

1. Introduction:

The Upper Arctic Ocean:

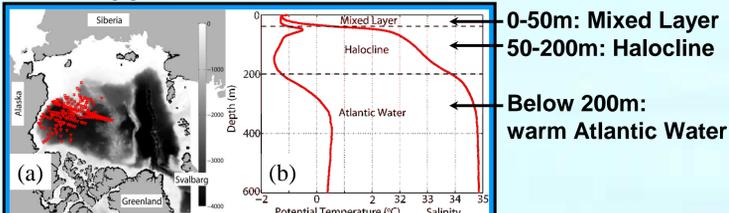


Fig.1: (a) Location of data and (b) data averaged vertical temperature and salinity profiles in the Canadian Basin in the Arctic.

The Halocline:

- ~ 50-200m, near freezing (-1.7°C), high salinity gradient
- Shields Atlantic Water heat from melting surface sea-ice
- Controls sea-ice mass balance and sea-ice / ocean energy exchange

State-of-the-Art coupled Ocean/Sea-ice Models:

Halocline missing

Fig.2: Model results (black lines) showing the missing halocline when compared to climatology (red line). Figure is taken from [Holloway, 2007].

The Problems:

- Salt (brine) rejection during sea-ice formation + low model horizontal resolution (~20km-100km):
- Large scale vertical mixing of salt in the mixed layer
- Deepening the mixed layer
- Destruction of the Halocline

2. Approach: sub-grid-scale brine rejection

Motivation:

a) Observations [Morison and McPhee, 1998]:

- Sea-ice forms → salt rejected back into the ocean → does not mix uniformly in the mixed layer → sinks to base of mixed layer → makes mixed layer shallower and more stratified.

b) Previous Laboratory Experiments [Helfrich, 1994]:

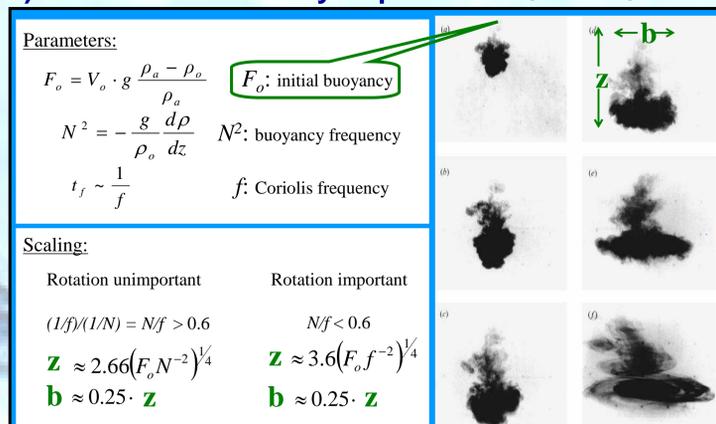


Fig.3: Laboratory result of salt rejected into a density-stratified fluid. The salt plume of horizontal extent b reaches the neutral buoyancy depth z before spreading out horizontally. Figure is taken from [Helfrich, 1994].

c) Previous Numerical Experiments: [Smith and Morison, 1998]

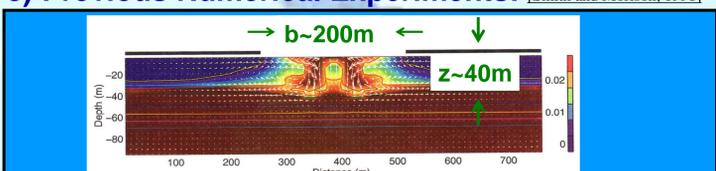


Fig.4: Numerical result of salt rejected into a density-stratified fluid. The salt plume of horizontal extent b reaches the neutral buoyancy depth z before spreading out horizontally. Figure is taken from [Smith, 1998].

6. Acknowledgments:

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7. References:

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- SCICEX: <http://boreas.coas.oregonstate.edu/scicex/scicex.html>
- WHOI: <http://www.whoi.edu/beaufortgyre>

3. Setup:

Brine Rejection Parameterization:

- 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:

$$s(z) = \begin{cases} Az^n, & |z| \leq D \\ 0, & |z| > D \end{cases} \quad \leftarrow A \text{ is a constant of normalization}$$

Model (1992-2006):

- Ocean:
 - 18 km horizontal resolution, 50 vertical levels
 - ECMWF / ERA-40 Forcings
 - K-profile parameterization (KPP) vertical mixing scheme [Large et al., 1994]

Sensitivity Experiments:

- Three experiments are performed (Table.1):
- A0: Baseline, brine rejection off.
- A1: Baseline, brine rejection on, $n=5$.
- A2: A1, with a lower KPP background diffusivity ν value which we have found to improve the results.

Table.1: List of sensitivity experiments

Experiment	Brine Rejection	ν (m ² /s)
A0	off	10^{-5}
A1	on	10^{-5}
A2	on	10^{-7}

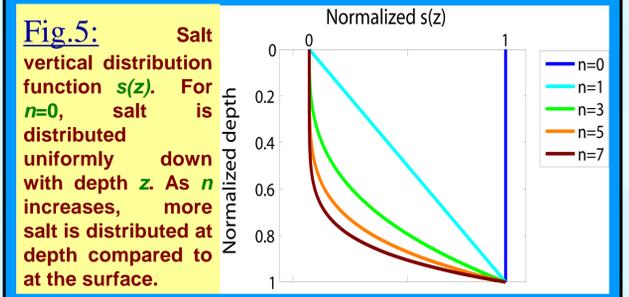


Fig.5: Salt vertical distribution function $s(z)$. For $n=0$, salt is distributed uniformly down with depth z . As n increases, more salt is distributed at depth compared to at the surface.

Sea-ice:

- 2-category zero-layer thermodynamics [Hibler, 1980]
- Viscous plastic dynamics [Hibler, 1979]

Assessment:

Data (Fig.1):

- Conductivity-Temperature-Depth (CTD) profiles:
 - a) Scientific Ice Expeditions 1995-2000 [SCICEX].
 - b) Beaufort Gyre Exploration Project 2003-2004 [WHOI]

Measure of Improvements:

- Improvements are measured in reduction of sum-of-squares (SSQ) of model minus data:

$$I = \frac{(SSQ_{A0} - SSQ_{A[1,2]})}{SSQ_{A0}} \times 100$$

- $I > 0$ when $SSQ_{A[1,2]} < SSQ_{A0}$ → Solution A[1,2] is better
- $I < 0$ when $SSQ_{A[1,2]} > SSQ_{A0}$ → Solution A[1,2] is worse

4. Results

- Results for 1995-2004 are summarized in Table.2
- Sub-grid-scale brine rejection produces more realistic mixed layer depth (Fig.6)
- Model maintains halocline over 14-year duration (Fig.7)
- Brine rejection gives improvements from ~10-30% in the early years to ~40-70% toward the end of the model-run (Table.2)
- Combination of brine rejection and smaller KPP background diffusivity produces best results, with 80-120% improvements of mis-fits at the end of the model-run (Table.2)

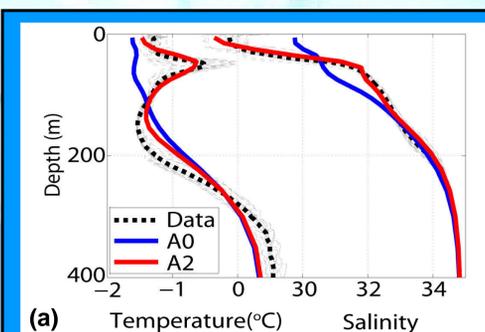


Fig.7: Vertical Temperature and Salinity profiles (a) and T/S diagram (b) of the Canadian Basin in the Arctic in August 2003. The actual CTD data are shown as thin gray lines in (a), with data mean shown as dashed black lines. The halocline is destroyed in solution A0 but is sustained for the duration of the model run in A1 and A2 (only A2 is shown here).

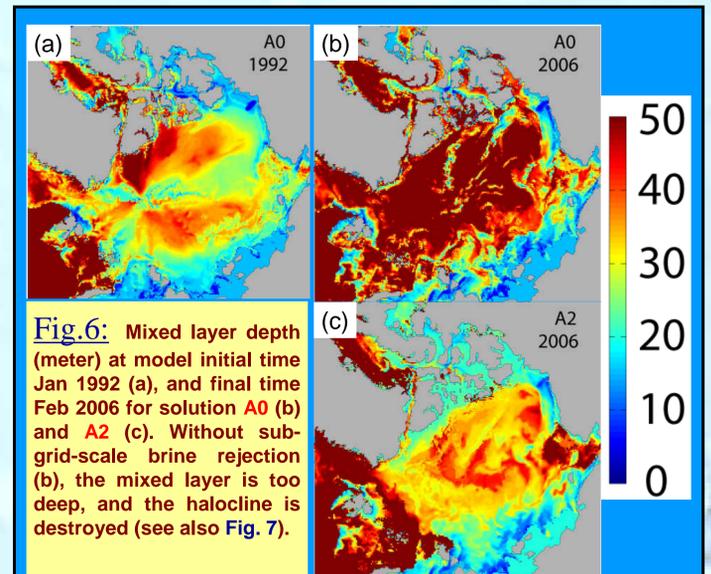


Table.2: Relative Improvements I (%) for experiments A1 and A2 with respect to A0 for the years 1995-2004.

Experiment	Data							
	1995	1996	1997	1998	1999	2000	BGEP 2003	2004
A0	0	0	0	0	0	0	0	0
A1	27	16	39	12	28	9	62	68
A2	-15	6	45	27	30	11	118	79

5. Summary

- Current State-of-the-Art coupled Ocean/Sea-ice models can not reproduce the halocline, a cold high salinity-gradient layer that stabilizes the upper Arctic Ocean
- Excessive grid-scale numerical vertical mixing is one of the major contributing factors to the failure
- Brine rejection → moves salt from surface and distributes it to greater depth → maintains the salinity-gradient in the halocline → **A halocline is successfully reproduced and maintained.**
- A combination of brine rejection scheme which distributes most of the salt to the bottom of the mixed layer and small KPP background diffusivity produces the best fits to Temperature/Salinity data in the Canadian Basin.
- Detailed results are in [Nguyen et al., 2008]