Strategy and issues to be addressed in the sea-ice assimilation

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(JMA/MRI)

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1. Introduction (Background)

Current practices of operational ice centers rely heavily on human interpretation and analysis of data (e.g., JMA). Ice analysts require extensive experience and specialized knowledge of ice physics, climatology and image/data interpretation. The analyst mentally assimilates large volumes of satellite and other data including previous ice charts, weather and ocean information ice observations and numerical model guidance. Satellite data interpretation is particularly labour intensive and subjective due to the volume and variety of data and because required physical quantities must be indirectly inferred.

We need to investigate the feasibility of transitioning from an "observation-based" to a "model-based" approach for the production of sea ice analyses in JMA.

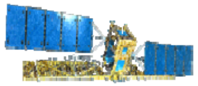
In this talk, let me show three examples about sea-ice assimilation/influence in the oceanic/coupled systems. Then I would like to show/discuss issues (perspective) related to sea-ice.

National/Naval Ice Center (NIC, USA)

Operations and Product Generation

Human, Derived, Automated, and Reconfigured

Inputs

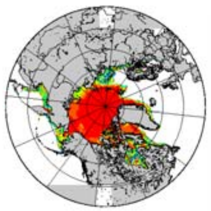


Satellites

Aircraft

Surface Obs

Buoys



Models

Expert Ice Analyses, Forecasting, and Quality Control

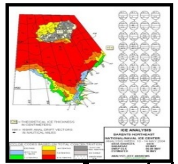
Data Fusion

Derived Data Automation

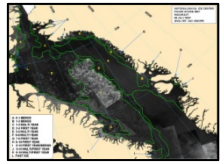
Direct Data Dissemination

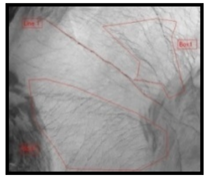
Products

Hemispheric and Regional Ice Charts



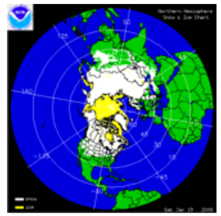
Annotated Images

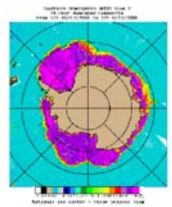




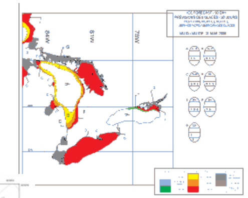
Fractures, Leads and Polynyas (FLAP)

IMS snow and ice maps

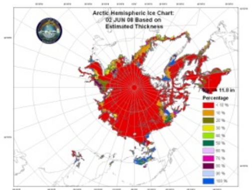




Microwave Sea Ice Concentration products



Ice Forecast Outlooks



Ice Thickness Estimations

Contents

2. Ocean data assimilation (Ocean only)
in the Okhotsk Sea
by N. Usui et al. (2010)

MOVE/MRI.COM_WNP

resional eddy resolving (0.1deg.),
sea-ice model (5 category)
ocean state: multivariate 3DVAR (MOVE)
sea-ice concentration:
analysis (min. var. est. (KF type))+nudging
category 1 (thinner ice) is corrected
=> volume is not so much changed after assimilation
when vol. changed, water flux is also changed

Exp.

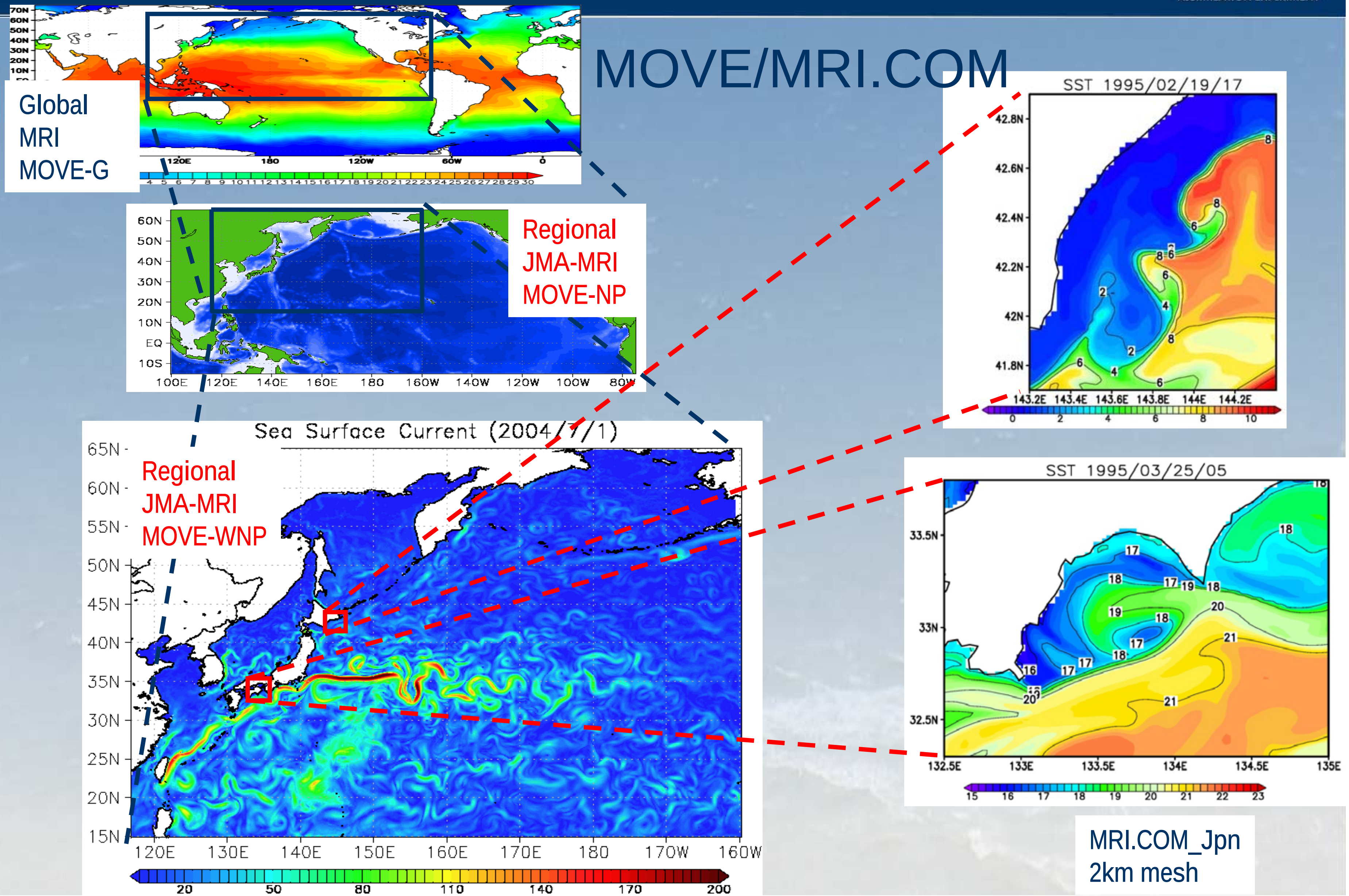
1. Univariate (SI only without water flux optimization)
2. Multivariate (SI only with water flux opt.)
3. Multivariate (SI + ocean state (T&S) + flux opt.)

OGCM: MRI.COM

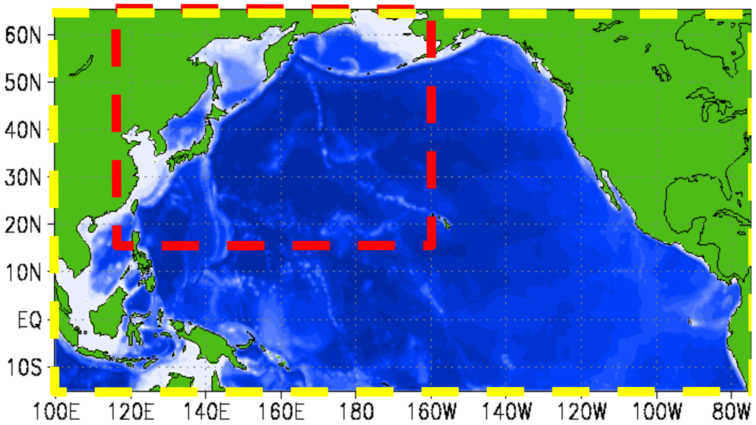
- vertical hybrid of z- and σ- coordinate with free surface
- turbulent mixed layer model Noh and Kim (1999) :
- horizontal viscosity: biharmonic Smagorinsky
（Griffies and Hallberg 2000)：
- heat flux bulk formula（Kondo 1975）
- tidal boundary mixing（St. Laurent et al. 2002）
- local Laplacian viscosity on steep bottom topography (Tsujino et al., 2006)
- sea ice model
  - 5 category sea ice & snow（Mellor and Kantha 1989）
  - Elast-visco-plastic rheology (EVP：continum)（Hunke and Dukowicz 2002）

Ishikawa et al., 2005, Tsujino et al, 2006

Geographical relations of global, regional, and coastal/shelf sea Model-Assimilation systems



Three OGCMs (Double Nesting)



Global Model-1 :
(1° ×1° :1/3°
tropical region, 54 Layer)

Nested-1 Model-2 :
15S-65N, 100E-75W
(0.5° ×0.5° , 54 Layer)

Nested-2 Model-3 :
15N-65N, 115E-160W
(0.1° ×0.1° , 54 Layer)

Usui et al. (2005)

Table 1. Model configurations

	model G	model NP	model WNP
horizontal resolution			
zonal	1°	0.5°	0.1°
meridional	0.3° (6°S-6°N) 1° (poleward of 15°)	0.5°	0.1°
vertical resolution			
total number of layers	50 layers	54 layers	
number above 200m	24 layers	17 layers	
surface layer thickness	2m	1m	
bottom layer thickness	500m	250m	
bottom depth	5000m	5625m	
bottom topography	ETOPO5	Smith-Sandwell	
diffusive coefficient (m^2s^{-1})			
isopycnal	1×10^3	1×10^2	not applied
diapycnal	1×10^{-5}	1×10^{-4}	not applied
thickness (GM)	1×10^3	1×10^2	not applied
horizontal (biharmonic)	not applied	not applied	1×10^{12}
vertical (background)	Tsujino00	Tsujino00	Tsujino00
viscosity coefficient (m^2s^{-1})			
horizontal (SMA63)	harmonic	biharmonic	
vertical	1×10^{-4}	1×10^{-4}	
vertical mixing scheme	MY2.5	Noh-Kim	
forcing data	NCEP R-1	NCEP R-2	
heat flux bulk formula	Kara00	Kondo75	
water flux correction			
time-independet term	applied	not applied	
nudging term	365 days	1 day	
sea ice model	not applied	EVP sea ice model	

3DVAR in MOVE/MRI.COM

Multi-variate system: horizontal inhomogeneous Gaussian, vertical T-S EOF .
Optimal amplitudes of T-S EOF (**y**) are calculated by minimizing the cost function (*J*) with a nonlinear descent scheme "POpULar". Model insertion: IAU

Analysis Increment is represented by the linear combination of the EOF modes.

$$\mathbf{x}(\mathbf{y}) = \mathbf{x}_f + \mathbf{S}\sum_l w_l \mathbf{U}_l \Lambda_l \mathbf{y}_l$$

→ Amplitudes of EOFs

Background Constraint **Constraint for T, S observation**

$$J = \boxed{\frac{1}{2}\sum_m \sum_l \mathbf{y}_{m,l}{}^T \mathbf{B}_l^{-1} \mathbf{y}_{m,l}} + \boxed{\frac{1}{2}\left[\mathbf{H}\mathbf{x}(\mathbf{y}) - \mathbf{x}^0\right]^T \mathbf{R}^{-1}\left[\mathbf{H}\mathbf{x}(\mathbf{y}) - \mathbf{x}^0\right]}$$

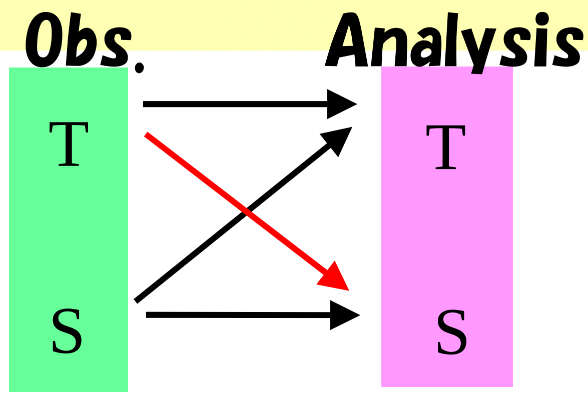
$$+ \boxed{\frac{1}{2}\left[\mathbf{h}(\mathbf{x}(\mathbf{y})) - \mathbf{h}^0\right]^T \mathbf{R}_h^{-1}\left[\mathbf{h}(\mathbf{x}(\mathbf{y})) - \mathbf{h}^0\right]} + \boxed{\alpha(\mathbf{y})}$$

Constraint for quality control

Constraint for SSH observation

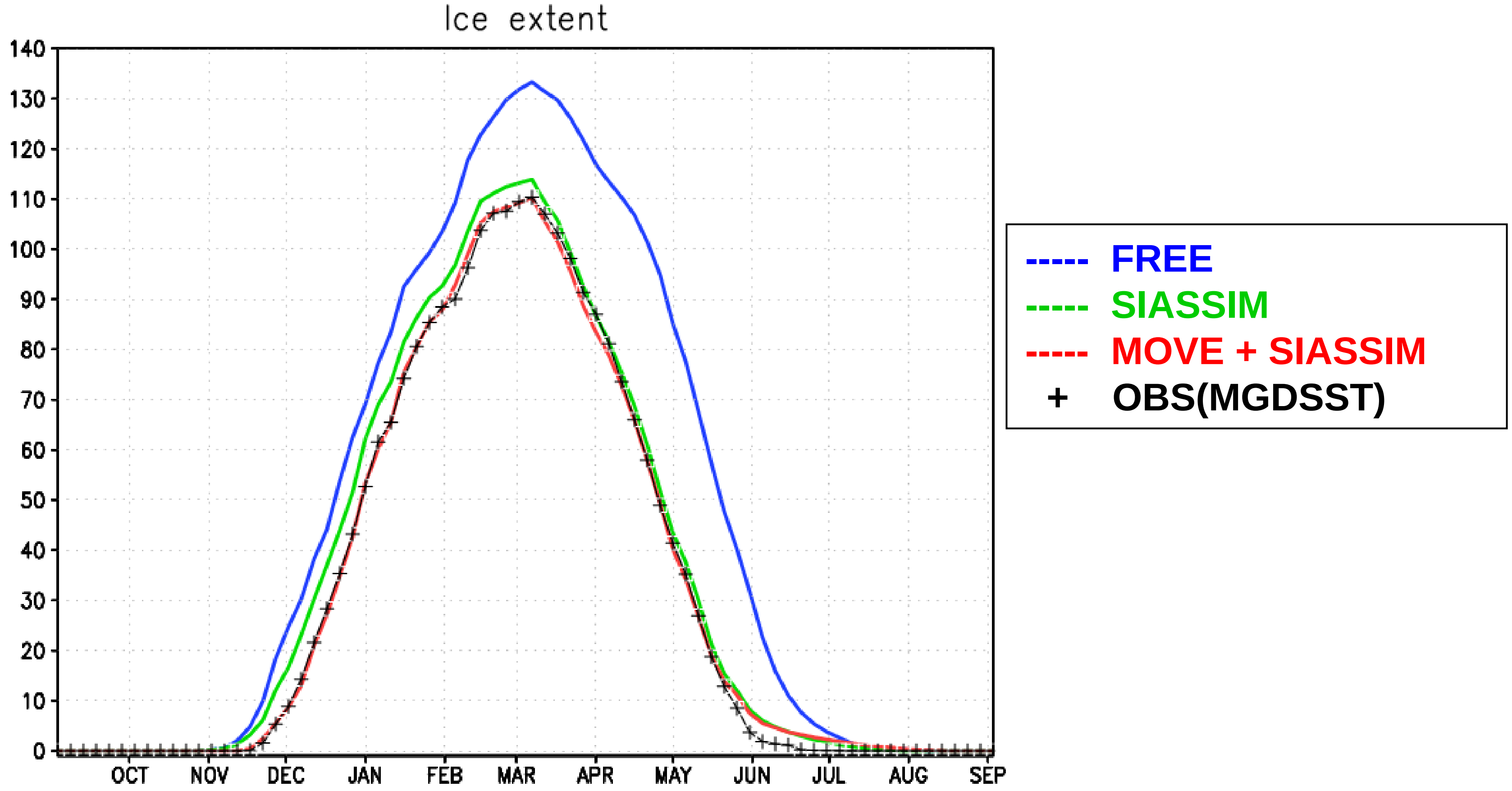
Seek the amplitudes of EOF modes **y** minimizing the cost function *J*.

→Analysis increment of T and S will be correlated.



Fujii and Kamachi, 2003a,b,c

Seasonal variation of sea-ice area

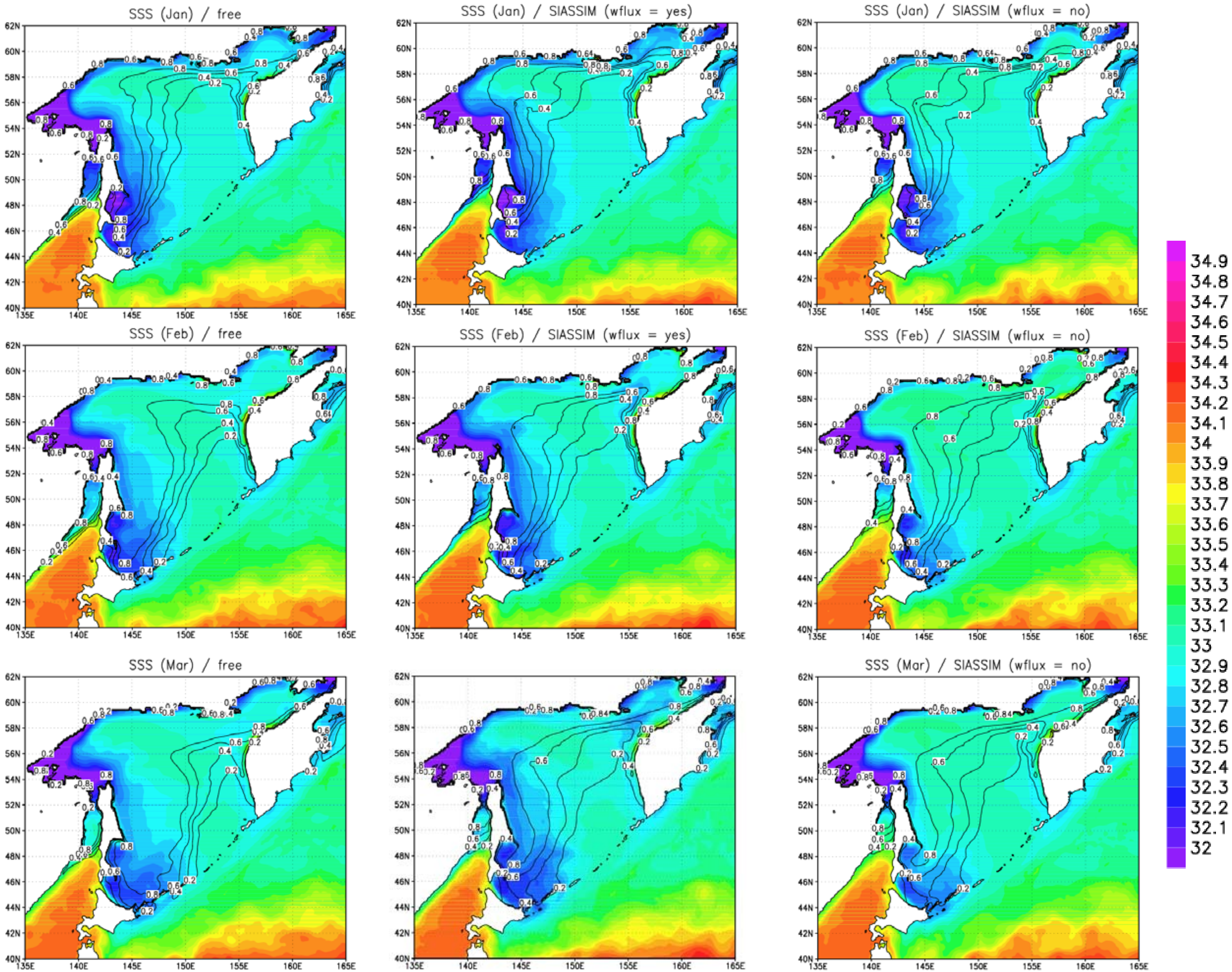


Free | **SIASSIM (with water flux)** | **SIASSIM (without water flux)**

Jan.

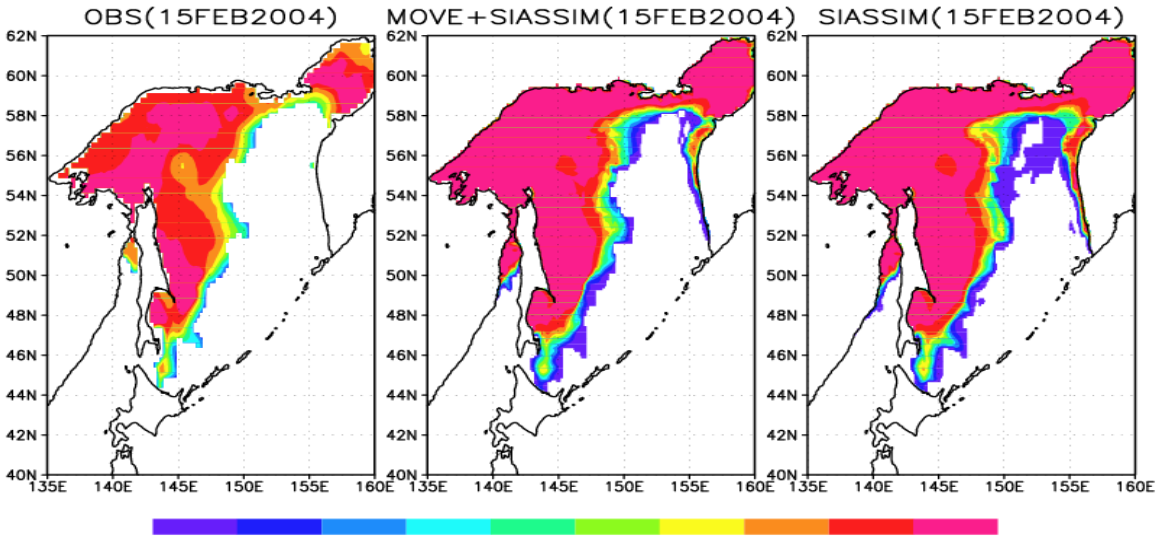
Feb.

March



Comparison

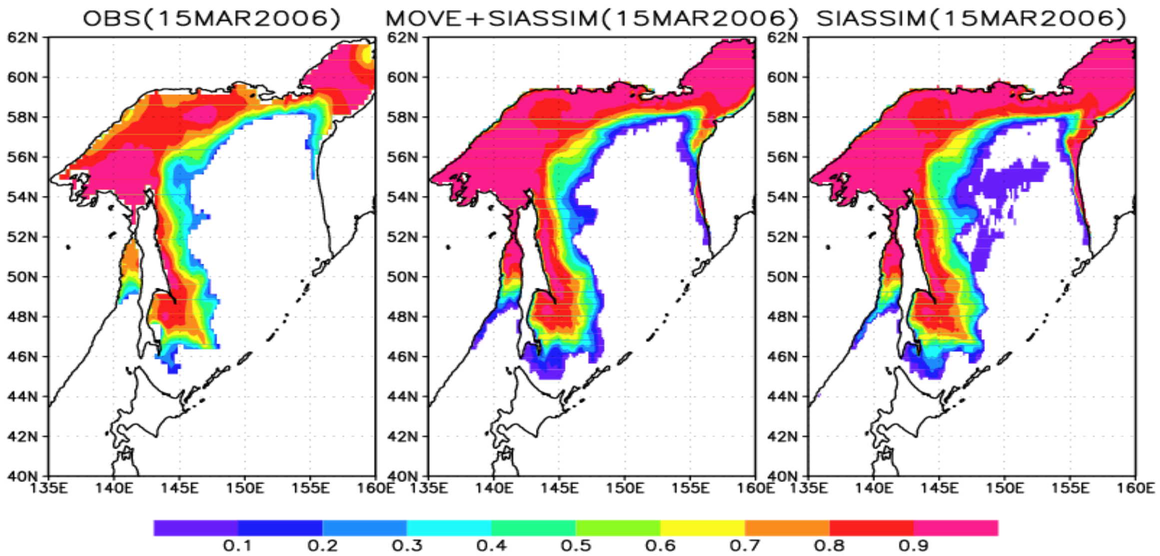
2004/2/15



Ocean state (T&S) +sea-ice

sea-ice only

2006/3/15



Results and issues:

1. category 1 (thinner ice) is corrected
   => volume is not so much changed after assimilation
   Is this conservation of volume before and after assimilation best? (cf. next experiments)

2. We need ice thickness data

3. Multivariate assimilation is better
   Ocean state + sea-ice + water flux opt.

(We expand the assimilation method in this Okhotsk sea case to the Arctic and Antarctic regions in MOVE/MRI.COM_G in JMA/MRI)

Contents

3. Coupled data assimilation in the Arctic Sea

by T. Toyoda et al. (2010; Kakushin Project)

MIROC (CCSR (AORI) model)

global model,

sea-ice model (zero layer no category)

ocean state: multivariate IAU

sea-ice concentration:

obs. (Ishii et al., 2003)+IAU

=> volume is changed after assimilation

Exp.

1. Univariate (SI only)

2. Multivariate (SI + ocean state (T&S) correction)

Examine feedback processes for better understanding and prediction of climate system

Introduction

- Sea ice reduction is observed from satellite, ship, submarine, station on
  extent/concentration, age/thickness
- Possible mechanism
  sea level pressure pattern (AO, NAO, dipole anomaly)
  ice-albedo feedback, ice-cloud feedback, Pacific Summer Water, and global warming
- Analysis in the atmosphere-ocean-sea ice coupled system
  use of numerical model, data assimilation
- Experiment using atmosphere-ocean-sea ice coupled model with assimilation of sea ice data, as a first step toward the realistic simulation of the Arctic Ocean climate sea ice feedback processes

Model

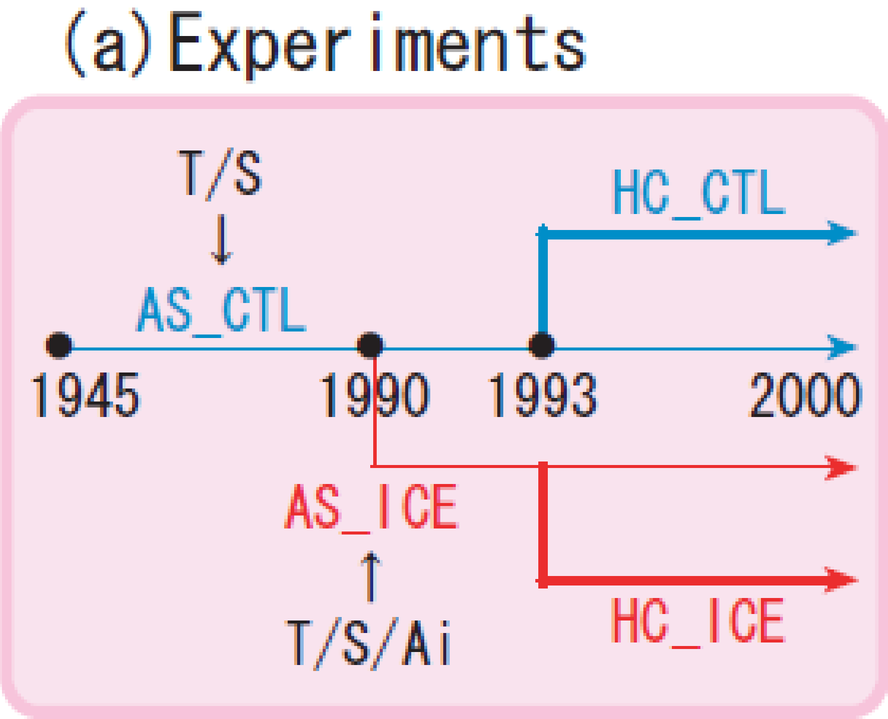
- Coupled atmosphere-ocean GCM: MIROC 3.2
  Resolution (Atmos) T42, L20 (Ocn) 1.4deg*0.56-1.4deg, 44 levels
  sea ice model
    zero layer thermodynamic of Semtner (1976)
    dynamic of Mellor and Kantha (1989)
    internal ice stress of elastic-plastic-viscous rheology (Hunke and Dukowicz, 1997)
    freezing point water when sea ice exists
    sea ice salinity of 5 psu

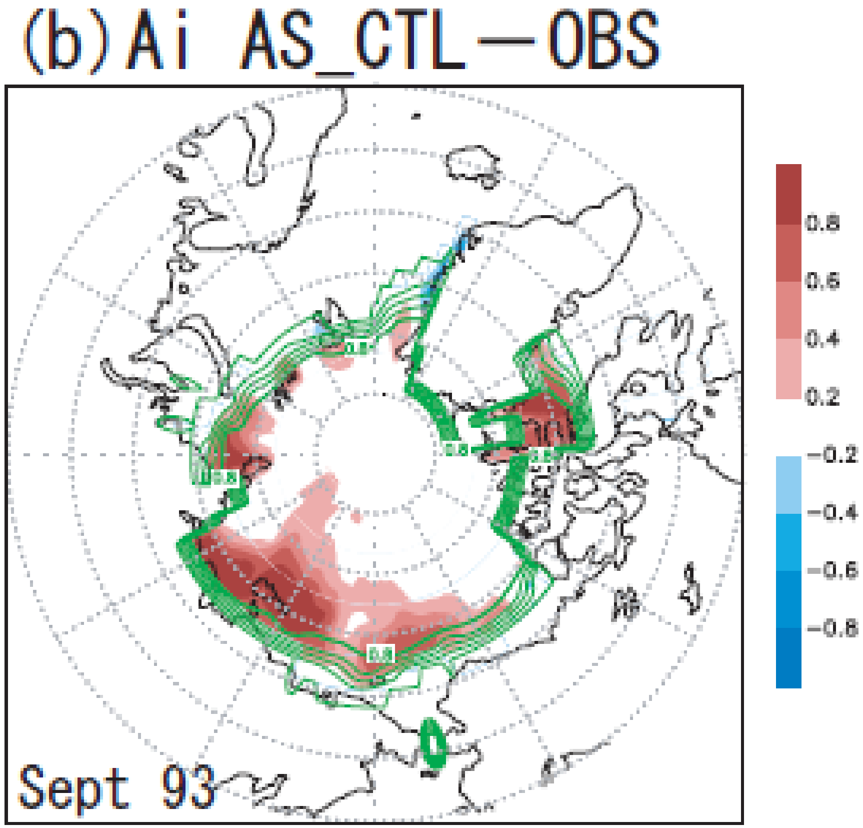
Experiments

- A data assimilation run: “AS_CTL”
  - 1945-1999
  - initial condition in 1945 from the IPCC AR4 run
  - natural and anthropogenic forcing
  - data assimilation
    - observational oceanic subsurface temperature and salinity fields
    - up to 700 m depth (Ishii et al., 2003)
    - IAU method with 1 month window
    - data in the sea ice region are not assimilated
- Another data assimilation run: “AS_ICE”
  - 1990-1999
  - start from the state in 1990 of AS_CTL
  - data assimilation
    - sea ice concentration data (Ishii et al., 2003) in addition to T/S
    - thickness is unchanged, i.e. volume is changed
    - mass and salt are conserved
    - sea ice velocity data are not used (c.f., Duliere and Fichefet, 2007)
- Hindcast experiments: ”HC_CTL” and “HC_ICE”
  - 1993-1999
  - initial conditions in 1993 from AS_CTL and AS_ICE respectively

Fig.1 (a) Schematic representation of numerical experiments

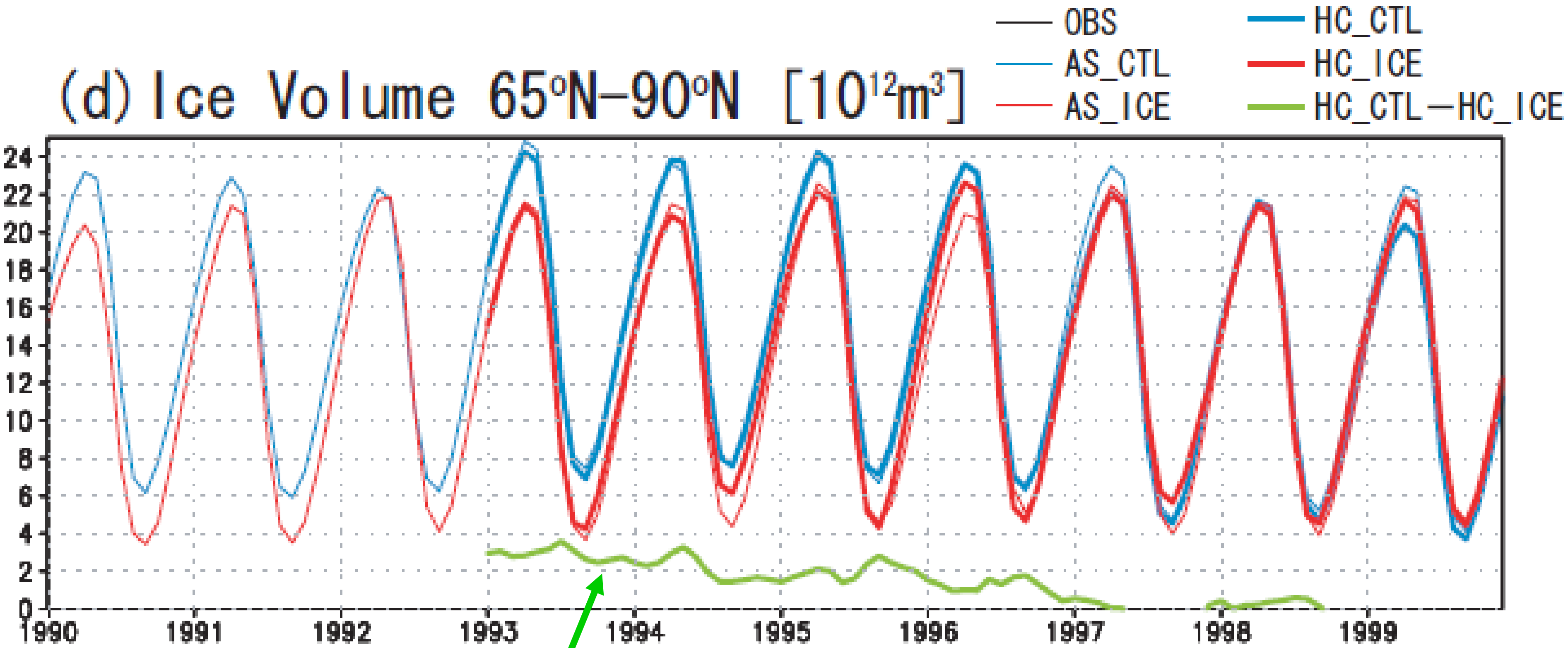
Fig.1 (b) Sea-ice concentration distribution in the observational data (Ishii et al., 2004; contour). The difference in sea-ice distributions in the AS_CTL run and the observational data for September 1993, are depicted by the shaded region.





- Model bias in AS_CTL (overestimate)
- Does the assimilation of the sea ice data improve it?
- How is in hindcast?

Results Fig.2(b) Time series of the sea-ice volume (in 10**12 m**3) in the Arctic Ocean (65-90N). Color denotes each experiments.

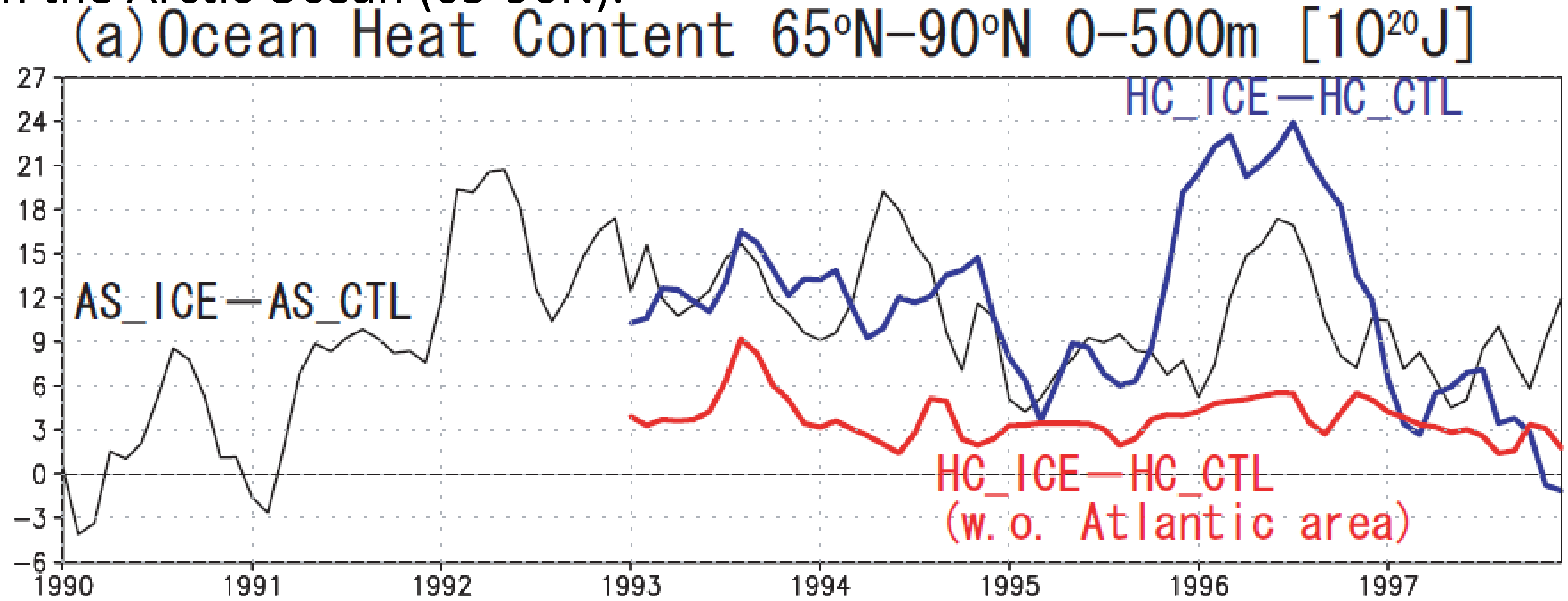


- Assimilation impact can be seen throughout the year for sea-ice volume

  ~ $3*10^{12}$ m^3

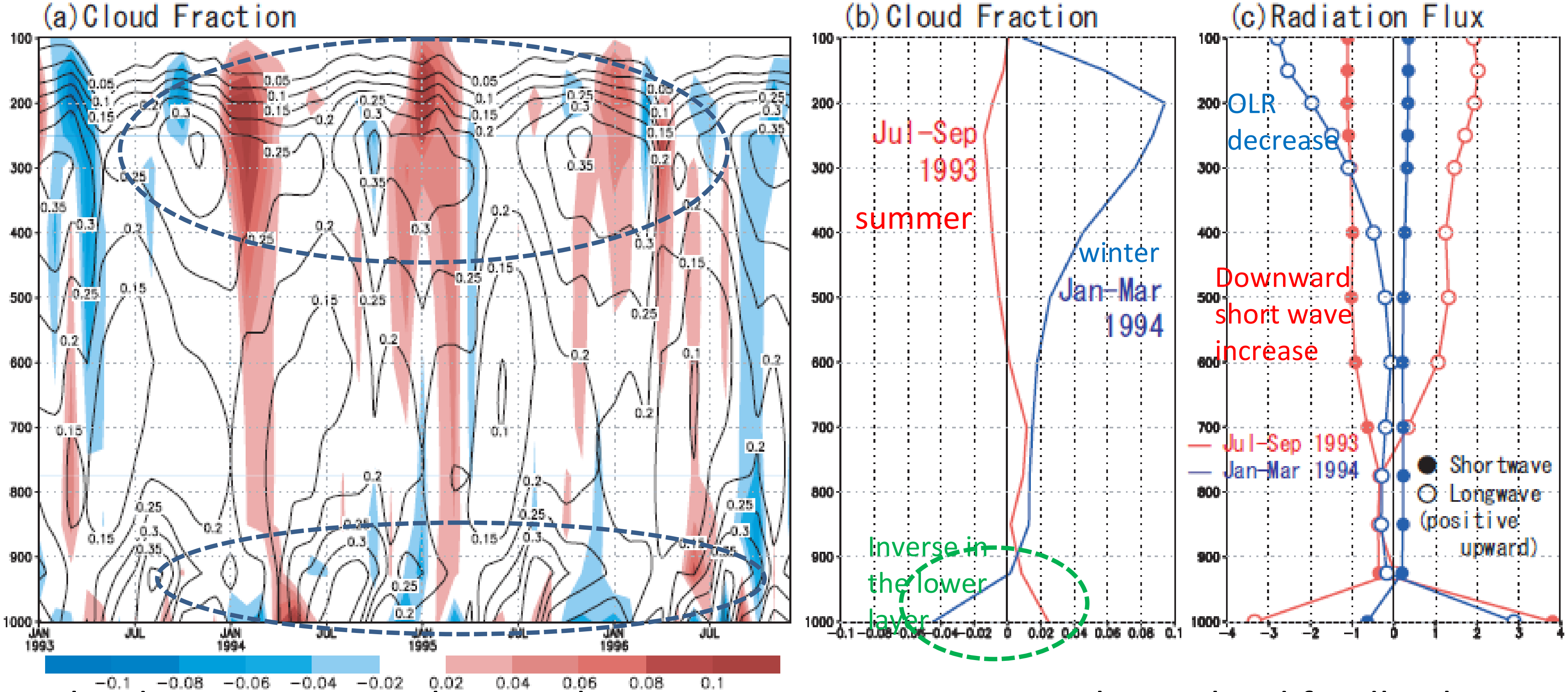
  heat amount of ~ 10^{21} J regarding the heat from sea ice fusion
- In hindcast, impact remains for 3-4 years (predominant role of surface fluxes in the summer seasons)
- Summertime increase in the hindcast anomaly in addition to the linear decrease

Results Fig.2(c) Time series of ocean heat storage anomaly (in 10**20 J) in the Arctic Ocean (65-90N).



- Ocean heat content anomaly ~ 10^{21} J, comparable to the heat amount from the sea ice anomaly
- Time length in which the impact of the initialization remains (3-4 years) is similar to that of the sea ice volume
- Both the sea ice volume and the heat content in the ocean are important as the initialization agencies
- Rapid changes, such as increase of hindcast anomaly in Autumn 1995, are generated in the open-water region close to the Atlantic Ocean by the atmospheric disturbances (out of scope)

Ikeda et al. (2003) indicated that, in autumn, winter and spring, the decrease of sea ice generates the increase of cloud amount, which causes the decrease of outgoing longwave radiation, while, in summer, the decrease of sea ice correlates with the decrease of cloud amount, which causes the increase of incoming shortwave radiation on the surface. These result in further decrease of sea ice (ice-cloud feedback).



•Cloud amount anomaly near the tropopause consistent with ice-cloud feedback

•In the near surface layer, cloud amount increases in summer and decreases in winter -> need improvement of cloud representation

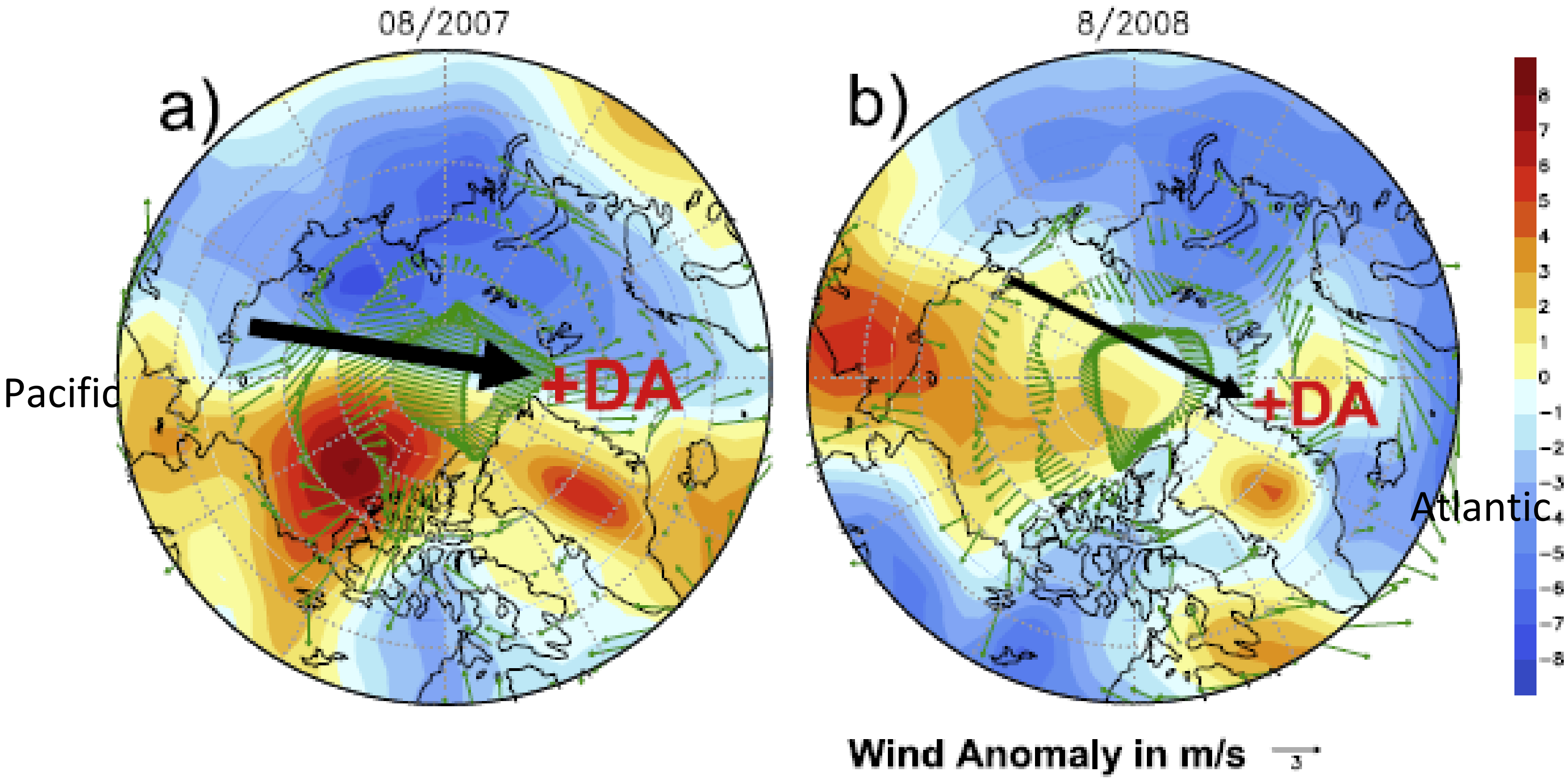
•Feedback does not work effectively

Sea level pressure anomaly

Recent study: not AO type, but dipole type（2nd EOF）of SLPA-> thinner ice (e.g., Wang et al., 2009)。

Dipole type SLPA -> transport ice from Pacific to Atlantic-> decrease arctic ice

(Not clear of the cause of SLPA)



Results and issues:

1. Sea-ice concentration assimilation in a coupled system
   => Examine feedback processes related to sea-ice

2. Ice volume is changed after assimilation.
   Is this better than the conservation of volume before and after assimilation? (cf. Usui's experiments in the Section2)

3. Multivariate assimilation is better
   Ocean state + sea-ice optimization
   Both the sea ice volume and the heat content in the ocean are important as the initialization agencies
   The effects remains in a few (3-4) years

4. Improvement of CGCM (e.g., cloud representation)

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2. Sea-ice assimilation in the Okhotsk Sea
   (OGCM+ocean data assimilation)
3. Sea-ice assimilation in the Arctic Sea
   (CGCM+ocean data assimilation)
4. Sea-ice thickness impact to the atmosphere
   (AGCM)
5. Issues

4. Influence of sea-ice thickness on the atmosphere in the winter Arctic region

by Adachi and Yukimoto (2006)

MRI-AGCM (TL95L40) (Mizuta et al., 2005)

sea-ice thickness impact

1-layer model

Exp.

set constant and uniform layer

-> 20 cases of different thickness

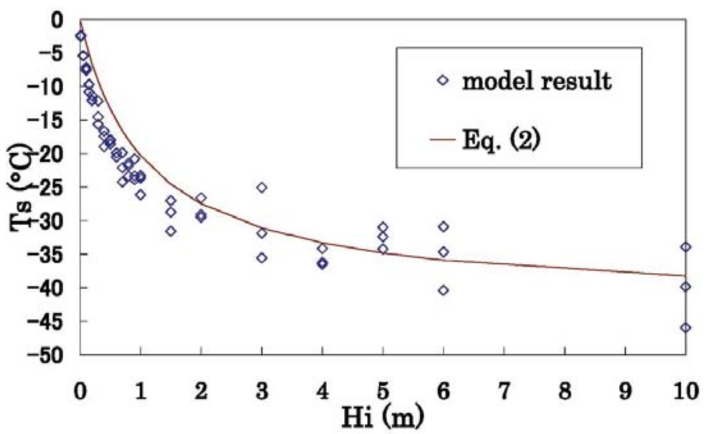

Fig. 1. Scatter plot of sea ice thickness (H_i) versus sea ice surface temperature (T_s) averaged over the region north of 80 °N. Each dot indicates the January mean of individual simulations. There are 60 (= 20 × 3) dots in this figure, since 3 years of data of each of the 20 simulations are used. The curve represents Eq. (2).

Hi->Surface Temperature

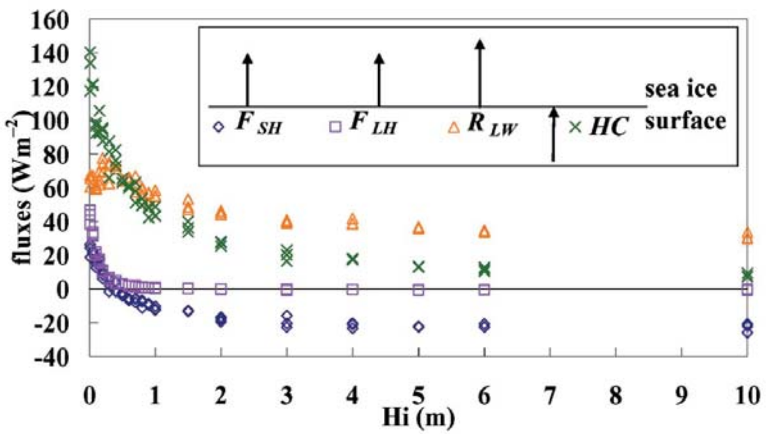

Fig. 2. Same as Fig. 1 except for sea ice thickness (H_i) versus the heat fluxes at the sea ice surface (sensible heat (F_{SH}), latent heat (F_{LH}), net longwave radiation (R_{LW}), and heat conduction through the sea ice (HC)). Positive values indicate upward fluxes. Directions of fluxes are also indicated in the legend.

Hi-> Fluxes

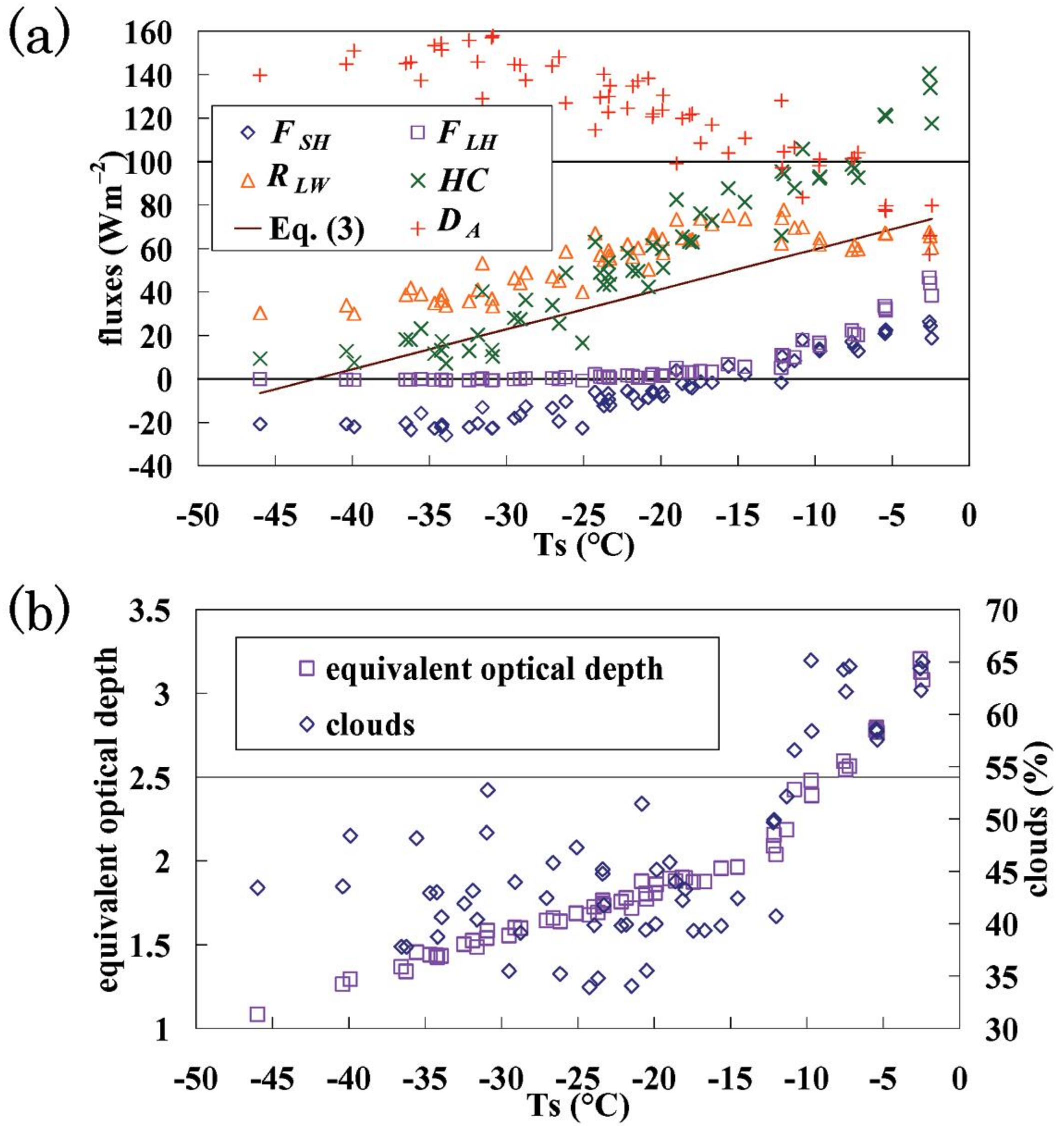

Fig. 3. Same as Fig. 2 except for sea ice surface temperature (T_s) versus (a) heat fluxes and atmospheric heat transport (D_A), and (b) equivalent optical depth (n_e) and clouds. Each dot indicates the results of the AGCM simulations. The line represents Eq. (3).

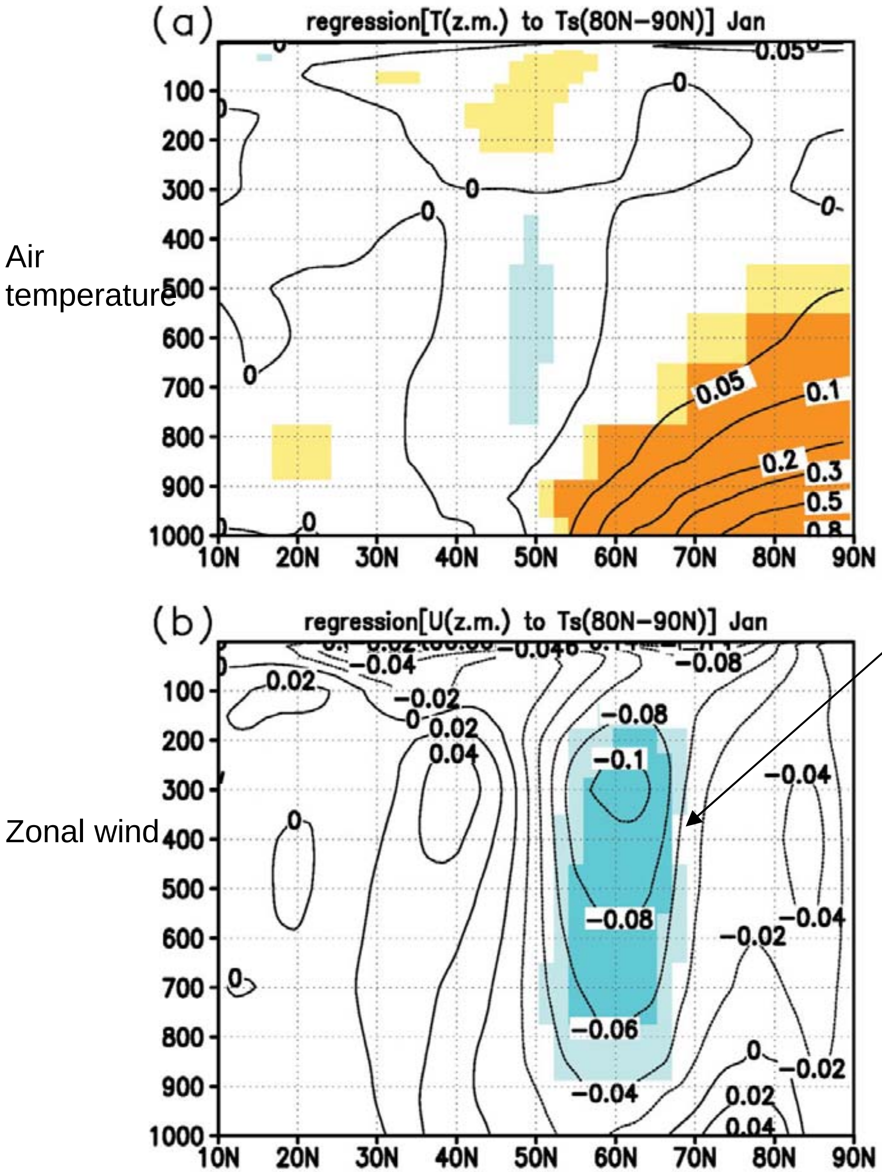

Fig. 4. The meridional-vertical cross section for the zonal mean (a) air temperature (°C) and (b) zonal wind (m s^{-1}) regressed to the sea ice surface temperature averaged over the same region as in Fig. 1 in January. Light (dark) shading indicates statistical significance at the 95 (99) % level.

Figure 4a indicates high positive correlation in the region from the North Pole to 50–60°N around the sea ice edge. Sea ice thickness appears to influence the air temperature over the surrounding land and sea out of the sea ice region, probably due to being directly mixed by atmospheric disturbances. The influence extends from the surface to an altitude of 500 hPa, a large portion of the troposphere in the Arctic region. The magnitude of the influence is more than 0.05°C per sea ice surface temperature variation of 1°C. The thinner sea ice leads to a higher temperature in the upper air over the Arctic, which moderates the temperature gradient between the polar region and the mid-latitudes, consistent with the weakened westerly wind in the upper air around 60°N (Fig. 4b). The magnitude of the influence is 0.1 m s^{-1} at the maximum per sea ice surface temperature variation of 1°C.

The importance of atmospheric circulation responses should be estimated compared with atmospheric internal variability. A 10-year control simulation with constant (2 m) sea ice thickness is performed to estimate the atmospheric internal variability in the model. The simulated interannual variability (contours in Fig. 5) agrees well with the observed one (not shown). The ratio of the response to possible sea ice thickness variability relative to year-to-year atmospheric model internal variability is illustrated in Fig. 5. The response is calculated as a regression coefficient (m s^{-1}/°C) (Fig. 4b) multiplied by 5 (°C). The possible sea ice thickness variability is assumed to be 2 to 4 m, based on observed typical variation (McLaren et al. 1992; Laxon et al. 2003). It corresponds to 5°C of sea ice surface temperature variation (Fig. 1), and is equivalent to 16 W m^{-2} of total heat flux variation (Fig. 3a). The magnitude of the response of the upper zonal wind to the possible sea ice thickness variability is 10–20% of the atmospheric interannual variability. This signal is large enough to investigate more detailed atmospheric circulation response to sea ice thickness variability.

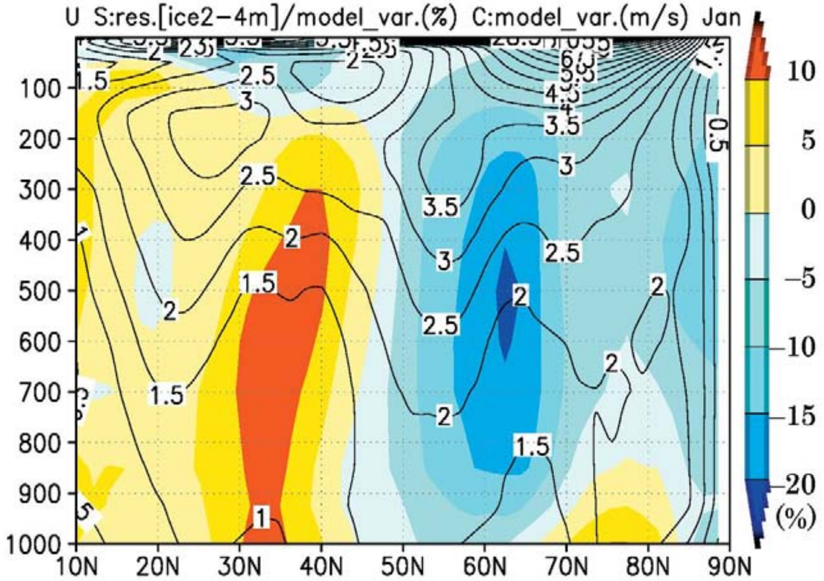

Fig. 5. The meridional-vertical cross section of zonal mean zonal wind response (shading) for possible sea ice thickness variability (2–4 m) as the ratio relative to year-to-year atmospheric model internal variability in percent, and year-to-year atmospheric internal variability in the model (contours) with the contour interval 0.5 m s^{-1}.

Results and issues:

1. Sea-ice thickness affects atmospheric interannual variability (through surface temperature, fluxes, atmospheric dynamics).

Thinner sea-ice (2-4m, larger Ts) leads to warming of a large part of troposphere in the Arctic region, causing a weakening of upper westerly wind in the sub-arctic region. The magnitude of such a wind response to possible sea-ice thickness variability can be 10-20% of interannual variability.

=> It also affects to atmospheric reanalysis (e.g., JRA) with constant, uniform thickness (We need thickness data!)

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4. Sea-ice thickness impact to the atmosphere
   (AGCM)
5. Issues : Just perspective

Reference:
Above three research works
JCOMM/IICWG white paper,
Ocean Obs 09 white papers,
GOOS/GODAE sea-ice intercomparison report

Data Issues

-Automated information extraction algorithms should be developed or improved within the context of objective, automated use (in JMA).

-Knowledge of error characteristics is essential: (mean error, spatial and temporal variability of errors)

-Higher resolution data is better for ocean forecasting, although data management then becomes an issue, may be better for climate also(?).

-A mix of derived fields and direct satellite measurements may provide the most useful combination of information such as GHRSST project.

-Sea-ice thickness data is needed as well as sea-ice concentration (need more cooperation with satellite community).

Model Issues

-operational ice forecasting is more of an initial value problem. But for seasonal forecasting with CGCM, boundary value problem (air-sea flux optimization) may also be needed.

-many complex processes have been modeled but very few ice characteristics are observed (need more observation!)

-one might also take the approach of incremental data assimilation, where a simpler model may be used as part of a 4D assimilation procedure. The resulting analysis increment is used to correct the full state of a more sophisticated model that is used to produce the forecasts, as incremental 4DVAR.

Data Assimilation Issues

-lack of in-situ observations and incomplete/inconsistent data sets complicates matters

-additional difficulties arise because we're dealing with the air/sea/ice interface

=> should be consistent to not only sea-ice concentration etc.
but also heat and water fluxes and oceanic/atmospheric states

-ice is a discontinuous, deformable medium and assumption of isotropy and homogeneity in the error variance/covariance (B & R matrices) fields is less valid

-a multivariate treatment (and consistent observations) is important

=> sea temperature consistent with ice extent,
ice variability with salinity/water flux
optimization of ice concentration with/without ice volume

-complex methods may be too computationally expensive, especially for sophisticated operational models (may change with increased computational efficiency)

=> simpler methods (OI, nudging 3DVAR-IAU…) may be enough?

- Improvement of observation operator for direct satellite assimilation (e.g., radiance), or relation between concentration and thickness (or other variables)

Thank you