<OPST meeting Science Day, November 9, 2023>

Impact of satellite thickness data assimilation on bias reduction in Arctic sea ice concentration

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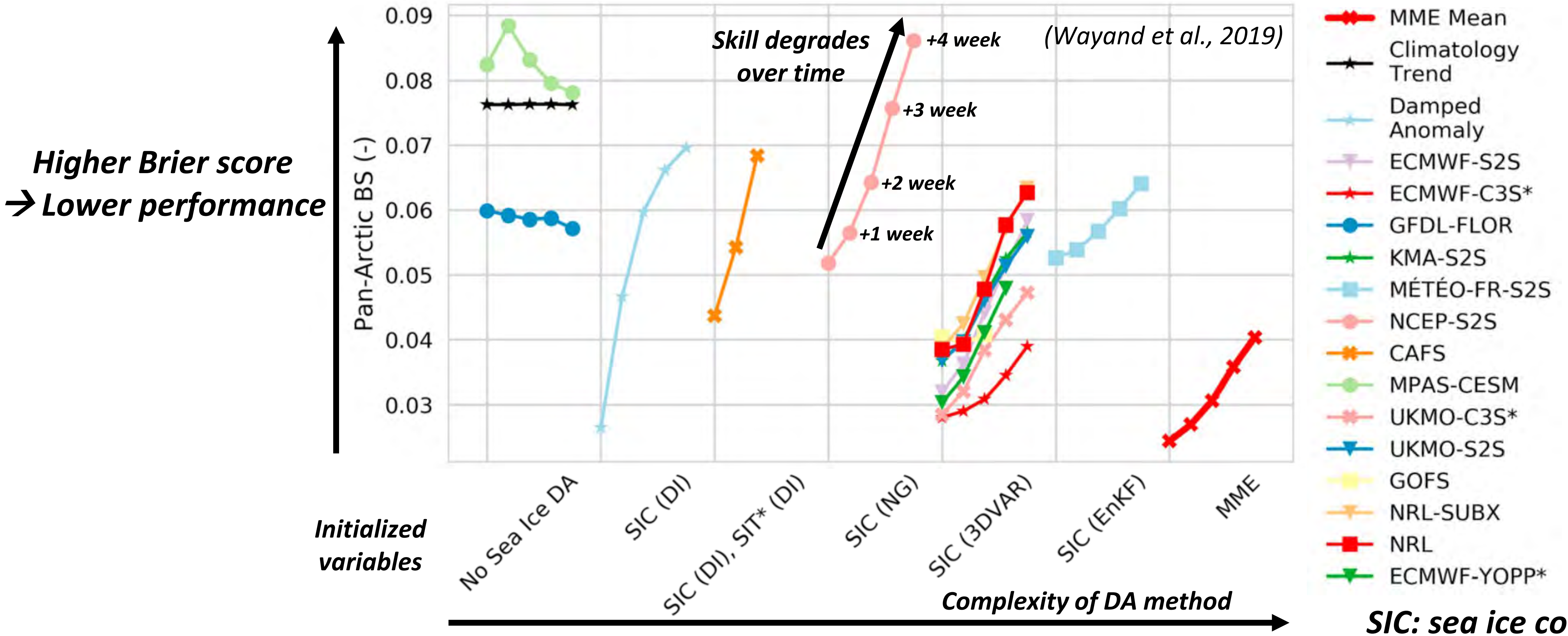
Current status of sea ice prediction (Sea Ice Prediction Protal)

Four weeks prediction of Arctic SIC
[Brier skill score]



Skill degrades over time

(Wayand et al., 2019)

Higher Brier score → Lower performance

Initialized variables

Complexity of DA method

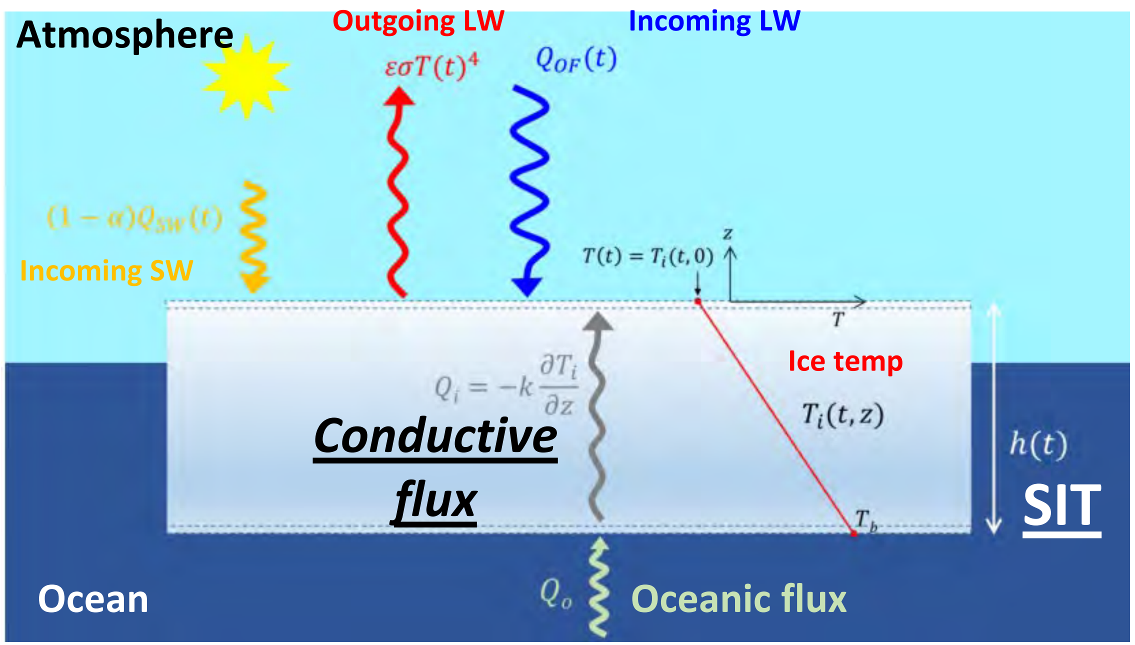
- SIC data assimilation (DA) only due to data abundance

SIC: sea ice concentration

the percent areal coverage of ice within grid cell

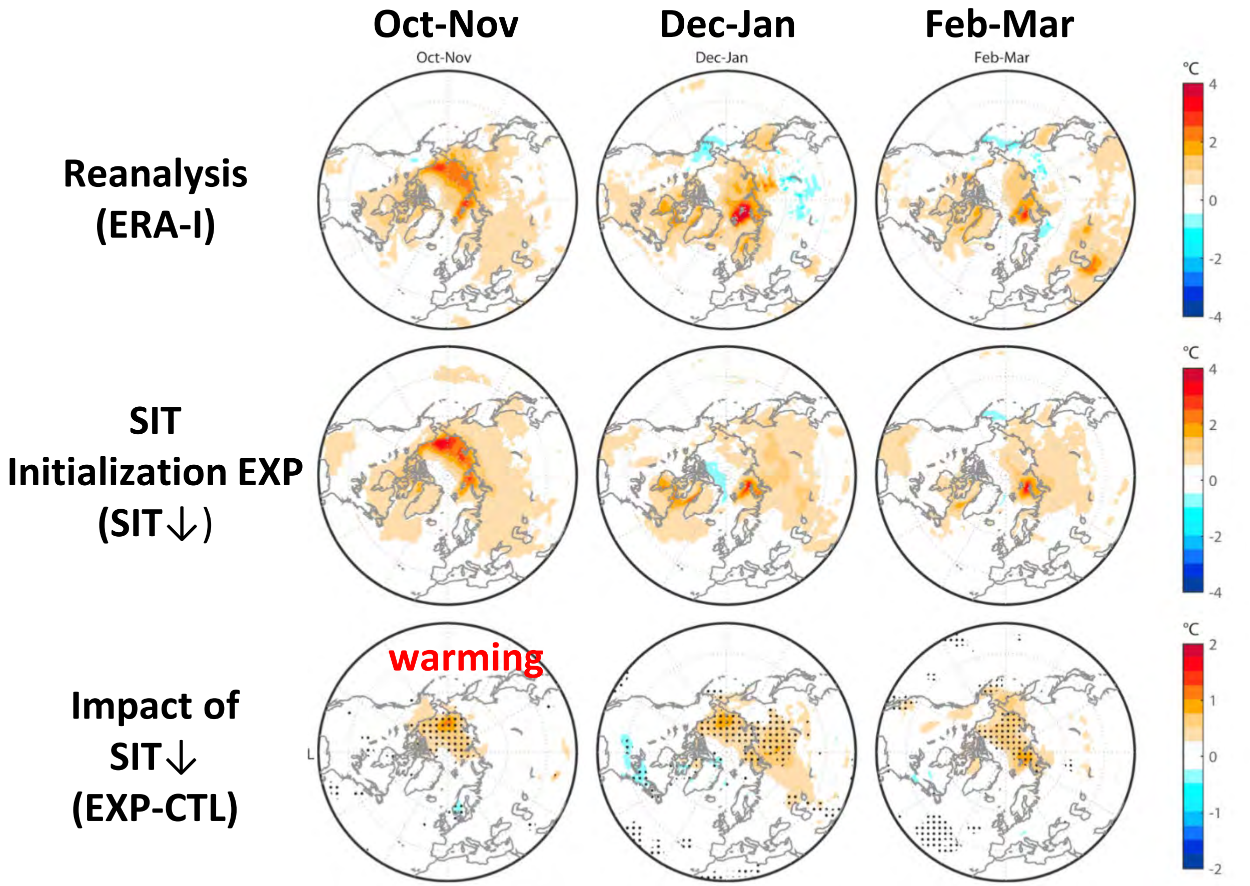
Impact of sea ice thickness on climate

Thermodynamics in sea ice



(Massonnet, 2017)

Surface air temperature change [linear trend, 1982-2013]



(Lang et al., 2017)

- Sea ice thickness (SIT)↓ --- vertical ice temp gradient↑ --- conductive flux↑ --- local surface temp↑

Experiment design of SIT DA

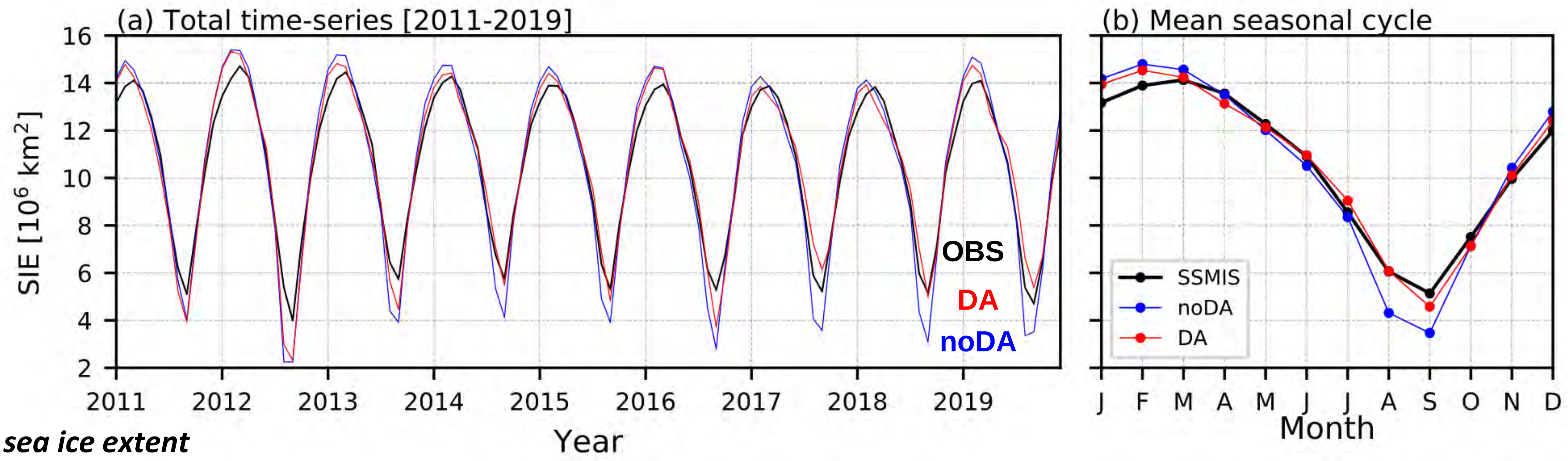
	Information	Reference
Model	CICE 5 (Community Ice CodE, v5.1.2, LANL)	*Hunke et al., (2015)*
Atmospheric/Oceanic Forcing	ATM: NCEP Reanalysis 2 OCN: NOAA Optimal Interpolation version 2 (nudging, 20 days)	*Kanamitsu et al., (2002)* *Reynolds et al., (2002)*
SIT Observation	**ESA CryoSat-2 daily SIT data for thick ice (> 1.0m)** **ESA SMOS daily SIT data for thin ice (< 1.0m)**	*Kurtz and Harbeck, (2017)* *Tian-Kunze et al., (2014)*
Data Assimilation scheme	Localized EnOI (Ensemble Optimal Interpolation) (Background error perturbations using long-term integration)	*Evensen, (2003)* *Sakov et al., (2011)* *Lee and Ham, (2022)*
Resolution	320 × 384 (1°, ~100 km) gx1v6	
	Daily DA cycle	
Ensemble size	38	
DA experiment period	Jan2011 – Dec2019 (September-May) (SIT OBS is provided during winter only)	

DA*: *The SIT data assimilation experiment

noDA: Control run (without any data assimilation, only boundary forcing)

Representation of sea ice extent (SIE) by SIT DA

Temporal evolution of sea ice extent [NH, 11-19]



SIE: sea ice extent
(cumulative are of all grid cells with SIC
greater than 0.15 over Northern hemisphere)

- The positive (negative) SIE bias during winter (summer) in noDA is improved by SIT DA.

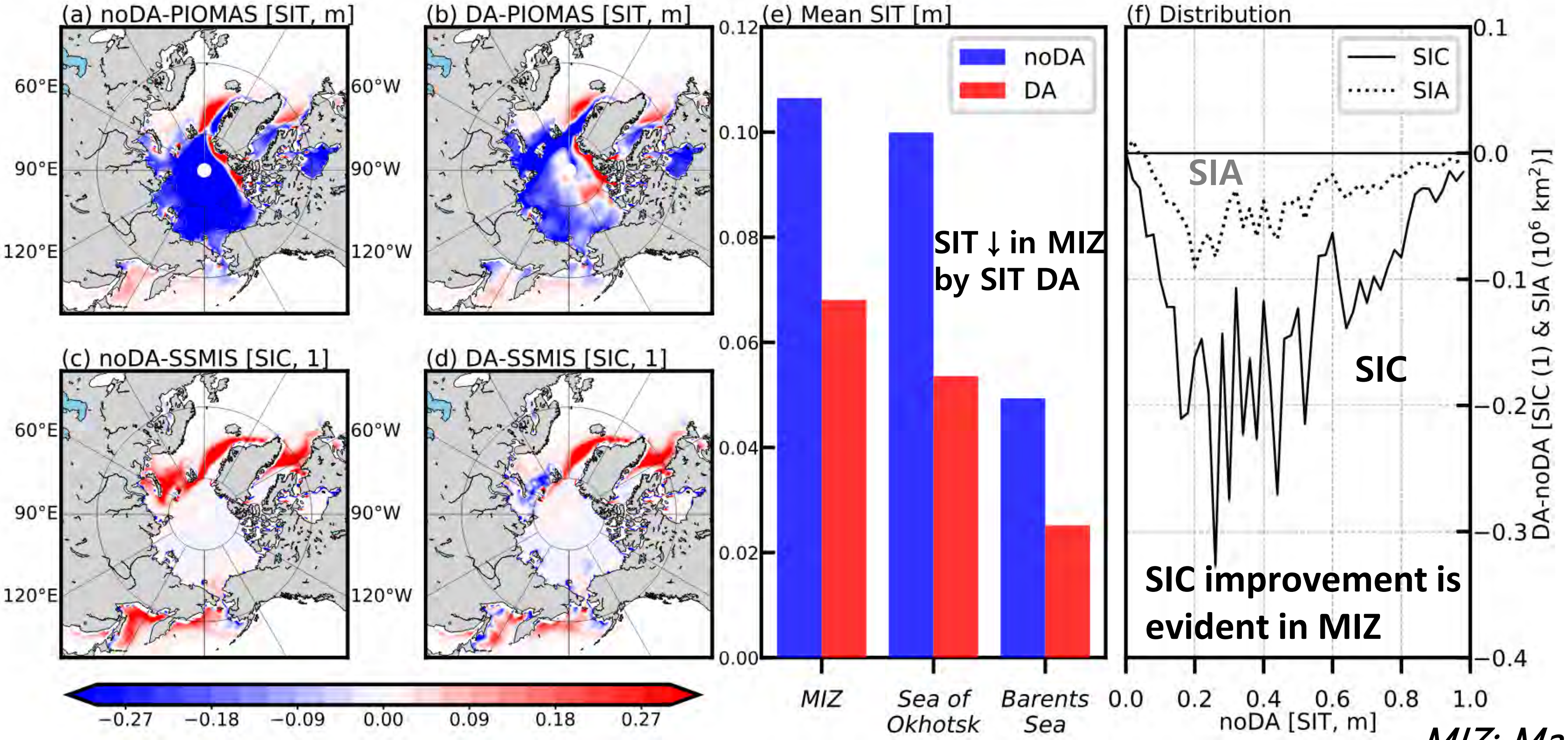
Representation of SIT and SIC during winter (SIT DA)

Mean differences of SIT and SIC in DJF season [11-19]

noDA-OBS **DA-OBS** **Mean SIT**

SIT

SIC



SIT ↓ in MIZ by SIT DA

SIA

SIC

SIC improvement is evident in MIZ

SIT↓ → SIC↓ in MIZ

MIZ: Marginal Ice Zone
SIA: Sea Ice Area

Idealized experiments by reducing SIT

Design of idealized experiment

	Information
Period	2000 – 2019 (20 samples)
Integration time	30-day
Initial conditions (ICs)	1st December of each year
Regulated factor	**Reducing the SIT by 0.25 m** (0.05 m of each category) of each IC
SIT condition (criteria)	SIT < 0.4 m (Marginal ice zone)

EXP: The SIT reduction experiment
CTL: Control run

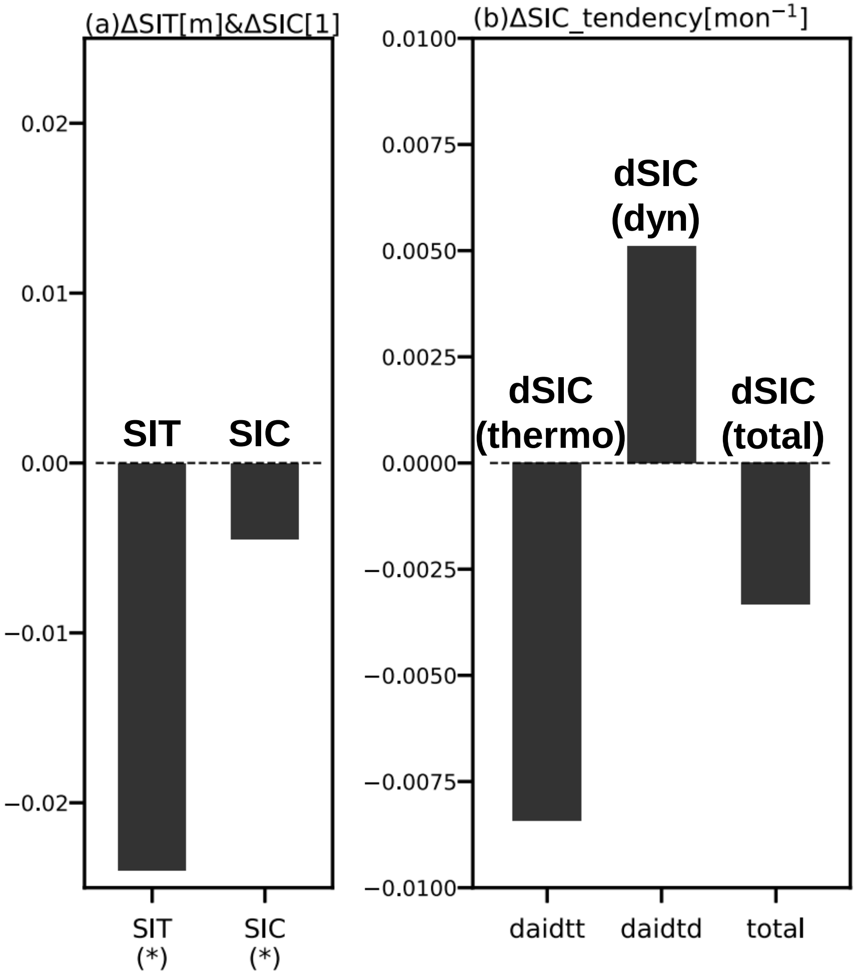
SIT reduction EXP → **SIC response**

Response of SIC and SIC tendencies led by SIT reduction

Monthly mean differences [EXP − CTL, Δ]

Δ: $\boldsymbol{EXP - CTL}$

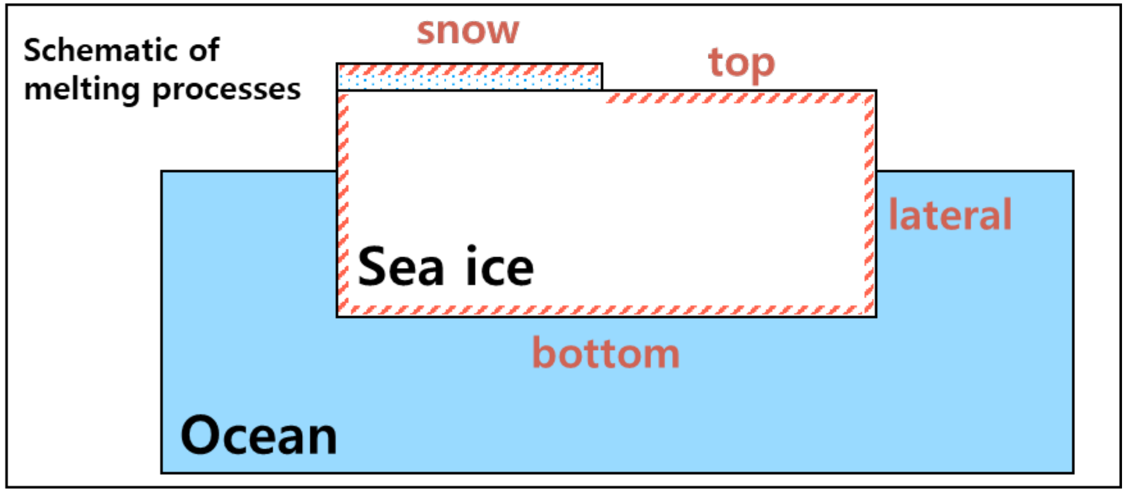
Response to SIT reduction



- SIC is decreased to the given SIT reduction in MIZ.
- Thermodynamic processes is important to SIC response.

Design of mechanism denial experiments

	Information	SIT reduction	Control
Mechanism denial experiments	1. Ice bottom melting	$\mathrm{EXP}_{\mathrm{BOTTOM}}$	$\mathrm{CTL}_{\mathrm{BOTTOM}}$
	2. Ice top melting	$\mathrm{EXP}_{\mathrm{TOP}}$	$\mathrm{CTL}_{\mathrm{TOP}}$
	3. Ice snow melting	$\mathrm{EXP}_{\mathrm{SNOW}}$	$\mathrm{CTL}_{\mathrm{SNOW}}$
	4. Ice lateral melting	$\mathrm{EXP}_{\mathrm{LATERAL}}$	$\mathrm{CTL}_{\mathrm{LATERAL}}$



*** SIC responses in each experiment (ΔSIC)**

$\mathbf{No\_denial} = \mathbf{EXP} - \mathbf{CTL}$ **Considering whole mechanism**

$\mathrm{BOTTOM\_denial} = \mathrm{EXP}_{\mathrm{BOTTOM}} - \mathrm{CTL}_{\mathrm{BOTTOM}}$

$\mathrm{TOP\_denial} = \mathrm{EXP}_{\mathrm{TOP}} - \mathrm{CTL}_{\mathrm{TOP}}$

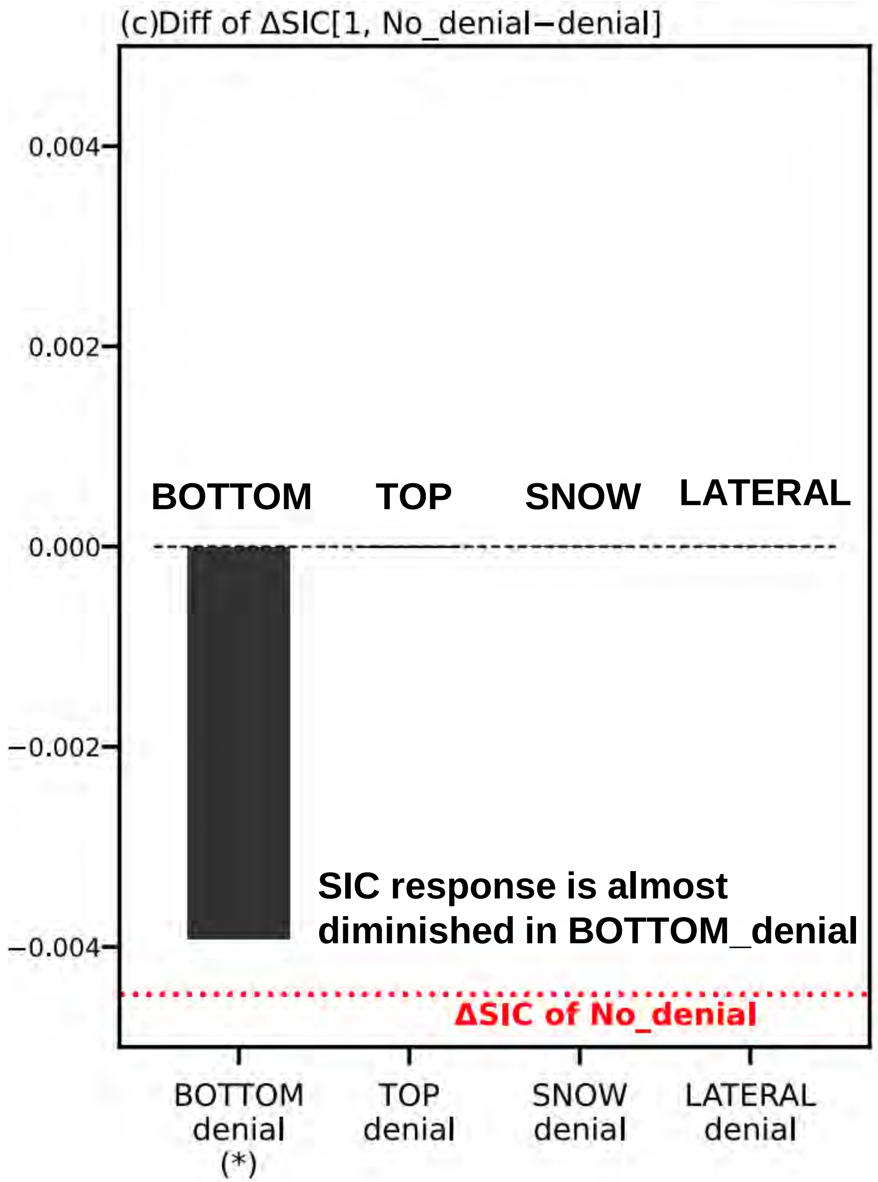
$\mathrm{SNOW\_denial} = \mathrm{EXP}_{\mathrm{SNOW}} - \mathrm{CTL}_{\mathrm{SNOW}}$

$\mathrm{LATERAL\_denial} = \mathrm{EXP}_{\mathrm{RATERAL}} - \mathrm{CTL}_{\mathrm{RATERAL}}$

$\mathbf{Diff(\Delta SIC) = No\_denial - each\_denial}$

SIT reduction EXP $\xrightarrow{\text{Mechanism denial}}$ **SIC response**

Important thermodynamic process (denial experiments)



SIC response is almost diminished in BOTTOM_denial

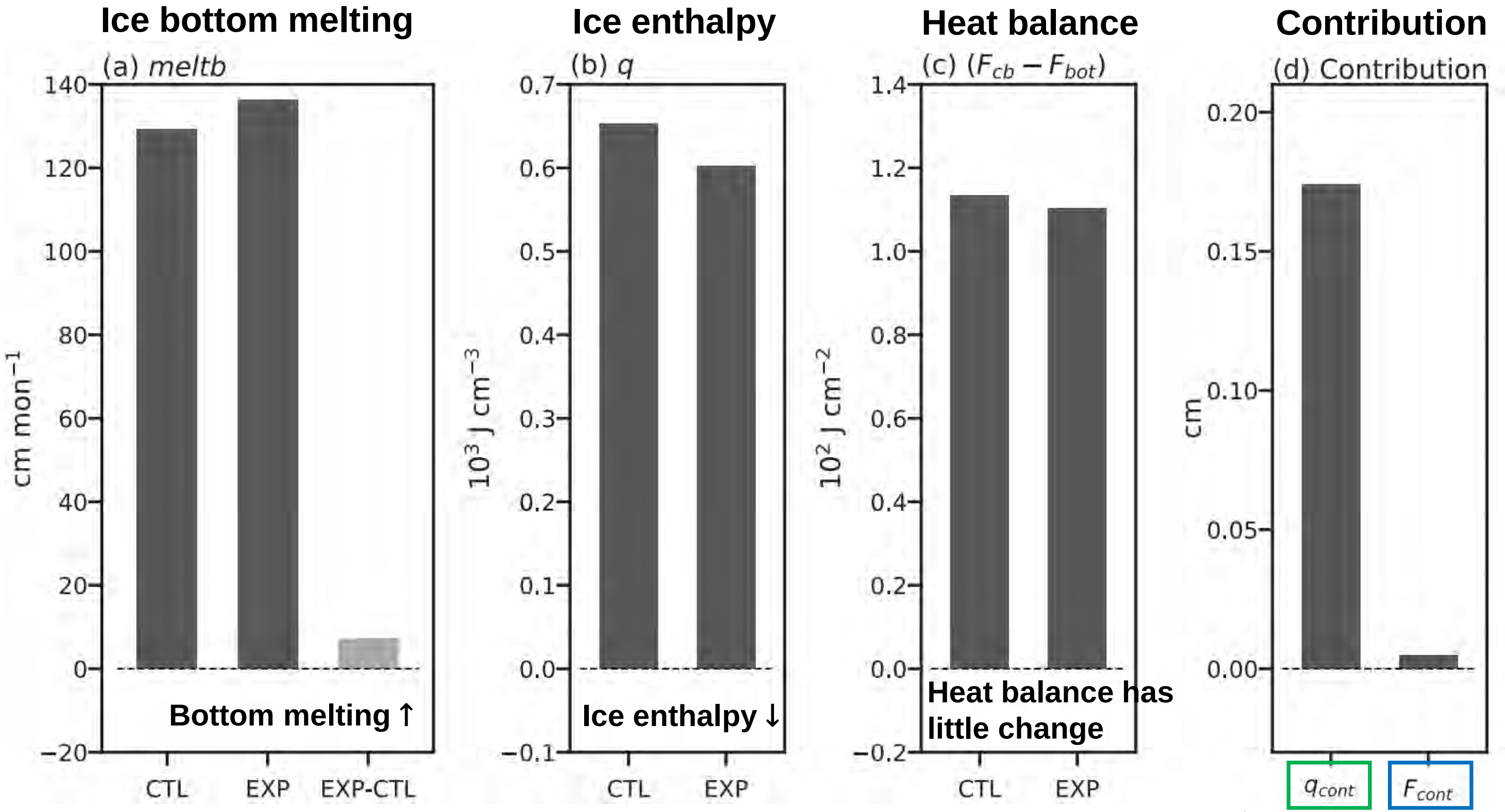
Differences in ΔSIC
[No_denial − denial experiments]

$$\mathbf{Diff(\Delta SIC) = No\_denial - each\_denial}$$
$$= (\mathrm{EXP} - \mathrm{CTL}) - (\mathrm{EXP}_{\mathrm{denial}} - \mathrm{CTL}_{\mathrm{denial}})$$

- The ice bottom melting process plays crucial role in SIC response to SIT reduction.
- The rest of the melting processes have little effect.

Intensification of bottom melting by thinning of SIT

Monthly mean and difference between EXP and CTL [No_denial]



Ice bottom melting

Ice enthalpy

Heat balance

Contribution

$$\Delta meltb = \frac{F_{EXP}}{q_{EXP}} - \frac{F_{CTL}}{q_{CTL}} = \frac{F_{EXP}\left(\frac{q_{CTL}}{q_{EXP}}\right) - F_{CTL}}{q_{CTL}} \Rightarrow \boxed{q_{cont}} = \left|\frac{F_{CTL}\left(\frac{q_{CTL}}{q_{EXP}} - 1\right)}{q_{CTL}}\right| \boxed{F_{cont}} = \left|\frac{F_{EXP} - F_{CTL}}{q_{CTL}}\right|$$

Sea ice bottom melting (meltb):

$$meltb = \frac{(F_{cb} - F_{bot})}{q}$$

→ $(F_{cb} - F_{bot}) > 0 \rightarrow$ ***bottom melting***

→ $(F_{cb} - F_{bot}) \uparrow$ **(input of heat ↑)→** $meltb \uparrow$

→ $q \downarrow$ **(sensitivity for heat ↑) →** $meltb \uparrow$

meltb: change in *SIT* (m/step) = (cm/day)

F_{cb}: conductive heat flux (ice bottom to top)(W/m^2)(< 0)

F_{bot}: oceanic heat flux(ocean to ice bottom)(W/m^2)(< 0)

q: energy of melting (J/m^3)(> 0)

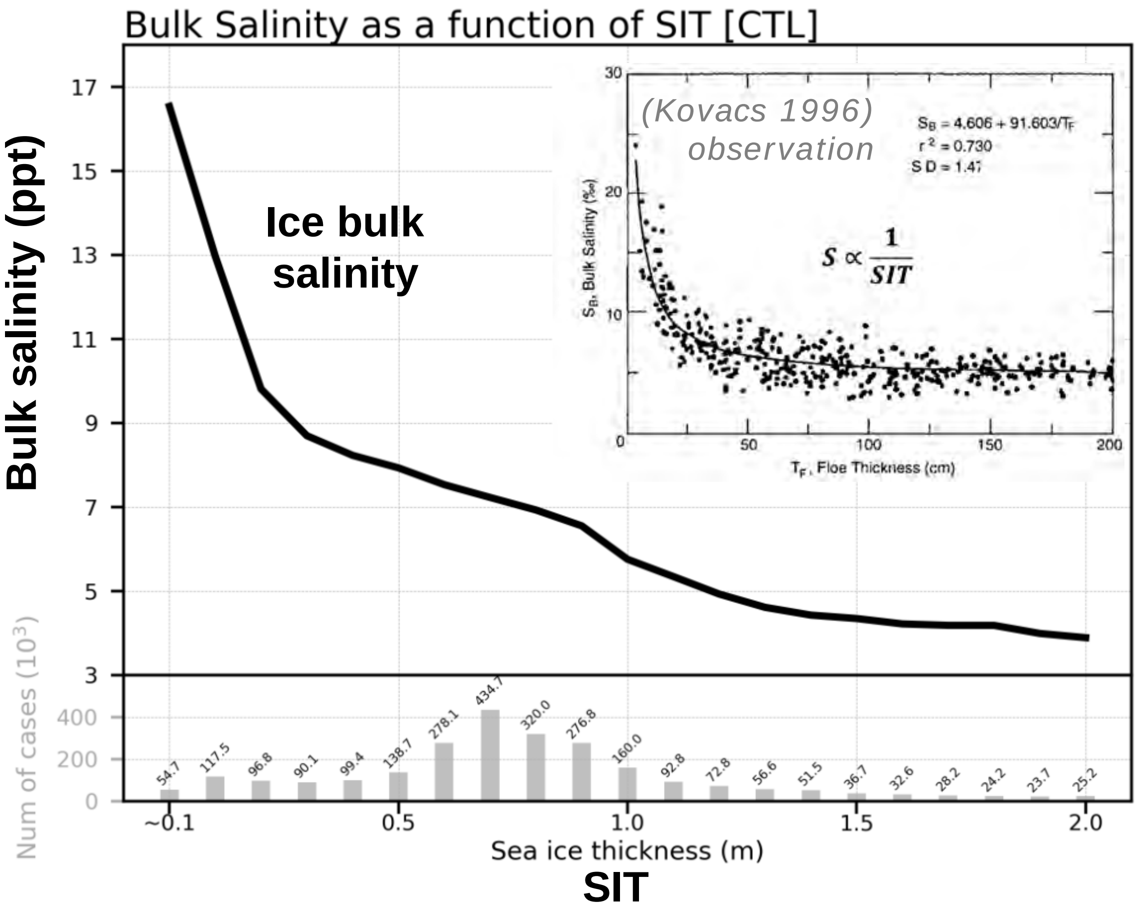
- The intensification of ice bottom melting dominantly comes from the decreasing in the enthalpy.
- Ice enthalpy is determined by ice bulk salinity and temperature in inverse relationship *(Lemieux et al., 2017)* **(i.e.,** $T\uparrow, S\uparrow \rightarrow q(T,S)\downarrow$**).**

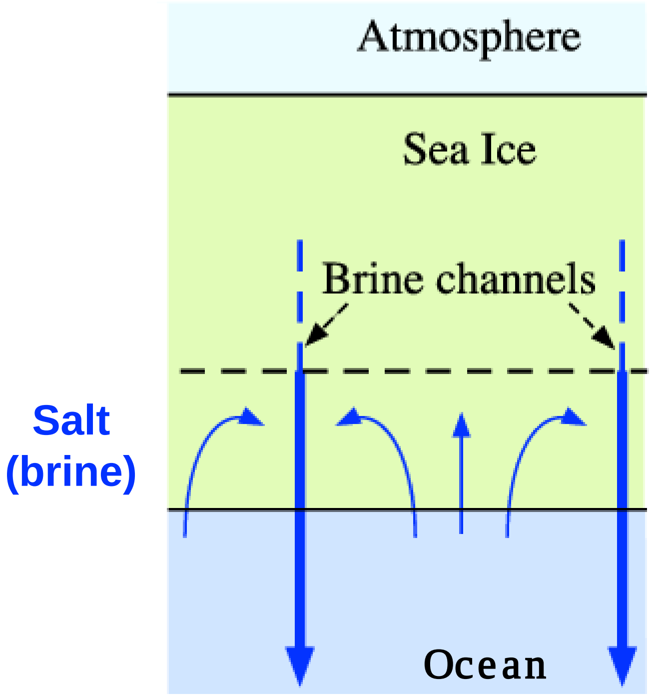
Ice enthalpy is key factor

Relationship between SIT and ice bulk salinity

Distribution of bulk salinity vs SIT [CTL]

Schematic of brine rejection process



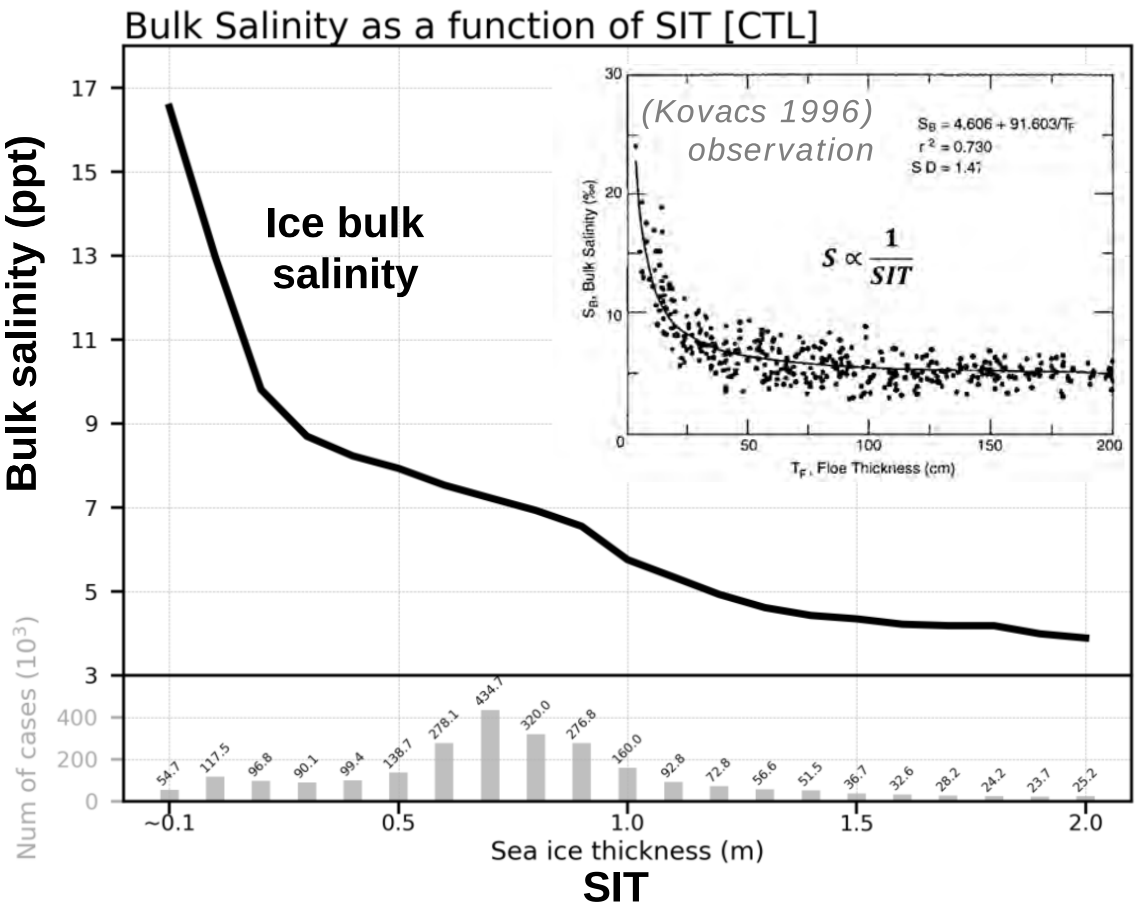


(Rees Jones and Worster, 2013)

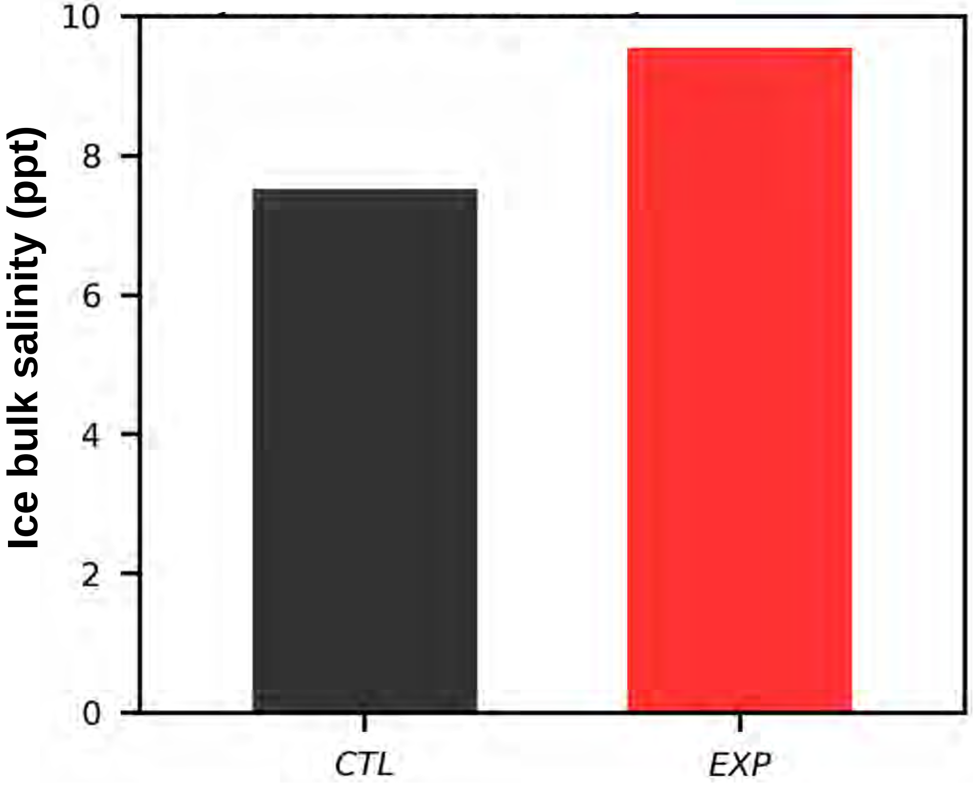
- Brine (salt water in ice) is rejected by gravity (brine rejection).
- SIT↓→ brine rejection↓→ salinity↑→ q↓

Relationship between SIT and ice bulk salinity

Distribution of bulk salinity vs SIT [CTL]



Mean of ice bulk salinity

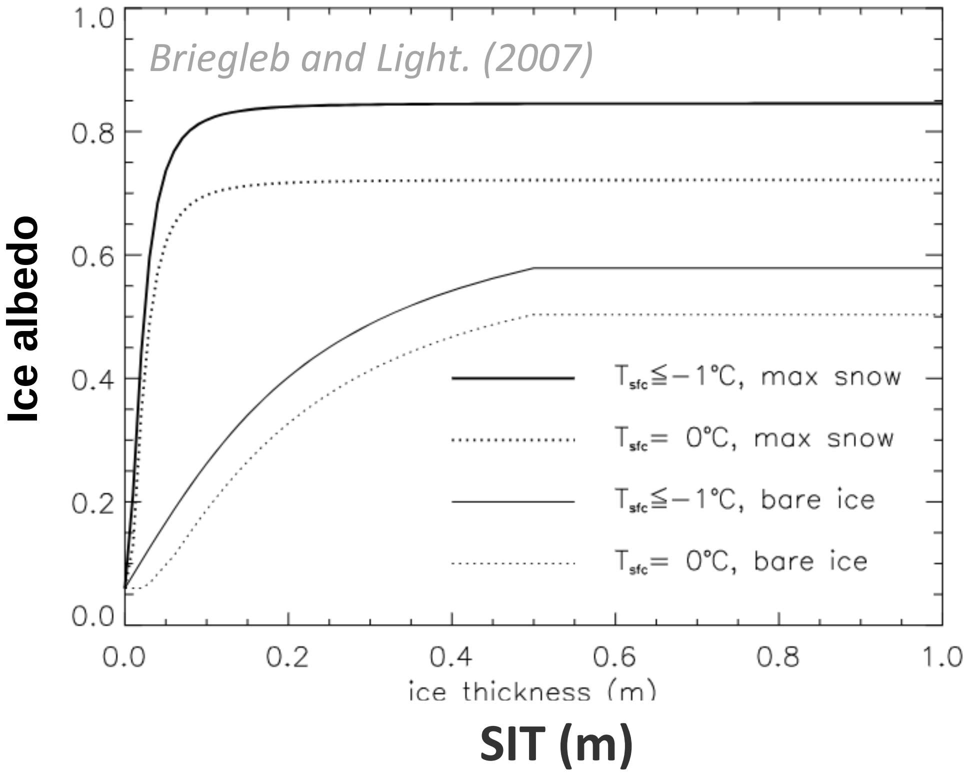


SIT↓ → **Brine rejection↓** → **Ice bulk salinity↑**

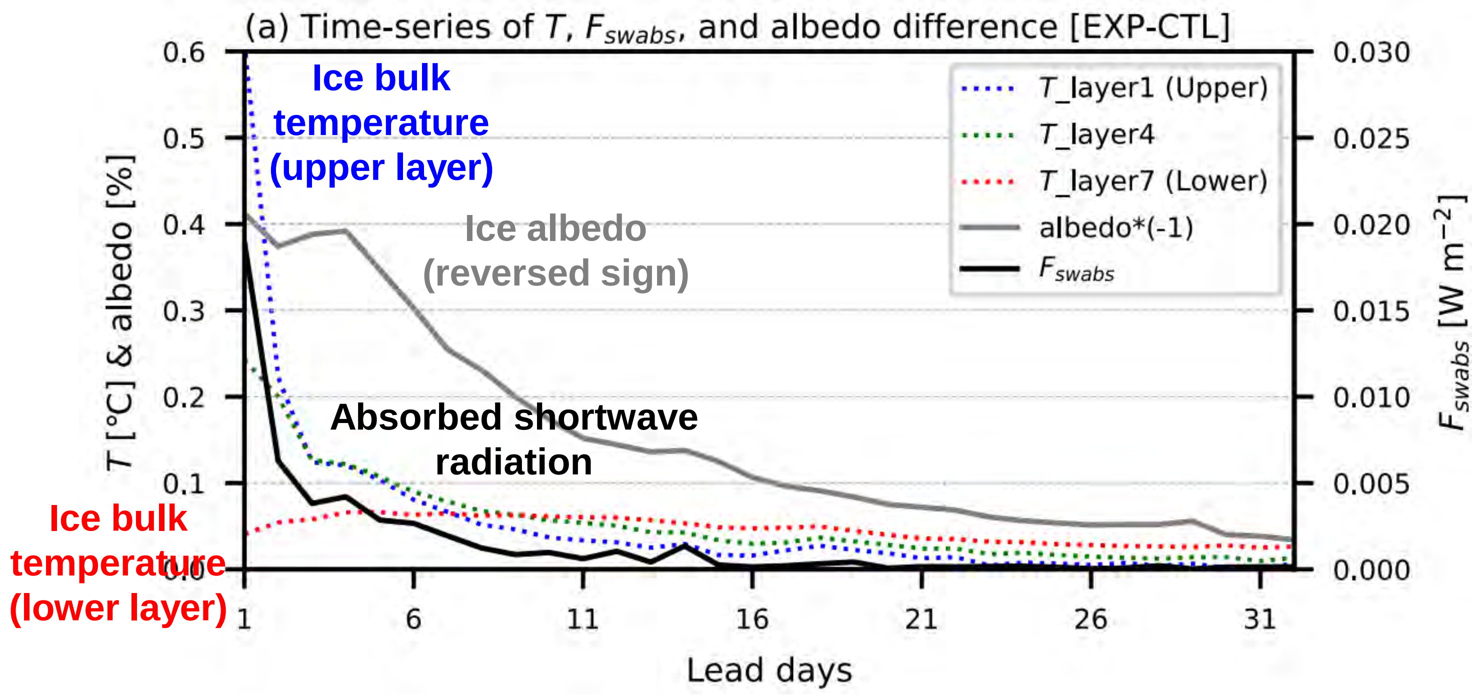
q ↓

Albedo-related mechanism induced by SIT reduction

Ice albedo as a function of SIT



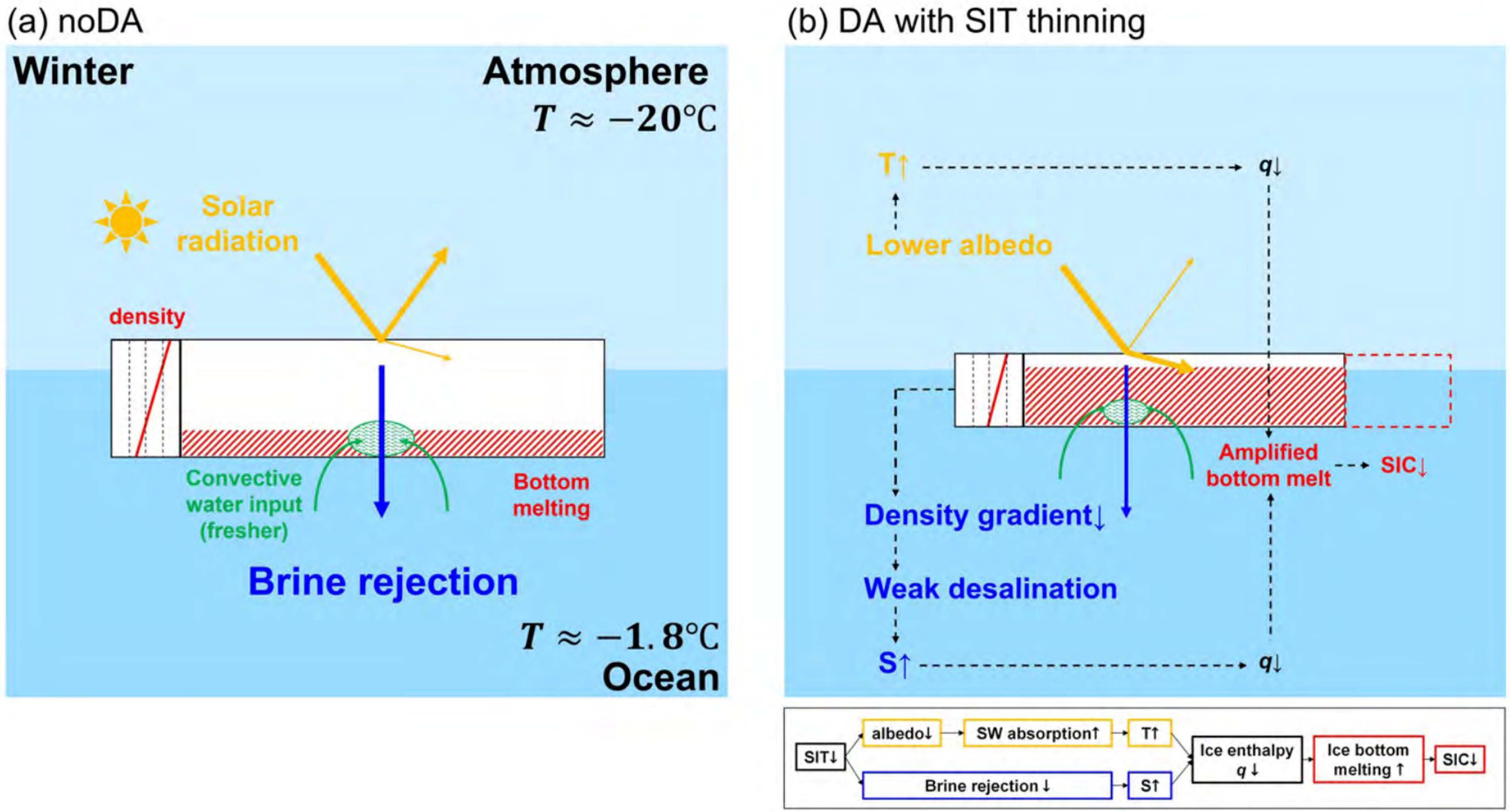
Changes in ice temperature, shortwave absorption, and albedo



SIT↓ → **albedo↓** → **SW absorption↑** → **Ice temperature↑** q↓

Possible mechanism (SIC response to SIT reduction)

Schematic of possible mechanism in SIT reduction experiment



Summary and discussion

- Reanalysis of sea ice is produced through **EnOI-based** data assimilation injecting **satellite-derived Arctic sea ice thickness** observation into **CICE5** during **2011-2019**

- The DA of SIT has **positive impact on representation of SIC climatology** during **winter and summer** season

- **Ice bottom melting**-related mechanism plays crucial role in **response of SIC to change in SIT**

- **The augmentation of ice bulk temperature (albedo related) and salinity (desalination related)** contribute towards **diminishing ice enthalpy** and **amplification of ice bottom melting**

- The physical relationship between SIC and SIT intimates that the **multivariate assimilation** using cross-covariance between SIC and SIT might further improve the quality of reanalysis

- Understanding of the physical mechanism suggests **potential factors related sea ice and climate prediction**

- The **internal positive feedback** between SIC and SIT might lead to Arctic amplification, even without the coupled processes with other climate components (e.g., atmosphere or ocean)

- However, it should be noted that the introduced physical mechanism is **dependent on the sea ice model only**.

Thank you very much!

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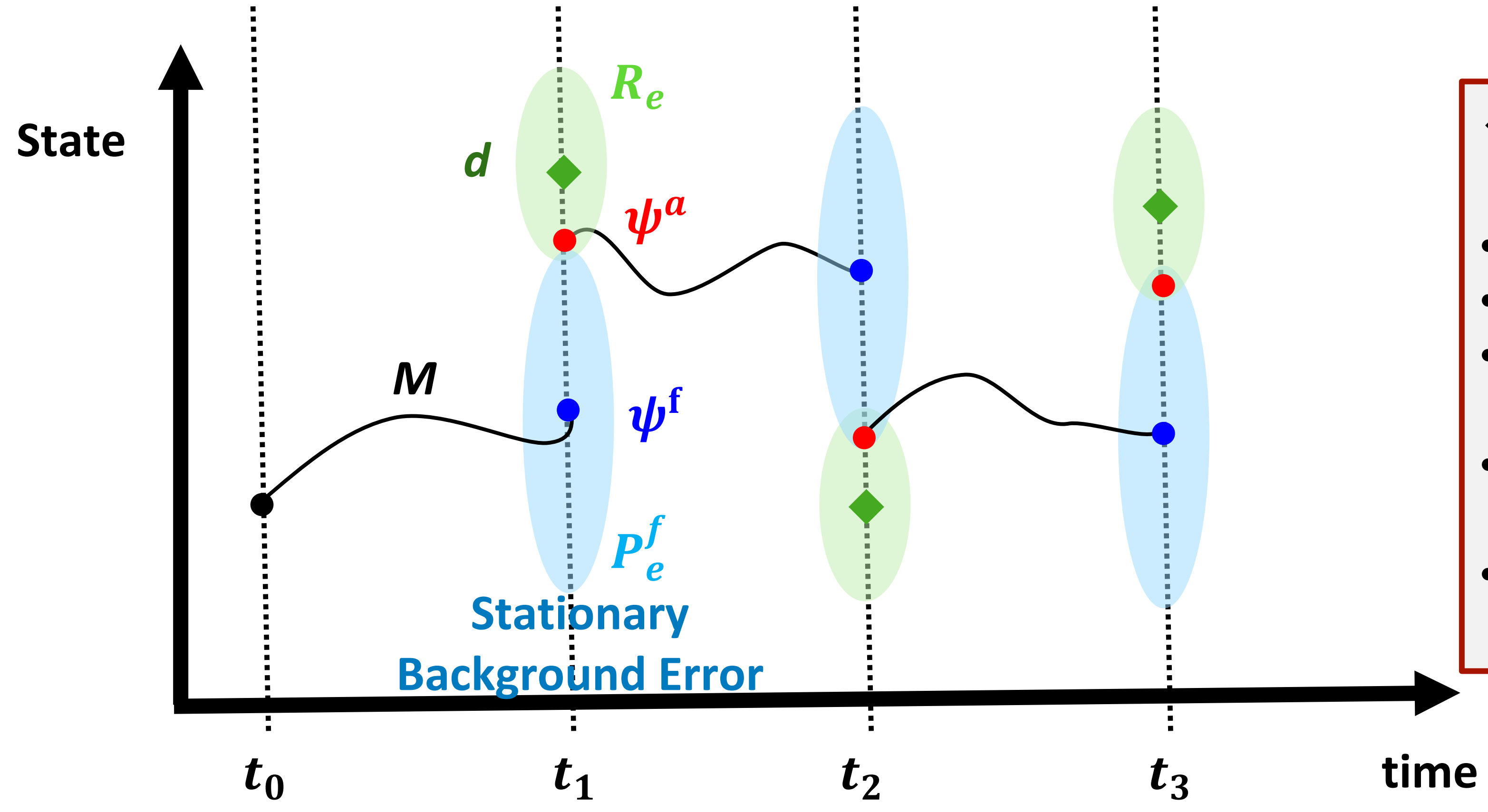
Supplementary
(sea ice DA)

Ensemble Optimal Interpolation (EnOI)

Schematic of the Ensemble Optimal Interpolation System



$$\psi^a = \psi^f + \mathrm{K}\left[\mathrm{d} - H\left(\psi^f\right)\right]$$

$$\mathrm{P^f} \equiv \mathrm{A'A'^T}[\mathrm{N} - 1]^{-1}$$

❖ Advantage of EnOI

- Cost-effective method
- The similar analysis step to that of a EnKF
- Quasi-dynamically consistent, inhomogeneous and anisotropic covariances.
- Simplicity of system (Single deterministic model run) and code
- Seasonally varying quasi-stationary ensembles

Mathematical aspect of EnOI (*Evensen, 2003*)

Analysis equation

$$\psi^a = \psi^f + K[d - H(\psi^f)]$$

Analysis Background Weight OBS Model

Kalman gain (weight)

$$K = P^f H^T [H P^f H^T + R]^{-1}$$

Background error covariance

Measurement error covariance

Background error covariance

$$P^f = A' A'^T [N - 1]^{-1}$$

Background ensemble perturbations

Num of ensembles

ψ^a = estimate of DA system state
ψ^f = background state
K = Kalman gain
H = observational operator
d = observation state vector
R = observation error covariance
A′ = EnOI anomalies
N = ensemble size

Ensemble perturbations of background

$$A' = A^f - \overline{A^f} = A(I - 1_N)$$

$$A^f = [\psi_1^f, \psi_2^f, \dots, \psi_N^f]$$

Construction of measurement error covariance

$$d_j = d + \epsilon_j, \qquad j = 1, \dots, N$$

$$D = [d_1, d_2, \dots, d_N]$$

$$\gamma = [\epsilon_1, \epsilon_2, \dots, \epsilon_N]$$

$$R_e = \frac{\gamma\gamma^T}{N-1}$$

P^f: background error covariance
A′ = ensemble perturbations
A^f = the matrix holding the ensemble members
$\psi_i^f = i^{th}$ ensemble state
1_N = *the matrix where each element is equal to* $1/N$
d_j = *perturbed observations*
D = *the matrix holding the observations*
γ = *the matrix holding the perturbations for OBS*
R_e = *ensemble representation of the measurement error covariance matrix*

Mathematical aspect of EnOI (*Evensen, 2003*)

Analysis equation

$$A^a = A + P_e^f H^T \left(H P_e^f H^T + R_e\right)^{-1} (D - HA)$$

$$A^a = A + A' A'^T H^T (H A' A'^T H^T + \gamma\gamma^T)^{-1} D'$$

Calculation of inversion matrix using EVD
(Eigenvalue decomposition, traditional way)

$$H A' A'^T H^T + \gamma\gamma^T = Z \Lambda Z^T$$

EVD of error covariance matrix

$$(H A' A'^T H^T + \gamma\gamma^T)^{-1} = Z \Lambda^{-1} Z^T$$

Calculation of inversion matrix using SVD
(Singular value decomposition, traditional way)

$$H A' A'^T H^T + \gamma\gamma^T = (HA' + \gamma)(HA' + \gamma)^T$$

$HA'\gamma^T \equiv 0$

$(uncorrelated\ ensemble\ perturbations\ and\ measurement\ errors)$

$$HA' + \gamma = U \Sigma V^T$$

$SVD\ of\ (HA' + \gamma)$

$$H A' A'^T H^T + \gamma\gamma^T = U \Sigma V^T V \Sigma^T U^T = U \Sigma \Sigma^T U^T$$

$$A^a = A^f + A' (HA')^T U \Lambda^{-1} U^T D'$$

$exploitation\ scheme$

$$X_1 = \Lambda^{-1} U^T$$

$$X_2 = X_1 D'$$

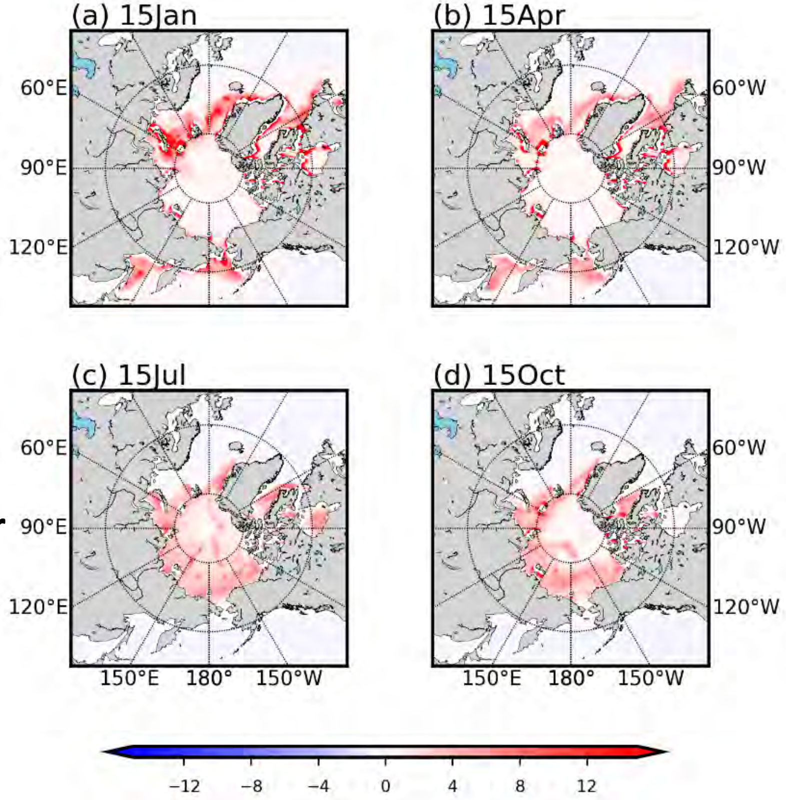
$$X_3 = U X_2$$

$$X_4 = (HA')^T X_3$$

$$\begin{aligned} A^a &= A + A' X_4 \\ &= A + (A - \bar{A}) X_4 \\ &= A + A(I - 1_N) X_4 \\ &= A(I - X_4) \\ &= A X_5 \end{aligned}$$

Healthiness of background error covariance matrix

**Standard deviation of perturbations (82-19)
(38 samples)**



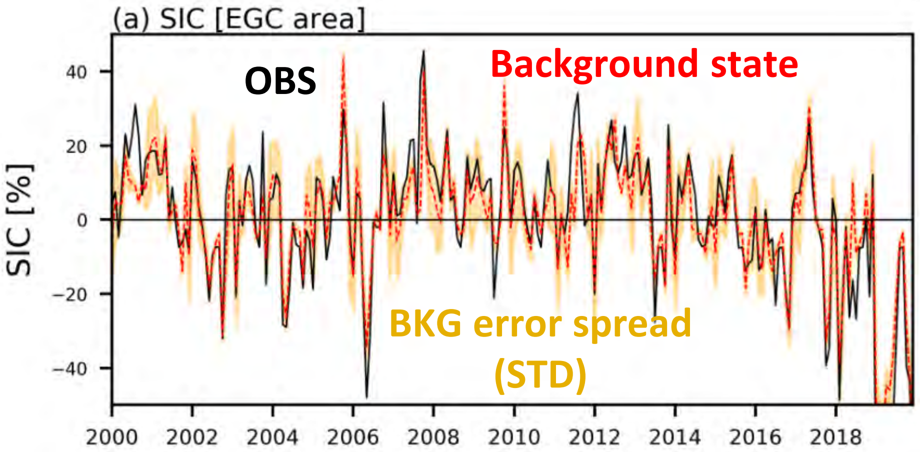
Winter

Spring

Summer

Fall

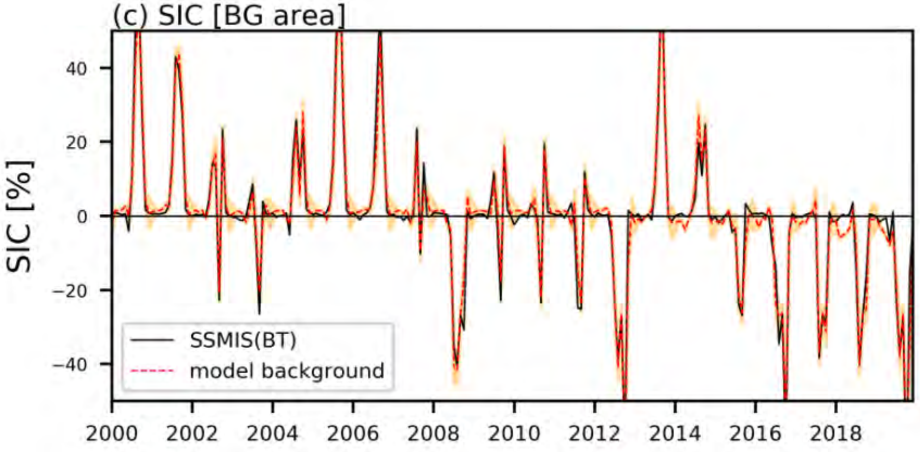
Time-series of SIC anomalies



OBS

Background state

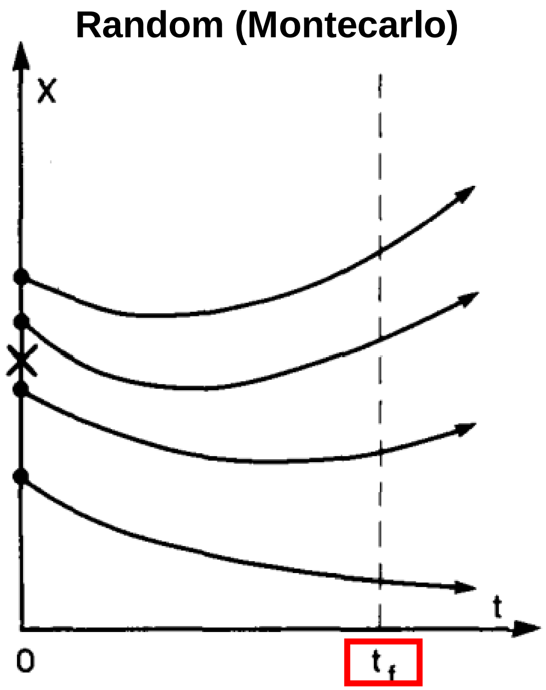
BKG error spread (STD)



- Background error perturbations reflect the inter-annual variability of the sea ice in observation and the numerical models.
- Instabilities in the model are captured by breeding

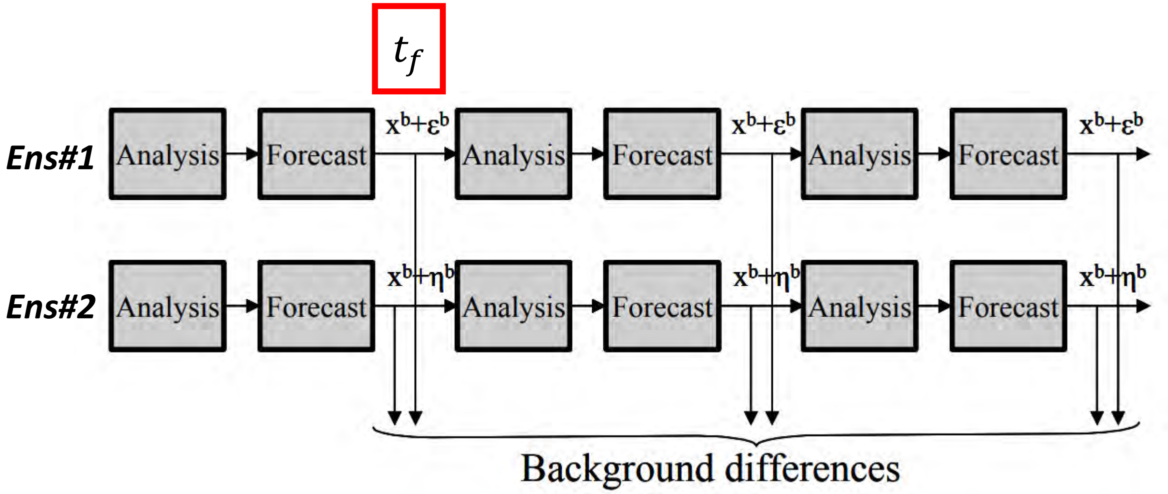
Forecast “errors of the day” (ensemble methods)

Schematic time evolution of ensembles (methods of ensemble forecast)



(Hoffman and Kalnay, 1983)

Schematic of analysis-ensemble method generating background differences



calculate “errors of the day”

(Fisher, 2003)

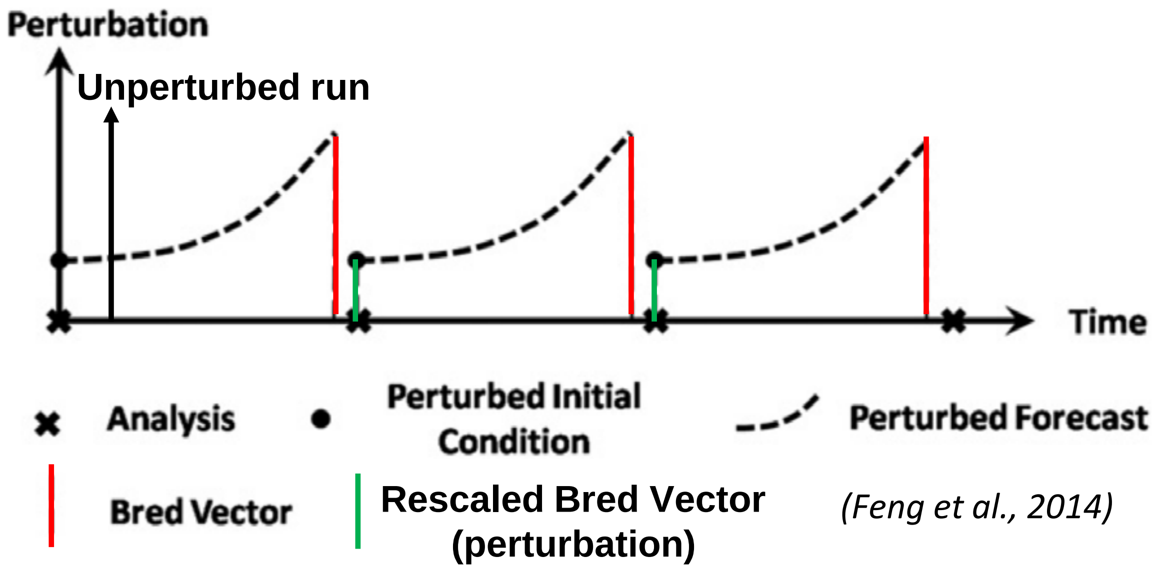
- In ensemble methods,

Calculation of forecast “errors of the day” (flow-dependent), but **expensive**

- **What is the cost-effective method? (available single or a pair of model runs)**

That is “Breeding method”

Schematic of breeding method



(Feng et al., 2014)

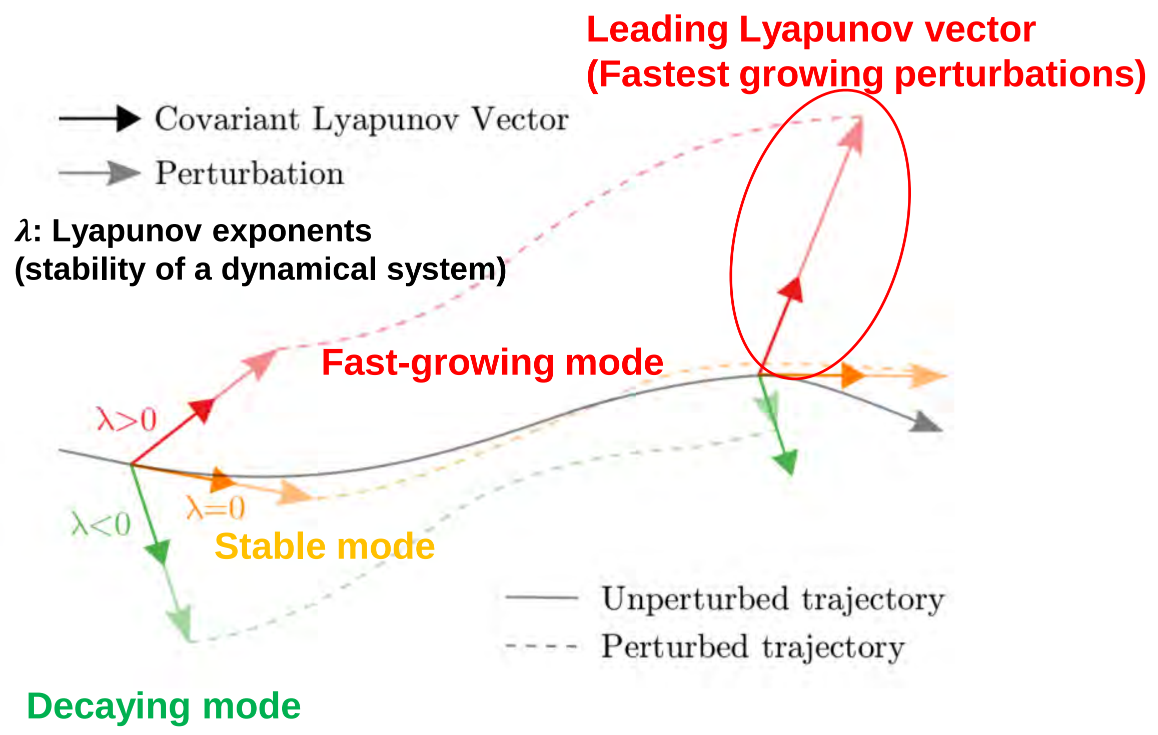
Breeding method *(Toth and Kalnay, 1997)*

→ *effectively represent the forecast errors by capturing instability of flow and the behavior of errors.*

computational cost *and* ***easy application to model***

→ *But, just a single perturbation have to account for “**Fast-growing errors**”*

Time-evolution of forecast error

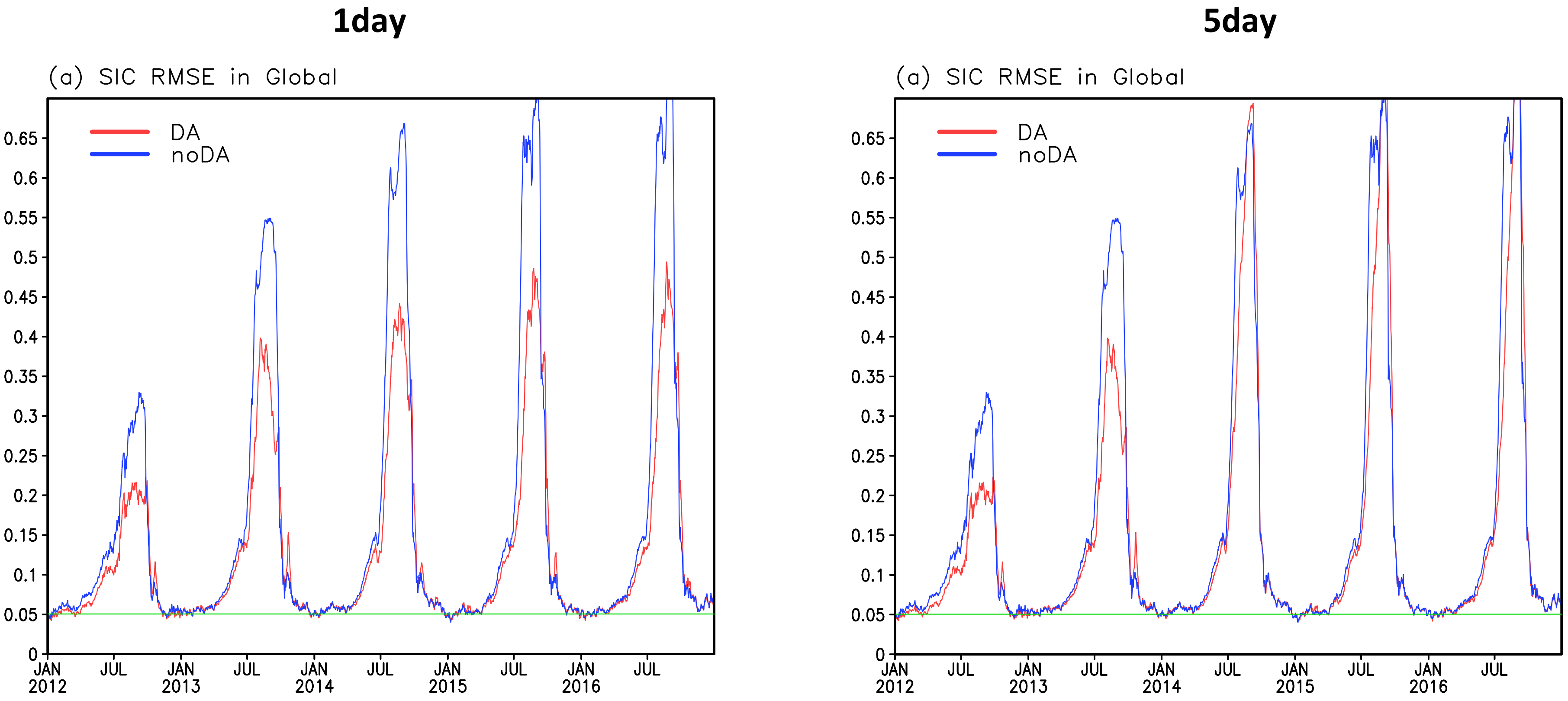


- Fast-growing errors dominate total forecast errors and effectively represent forecast uncertainty

→ Capture the fundamental characteristic of dynamical system

Sensitivity experiments of breeding time intervals

Time-series of SIC RMSE for NH [2012-2016]

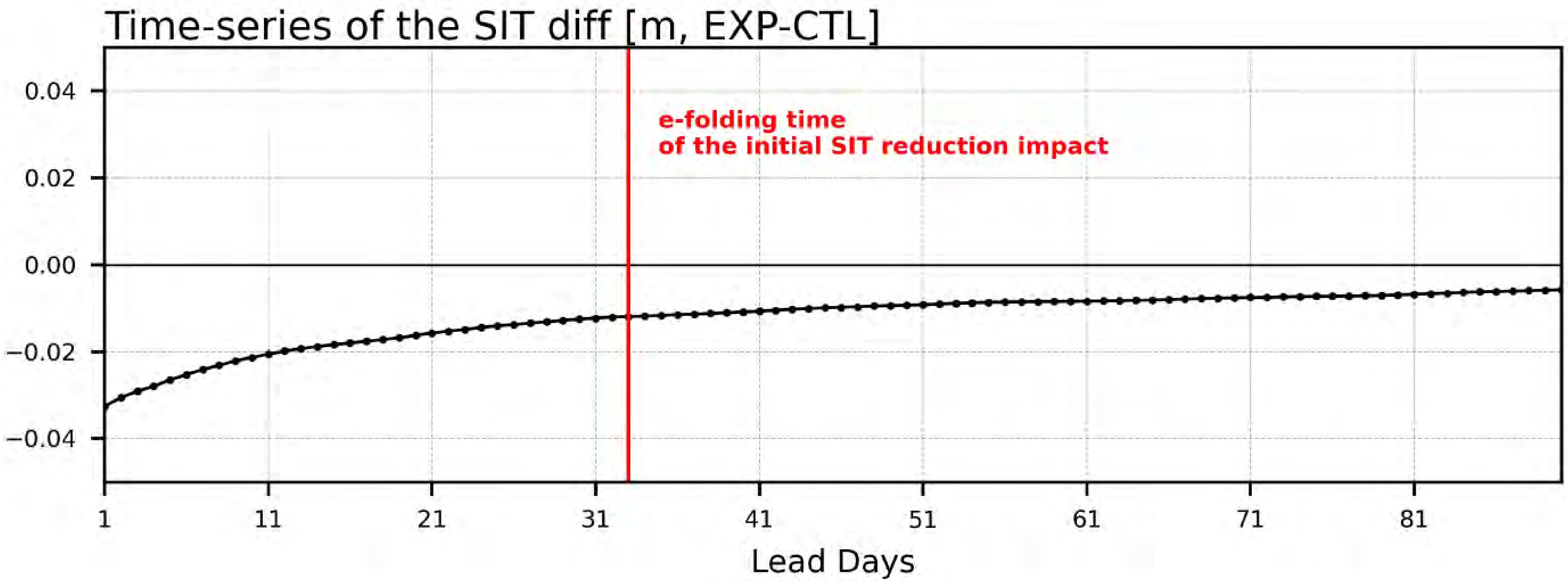


1day

5day

Why 1-month integration (idealized experiment)

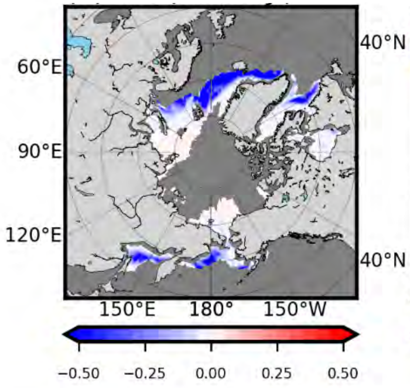
Impact of initial conditions with SIT reduction



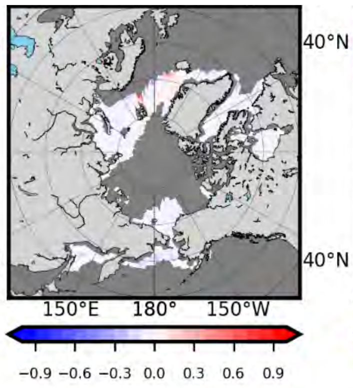
Results of idealized experiment: bottom melting, and T/S

Differences between EXP and noDA

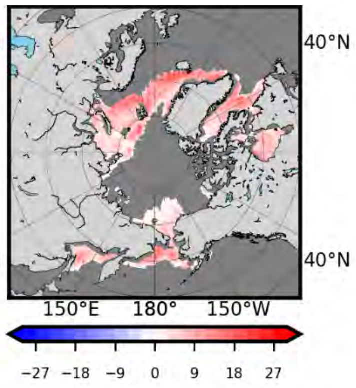
$meltb$



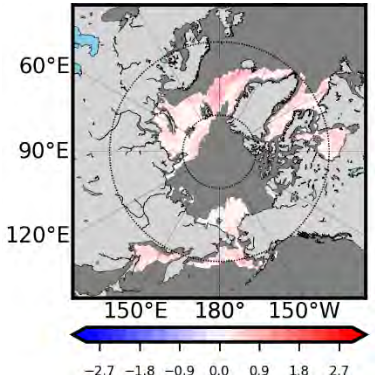
$(F_{cb} - F_{bot})\Delta t$



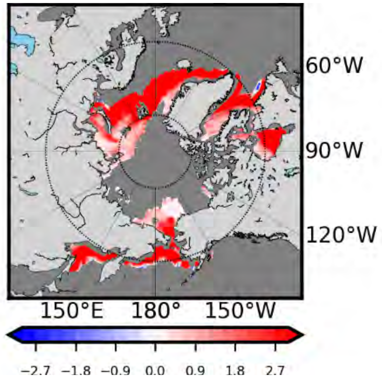
q



T (℃)

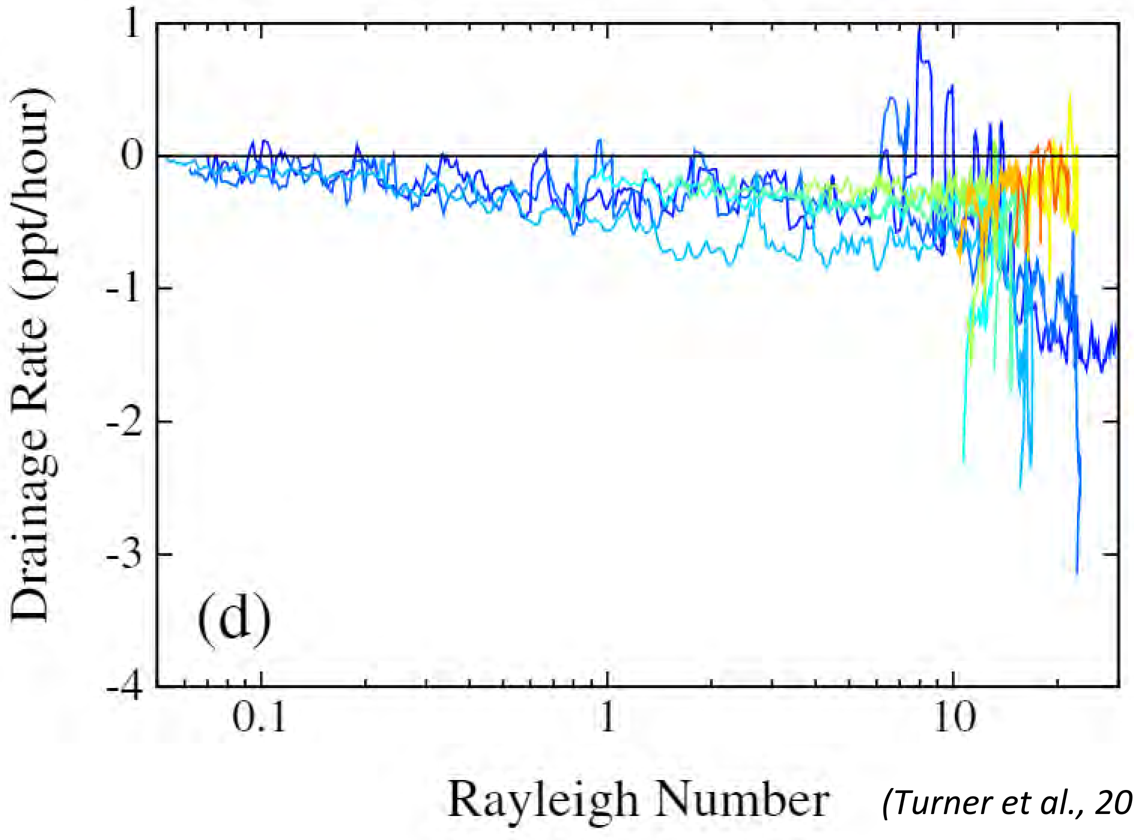


S (ppt, g/kg)



$$meltb = \frac{(F_{cb} - F_{bot})\Delta t}{q}$$

Relationship between drainage rate and Rayleigh number



(Turner et al., 2013)

Rayleigh number
(flow strength of brine)

$$Ra = \frac{g \Delta \rho \Pi h}{\kappa \eta}$$

$\boldsymbol{g}$: *gravitational constant*
$\boldsymbol{\Delta\rho}$: *brine density difference across the ice layer*
$\boldsymbol{\Pi}$: *permeability of the ice*
$\boldsymbol{h}$: *length scale (SIT)*
$\boldsymbol{\kappa}$: *thermal diffusivity of the brine*
$\boldsymbol{\eta}$: *dynamic viscosity of the brine*

h↓ → Ra↓ → drainage rate↓ → S↑

Qualitative comparison of contribution by T and S

Ice enthalpy equation

$$q_i(T,S) = -\rho_i\left[c_0(T_m - T) + L_0\left(1 - \frac{T_m}{T}\right) - c_w T_m\right]$$

$$T_{cont} = q_i(T_{EXP}, S_{CTL}) - q_i(T_{CTL}, S_{CTL})$$
$$S_{cont} = q_i(T_{CTL}, S_{EXP}) - q_i(T_{CTL}, S_{CTL})$$

$\rho_i = 917 \times 10^{-6}\ km/cm^3$ (the density of ice)
$T_m = \mu S$(temperature at which the ice is completely melted)
$c_0 = 2{,}106\ J/kg/$°C (specific heat of fresh ice at 0 °C)
$c_w = 4{,}218\ J/kg/$°C (specific heat of the ocean)
$L_0 = 3.34 \times 10^5\ J/kg$ (latent heat of fusion of fresh ice at 0 °C)
$\mu = 0.054$ °C$/ppt$ (empirical constant from the relationship between the melting temperature and salinity of brine, determined by (Assur, 1958))

Mean	EXP	CTL
T	-2.391	-2.688
S	9.55	7.52

$$T_{cont} = 5.17\quad J/cm^3$$
$$S_{cont} = 12.24\ J/cm^3$$

Mechanism of response of SIC to SIT reduction

Flow-chart of mechanism in SIT reduction experiment

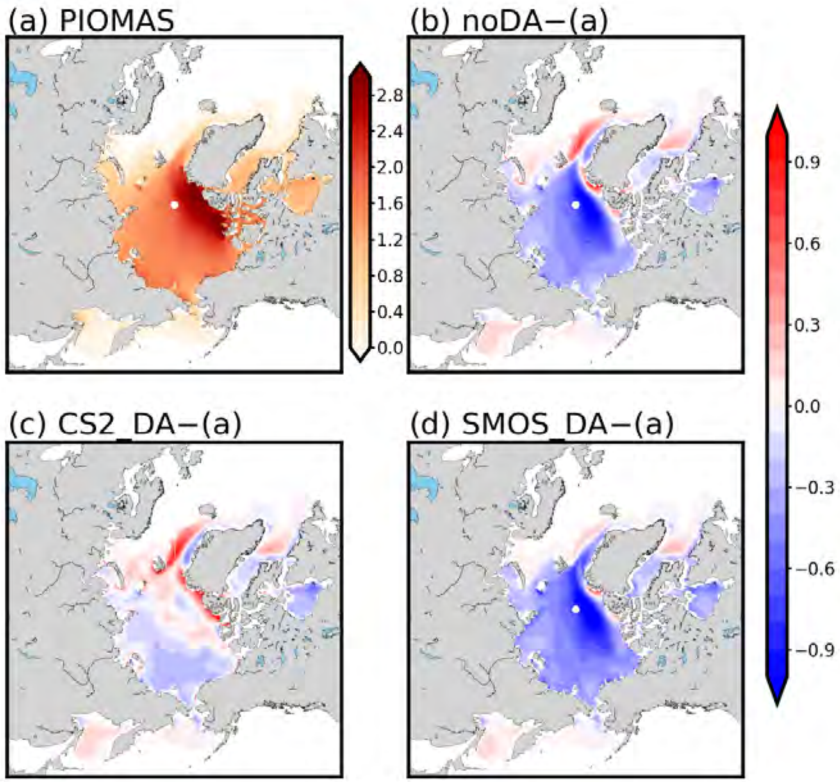
- Understanding of the physical mechanism suggests potential factors related sea ice prediction.

Experiment design to explore seasonal impact of SIT DA

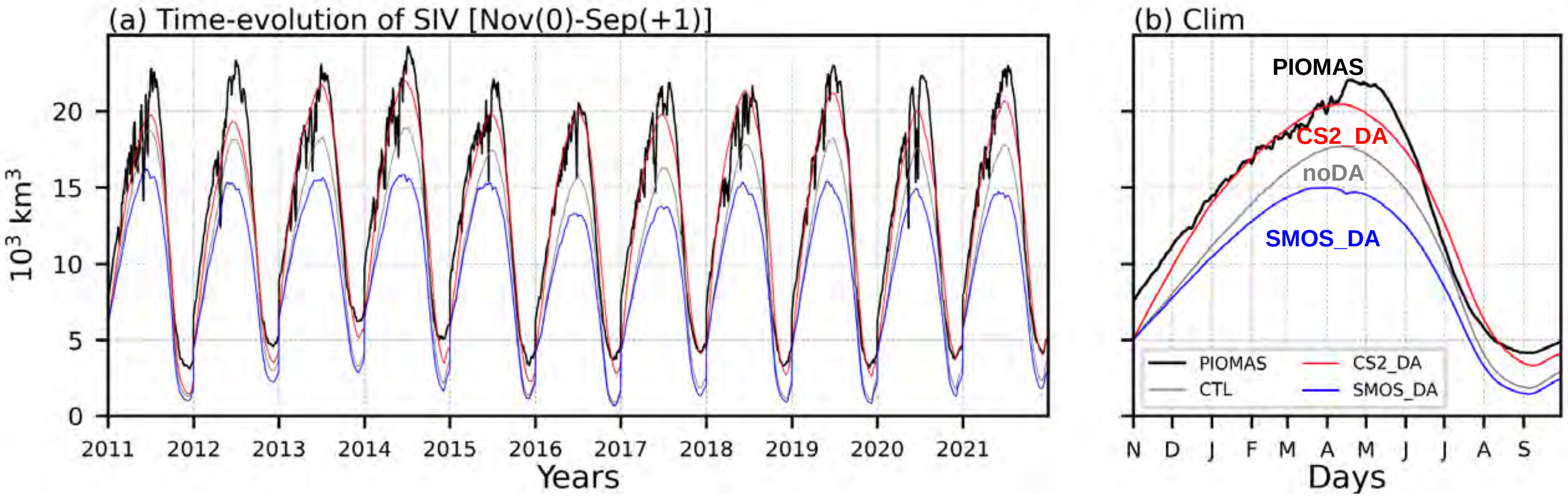
<table>
<tr><th></th><th>Information</th><th colspan="2">Reference</th></tr>
<tr><td>Model</td><td>CICE 5 (Community Ice CodE, v5.1.2, LANL)</td><td colspan="2"><i>Hunke et al., (2015)</i></td></tr>
<tr><td>SIT Observation</td><td>ESA CryoSat-2 daily SIT data for thick ice (> 1.0m)
ESA SMOS daily SIT data for thin ice (< 1.0m)</td><td colspan="2"><i>Kurtz and Harbeck, (2017)</i>
<i>Tian-Kunze et al., (2014)</i></td></tr>
<tr><td>Data Assimilation scheme</td><td>Localized EnOI</td><td colspan="2"><i>Evensen et al., (2003)</i>
<i>Sakov and Bertino, (2010)</i></td></tr>
<tr><td rowspan="2">Resolution</td><td>320 × 384 (1°, ~100 km)
gx1v6</td><td colspan="2"></td></tr>
<tr><td>Daily DA cycle</td><td colspan="2"></td></tr>
<tr><td rowspan="3">DA experiment period</td><td rowspan="3">2011-2022 (12-cases)
Integration: Nov – Sep (11-month)
(Nov-Apr DA only)</td><td rowspan="3">EXP list</td><td><i>noDA</i></td></tr>
<tr><td><i>CS2_DA</i>
<i>(CryoSat-2, > 1.0m, thick)</i></td></tr>
<tr><td><i>SMOS_DA</i>
<i>(SMOS, < 1.0m, thin)</i></td></tr>
</table>

Impact of winter SIT DA on winter and summer SIV bias

Mean bias of SIT
[DJFM, 11-22]



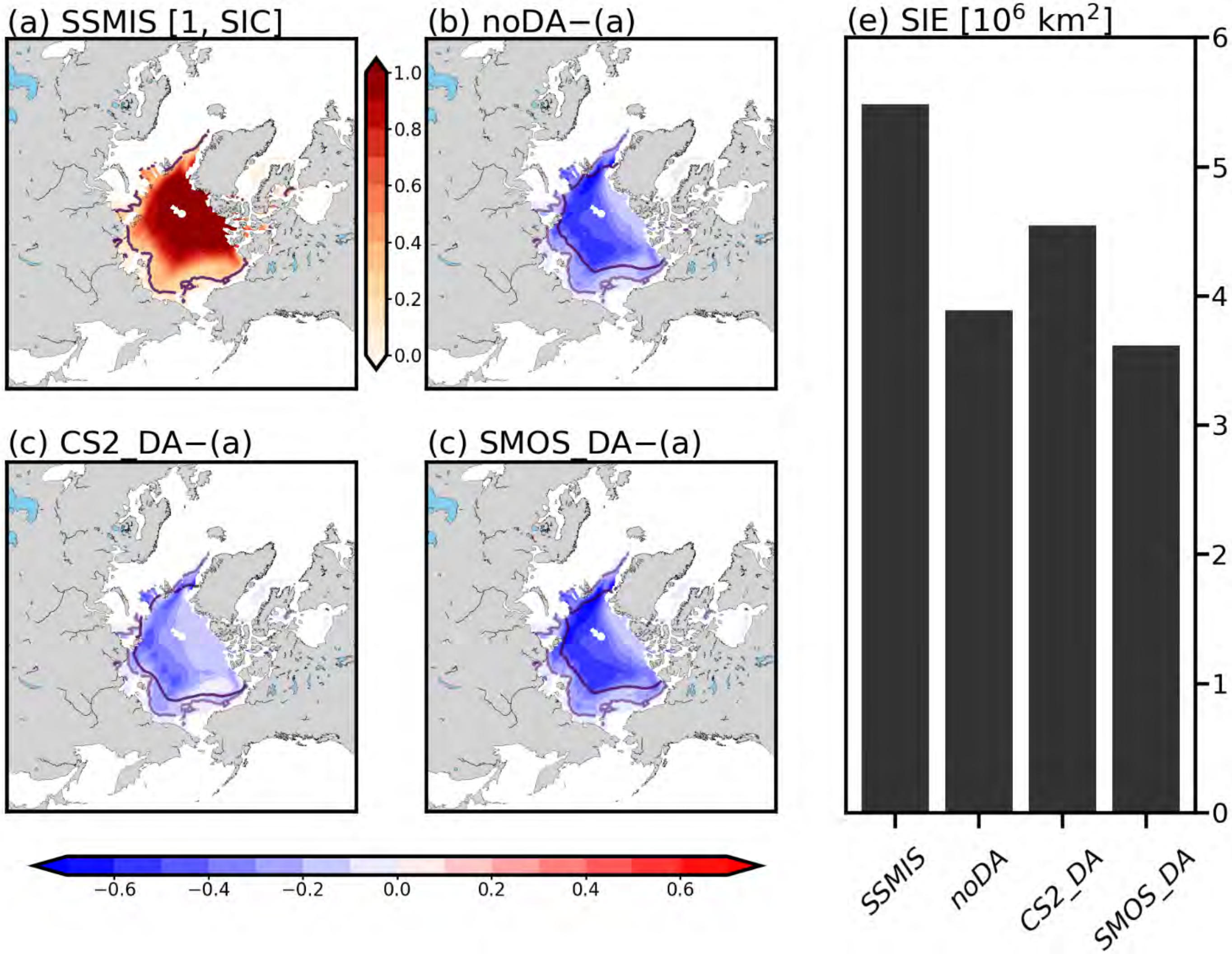
Time-evolution of Arctic sea ice volume (SIV)



- DA of SIT from CS2 (SMOS) reduces negative (positive) bias in inner (marginal) ice zones.
- Strong negative biases of SIV during winter and summer seasons are effectively corrected by CS2_DA.

Improved summer SIC bias through winter SIT DA

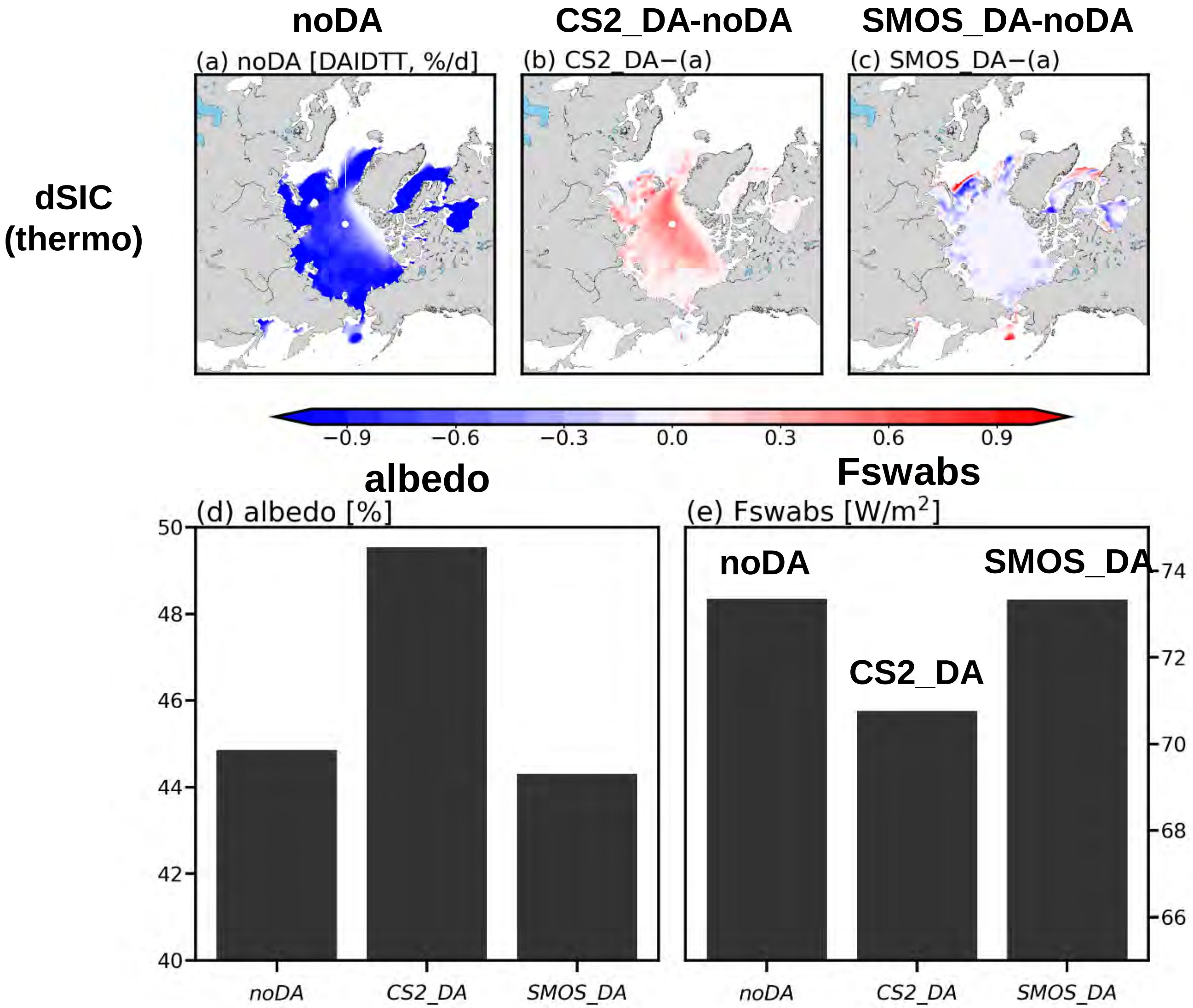
Mean bias of SIC [AS, 11-22]



- The strong negative bias of SIC and SIE in noDA is significantly improved by CS2 DA.

Albedo-related mechanism in SIC improvement by SIT DA

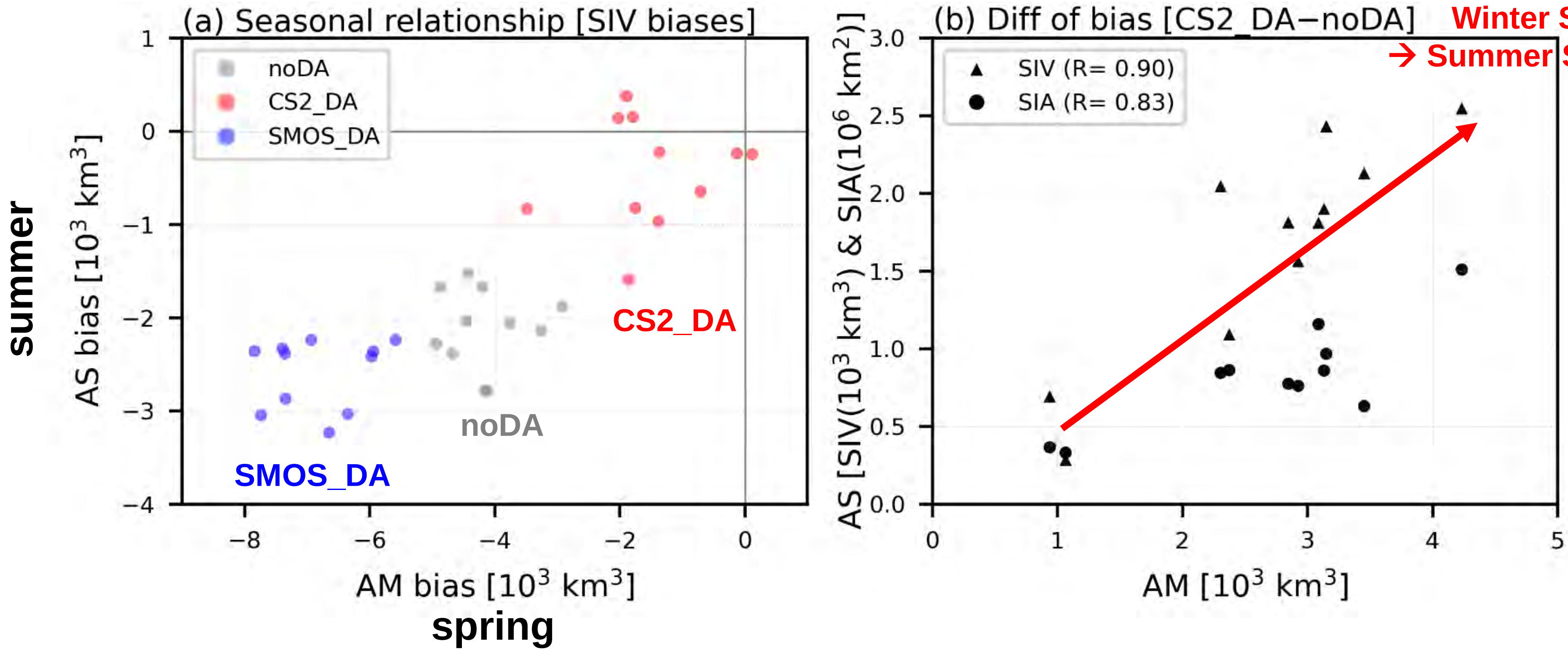
JJA-averaged dSIC, albedo, and Fswabs [2011-2022]



- The melting of sea ice is attenuated in CS2_DA compared to noDA during melting season.
- The albedo (shortwave absorption) is increased (decreased) by thickened ice in CS2_DA.

Impact of winter SIT DA on winter and summer SIV bias

Relationship between winter SIV bias and summer SIV/SIE bias



Winter SIV bias improve
→ Summer SIV/SIA bias improve

- The clear positive relationship between winter SIV and summer SIV/SIE biases
- Realistic winter/spring SIT states → accurate summer simulation