Don't let your PBL scheme be rejected by brine: Parameterization of salt plumes under sea ice in climate models

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Frontiers in Oceanic, Atmospheric, and Cryospheric Boundary Layers

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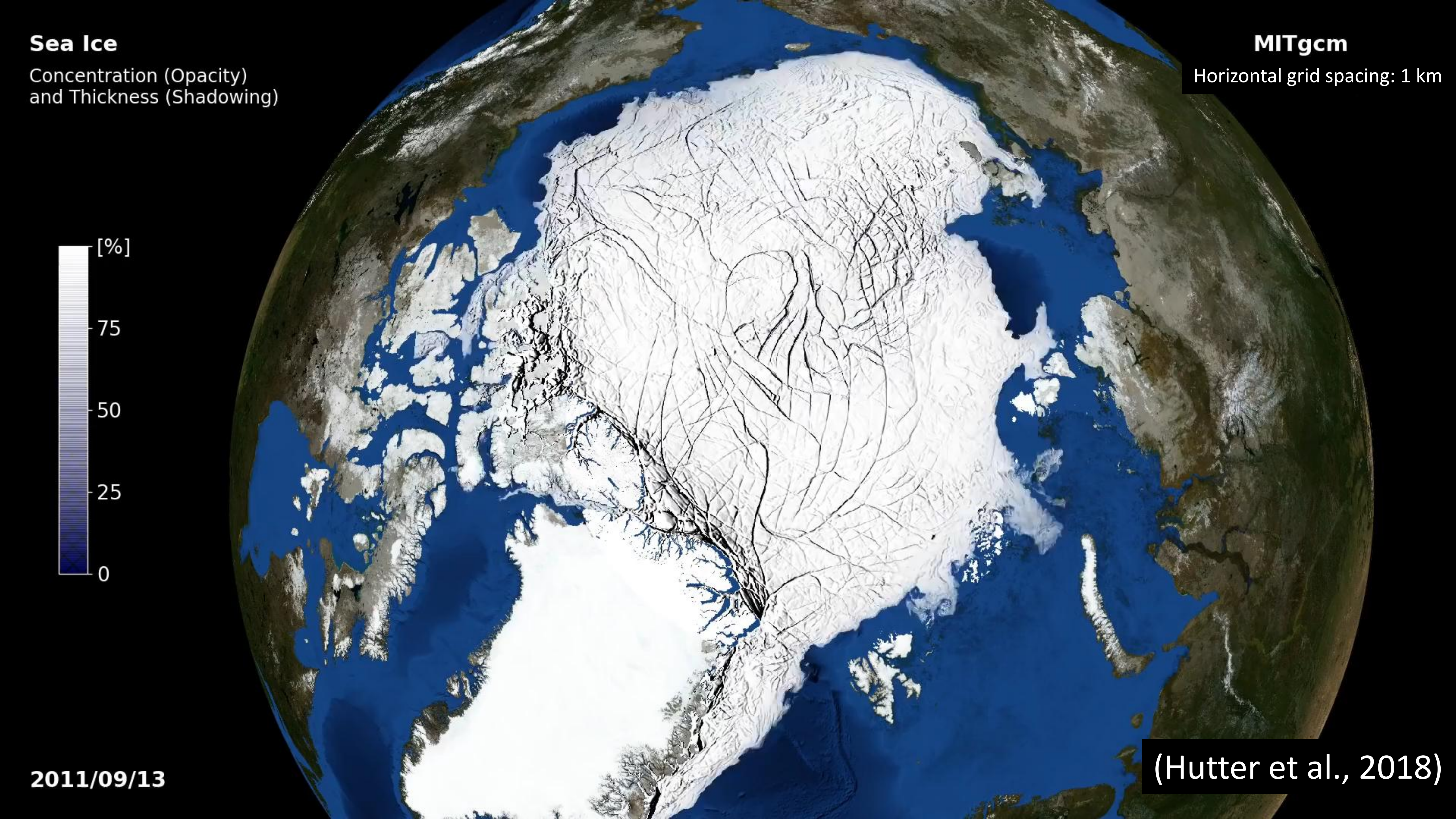
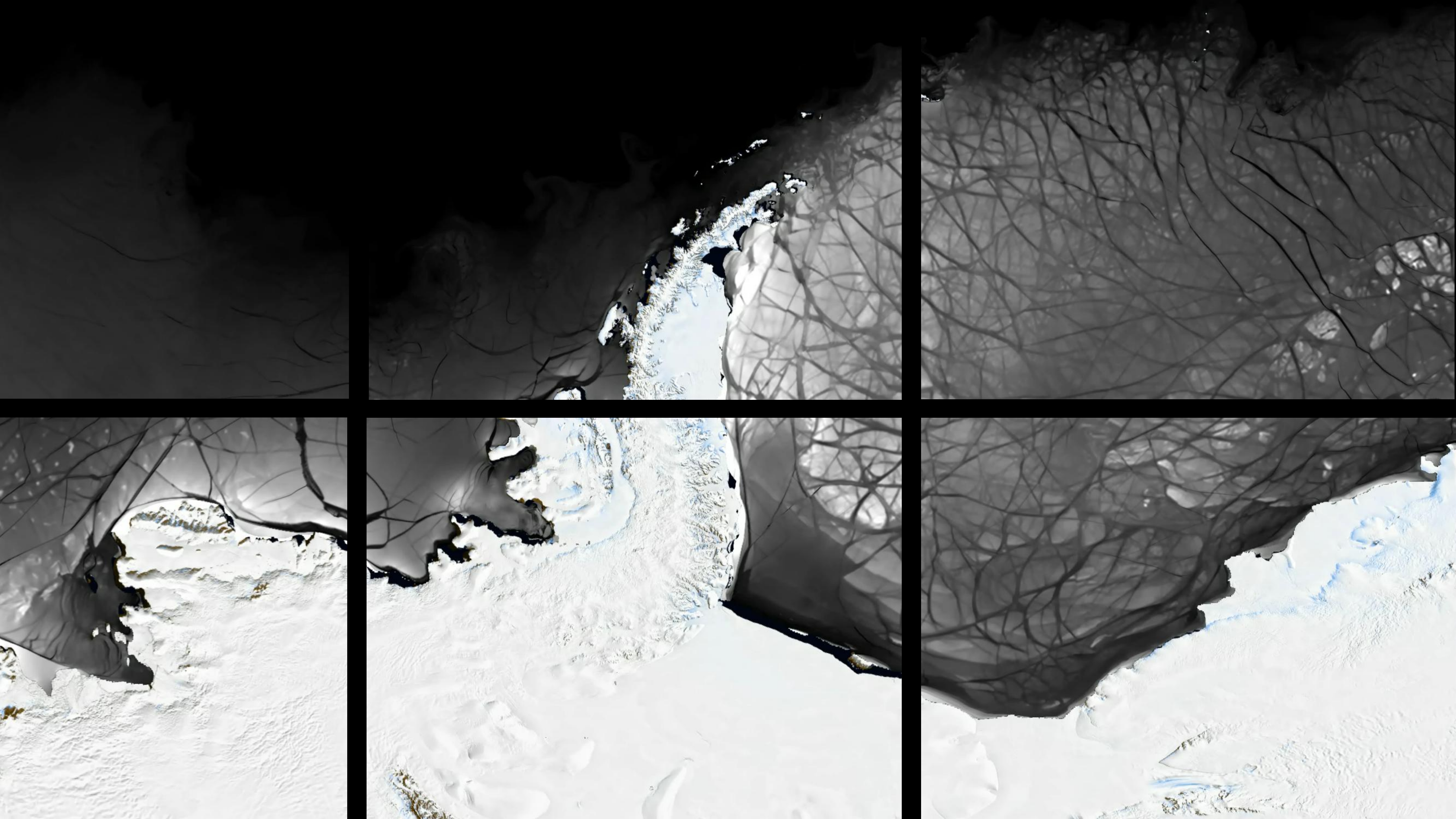
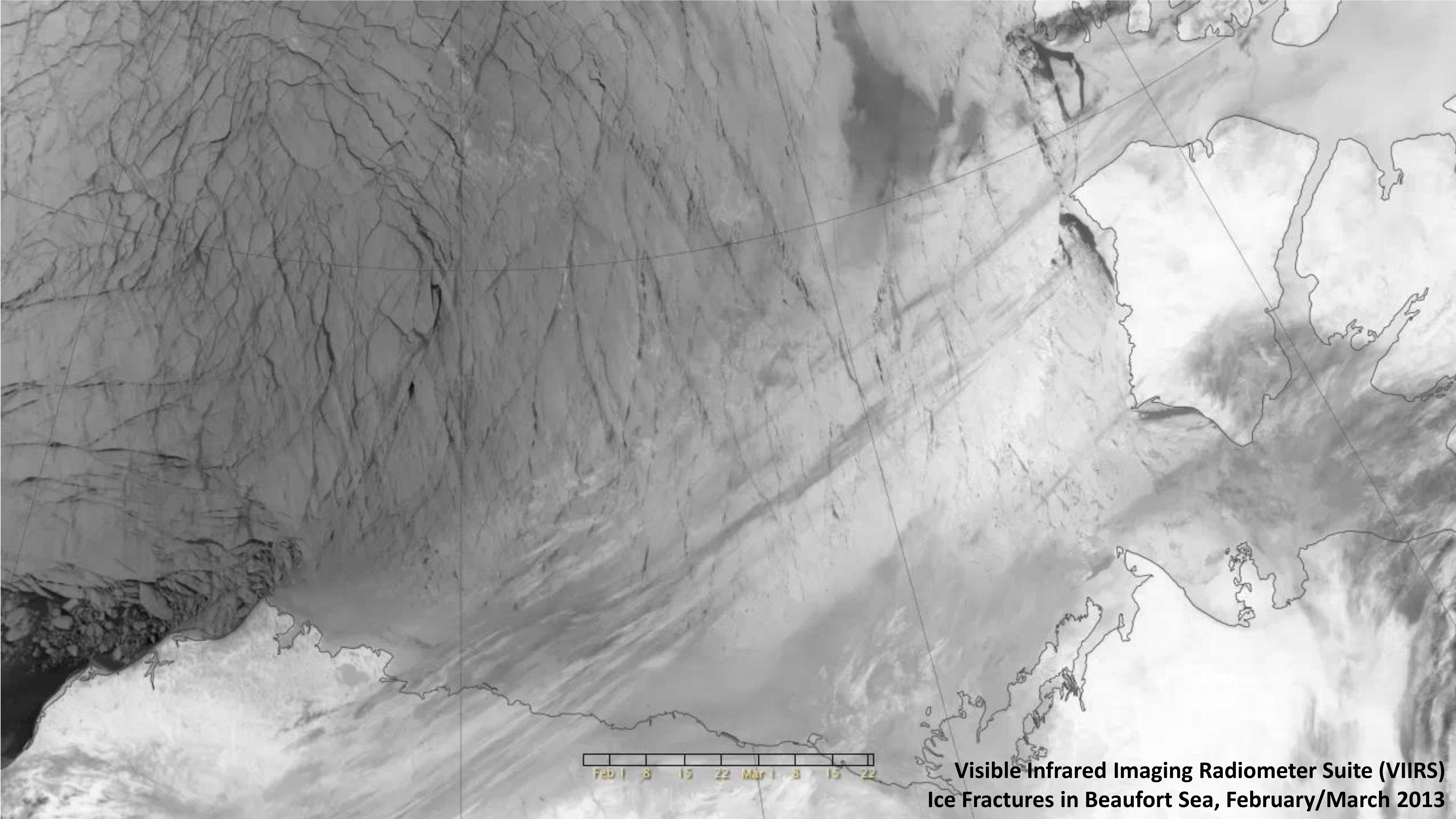
May 22, 2018

(based on Nguyen, Kwok, et al., 2009, 2011, 2012)


Sea Ice
Concentration (Opacity)
and Thickness (Shadowing)
[%]
75
50
25
0
2011/09/13
MITgcm
Horizontal grid spacing: 1 km
(Hutter et al., 2018)





Visible Infrared Imaging Radiometer Suite (VIIRS)
Ice Fractures in Beaufort Sea, February/March 2013

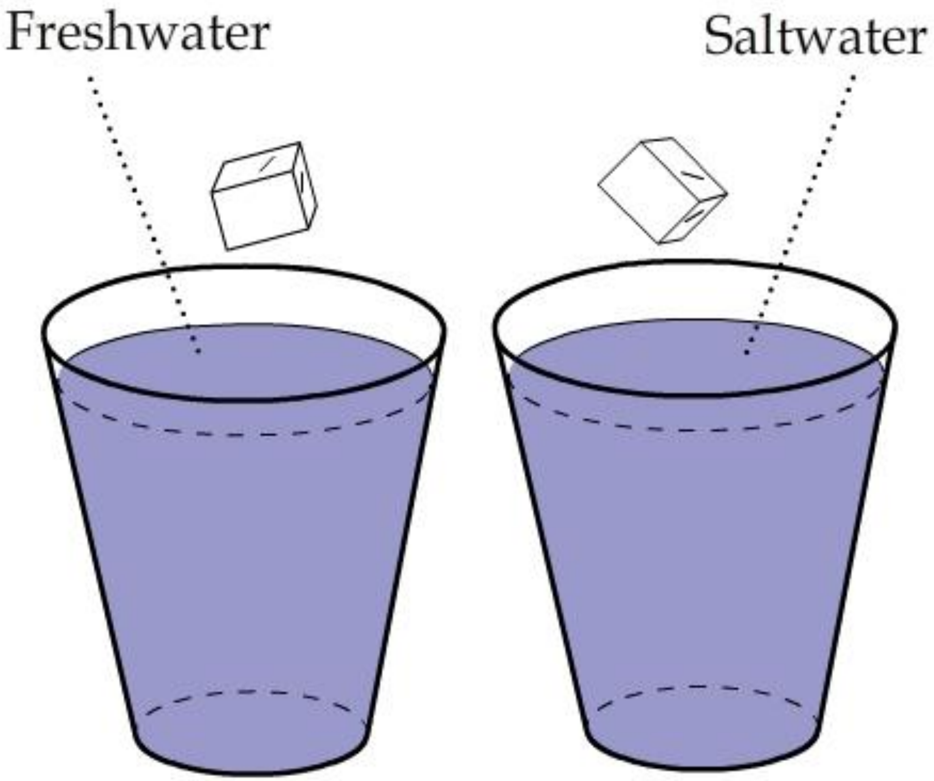
Outline

Improved Modeling of the Arctic Halocline with a Subgrid-Scale Brine Rejection Parameterization
(Nguyen, Menemenlis, and Kwok, 2009, *J. Geophys. Res*.)

Arctic Ice-Ocean Simulation with Optimized Model Parameters: Approach and Assessment
(Nguyen, Menemenlis, and Kwok, 2011. *J. Geophys. Res*.)

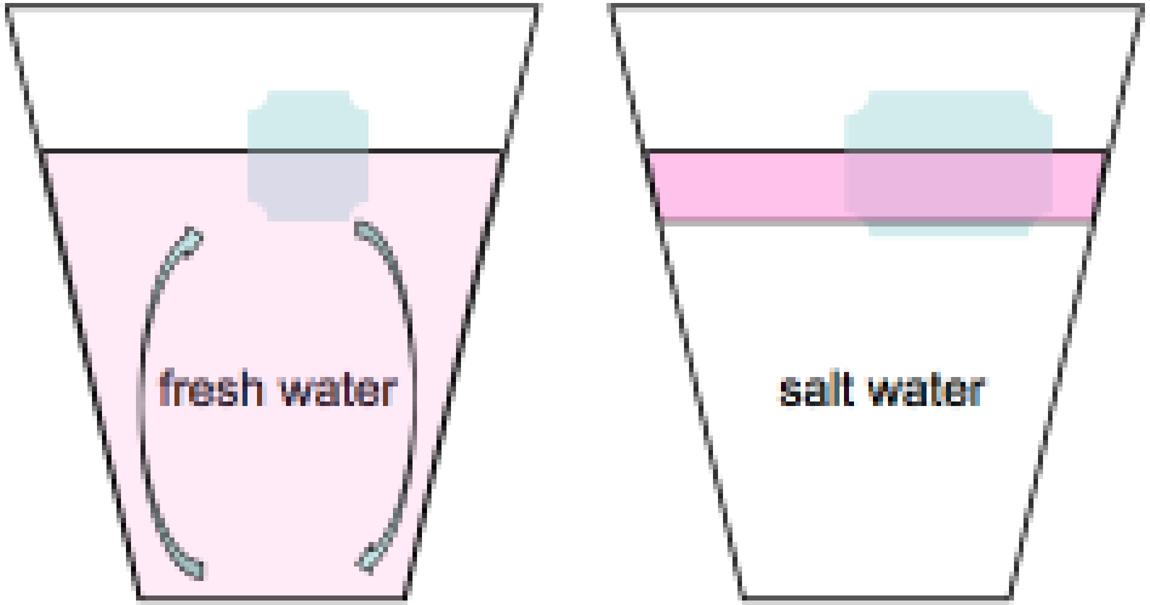
Source and Pathway of the Western Arctic Upper Halocline in a Data-Constrained Coupled Ocean and Sea Ice Model
(Nguyen, Kwok, and Menemenlis, 2012, *J. Phys. Oceanogr*.)

Ice cube in fresh and salty water experiment



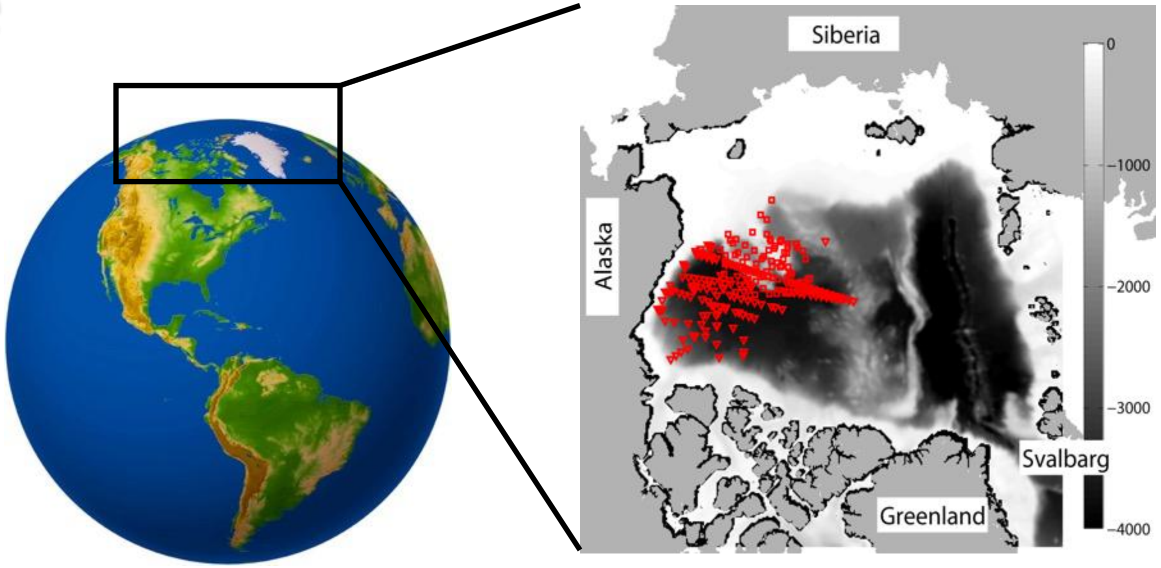
Which ice cube will melt faster?

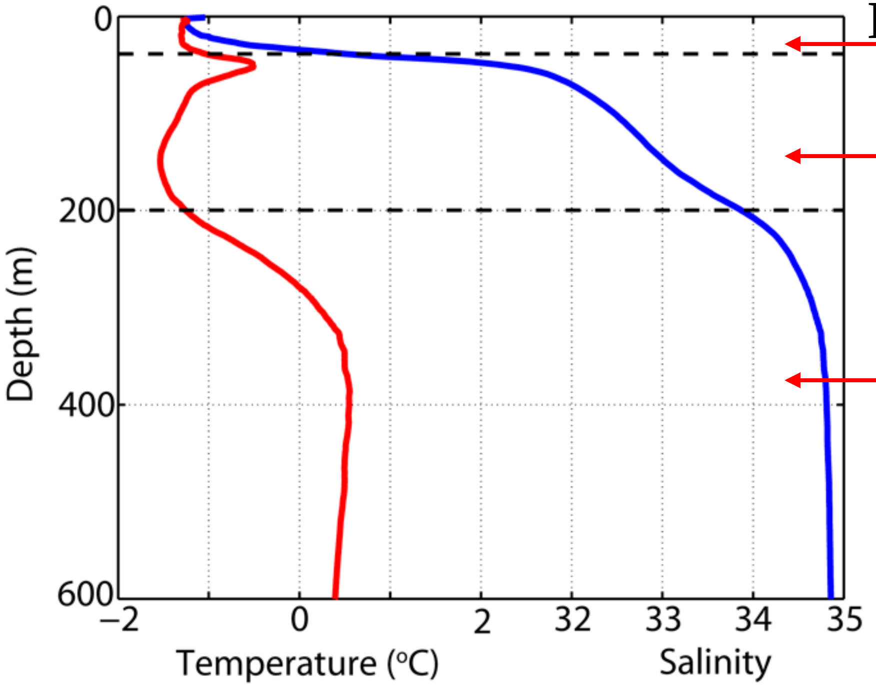
Ice cube in fresh and salty water experiment

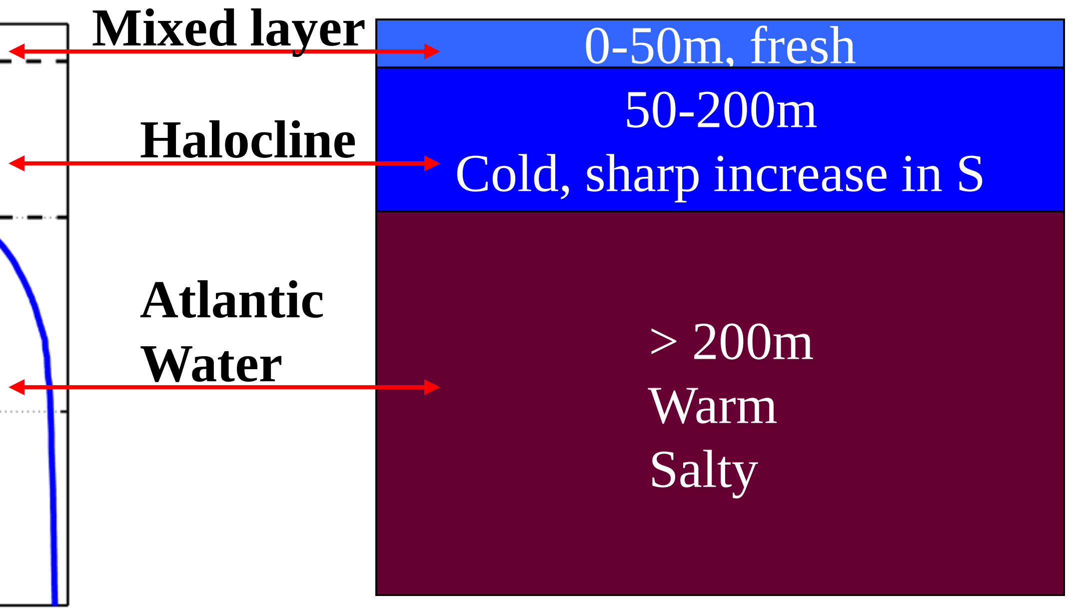


Why does the ice cube in freshwater melt faster?

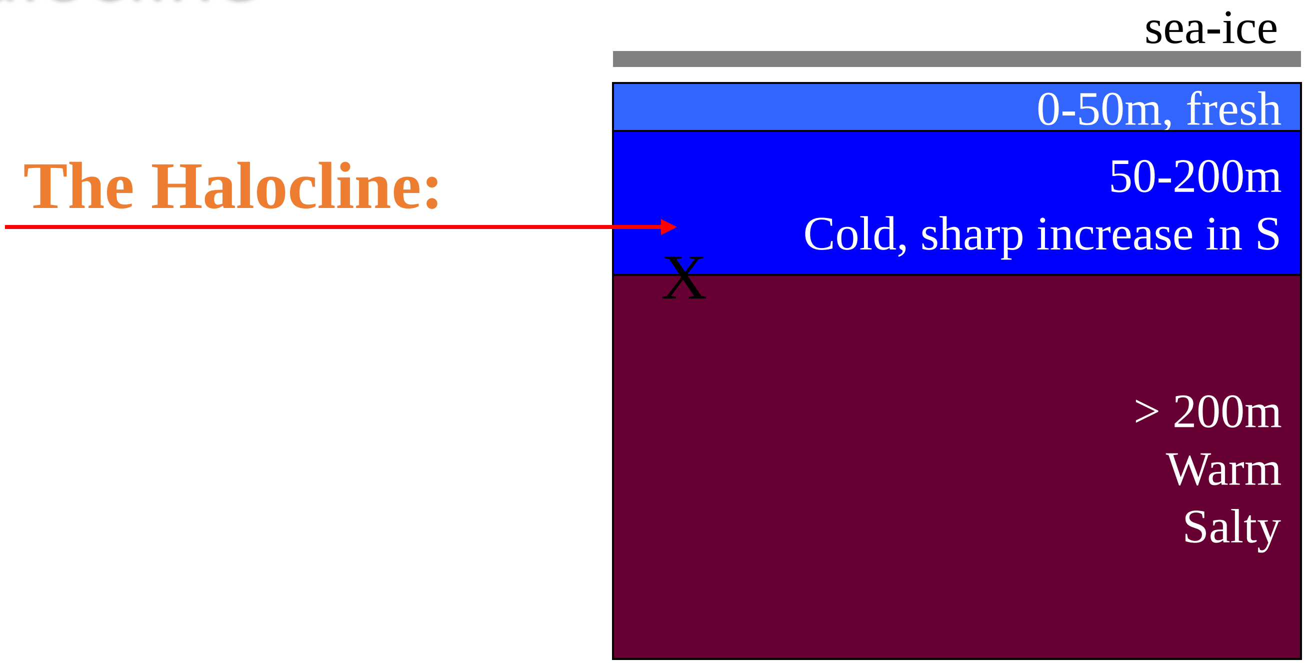
The Arctic Halocline





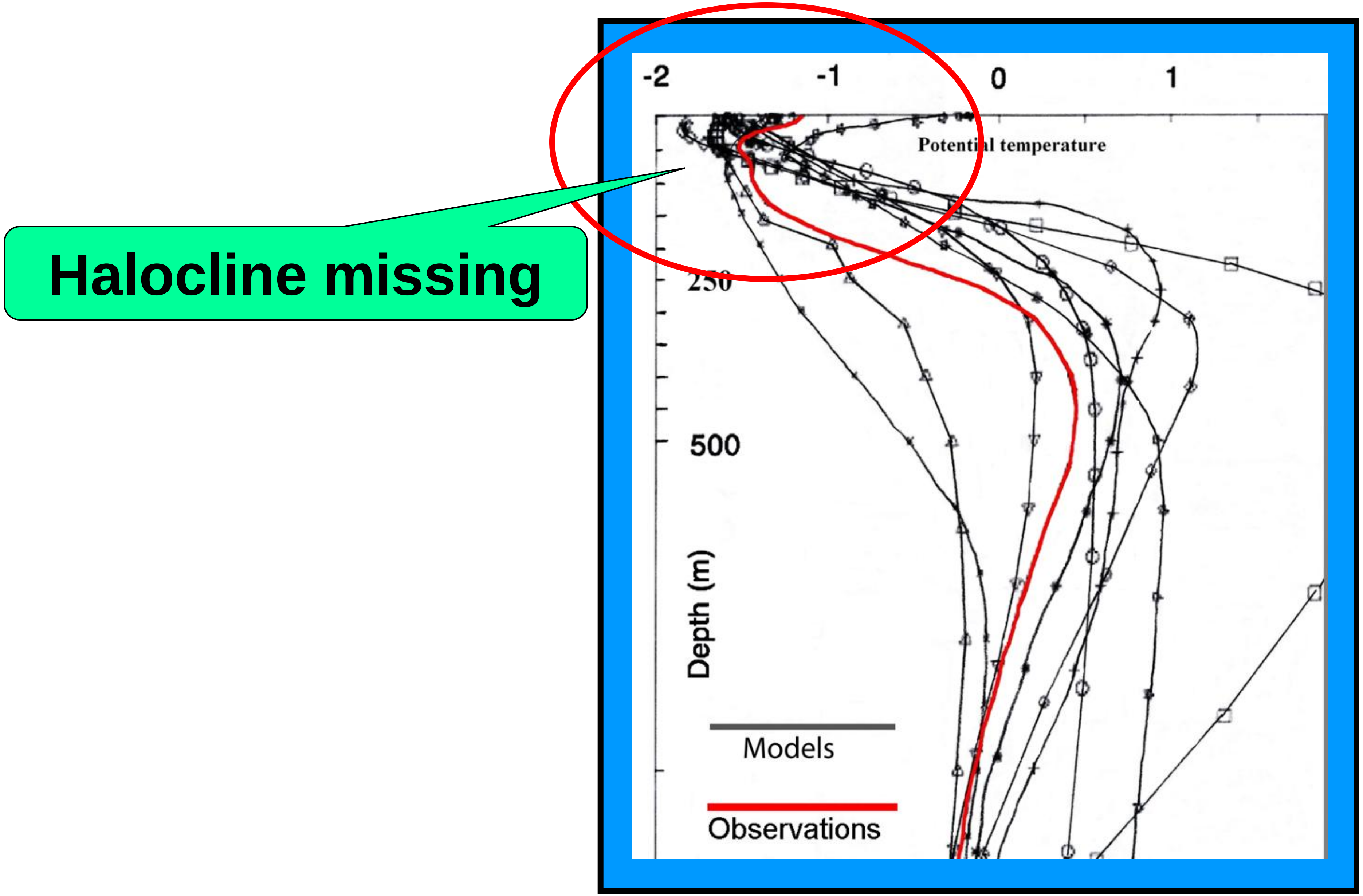


The Arctic Halocline



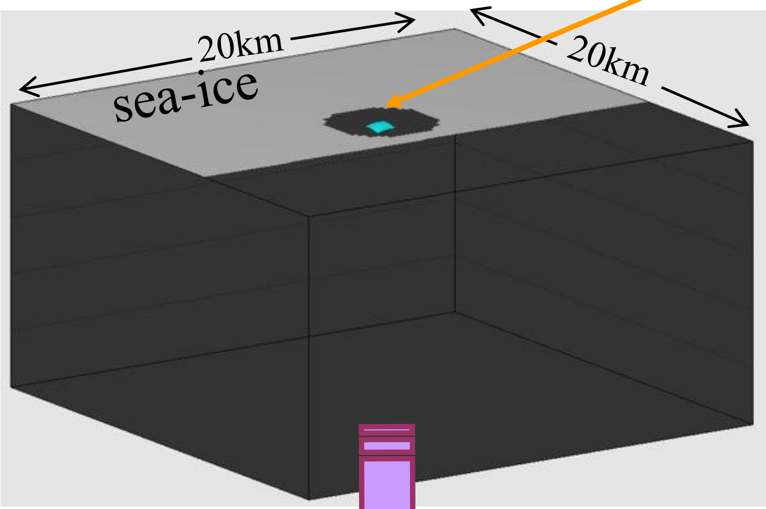
- ➢ **Insulator → prevents sea-ice melting**
- ➢ **Important to sea-ice stability**

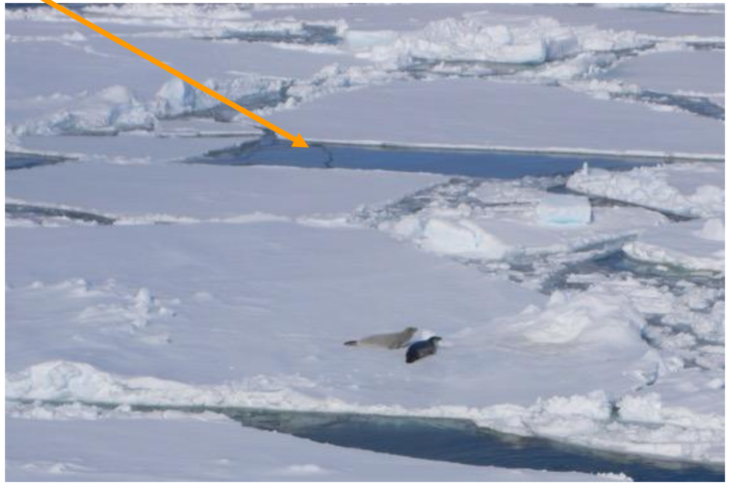
Arctic Ocean Model Intercomparison (AOMIP) simulations (Holloway, 2007)

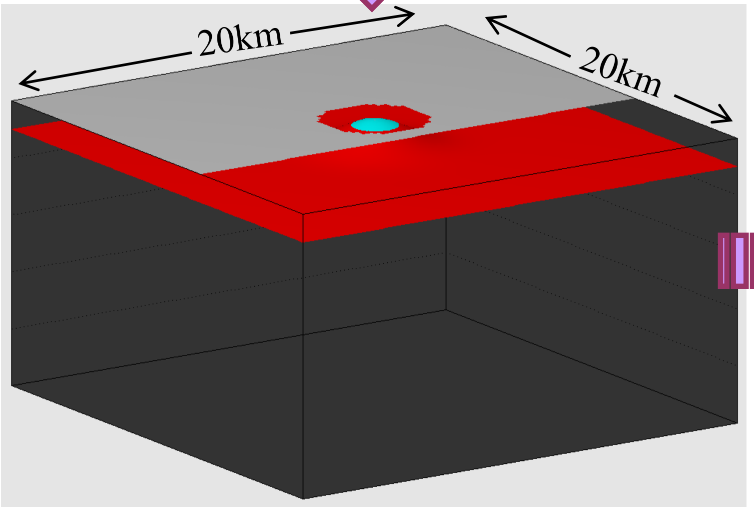


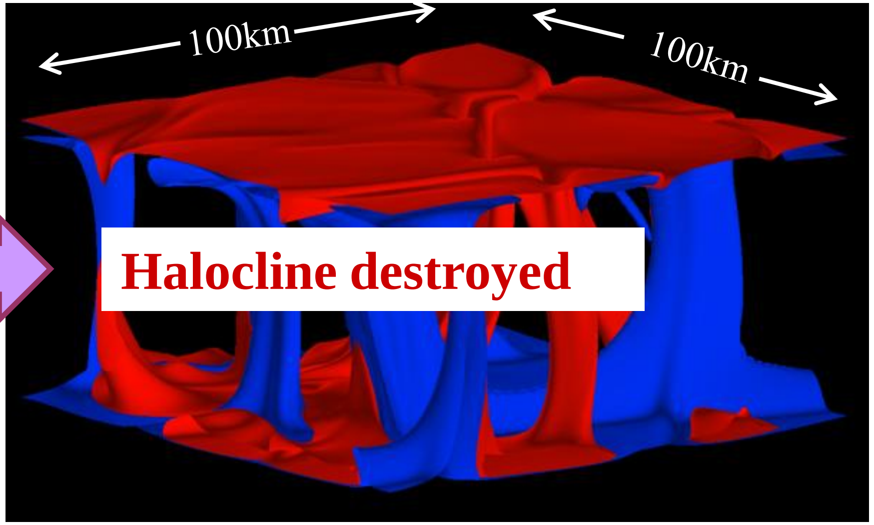
Problem

rejected salt



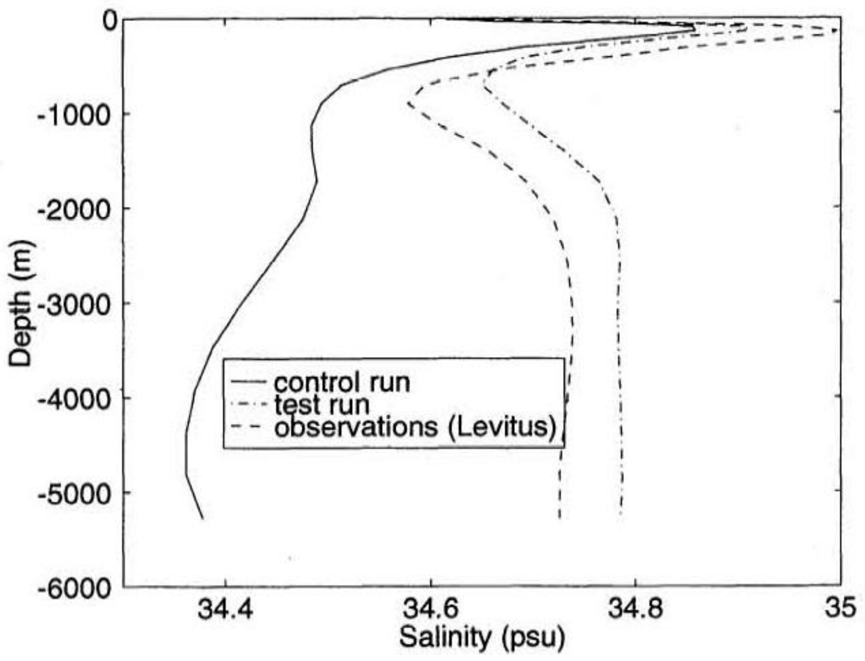


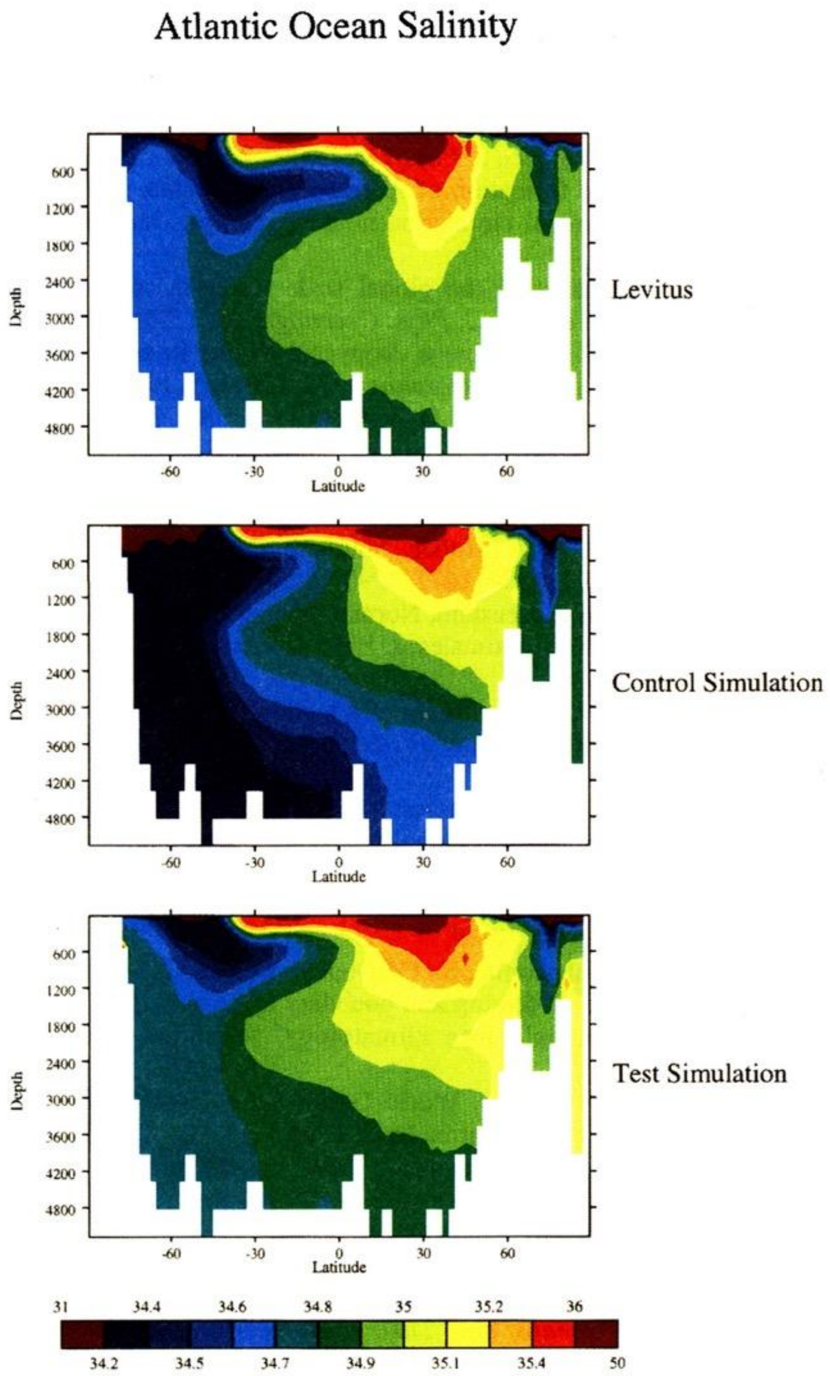




Salt plume scheme:

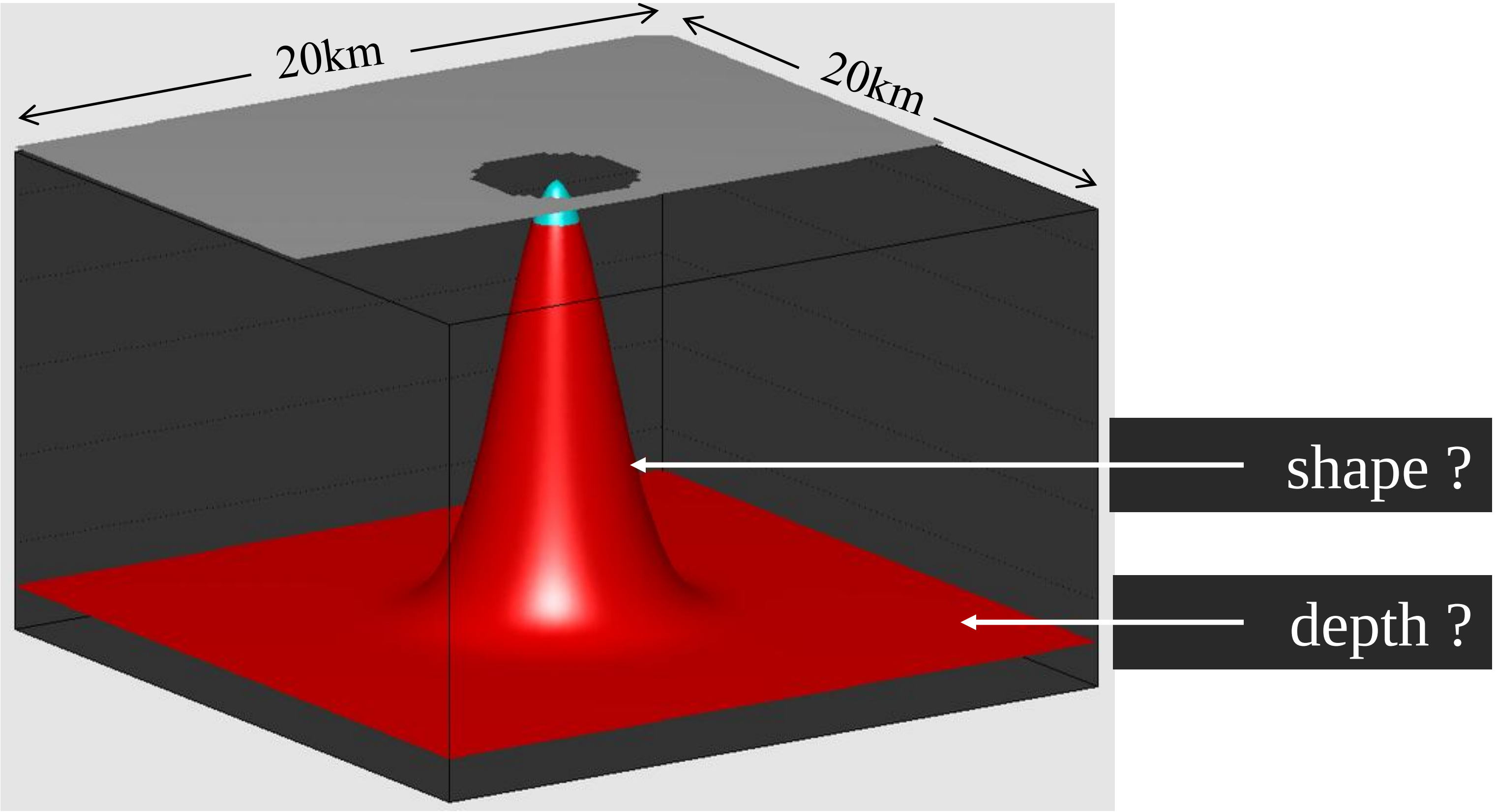
1. Duffy et al. [1997, 1999] in the Southern Ocean



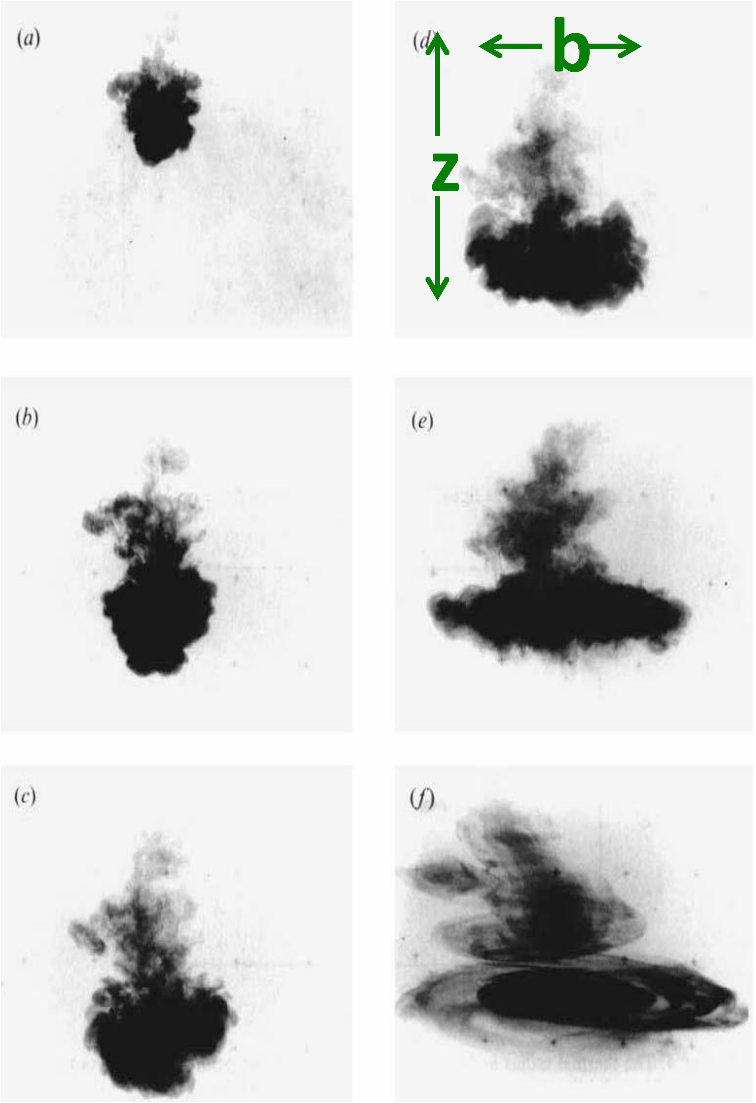


Hypothesis: **Sub-grid-scale Salt Rejection**

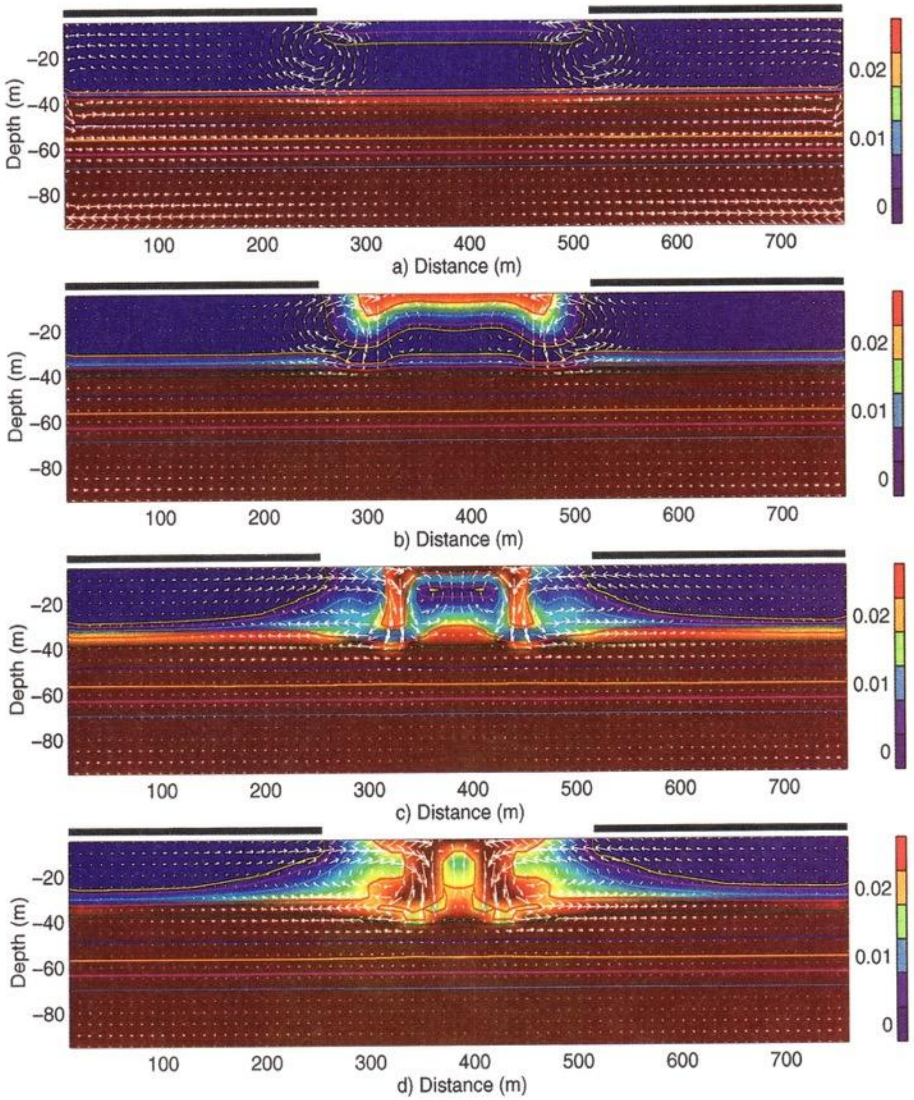
(less than 20km)



Laboratory and numerical simulations of salt plumes



(Helfrich, 1994)



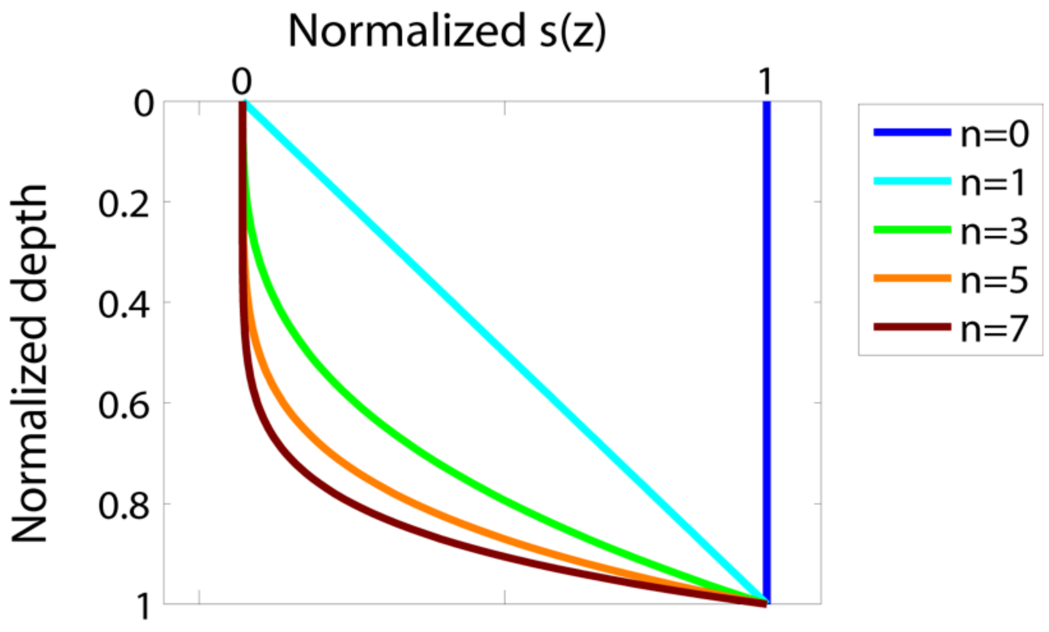
(Smith and Morison, 1998)

Parameterization

Brine Rejection Parameterization: Shape

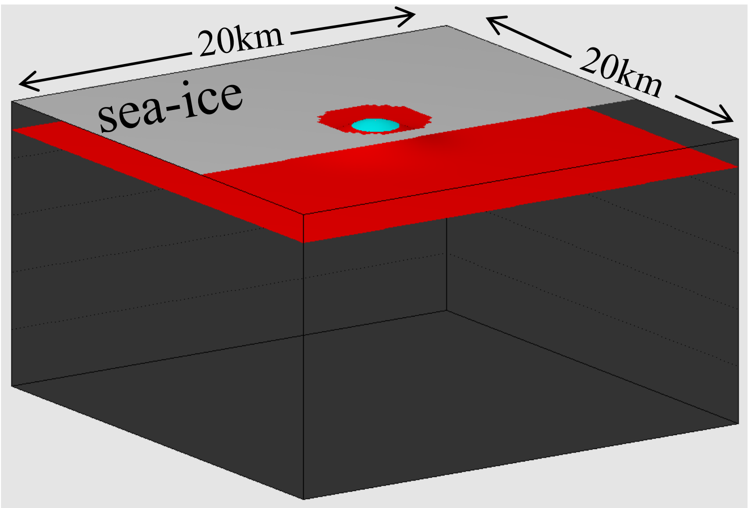
- **Sea-ice retains 33% of salt**
- **67% of salt rejected back to the ocean**
- **Rejected salt *s(z)* is distributed down to bottom of mixed layer *z=D* according to:**

$$s(z) = \begin{cases} Az^n, |z| \le |D| \\ 0, |z| > |D| \end{cases}$$

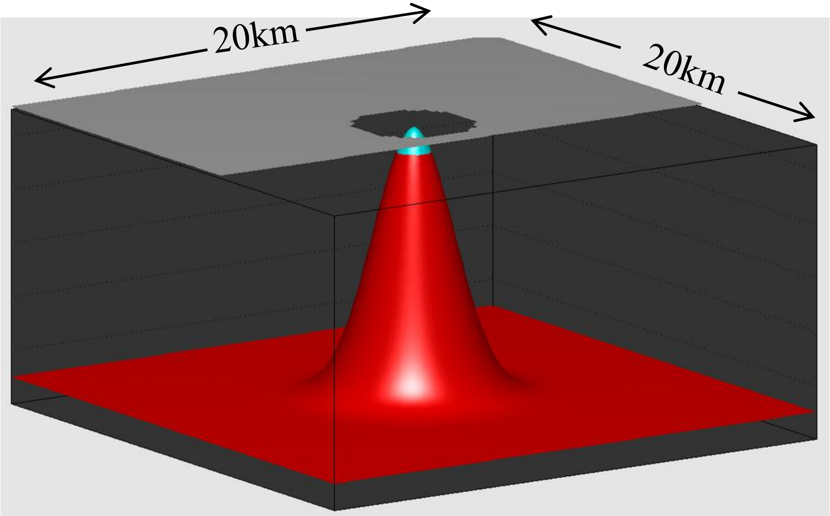


Results:

A0:
without salt-rejection scheme

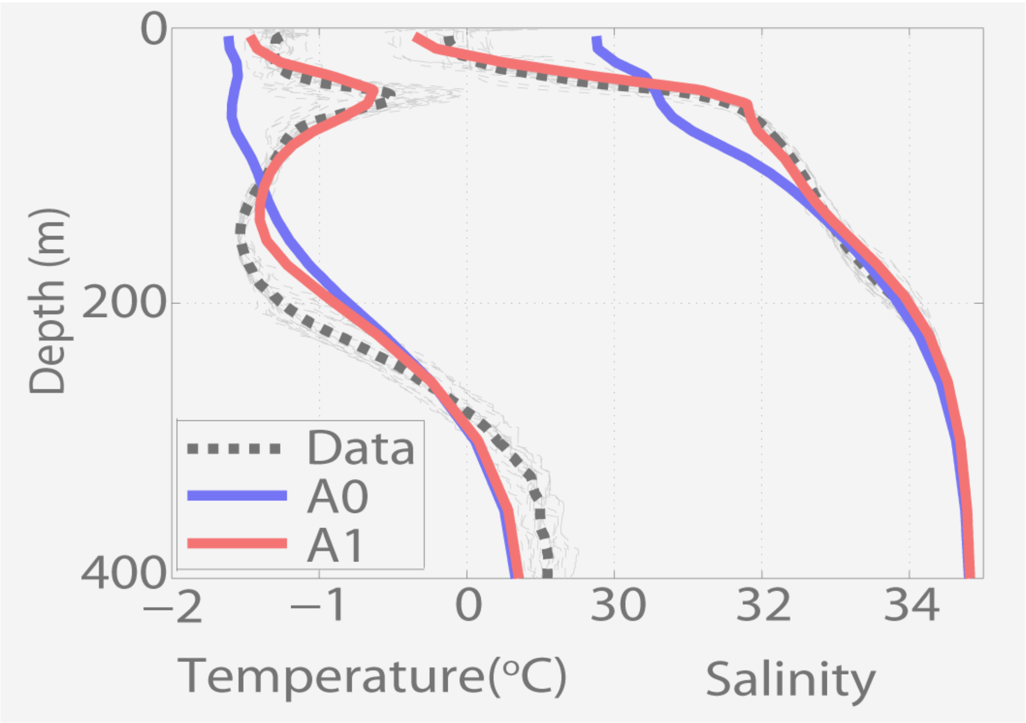


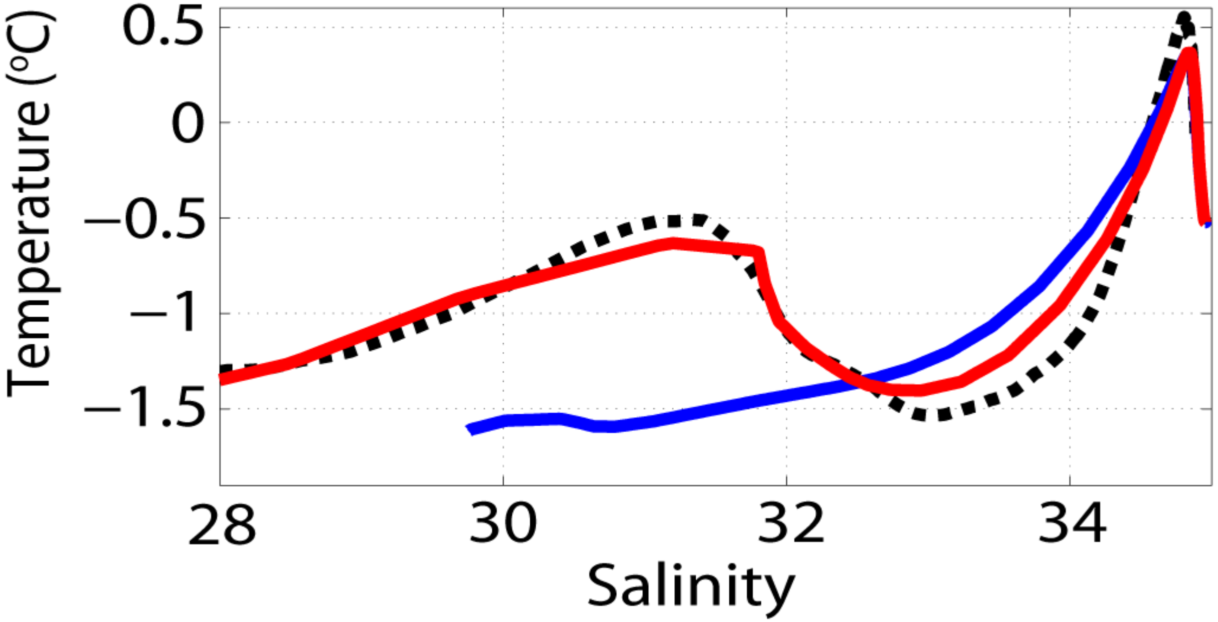
A1:
with salt-rejection scheme



Results:

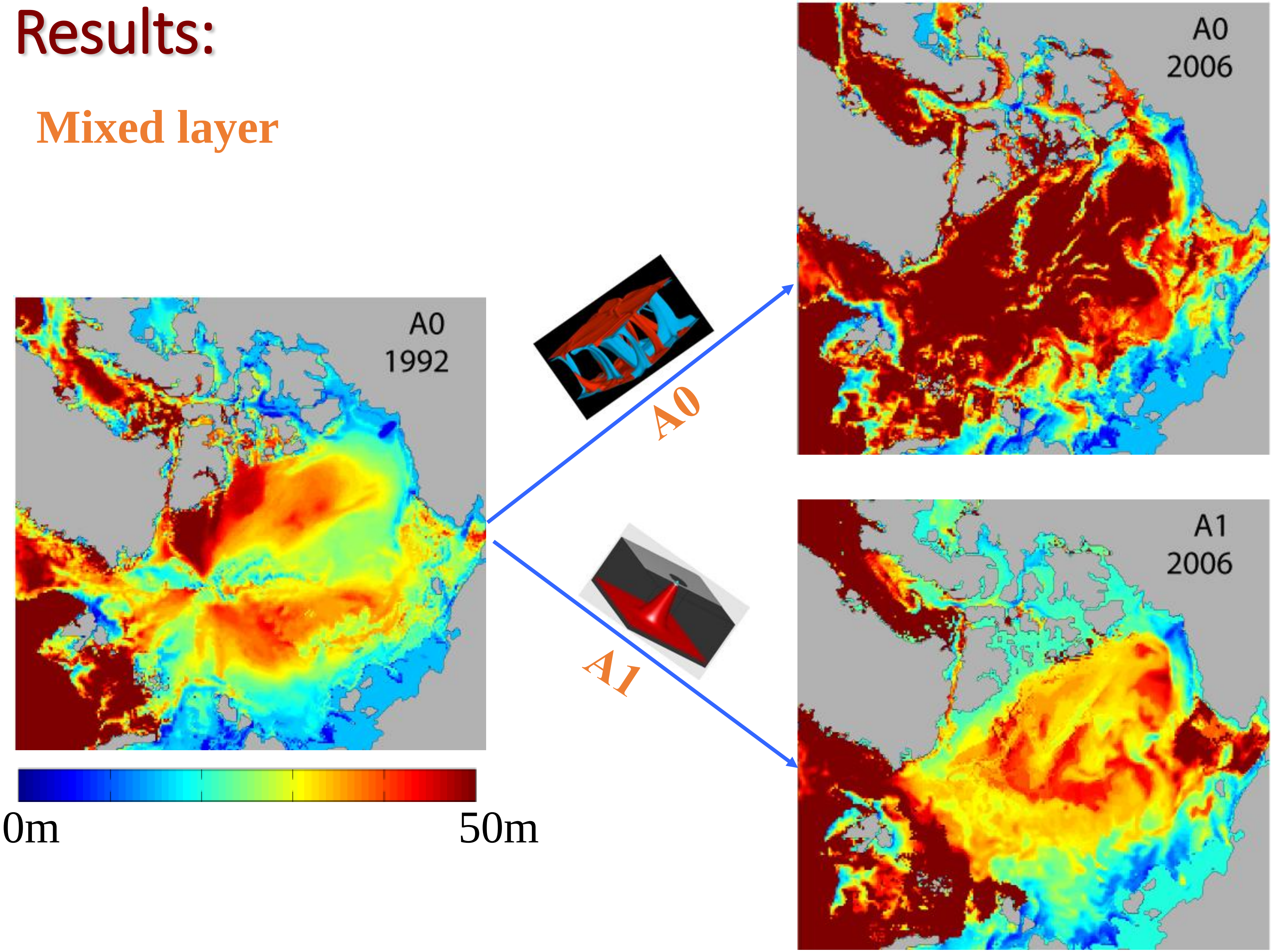
Temperature
Salinity





Results:

Mixed layer



Conclusion:

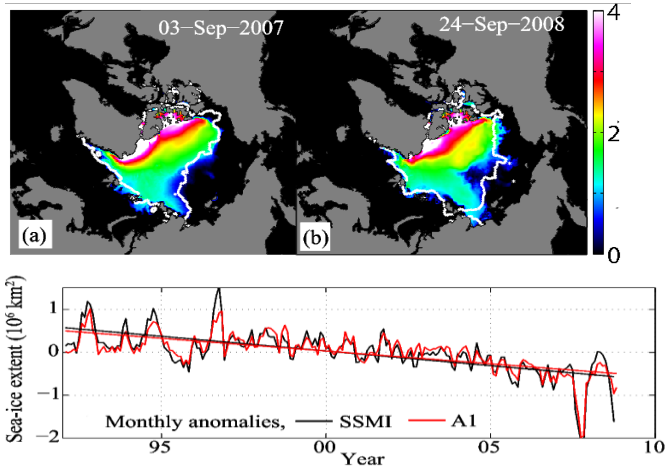
Successfully reproduce Halocline

resolution problem: salt rejection occurs at < 20km scale
→ common practice in ocean & atmosphere models

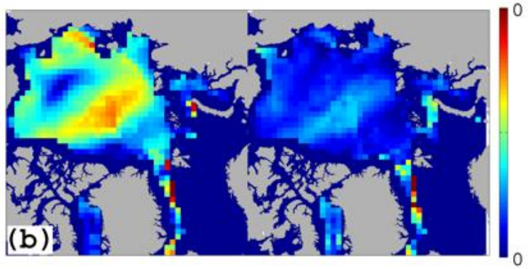
halocline: → prevents heat in Atlantic Water from melting sea-ice
→ important to sea-ice stability & climate change studies

An optimized, property-conserving Arctic Ocean simulation

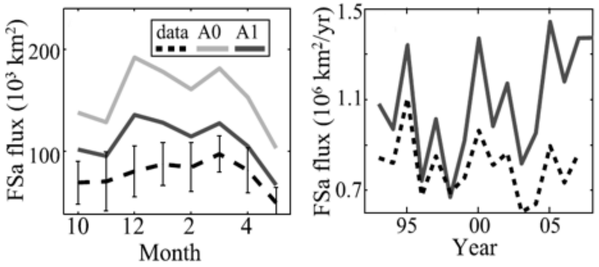
Sea ice extent



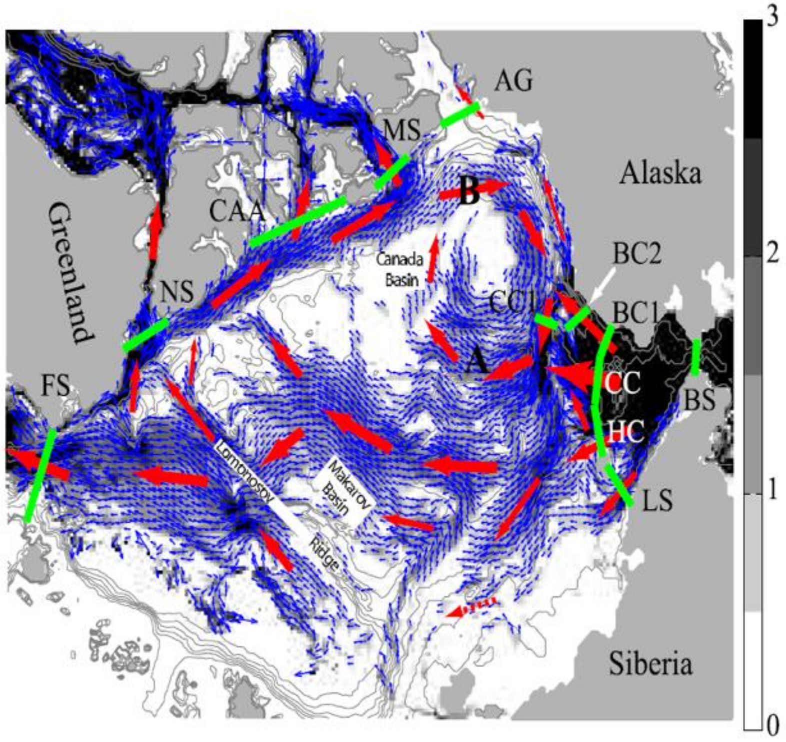
Sea ice velocity



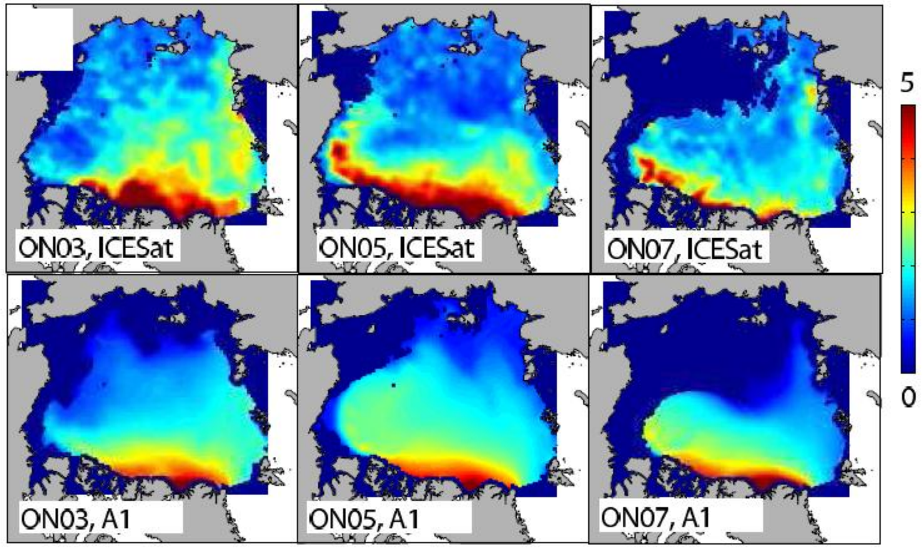
Sea ice flux



Pacific water circulation, upper 200 m (1994-2004)



Sea ice thickness



(Nguyen, Menemenlis, and Kwok, 2011)

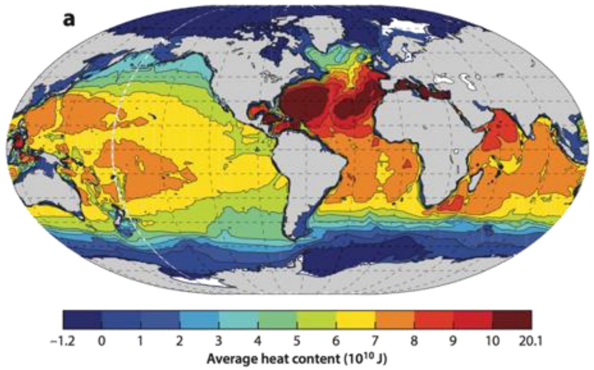
Estimating the Circulation and Climate of the Ocean (ECCO)

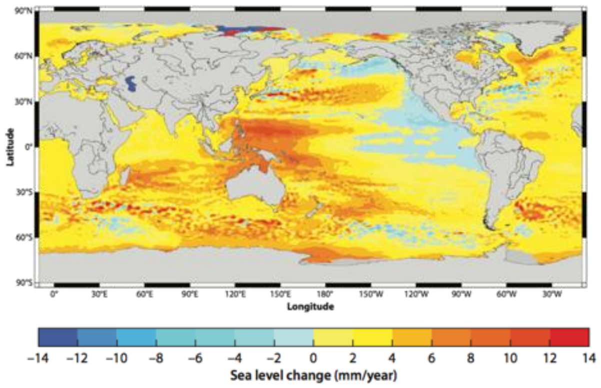
- ***The ECCO consortium*** *aims to make the best possible estimates of ocean circulation and its role in climate.*
- ***Solutions are obtained*** *by combining state-of-the-art ocean circulation models with nearly complete global ocean data sets in a physically and statistically consistent manner.*
- ***Products are being utilized*** *in studies on ocean variability, biological cycles, coastal physics, water cycle, ocean-cryosphere interactions, and geodesy, and are available for general applications.*

$$J = \sum_{t=0}^{t_f} (y_t - \Gamma_t x_t)' P_t (y_t - \Gamma_t x_t)$$

$$L = J(x_{[0,t_f]}) + \sum_{t=0}^{t_f-1} \lambda_t' \left(x_{t+1} - M(p_t, x_t)\right)$$

$$\lambda_0 = \sum_{t=1}^{t_f-1} \{A_1' A_2' \cdots A_t' G_{t+1}\} + G_1$$





(slide prepared by I. Fenty for ECCO Workshop, Ocean Sciences 2018)

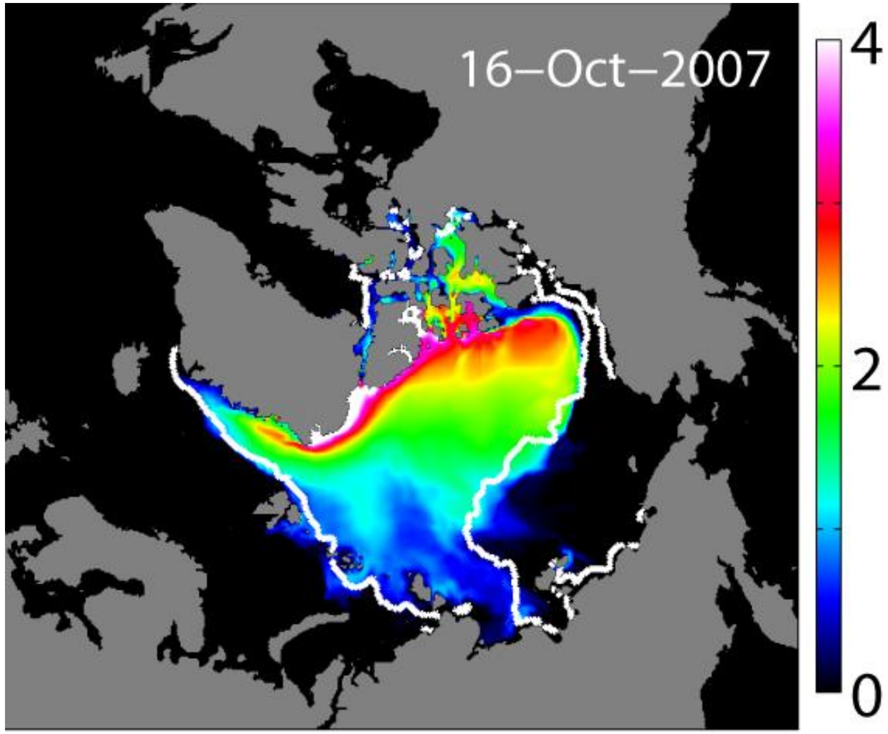
Regional Arctic solution:

<u>Ocean model:</u>

- ~ 18km horizontal, 50 vertical levels
- volume-conserving, C-grid
- Surface BC's: ECMWF / ERA-40
- Initial conditions: WOA05
- bathymetry: GEBCO
- KPP mixing [Large et al., 1994]

<u>Sea ice model:</u>

- C-grid, ~ 18km
- 2-catergory zero-layer thermodynamics [Hibler, 1980]
- Viscous plastic dynamics [Hibler, 1979]
- Initial conditions: Polar Science Center
- Snow simulation: [Zhang et al., 1998]



Green's Function Estimation Approach

(Stammer and Wunsch 1996; Menemenlis and Wunsch 1997; Menemenlis, Fukumori, and Lee 2005)

controled parameters

GCM: $\mathbf{x}(t_{i+1}) = M(\mathbf{x}(t_i), \boldsymbol{\eta})$

Data: $\mathbf{y}^o = H(\mathbf{x}) + \boldsymbol{\varepsilon} \qquad = G(\boldsymbol{\eta}) + \boldsymbol{\varepsilon}$

Cost function: $J = \boldsymbol{\eta}^T \mathbf{Q}^{-1} \boldsymbol{\eta} + \boldsymbol{\varepsilon}^T \mathbf{R}^{-1} \boldsymbol{\varepsilon}$

Linearization: $G(\boldsymbol{\eta}) \approx G(\mathbf{0}) + \mathbf{G}\boldsymbol{\eta}$

$\mathbf{G}$ is an $n \times p$ matrix, where n is the number of observations in vector $\mathbf{y}^o$ and p is the number of parameters in vector $\boldsymbol{\eta}$. Each column of matrix $\mathbf{G}$ can be determined by perturbing one element of $\boldsymbol{\eta}$, that is, by carrying out one GCM sensitivity experiment.

GCM-data residual: $\mathbf{y}^d = \mathbf{y}^o - G(\mathbf{0}) \qquad \approx \mathbf{G}(\boldsymbol{\eta} - \boldsymbol{\eta}_o) + \boldsymbol{\varepsilon}$

Solution: $\boldsymbol{\eta}^a = \mathbf{P}\mathbf{G}^T\mathbf{R}^{-1}\mathbf{y}^d$

Uncertainty covariance: $\mathbf{P} = (\mathbf{Q}^{-1} + \mathbf{G}^T\mathbf{R}^{-1}\mathbf{G})^{-1}$

Modified Cost:

$$J = (\mathbf{y}^o - G(\mathbf{0}))^T \mathbf{W} (\mathbf{y}^o - G(\mathbf{0}))$$
$$\approx (\mathbf{G}(\boldsymbol{\eta} - \boldsymbol{\eta}_o) + \boldsymbol{\varepsilon})^T \mathbf{W} (\mathbf{G}(\boldsymbol{\eta} - \boldsymbol{\eta}_o) + \boldsymbol{\varepsilon})$$
$$\approx (\boldsymbol{\eta} - \boldsymbol{\eta}_o)^T \mathbf{G}^T \mathbf{W} \mathbf{G} (\boldsymbol{\eta} - \boldsymbol{\eta}_o) + \boldsymbol{\varepsilon}^T \mathbf{W} \boldsymbol{\varepsilon}$$

Optimization details:

$[\mathbf{y}^o]$

Data constraints:
- sea level anomaly from altimeter data
- time-mean sea level from Maximenko and Niiler (2005)
- sea surface temperature from GHRSST-PP
- temperature and salinity profiles from WOCE, TAO, ARGO, XBT, etc.
- sea ice concentration from passive microwave data
- sea ice motion from radiometers, QuikSCAT, and RGPS
- sea ice thickness from ULS

Control parameters:

$[\eta]$

- initial temperature and salinity conditions
- atmospheric surface boundary conditions
- background vertical diffusivity
- critical Richardson numbers for Large et al. (1994) KPP scheme
- air-ocean, ice-ocean, air-ice drag coefficients
- ice/ocean/snow albedo coefficients
- bottom drag and vertical viscosity

Regional optimized solution:

- Data: [$\mathbf{y}^o$]
  - Sea-ice velocity, sea-ice thickness, CTD profiles,

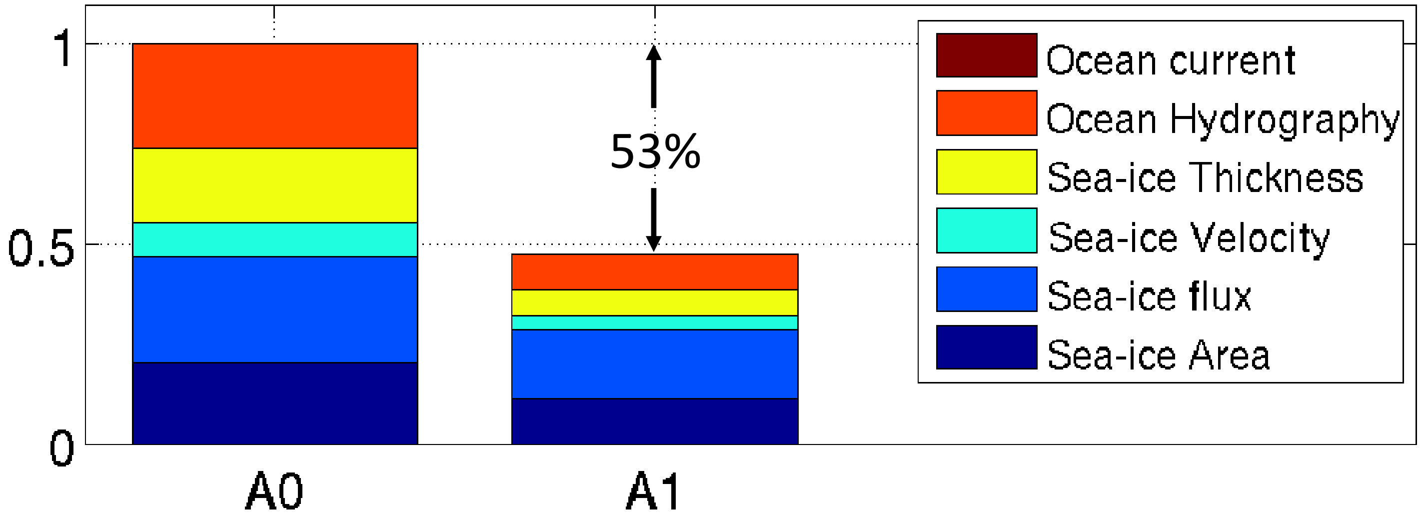
- Parameters: [η]
  - Salt-plume parameters, air / sea-ice drag coefficients, sea-ice and ocean albedos, sea-ice strength, initial conditions, freshwater content, etc.

- Solutions:

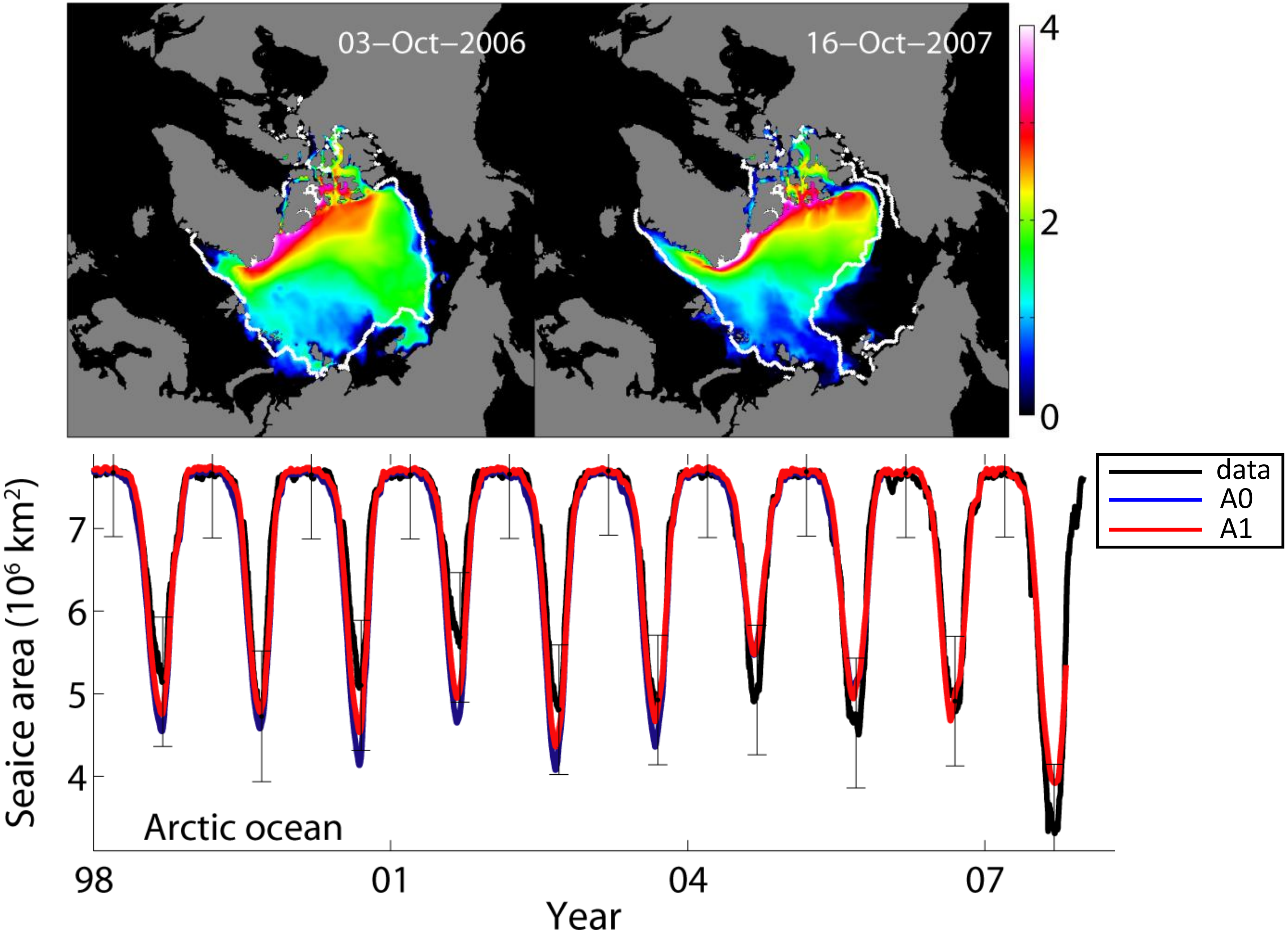
  Baseline: A0

  Optimized: A1

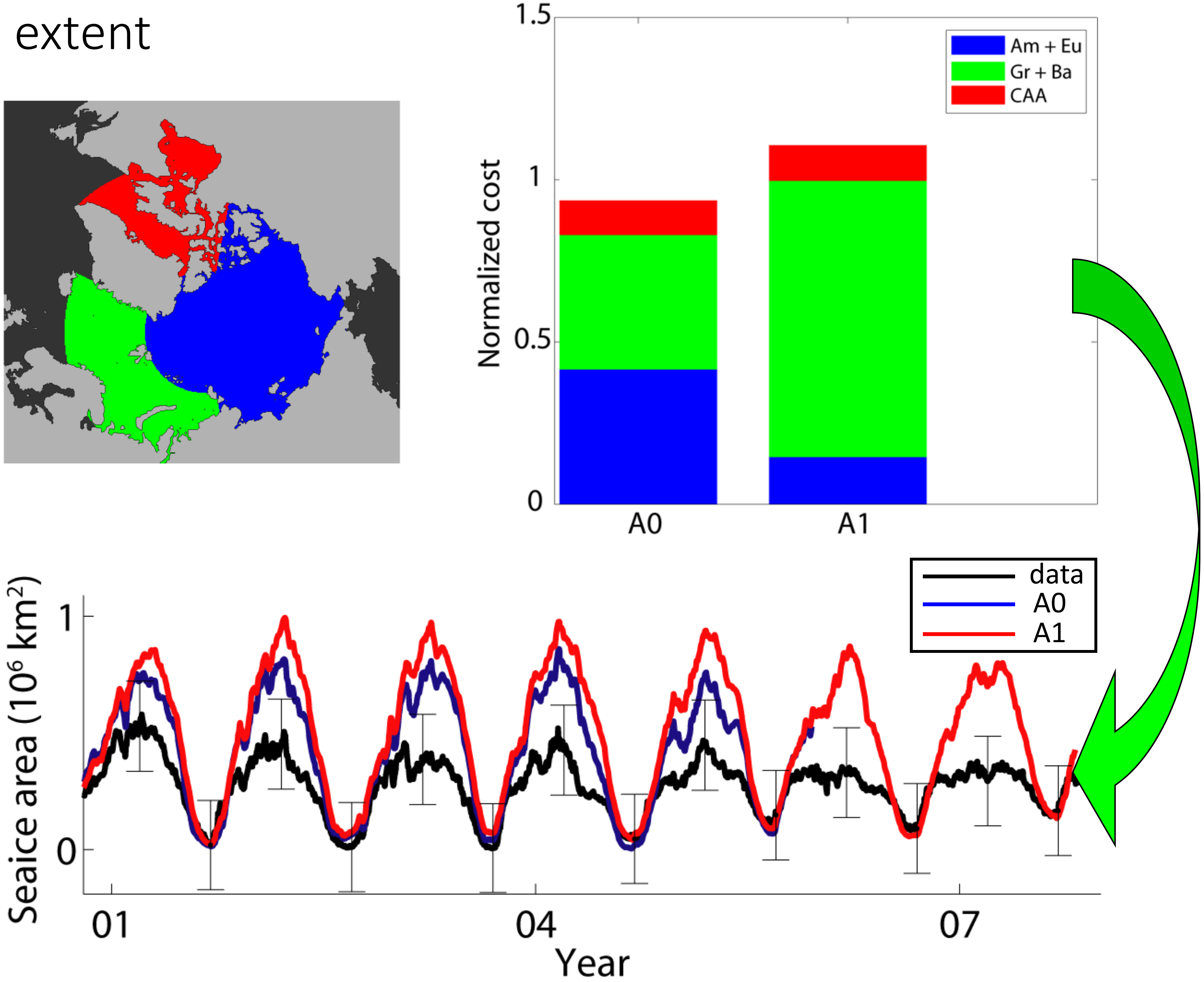
- Cost: $(m-d)^T W (m-d)$



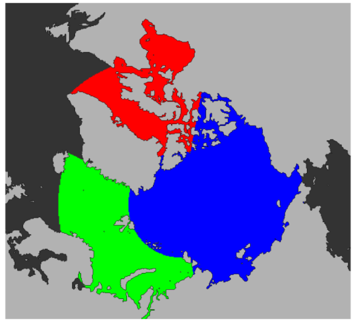
Sea ice extent

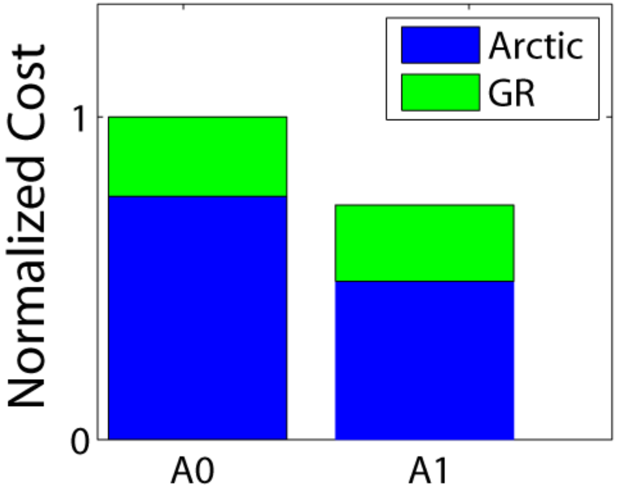


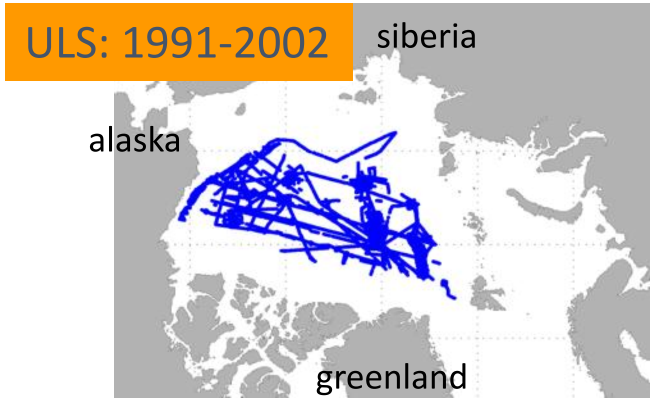
Sea ice extent

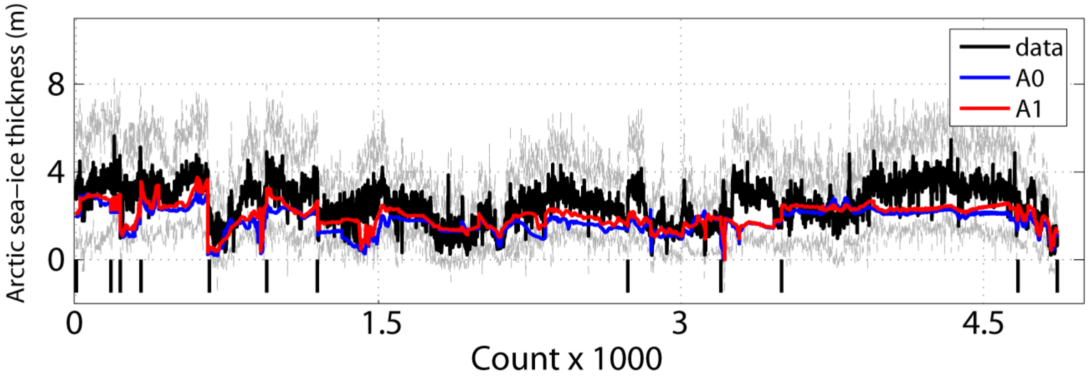


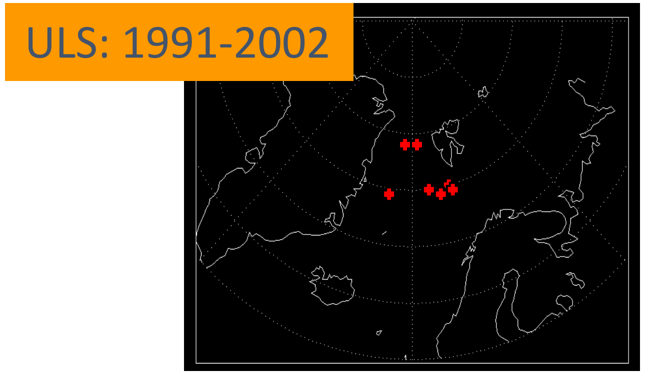
Sea ice thickness

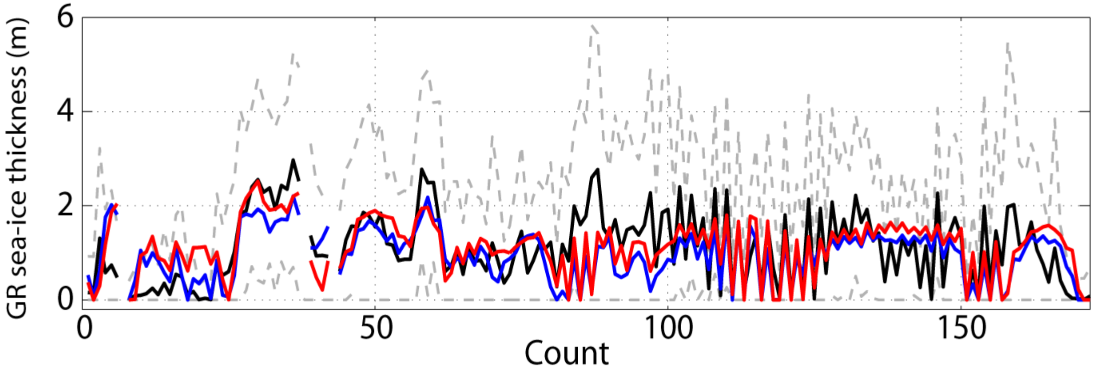








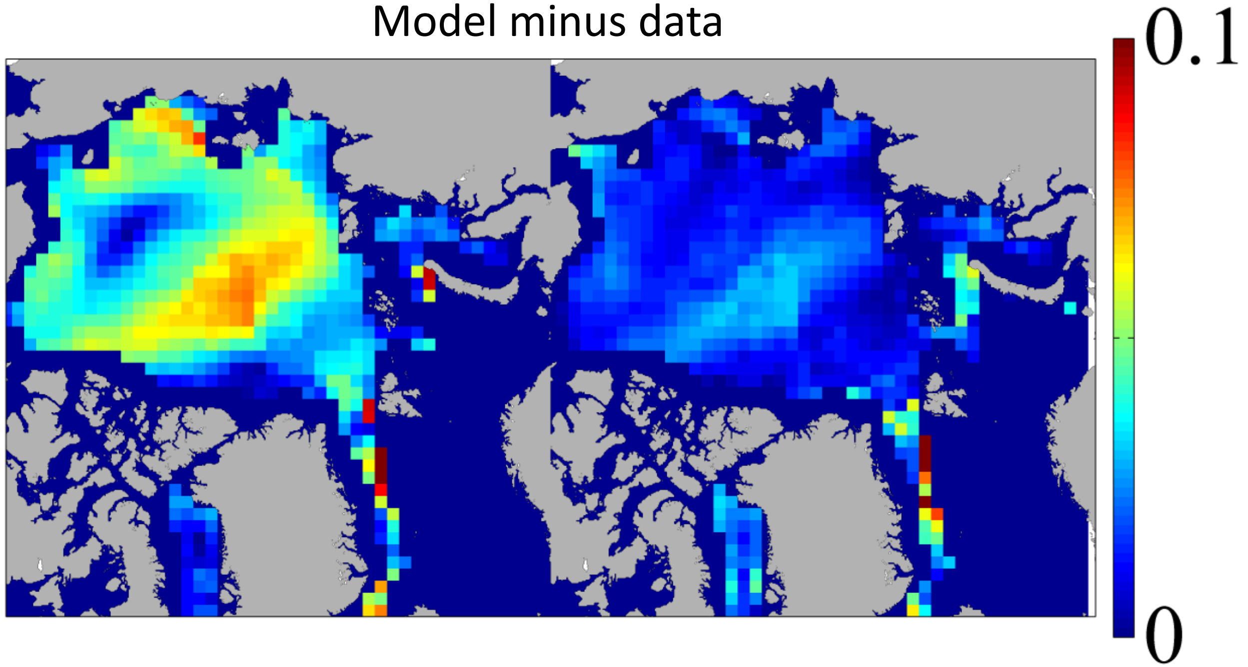


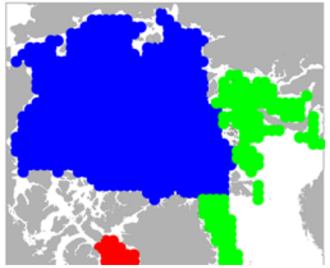


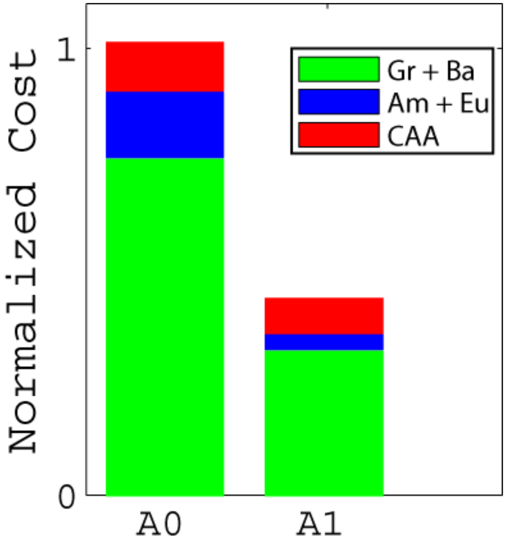
Sea ice velocity

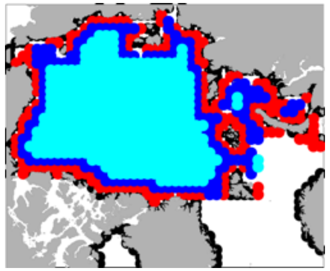
Passive microwave derived
1992-2002

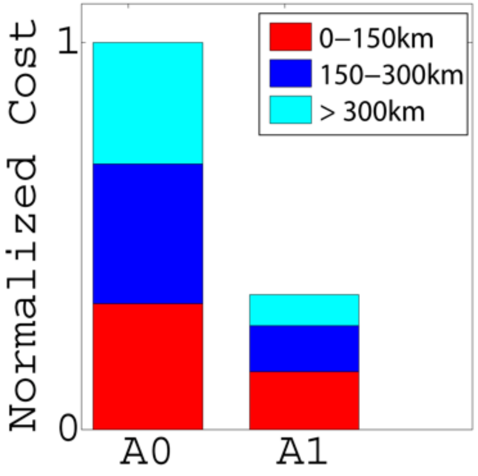
Model minus data





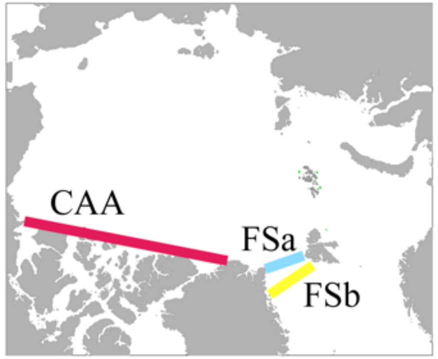


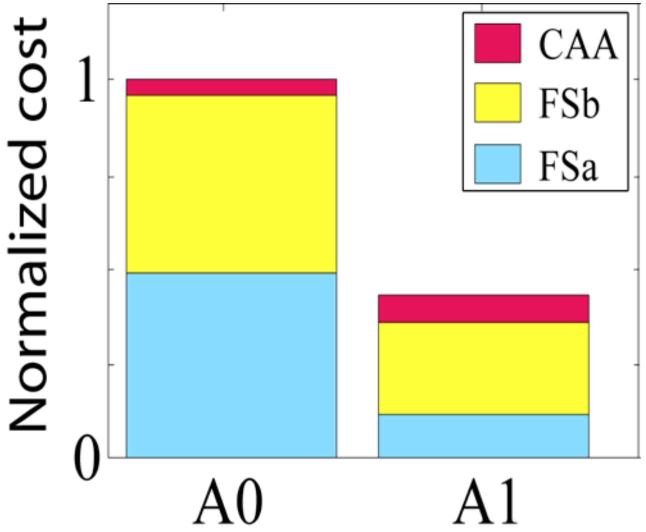


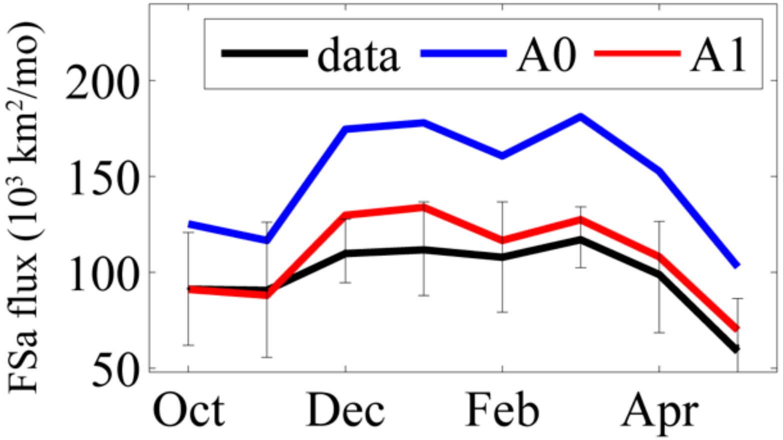


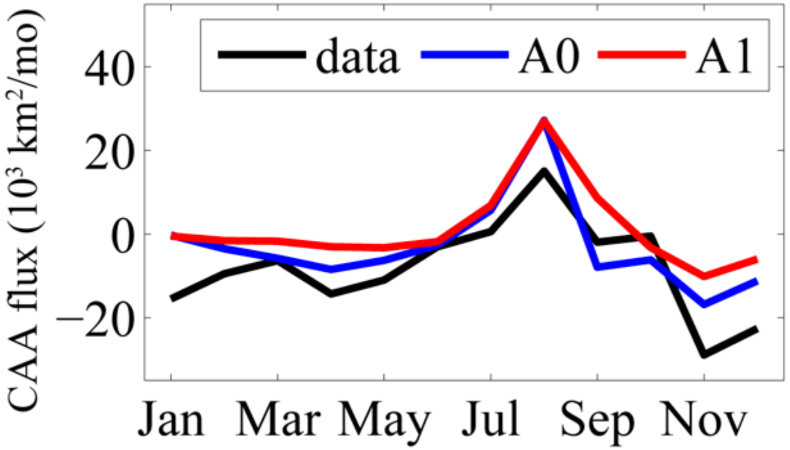
Sea Ice flux:

Passive Microwave data: 1991-2002

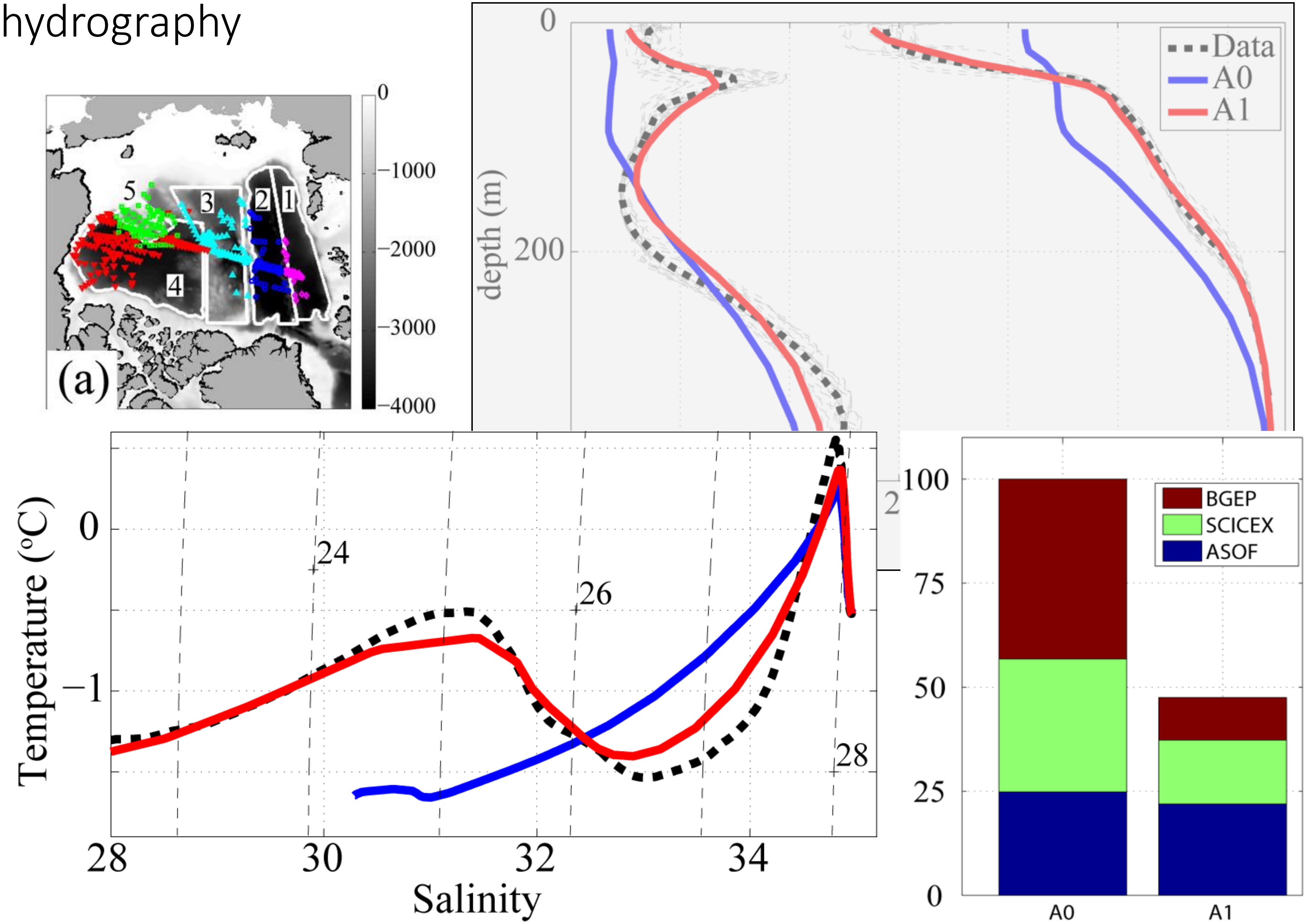




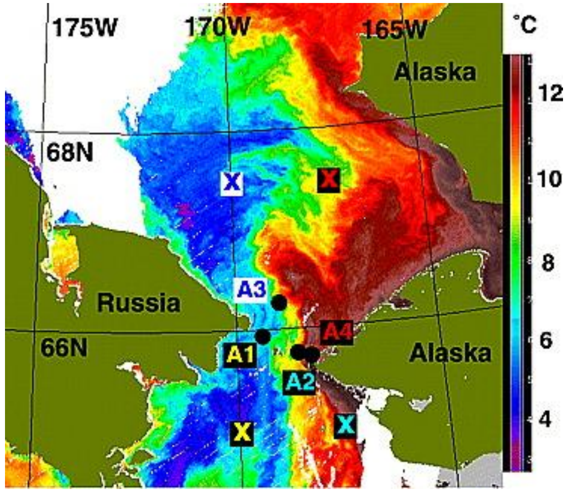




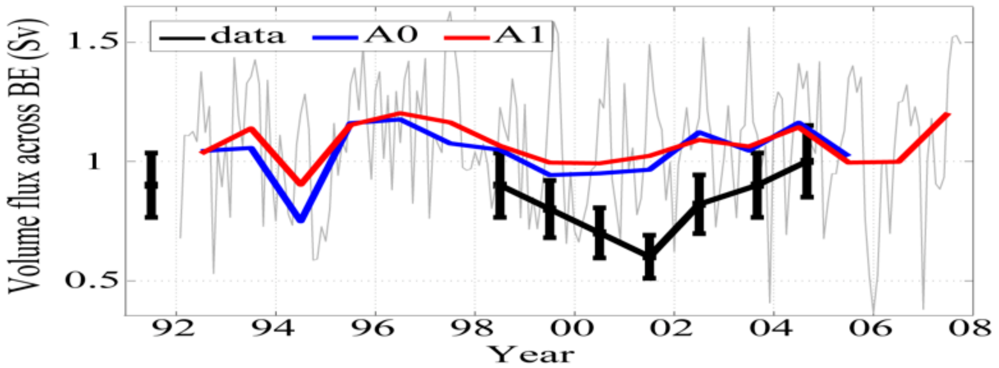
Arctic ocean hydrography

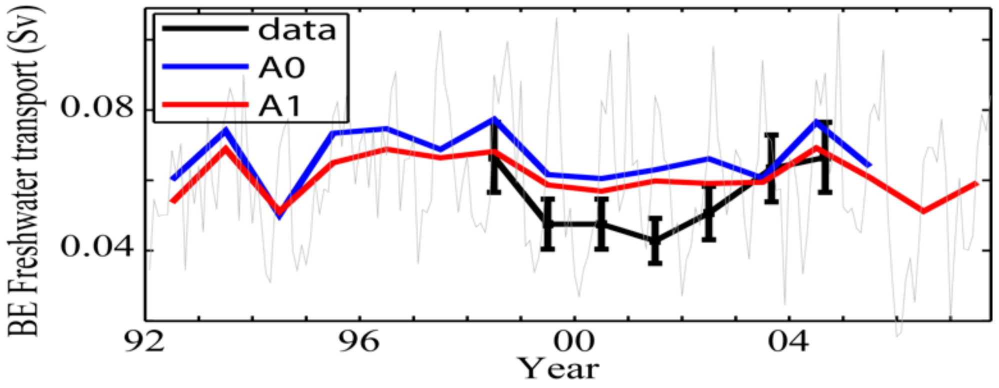


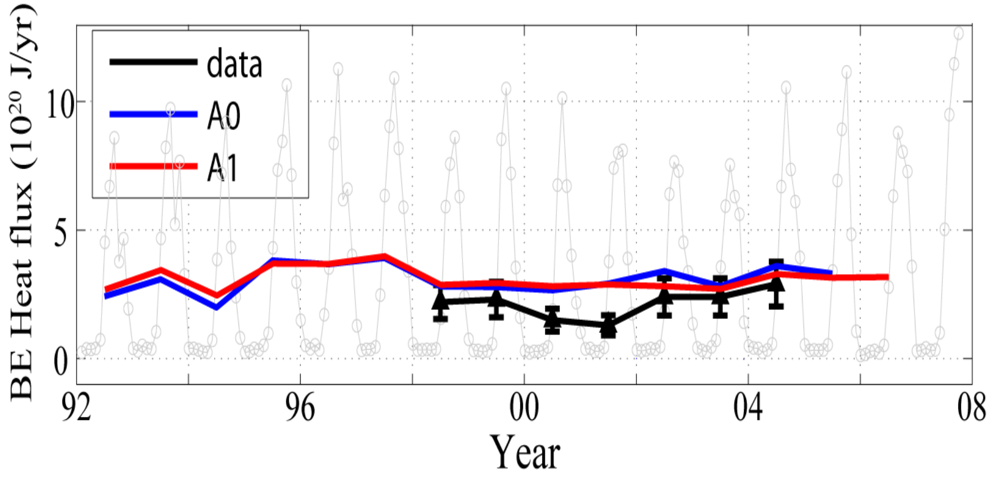
Arctic ocean fluxes: Bering Strait



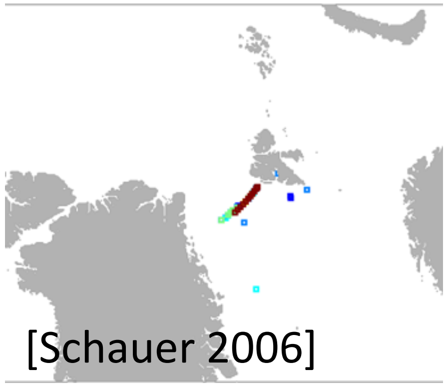
[Woodgate, 2006]

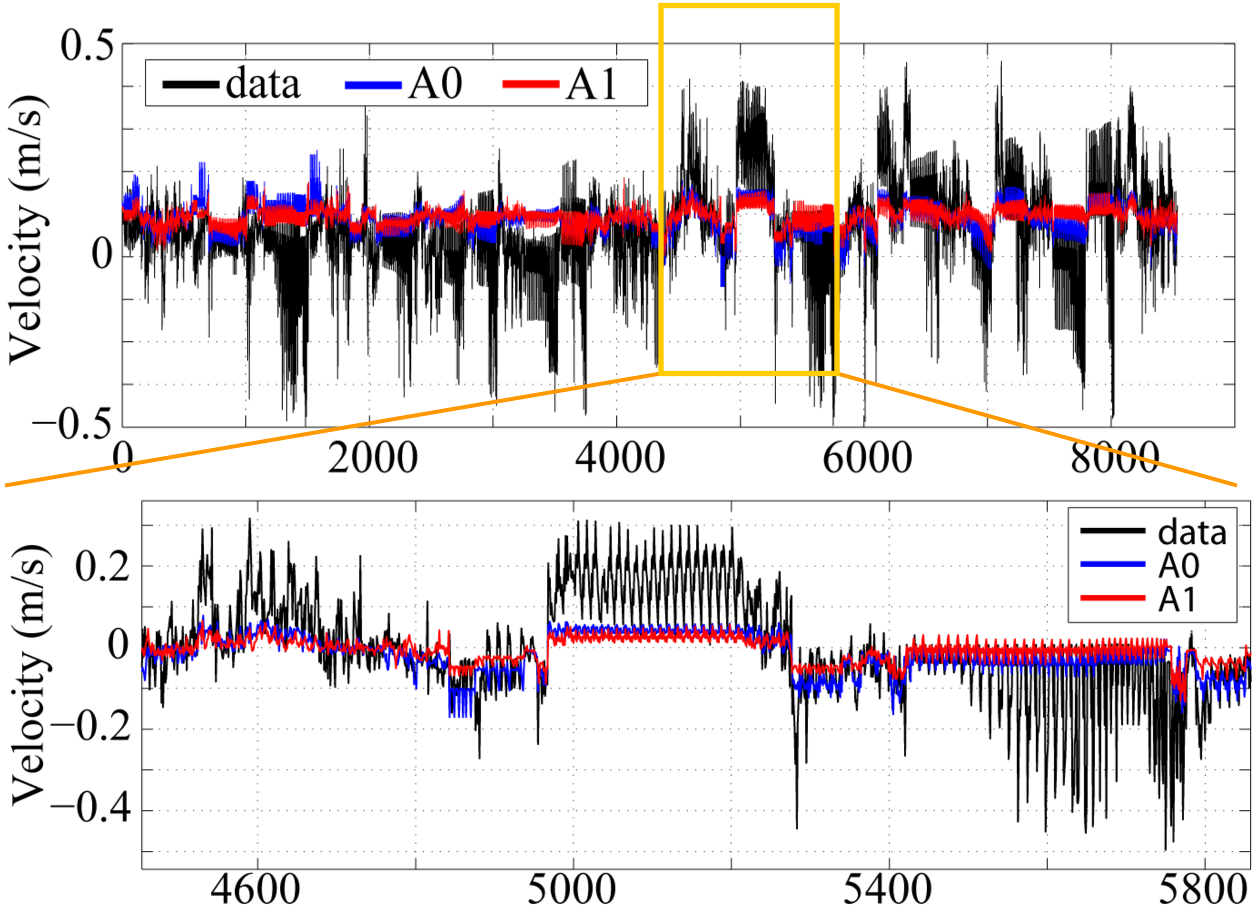


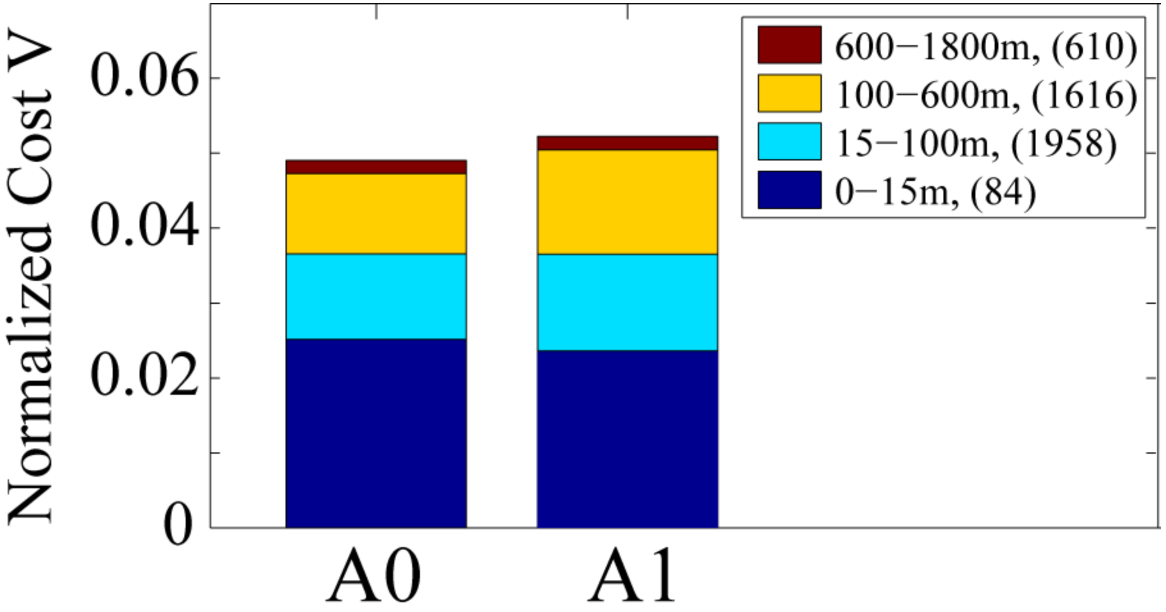




Arctic ocean flux: Fram Strait



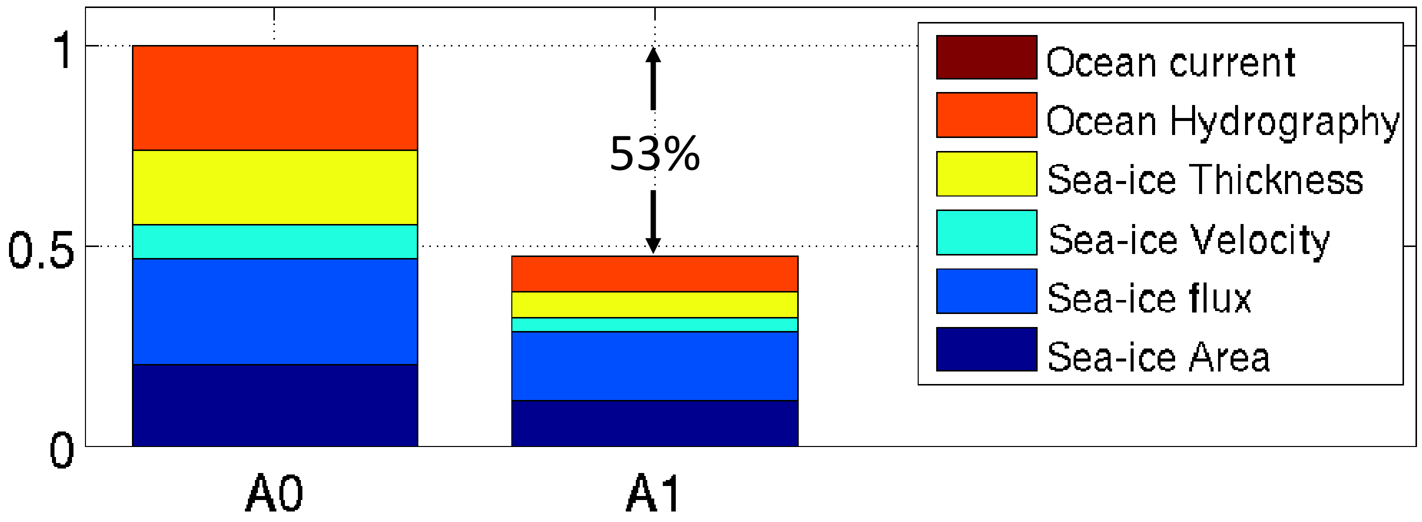




Summary:

Arctic Ocean:

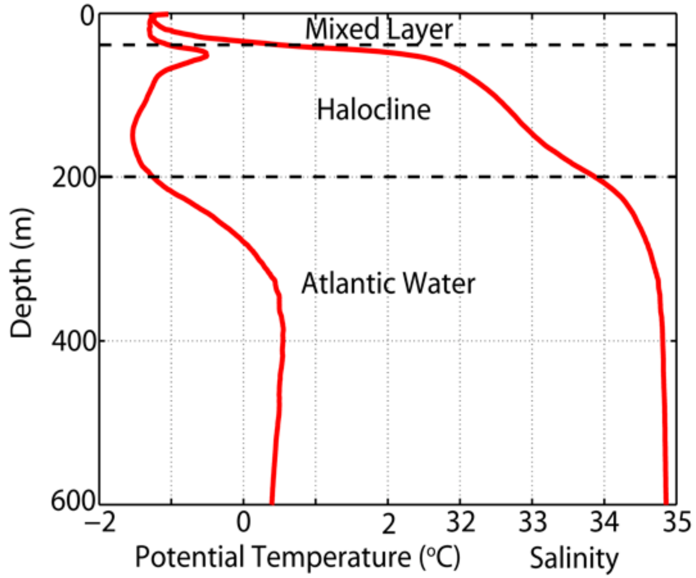
- Summer 2007 sea-ice minimum
- Realistic Halocline
- Freshwater: consistent with Serreze estimates
- Bering Strait: all fluxes consistent with measurements from Woodgate [2006]
- Fram Strait: all fluxes too low compared to Schauer [2006]



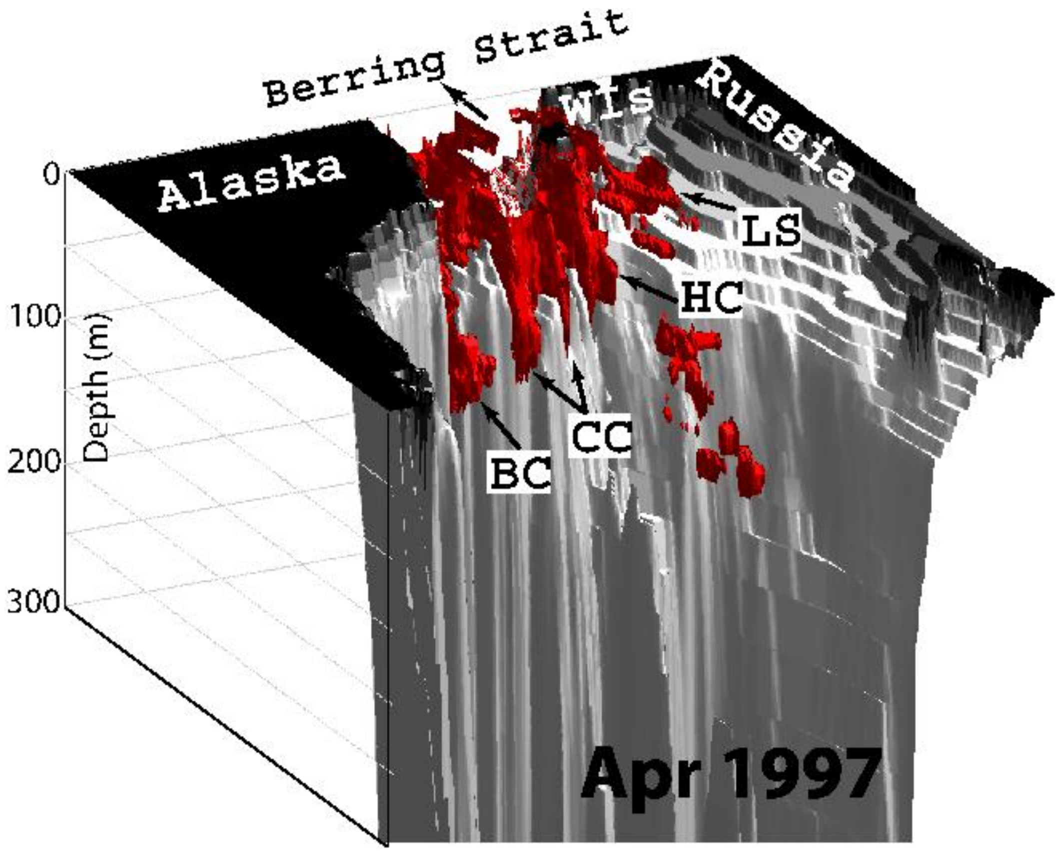
Formation of the Arctic Upper Halocline in a Coupled Ocean and Sea-ice Model

Questions:

1) Source of Upper Halocline Water?
2) Volume budget of source water?



Typical Central Arctic temperature and salinity profile

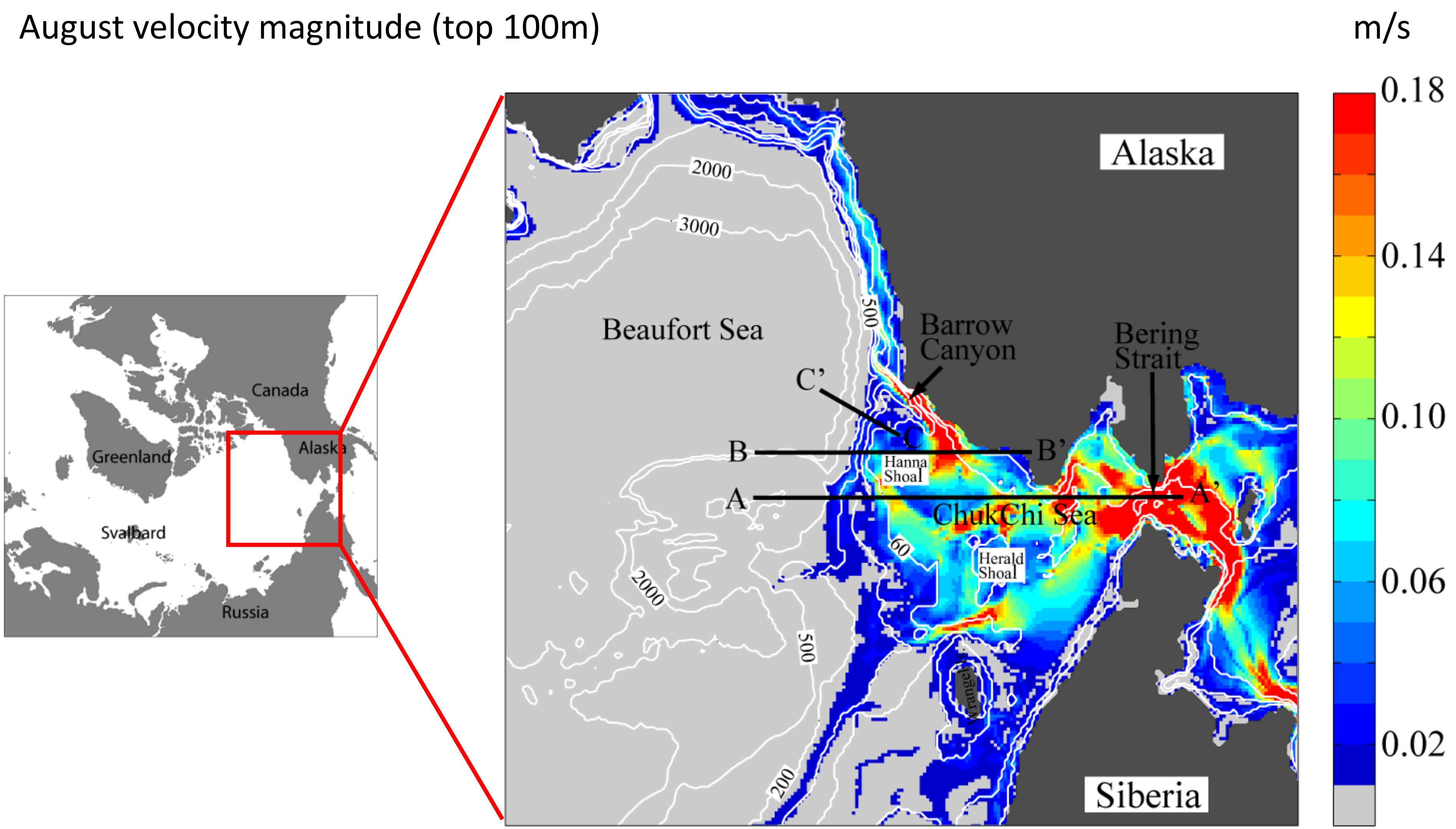


Spatial distribution of dense water (T<-1.5°C, S>32.4) through Barrow Canyon (BC), Central Canyon (CC), Herald Canyon (HC), and Long Strait (LS). Dense water flow down BC typically takes place in Feb/Apr and precedes off-shelf flow in CC and HC.

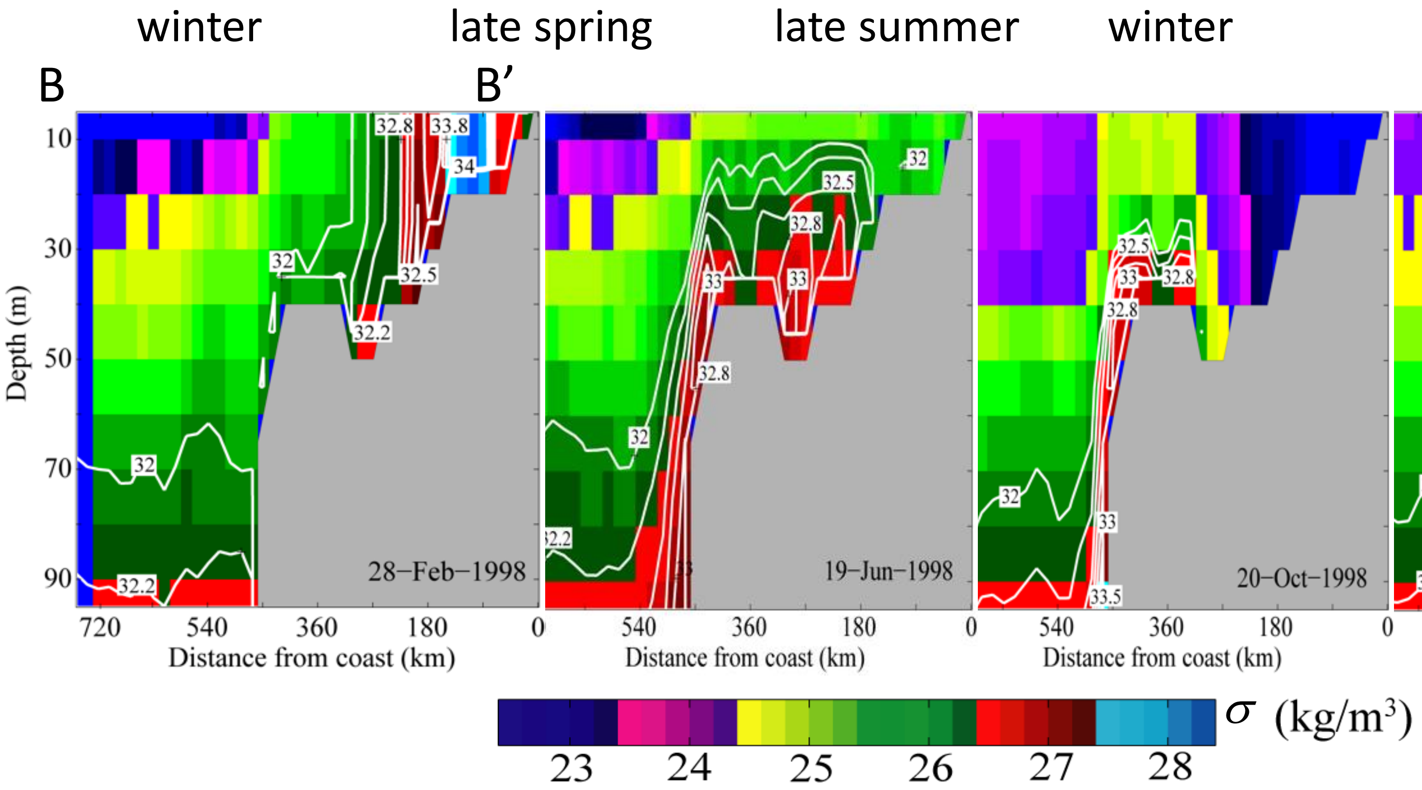
(Nguyen, Kwok, and Menemenlis, 2012)

1992-2005 Mean

August velocity magnitude (top 100m)

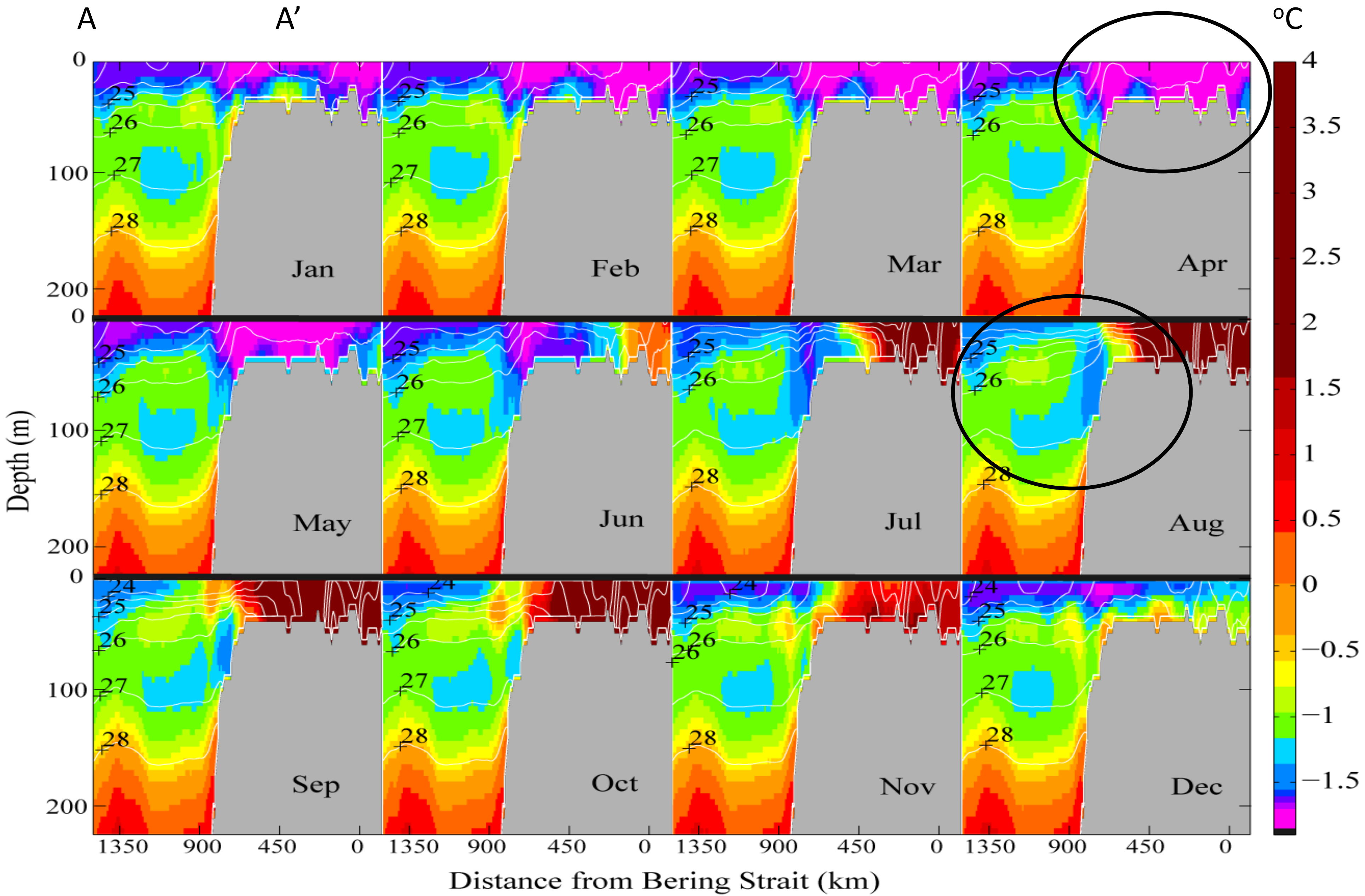


Snap shots



winter
late spring
late summer
winter
B
B’
Depth (m)
Distance from coast (km)
28−Feb−1998
19−Jun−1998
20−Oct−1998
26−Feb−1999
σ (kg/m³)
23
24
25
26
27
28

1992-2005 Mean Temperature



Heat Loss, Ice and Dense-water and Halocline water productions

[Cavalieri 1994]

Heat Loss: $H_L = (8.64\times10^4) \cdot A \cdot F_{net}$

Ice Production: $V_i = (8.64\times10^4) \cdot H_L / (\rho_i \cdot L)$

Salt Production: $S_F = \rho_i \cdot V_i \cdot 0.69 \cdot s_w$

Dense Water: $V_D = S_F / [\rho_e s_e - \rho_w s_w]$

Halocline Water**: $V_H = V_D (s_e - 32) / (32.85 - 32)$, $s_e > 32.85$

$= S_F / [\rho_h s_h - \rho_w s_w]$, $s_e < 32.85$

** Assumptions:

a. sea-ice production yields enriched water with salinity increases 1.5-2 psu

b. enriched water mixes with mixed-layer water to produce halocline water

c. cold halocline water has an average salinity s_h=32.85 psu

d. enriched water has salinity $s_e > s_h$

Variables:

F_{net}: total ocean-to-atmosphere heat flux

A: open-water area

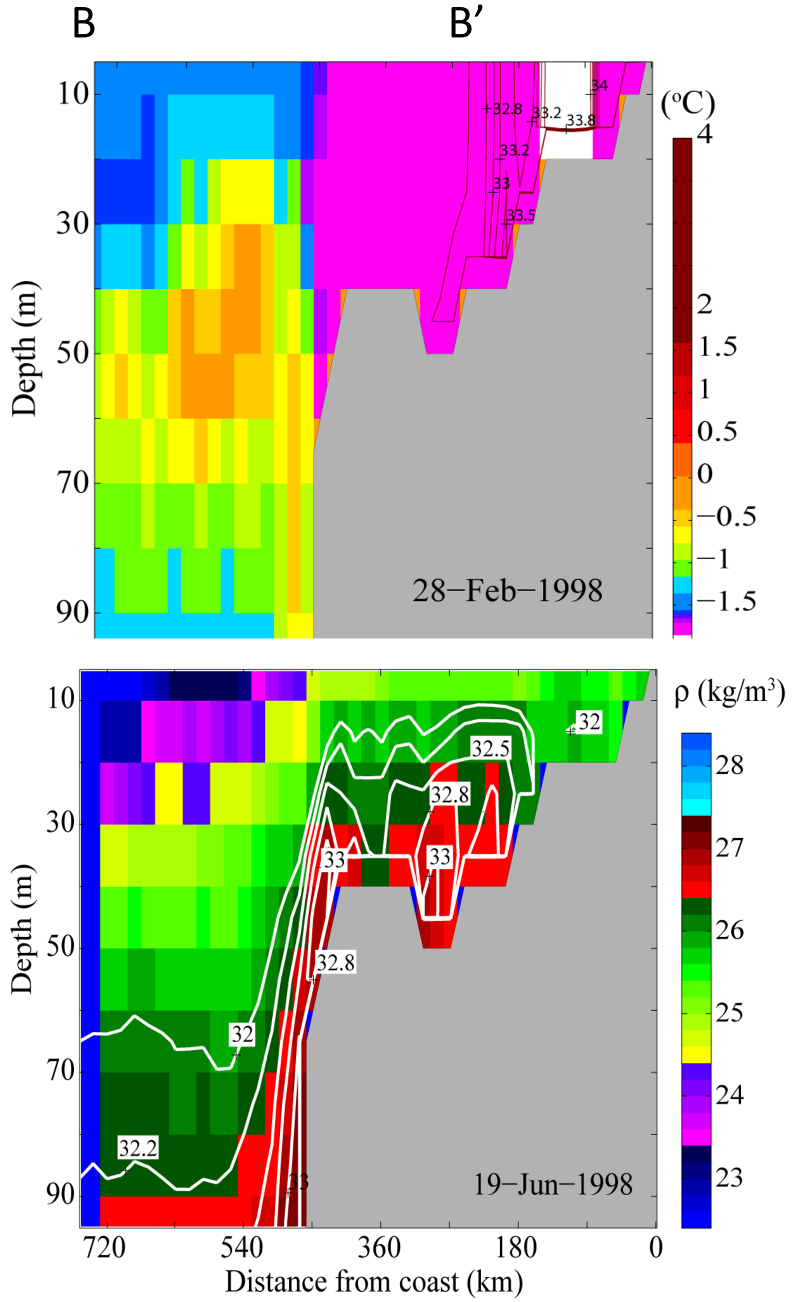
L: latent heat of fusion

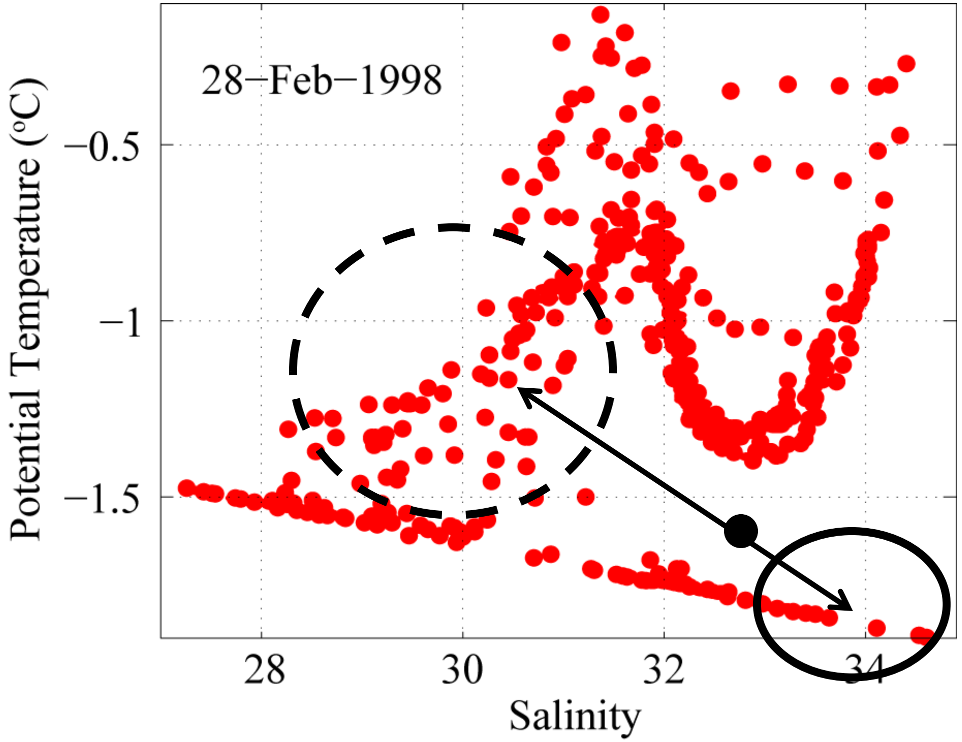
ρ_i, V_i : sea-ice density and volume

ρ_e, s_e: enriched water density and salinity

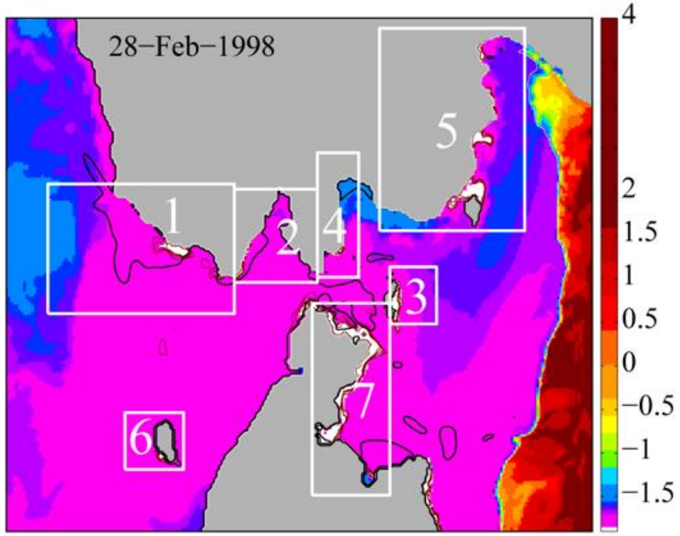
ρ_w, s_w: background water density and salinity

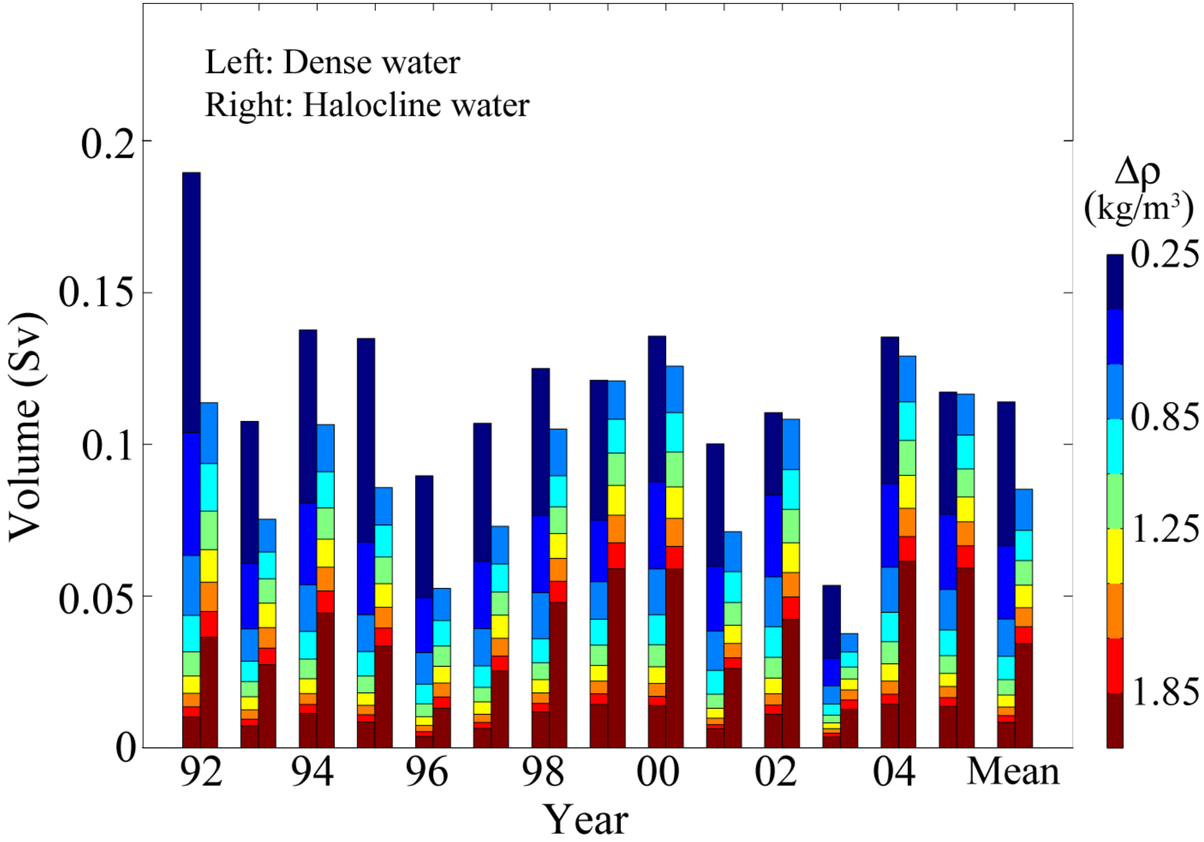
Dense water and Halocline water calculations:





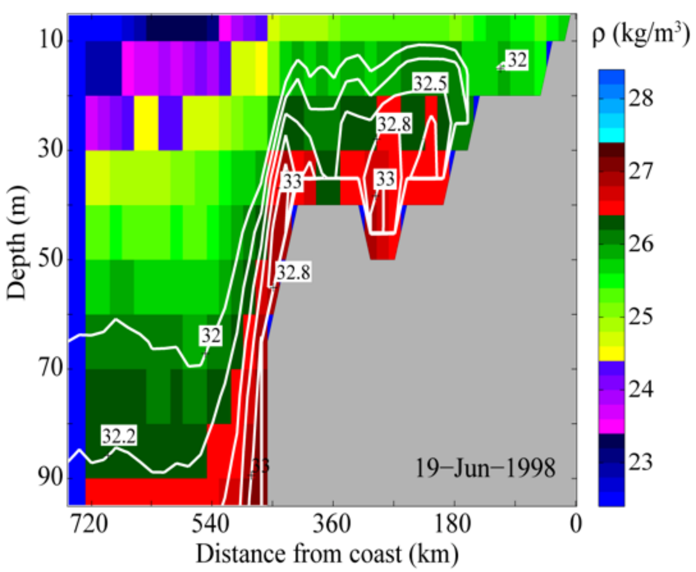
Net Halocline Water Production (observational estimate)

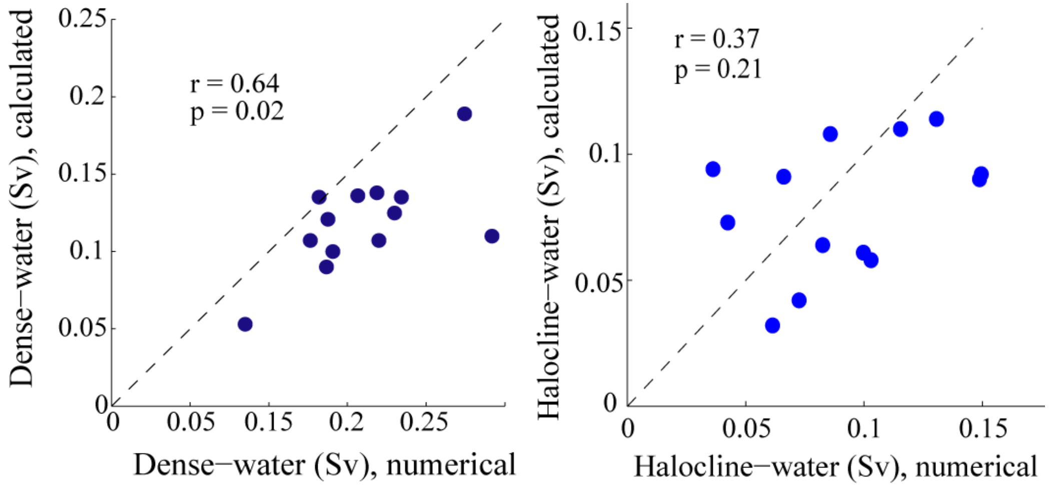


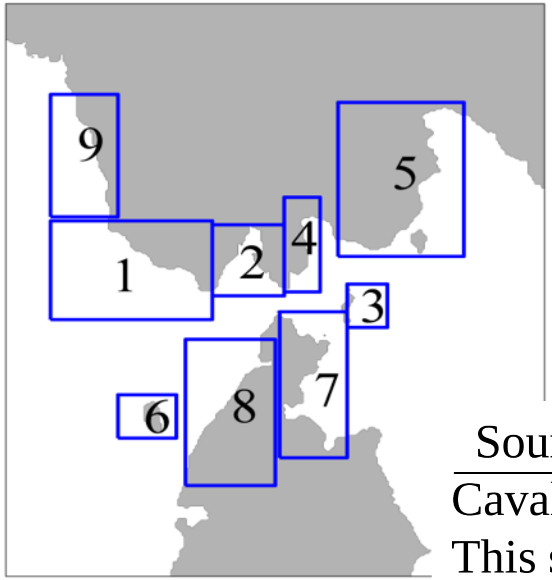


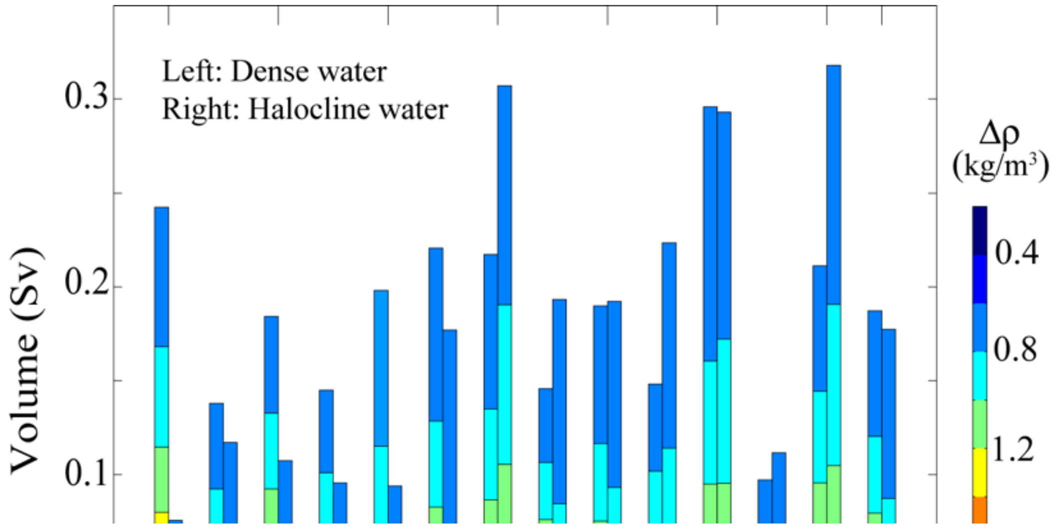
Source	Period	Dense Water	Halocline Water
Cavalieri, [1994]	1978-1987	0.24 ± 0.04 Sv	---
This study	1992-2005	0.12 ± 0.03 Sv	0.09 ± 0.03 Sv

Numerical Calculation (9-km model)



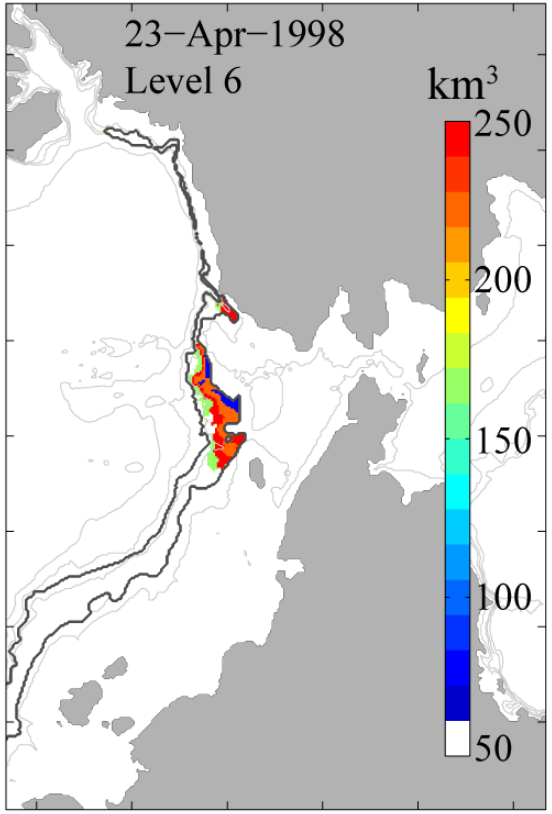


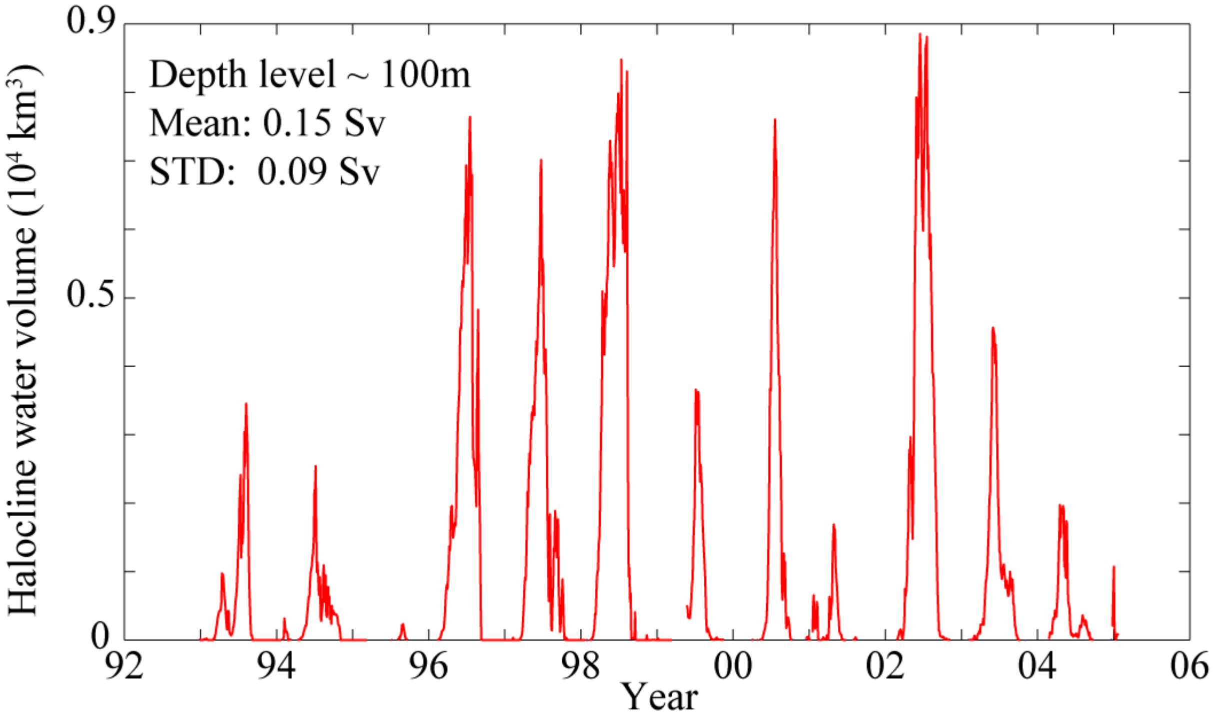




Source	Period	Dense Water	Halocline Water
Cavalieri, [1994]	1978-1987	0.24 ± 0.04 Sv	---
This study	1992-2005	0.12 ± 0.03 Sv	0.09 ± 0.03 Sv
	1993-2005	0.19 ± 0.05 Sv	0.18 ± 0.09 Sv

Numerical Calculation (4-km model)





Source	Period	Dense Water	Halocline Water
Cavalieri, [1994]	1978-1987	0.24 ± 0.04 Sv	---
This study	1992-2005	0.12 ± 0.03 Sv	0.09 ± 0.03 Sv
	1993-2005	0.19 ± 0.05 Sv	0.18 ± 0.09 Sv
	1993-2005		0.15 ± 0.09 Sv

Summary

- Model shows that:
    1. winter sea ice growth results in brine rejection and dense water (DW) formation,
    2. DW flows primarily down Barrow and Central–Herald Canyons as bottom-trapped, intermittent currents to depths of 50–150 m from the late winter to late summer seasons, and
    3. mean current and eddies carry the cold DW from the shelf break into the Canada Basin interior.

- Upper halocline water (UHW) formation rate, estimated from observations and simulation, is 4000-6000 km^3/yr, implying replenishment period of 10-20 years.

Cautionary tale for limitation of PBL parameterizations: they can fail when applied to new regimes or conditions.

On the positive side: when applied in correct context and rigorously evaluated against observations, they can enable interesting new science and model predictions!