Assessing ocean mixing under heterogeneous sea ice cover and subgrid-scale brine rejection parameterization in climate models

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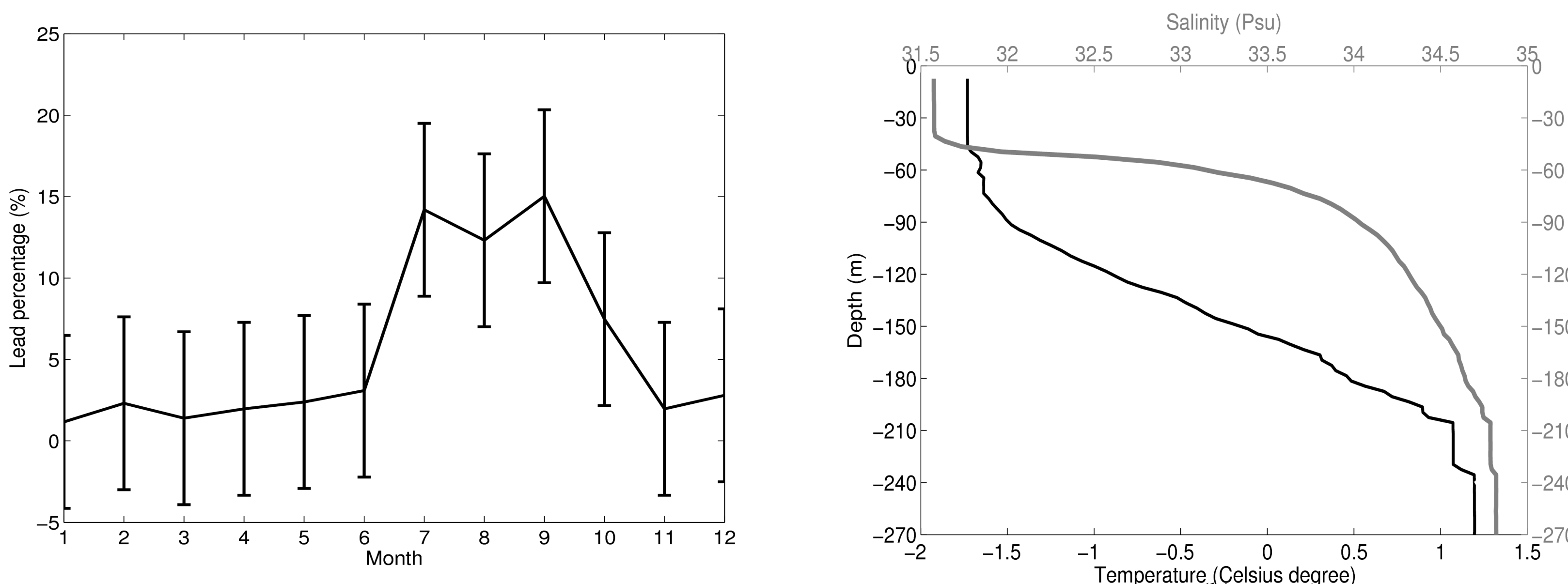
Contents

1. Introduction

•**Sea ice thickness is highly heterogeneous** spanning a wide range of spatial scales from several meters to hundreds of kilometers in the polar oceans.

•Convergence and divergence of sea ice in the polar oceans can produce stripes of thick ridged ice and **lead with a typical range of 5-1000m in width and 1-50km** in length (Morison et al., 1992), **which is unresolved by current climate model grid**.

•The fluxes of **brine rejection** during ice formation and freshwater while ice melt exert **strong impacts on the seasonal cycle of the ocean upper halocline**. Although lead accounts for less than 10% (average around 2.0%) in the Arctic Ocean in winter months it is estimated to contribute 50% of the ice formation in winter.

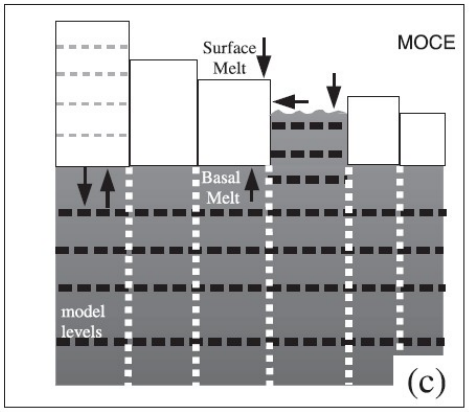


(a) (b)

Fig. 1. (a) Monthly mean lead percentages from NIMBUS-7 SMMR and DMSP SSM/I passive microwave remote sensing data in the Arctic Ocean with one standard deviation error bar above and below the mean, and (b) the initial water temperature and salinity profiles on April 17 2011 for all cases in Table 1 and some in Talbe 2.

Unresolved lead in ocean grid is a subgrid scale problem.

1) **Summer ice melting case**: A vertically 1-D ice-ocean model of NCAR-CCSM 2.0 by Holland (2003) using a multi-column ocean grid (MCOG, corresponding to multi-category ice thickness) produced more realistic results compared to observations that the runs using a conventional single column ocean grid (SCOG).

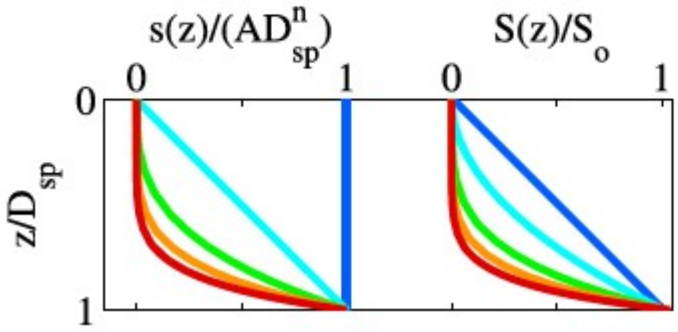


2) Winter ice formation case

All 10 models in the Arctic Ocean Model Intercomparison Project (AOMIP) failed to reproduce the halocline partly due to lack of physics in vertical mixing process and/or shelf/basin exchanges (Holloway et al., 2007). Problems with salinity gradient degradation was observed in ocean general circulation models in the Southern Ocean (Duffy and Caldeira, 1997 and Duffy et al. 1999). Implications include deeper MLD, saltier surface and impacts on vertical heat fluxes in the ocean and to the sea ice.

Parameterization in the following form of vertical distribution of added salinity in the upper mixed layer (Nguyen et al., 2009):

$$s(z) = \begin{cases} Az^n & if\ |z| \le |D_{sp}| \\ 0 & if\ |z| > |D_{sp}| \end{cases}$$



Questions to answer in this presentation:
1) How significant are the impacts of the subgrid brine rejction on climate model results.

2) Why there is an uncertainty of parameter n:
n=0 in Duffy and Calderia (1997) and Duffy et al. (1999)
N=5 in Nguyen et al. (2009)

3) A new parameter n as a function of lead percentage

Method

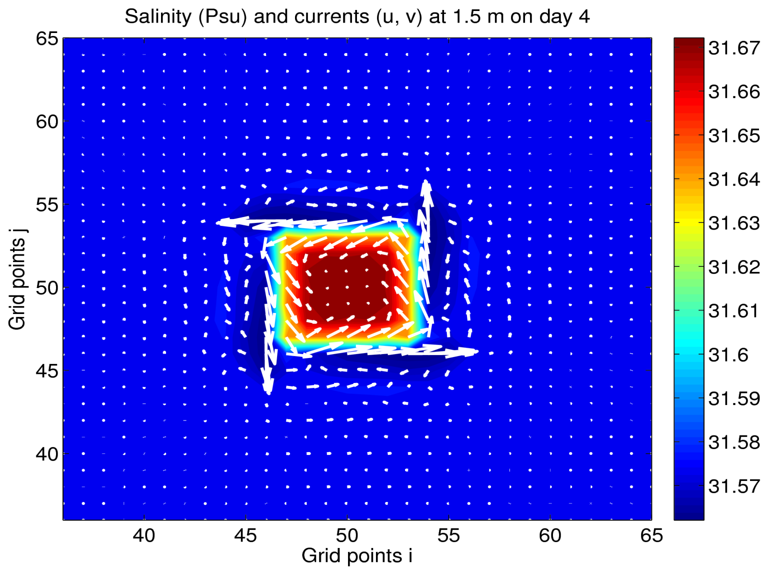
Climate model solution : 30km grid model results

'True' solution : 1km grid model results averaged in climate model grid size

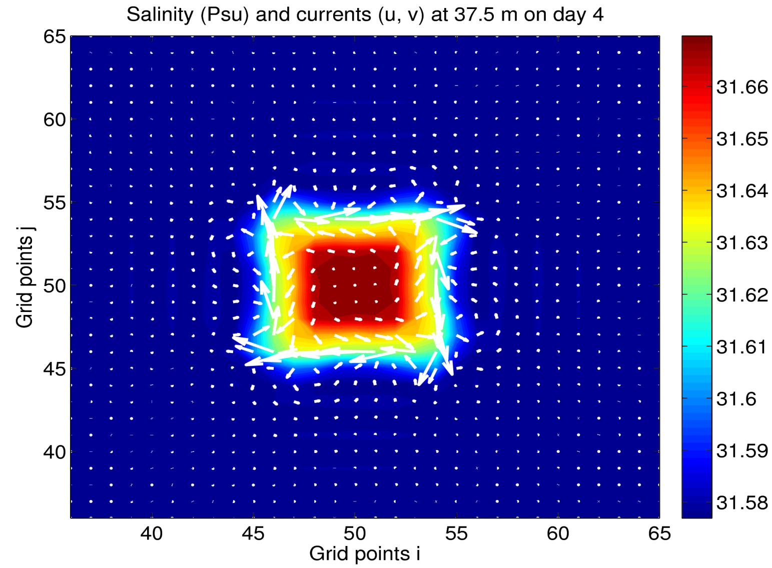
Idealized model domain of (100 * 100) and vertically 3 m per layer and totally 270m.

Initial T, S profile from NPEO CTD data.

3. Salinity anomaly distributions when lead is resolved



(a)



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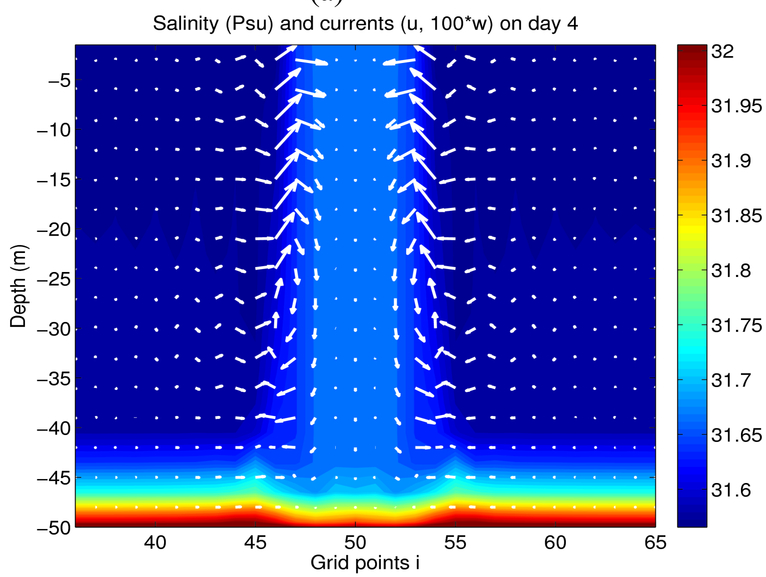

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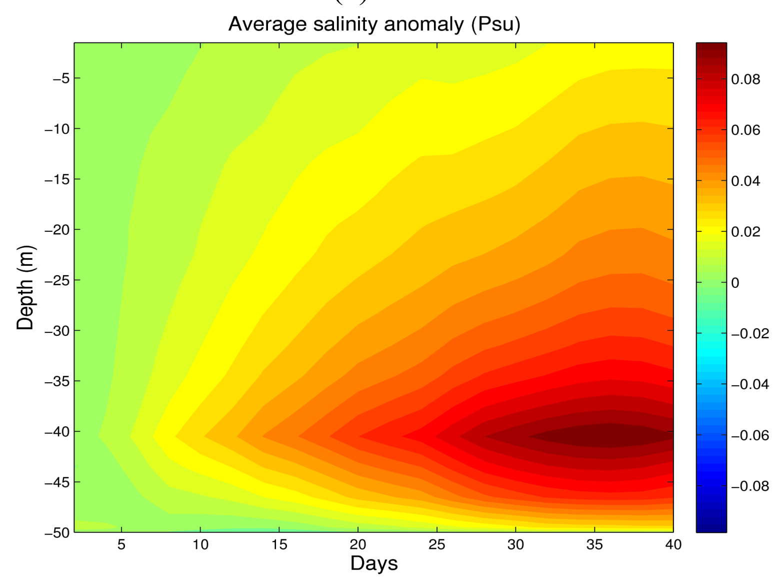
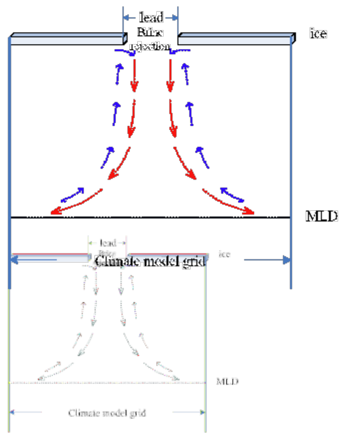
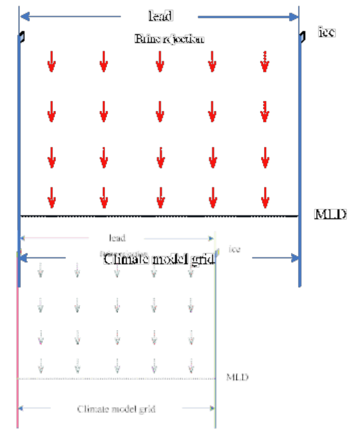


(d)

When lead << climate model grid



When lead ~ climate model grid



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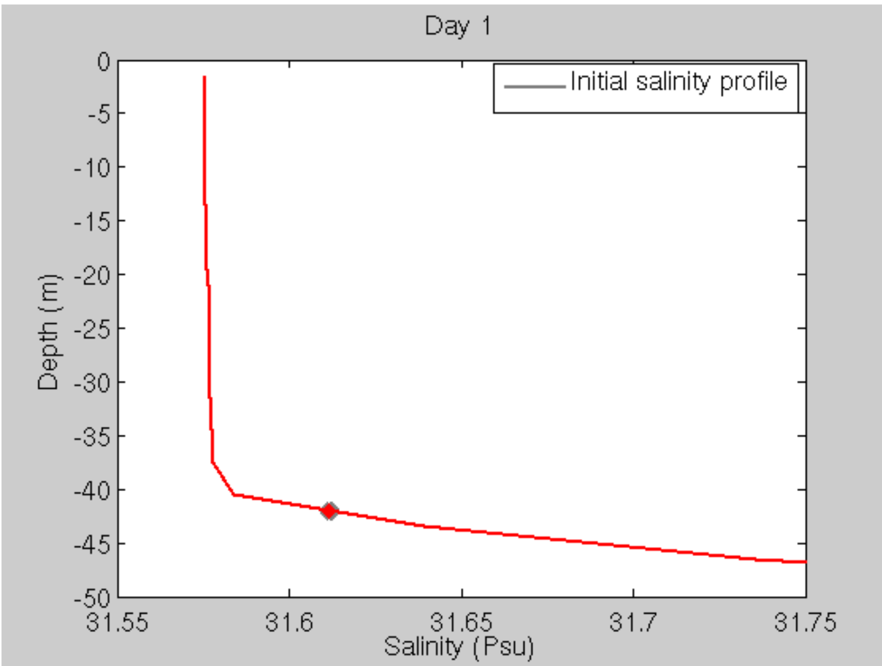
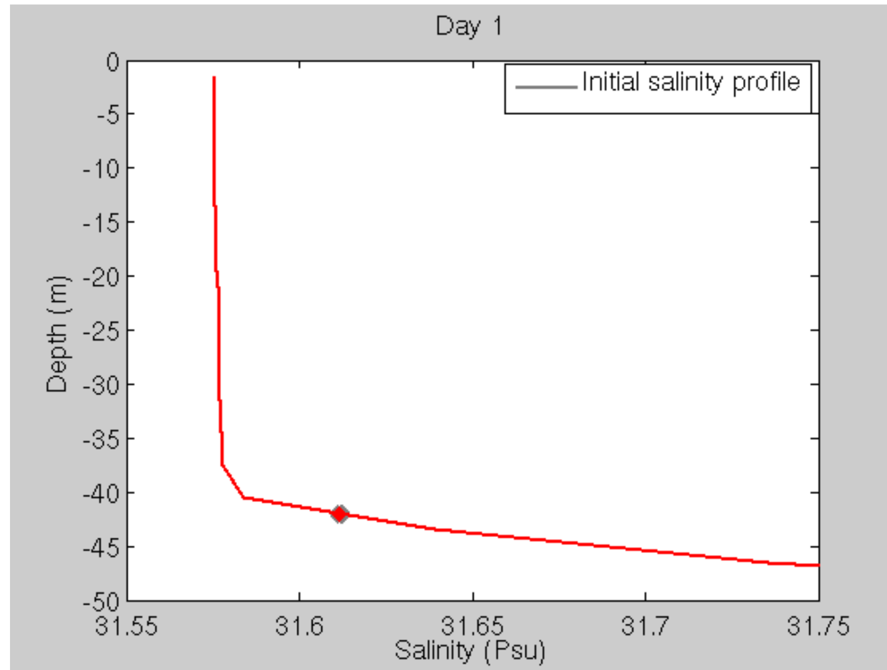

Day 1
Initial salinity profile
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Depth (m)
31.55
31.6
31.65
31.7
31.75
Salinity (Psu)


Day 1
Initial salinity profile
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
Depth (m)
31.55
31.6
31.65
31.7
31.75
Salinity (Psu)

4. Deviations of coarse climate model (30km)

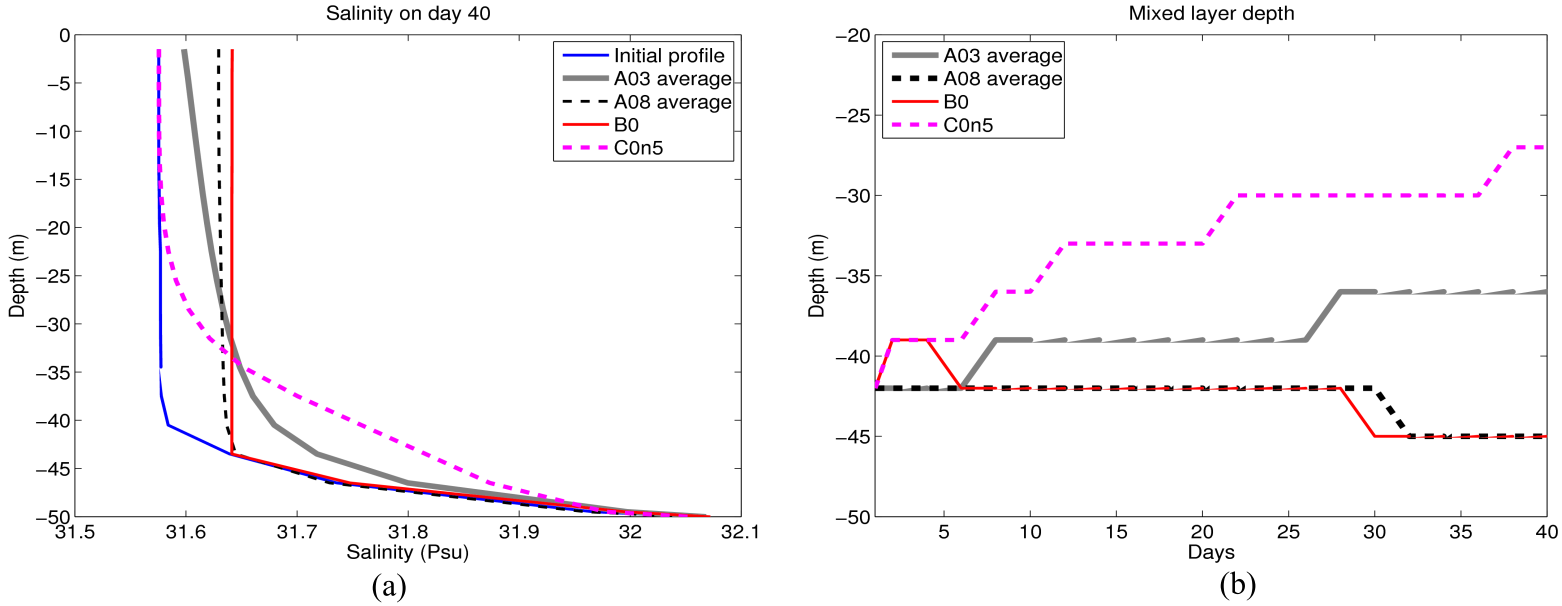
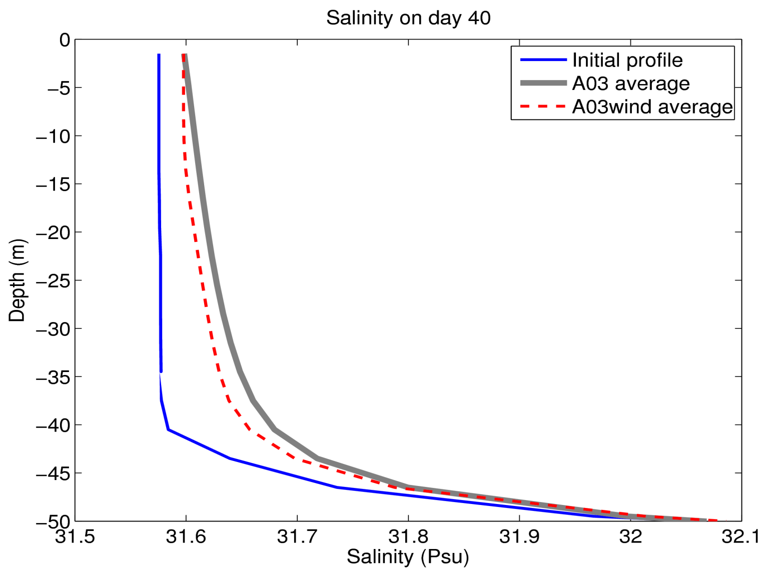
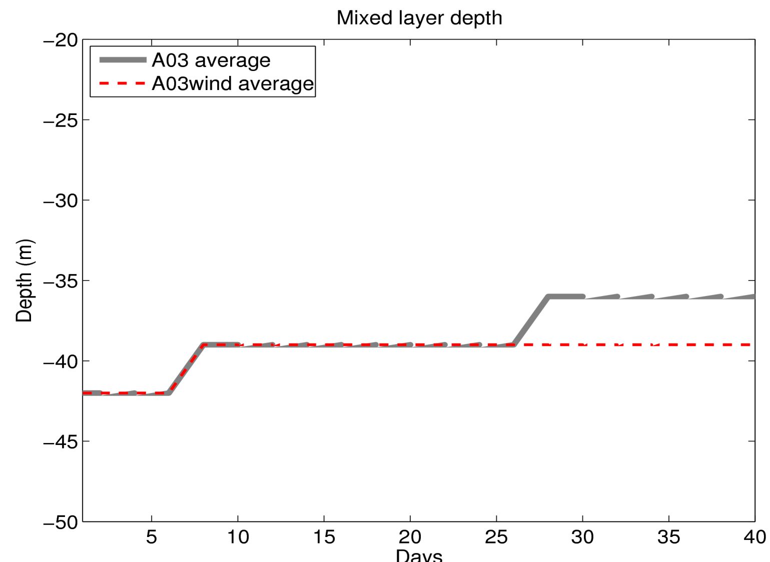


Fig. 3 Comparison of (a) vertical salinity profiles and (b) mixed layer depths among cases A03, A08, B0 and C0n5 using A03 as 'true' solution.

Wind effects on the salinity addition is modest, because
1) It is mostly blocked by sea ice
2) The effects of a arctic mean wind ~5.5m/s without sea ice blocking are small as shown below



(a)



(b)

5. Effects of Ngugen et al. (2009) parameterization with constant n

The larger the n, the more saline is added to the base on the mixed layer.

n=0 in Duffy et al. (1999) and =5 in Ngugen et al. (2009)

But how to determine the best n-value?

$$s(z) = \begin{cases} Az^n & if\ |z| \le |D_{sp}| \\ 0 & if\ |z| > |D_{sp}| \end{cases}$$

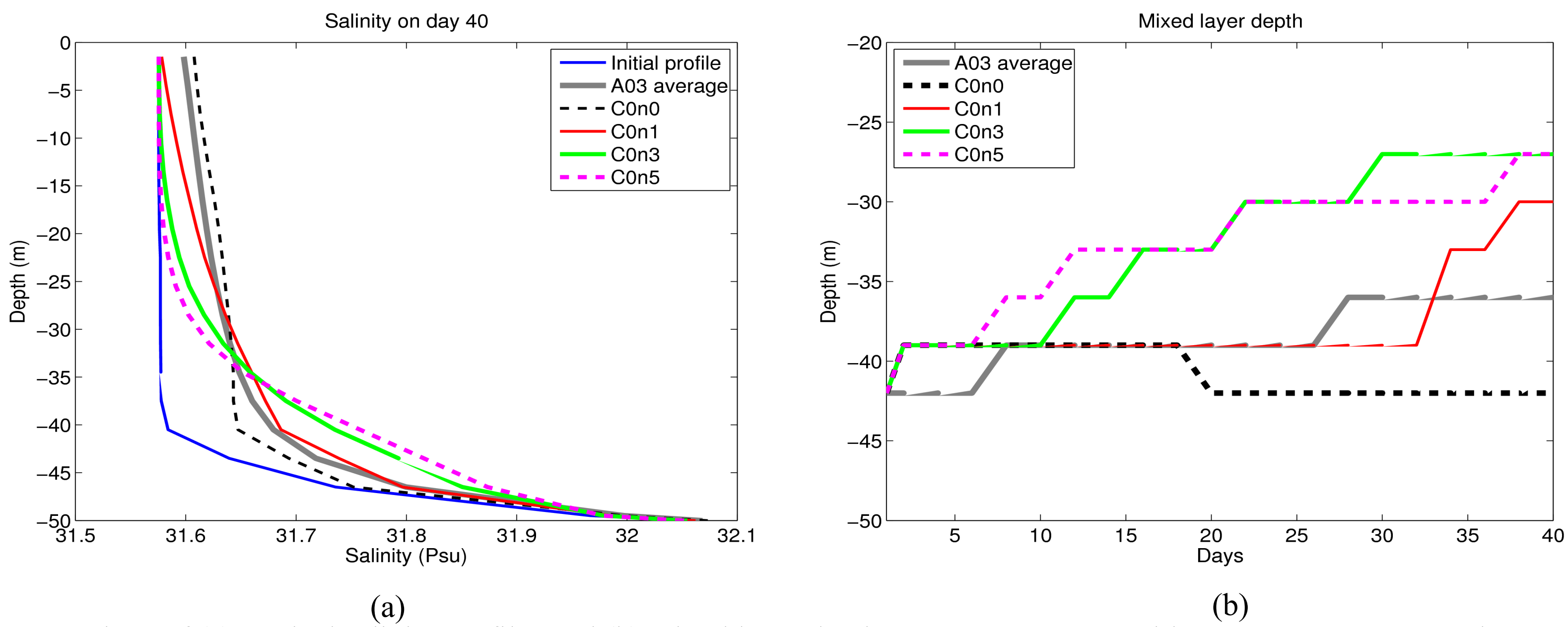


Fig. 5. Comparison of (a) vertical salinity profiles and (b) mixed layer depths among cases A03 with C0n0, C0n1, C0n3 and C0n5 using A03 as 'true' solution.

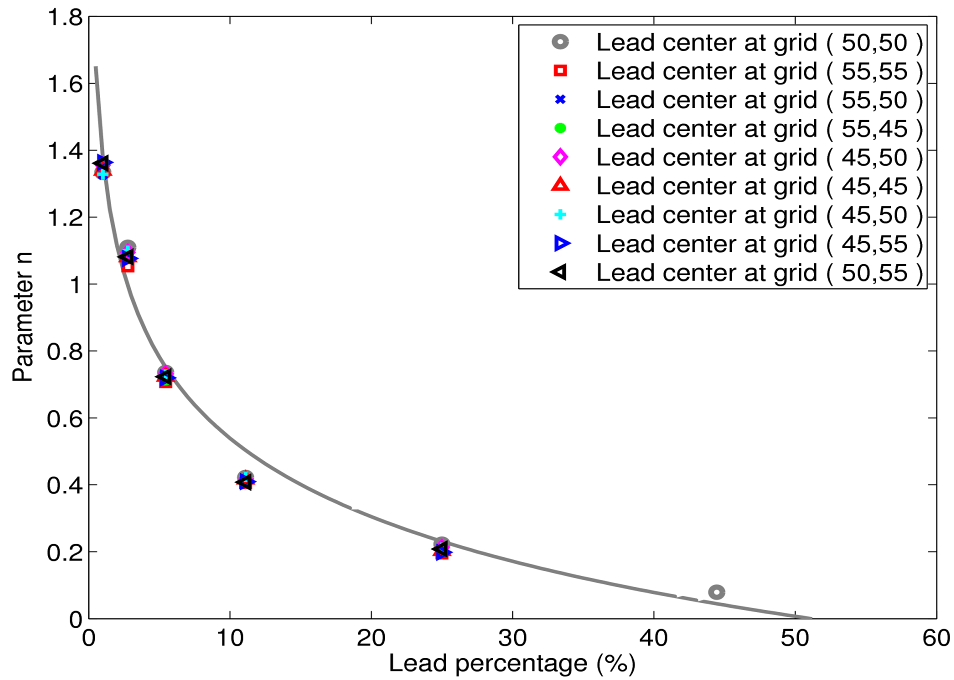
6. New parameterization with n as a function of lead percentage

Estimate n using 1km grid cases A01 ~A07 with different lead percentage.

The pairs of lead percent (p) vs. parameter n (>0) are used to further best fit into a curve.

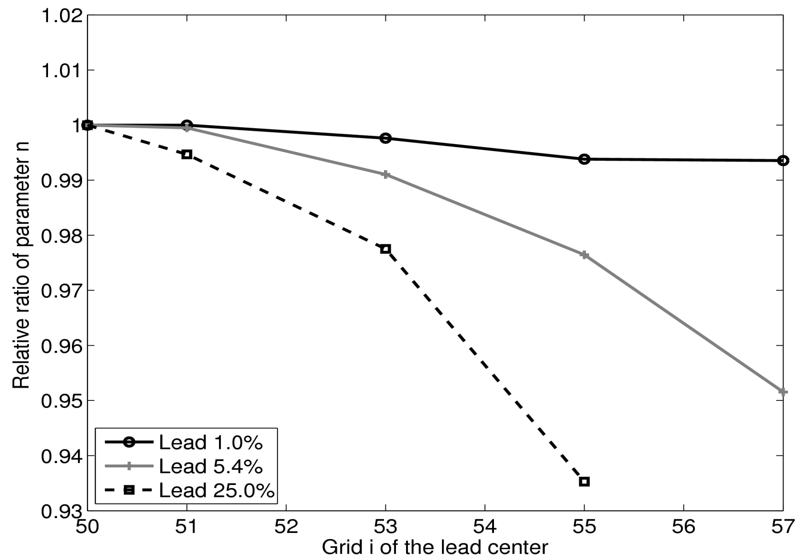
$$n = a \cdot p^b + c$$

The n-value turns negative when lead percentage is greater than 51%, indicating that parameterization is unnecessary under these ice conditions.

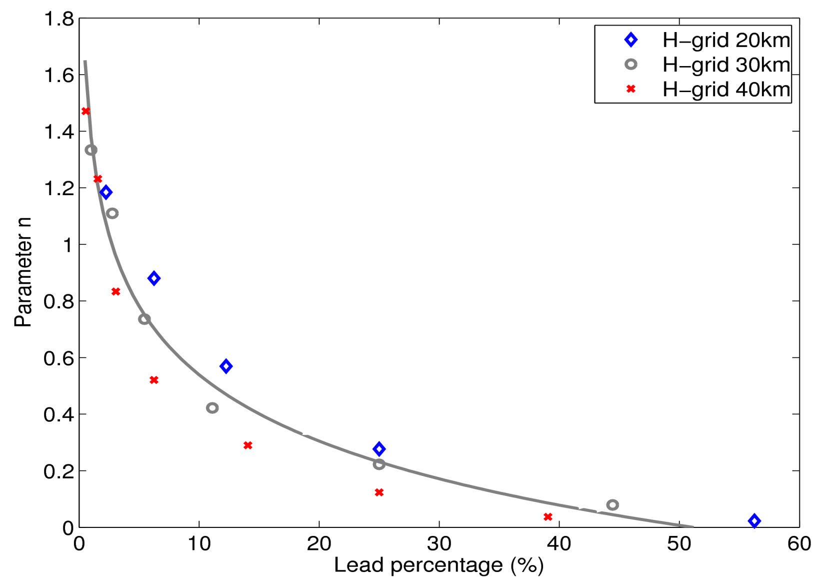


6.1 How does the parameterization fit with climate model with unknown lead position in a grid cell and varying horizontal grid scales.

Ratio of the parameter n with deviated the lead center over parameter n with lead centered at (50, 50).



The fit curve from results averaged in 20km, 30km and 40km grid area are converged together especially at low lead percentage.



7. Effects of new parameterization with fitted n: consistent improvements over time

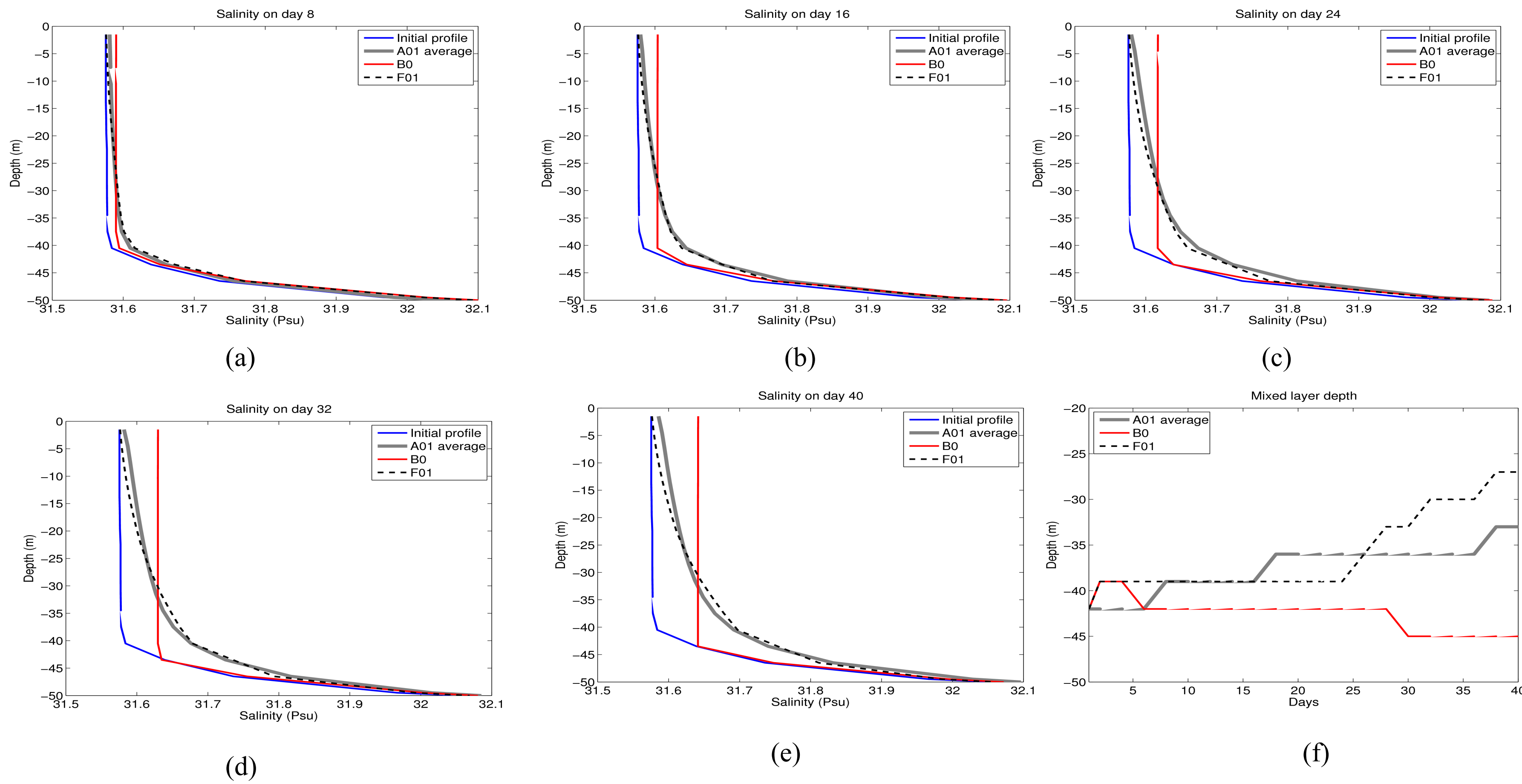
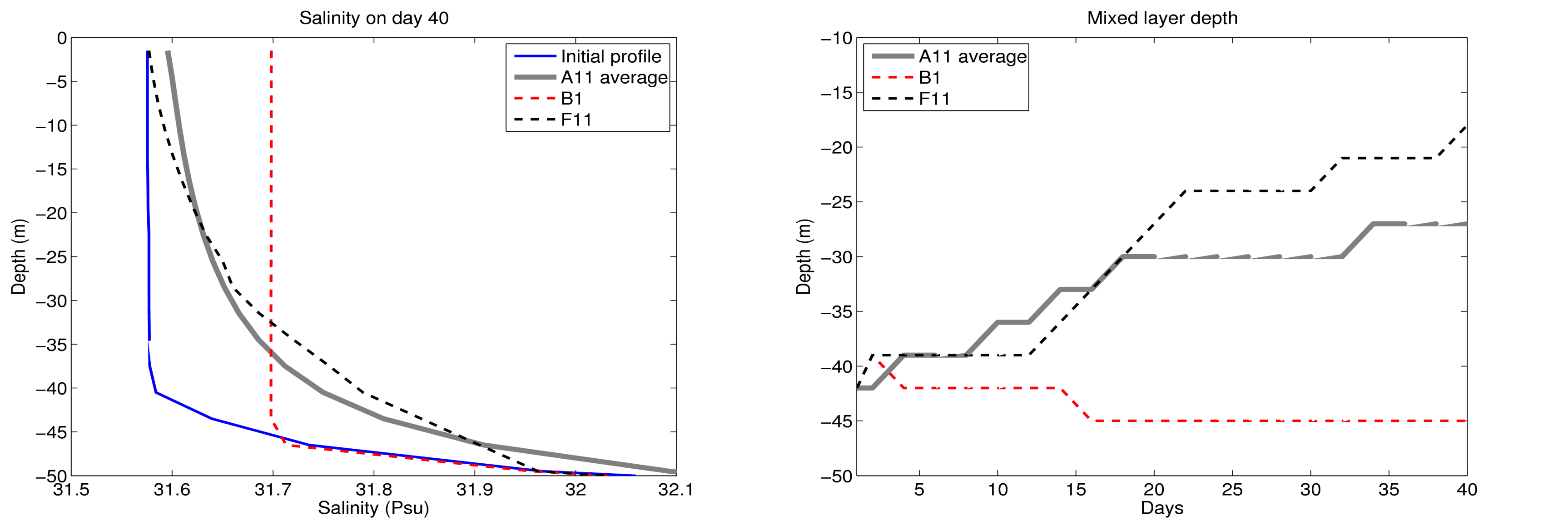


Fig. 7. Comparison of vertical salinity profiles from (a) to (e) on different running days and (f) mixed layer depths from cases B0 and F01 using case A01 as 'true' solution.

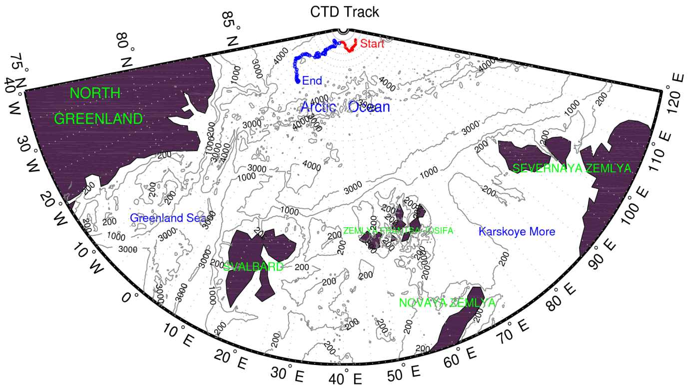
7.1 The parameterization works with different freezing rate in lead.



(a) (b)

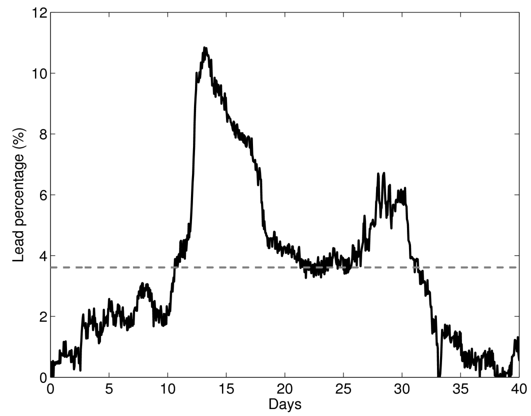
Fig. 8. Comparison of (a) vertical salinity profiles and (b) mixed layer depths from cases B1 and F11 using A11 as 'true' solution.

7.2 Test of the new parameterization in real ice-ocean conditions with time-varying lead percentage and freshwater equivalent freezing rate in lead

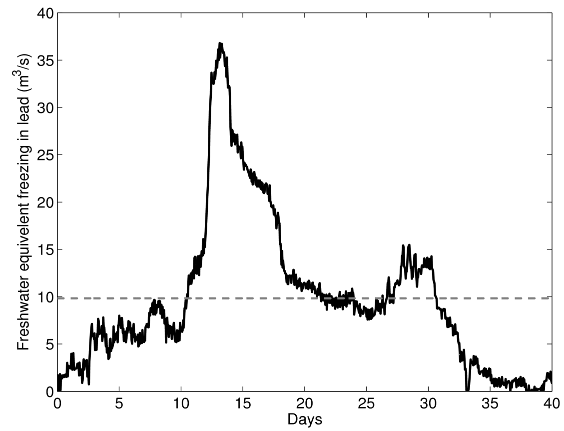


NPEO Day 1 (N 89.26 D, E 88.71 D)

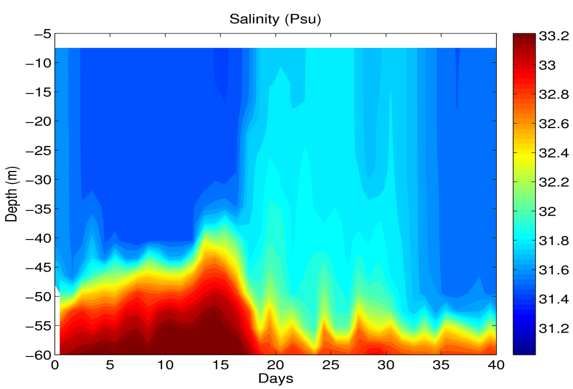
NEPO Day 40 (N 86.82 D, W 0.50 D)



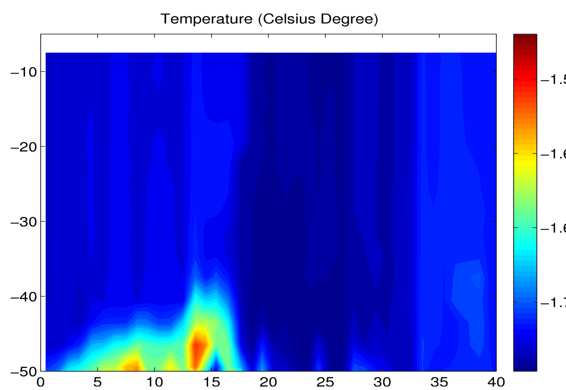
Lead Percentage



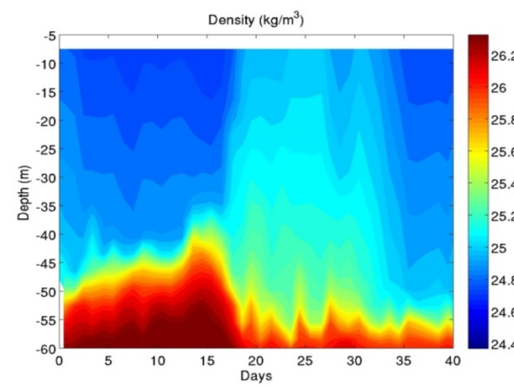
Equivalent freezing rate



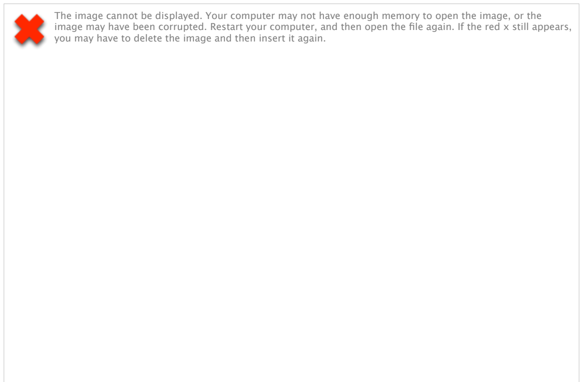
Salinity



Temperature



Density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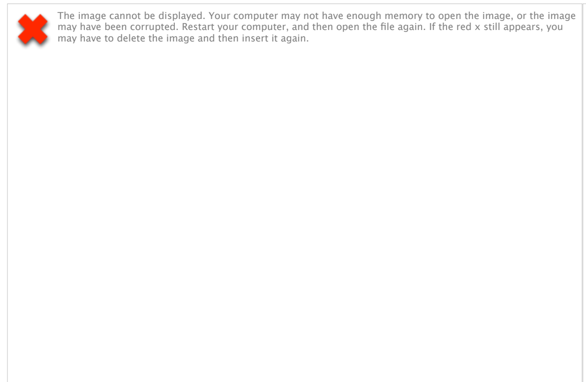
(a)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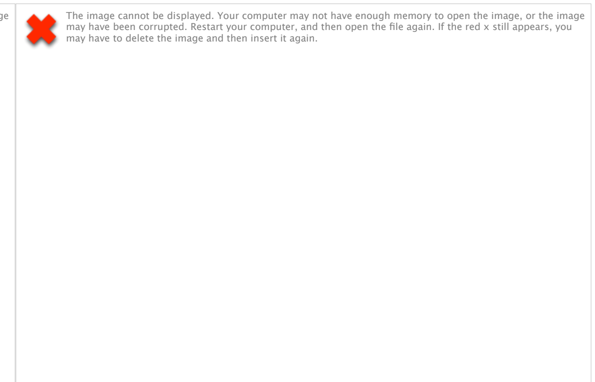
(b)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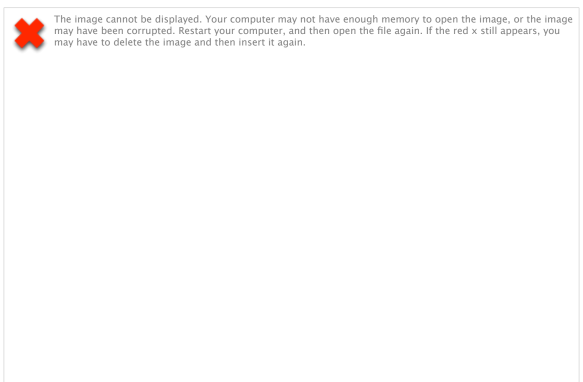
(c)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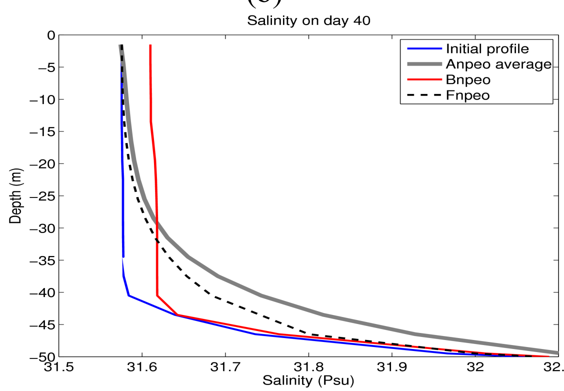
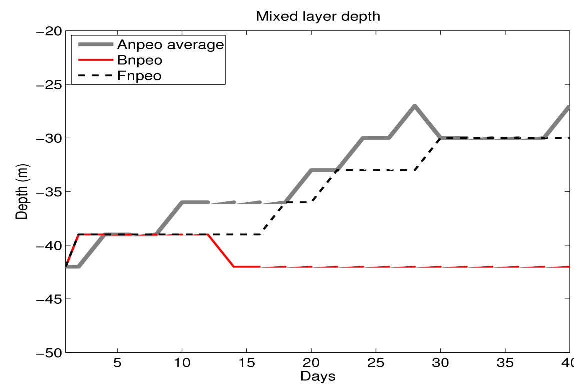
(d)

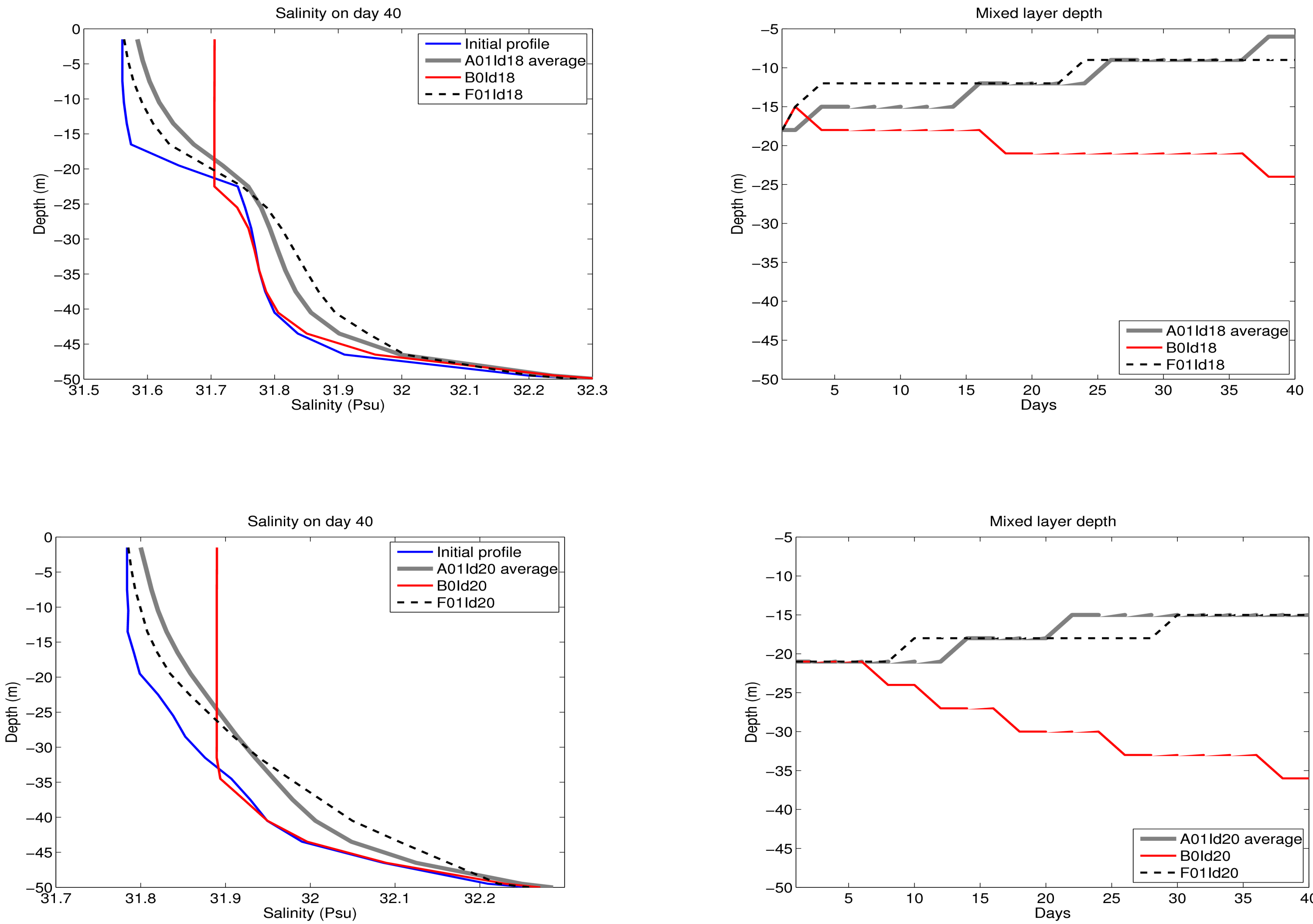

Salinity on day 40
Initial profile
Anpeo average
Bnpeo
Fnpeo
Depth (m)
0
−5
−10
−15
−20
−25
−30
−35
−40
−45
−50
31.5
31.6
31.7
31.8
31.9
32
32.1
Salinity (Psu)

(e)

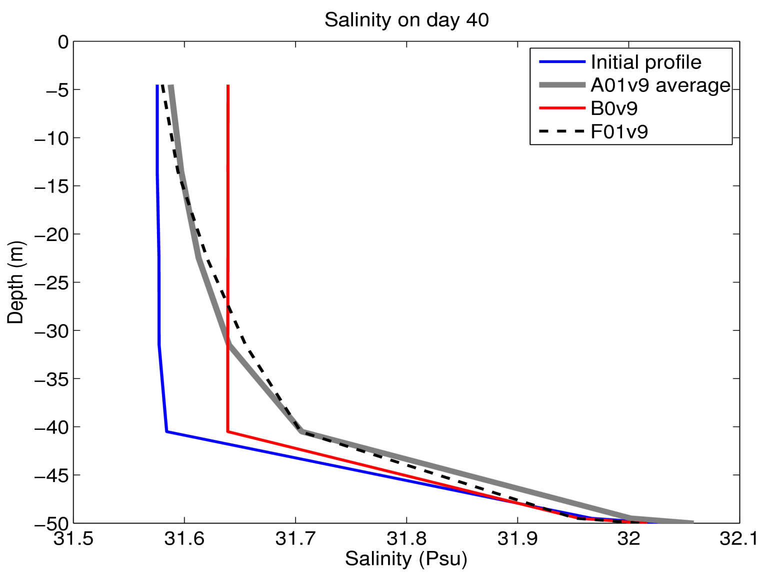

Mixed layer depth
Anpeo average
Bnpeo
Fnpeo
Depth (m)
−20
−25
−30
−35
−40
−45
−50
5
10
15
20
25
30
35
40
Days

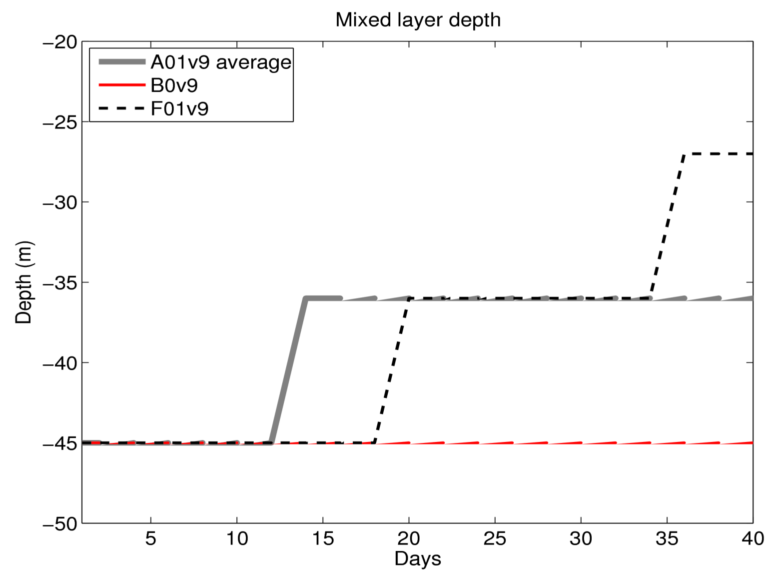
(f)

7.3 The new scheme shows similar improvements for different initial vertical salinity profiles (and MLD).



7.4 Improvements are shown in model results with 9m vertical resolution.





8. Model error comparison of all cases

In order to quantitatively measure and compare model errors in different cases, the salinity profiles in each case is averaged in days 20~40 in a 30km by 30km area for 30km grid cases:

$$\bar{S}(k) = \begin{cases} \frac{1}{30*30*20}\sum_{i=36}^{65}\sum_{j=36}^{65}\sum_{t=20}^{40} S\,(i,j,k,t), & for\ 1km\ grid\ cases \\ \frac{1}{20}\sum_{t=20}^{40} S(50,50,k,t), & for\ 30km\ grid\ cases \end{cases}$$

The sum of squares of residuals (SSQ) of the averaged salinity profiles are calculated as:

$$SSQ_{baseline} = \sum_{k=k_{lower}}^{k_{upper}} (\bar{S}_{baseline}(k) - \bar{S}_{true}(k))^2$$

$$\mathrm{SSQ}_{\mathrm{sensitivity}} = \sum_{\mathrm{k=k_{lower}}}^{\mathrm{k_{upper}}} (\bar{S}_{\mathrm{sensitivity}}(k) - \bar{S}_{true}(k))^2$$

Here subscript 'true', 'baseline', and 'sensitivity' denote case names started with 'A', 'B' and all others, respectively. Then the percentage of improvement *I* is defined similar to the approach in Nguyen et al. (2009) as follows:

$$I = \frac{SSQ_{baseline} - SSQ_{sensitivity}}{SSQ_{baseline}} \times 100$$

Table 3 . Improvement percentage *I* of model experiments in Table 1

Freshwater equivalent freezing rate 50 m^3/s and lead percentage 1%		A01 as true values, B0 as baseline								
		C0n0	C0n1	C0n2	C0n3	C0n4	C0n5	C0n6	C0n7	F01 (n=1.38)
Layers	0-12 m	77	98	92	90	89	89	88	88	96
	30-42m	21	94	93	71	40	11	-14	-34	98
	0-42 m	60	97	88	71	54	38	26	17	96
Freshwater equivalent freezing rate 50 m^3/s and lead percentage 5.4%		A03 as true values, B0 as baseline								
		C0n0	C0n1	C0n2	C0n3	C0n4	C0n5	C0n6	C0n7	F03 (n=0.75)
Layers	0-12 m	92	70	44	35	33	32	32	32	80
	30-42m	21	99	88	53	10	-89	-24	-64	93
	0-42 m	62	79	40	-3	-43	-99	-63	-118	85
Freshwater equivalent freezing rate 100 m^3/s and lead percentage 1%		A11 as true values, B1as baseline								
		C1n0	C1n1	C1n2	C1n3	C1n4	C1n5	C1n6	C1n7	F11 (n=1.38)
Layers	0-12 m	85	99	96	95	94	94	94	94	98
	30-42m	18	66	11	-66	-125	-164	-190	-207	52
	0-42 m	73	95	88	77	68	61	57	54	94

Table 4 . Improvement percentage *I* in different layers of model experiments in Table 2. The three cases in the second column represent the true, baseline and sensitivity cases, respectively.

NPEO cases	Anpeo Bnpeo Fnpeo	0-12m	96
		30-42m	75
		0-42m	77
Initial salinity and temperature on NPEO day 18	A01Id18 B0Id18 F01Id18	0-12m	93
		30-42m	67
		0-42m	85
Initial salinity and temperature on NPEO day 20	A01Id20 B0Id20 F01Id20	0-12m	90
		30-42m	88
		0-42m	81
Horizontal model grid 20km	A01 B0h20 F01h20	0-12m	98
		33-45m	54
		0-45m	92
Horizontal model grid 40km	A01 B0h40 F01h40	0-12m	93
		30-42m	99
		0-42m	95
Vertical model grid 9m	A01v9 B0v9 F01v9	0-18m	94
		27-45m	93
		0-45m	93

9. Summary and outlook

•When lead is unresolved, both vertical salinity profile and MLD show systematic errors with saltier sea surface and deeper MLD. These errors in climate models can be magnified each year in a multi-decadal runs (or spin-up) and cause severe model drift.

•Parameterization of the sub-grid scale mixing of rejected brine in climate models have been found to improve the overall model comparison with observations in regional ice-ocean models in the Antarctica and Arctic Oceans.

•The proposed new parameter n determined as a function of lead percentage in a model grid cell is proved to improve modeled salinity profile and MLD under various sea ice conditions in the polar oceans. It is also proved that the parameterization is suitable for model runs with different initial salinity profiles and different horizontal and vertical model grid resolutions.

The parameterization scheme is for ice formation only. It is also not applicable when ice concentration is low (or lead percentage is more than 51%).

In summer melting seasons, the lead area will be warmer and fresher than its surroundings and thus form a stable stratification in the local water column. The MCOG scheme (Holland, 2003) is found to improve model results of both ocean temperature and salinity structure and sea ice mass balances. Studies are under way to implement MCOG and the new parameterization scheme in climate models in separate ice formation/melt conditions or combined.

Assessment of the global climate model performance with the new scheme is our next step.

Acknowledgments.

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