strait
- Flow structure is too barotropic
- Alaskan coastal buoyant jet is not represented

- The Strait is represented by 45 grid points
- The model reproduces major features of the water mass structure in the strait
- The flow structure is more baroclinic
- Buoyant jet is not represented