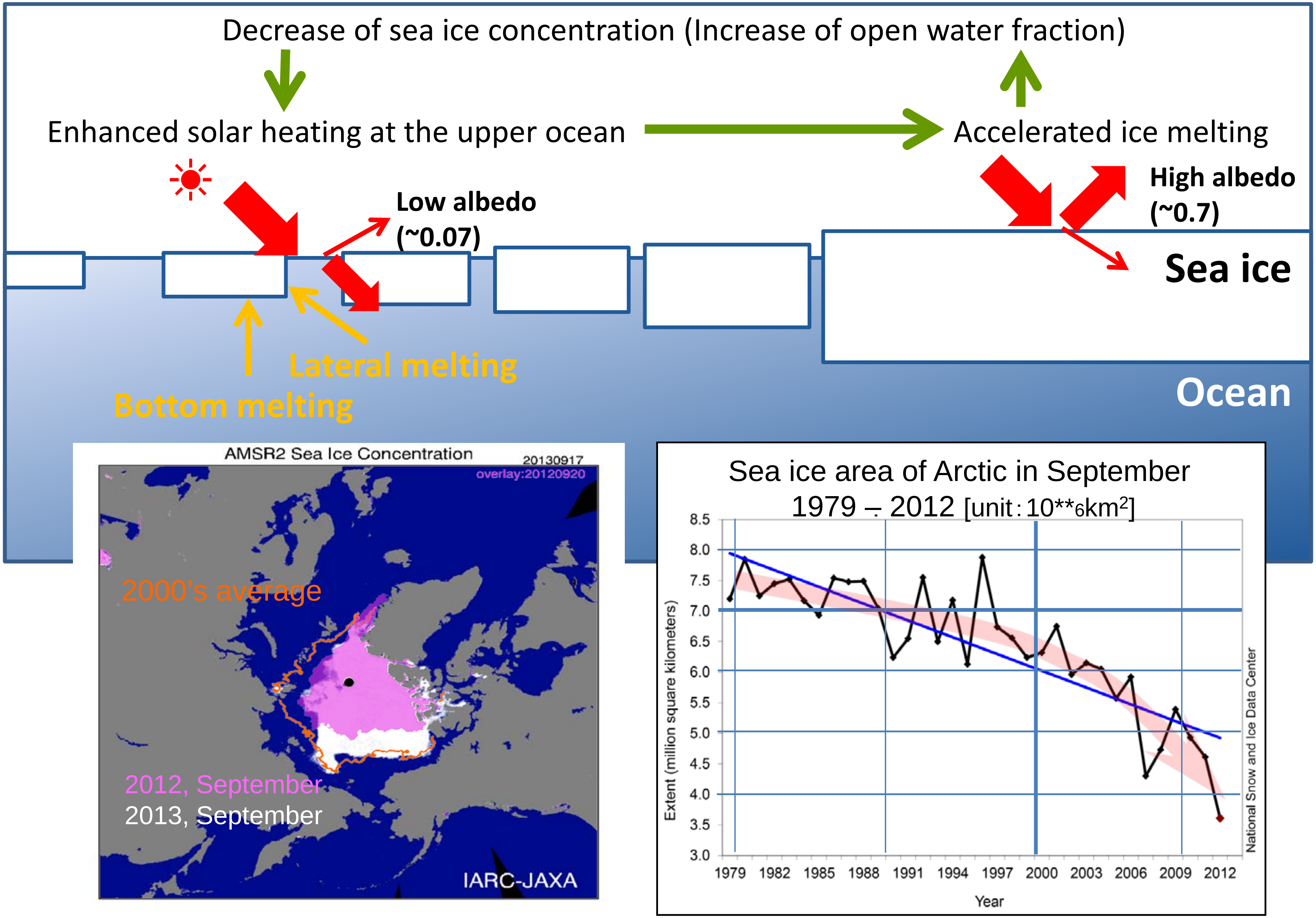
Ice-albedo feedback in the Arctic Ocean shifting to seasonal ice zone



Sea ice Iceberg

The origins are same or different ?

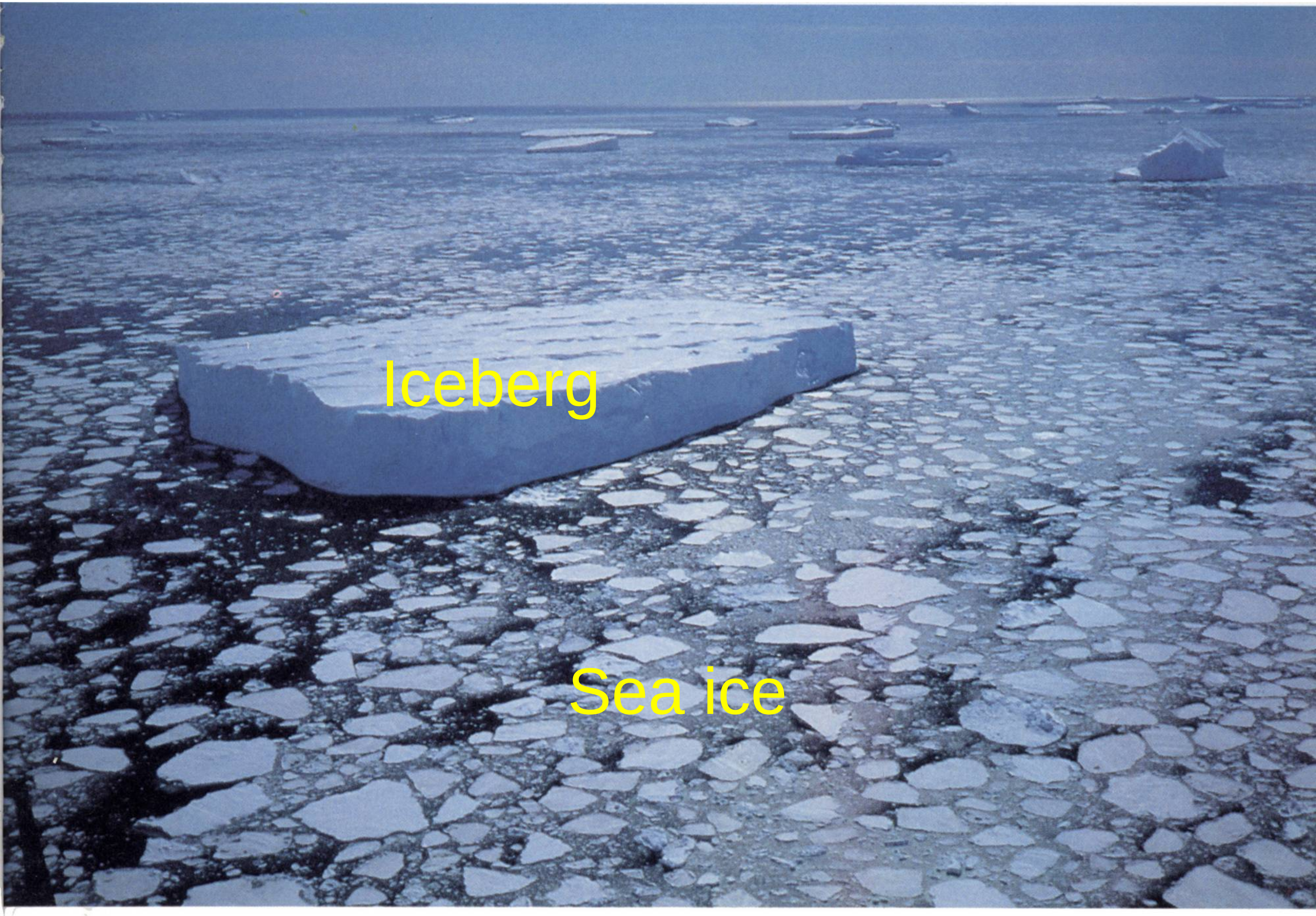
Sea ice = frozen sea water

contain some salt **1−3m**

Iceberg = calving from glacier or ice shelf

originating from snow

contain no salt **200-300m**



海氷と氷山

Existing amount of ice in the earth

- Ice sheet, Glacier

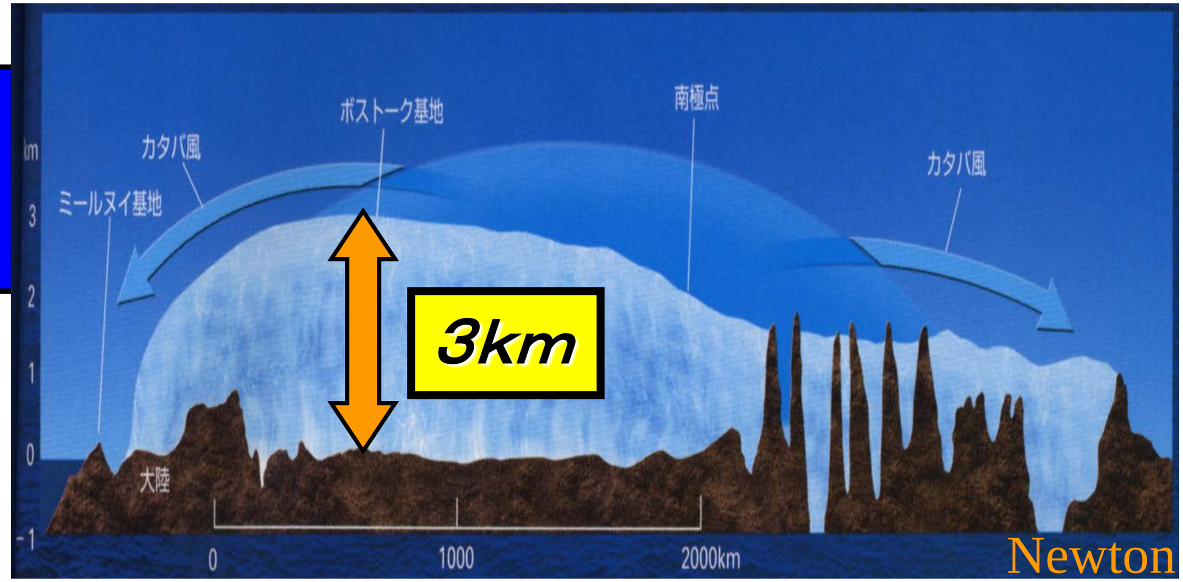
Antarctic	**89%**
Greenland	**9%**
the others	**1%**

- Sea ice

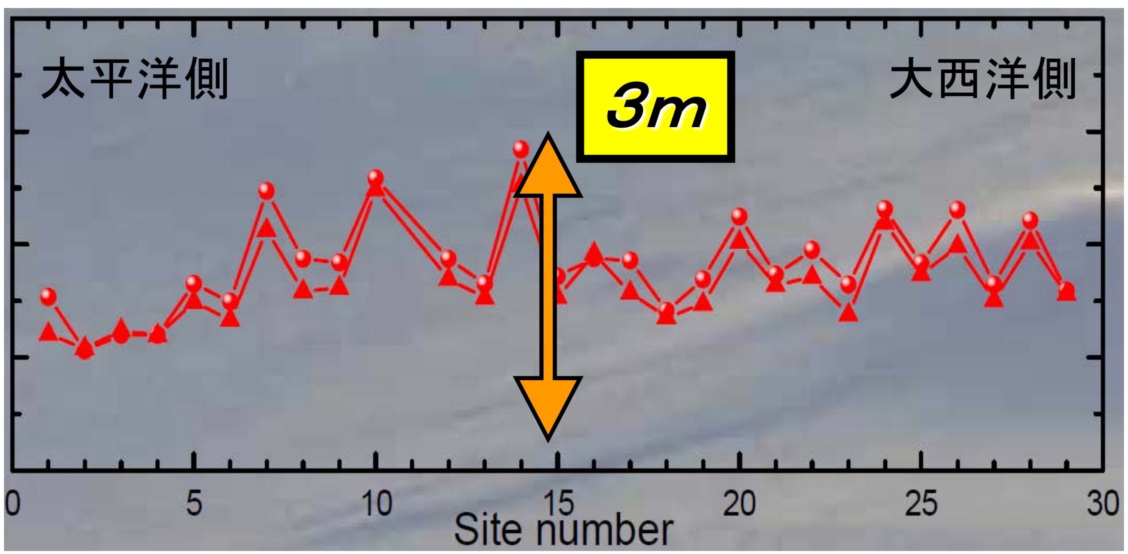
0.1%

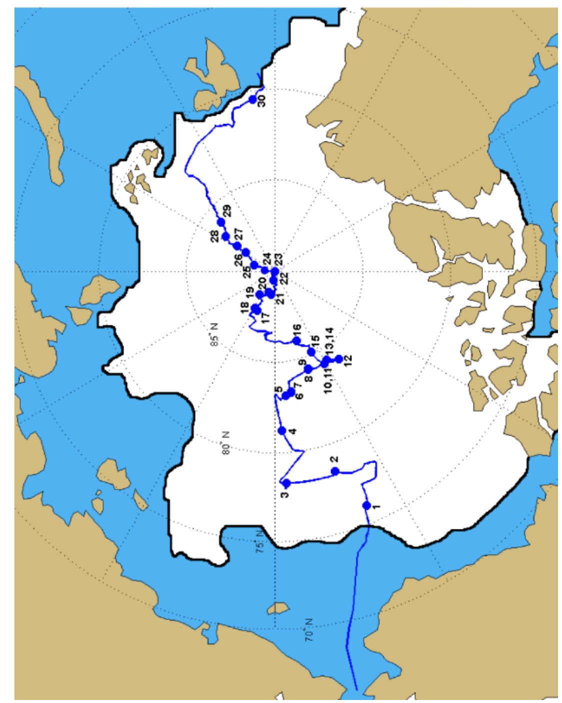
- Permafrost **1%**

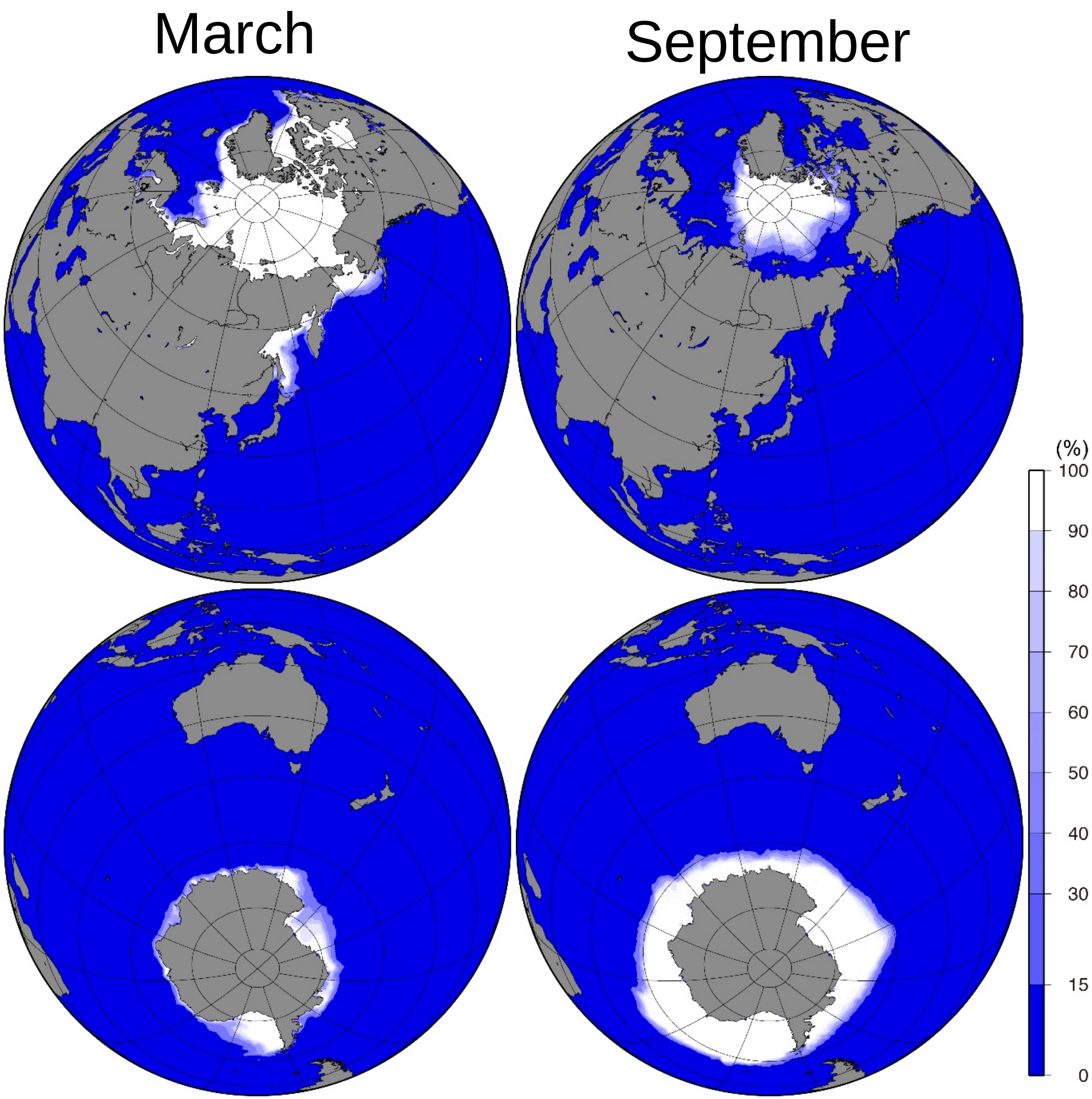
Antarctica
Ice sheet thckness



Arctic Ocean
Sea ice thckness







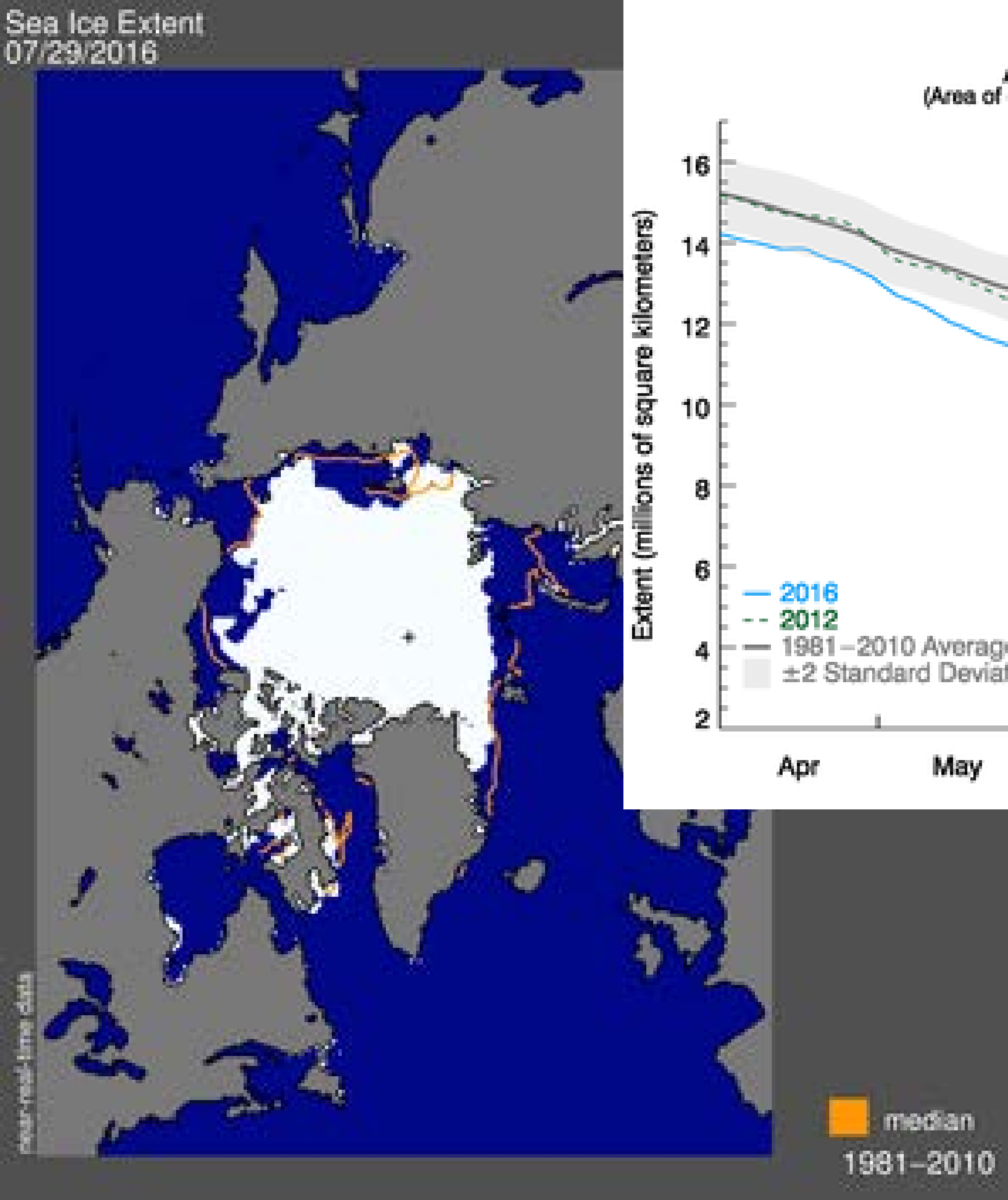
Arctic Ocean

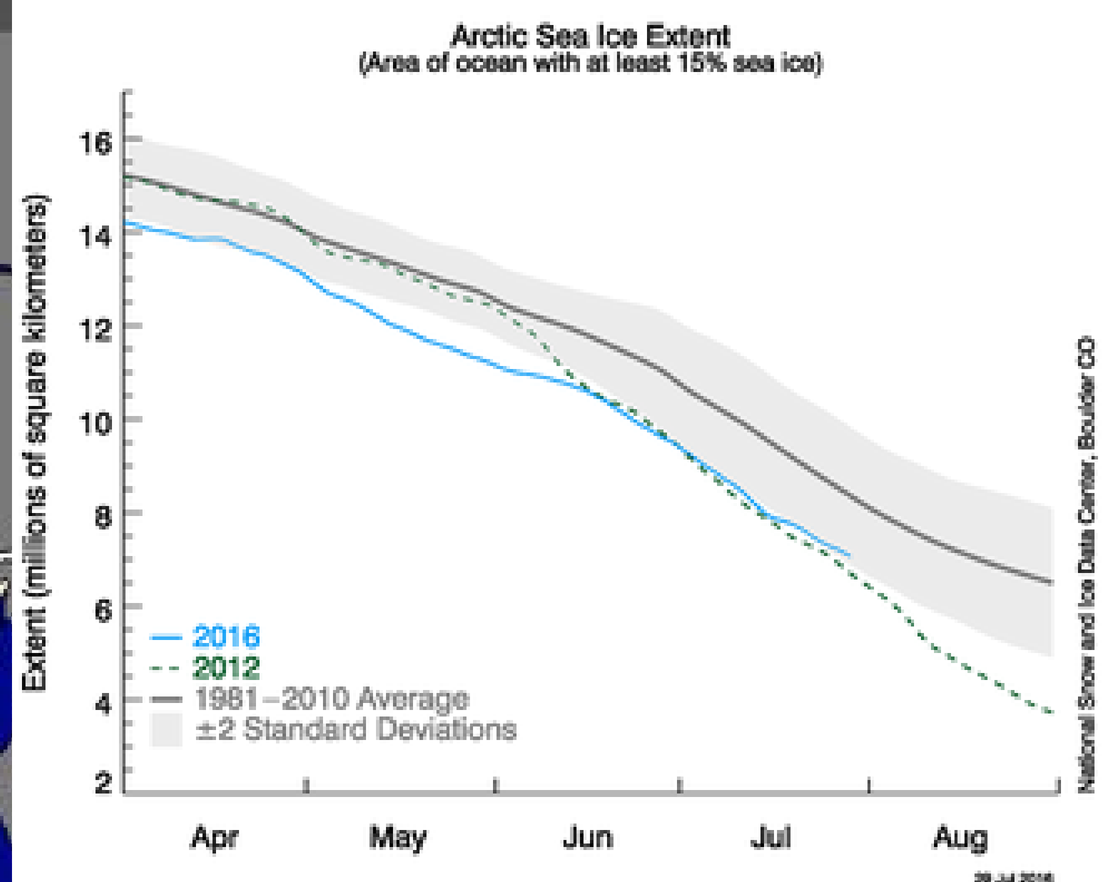
multi-year ice zone

→seasonal ice zone?

Antarctic, Okhotsk Sea

seasonal ice zone


Sea Ice Extent
07/29/2016
median
1981–2010


Arctic Sea Ice Extent
(Area of ocean with at least 15% sea ice)
Extent (millions of square kilometers)
16
14
12
10
8
6
4
2
Apr
May
Jun
Jul
Aug
2016
2012
1981–2010 Average
±2 Standard Deviations
National Snow and Ice Data Center, Boulder CO

Satellite Remote Sensing

- Active sensor; Radar : strong power

  （emit the electromagnetic wave & measure its reflection）

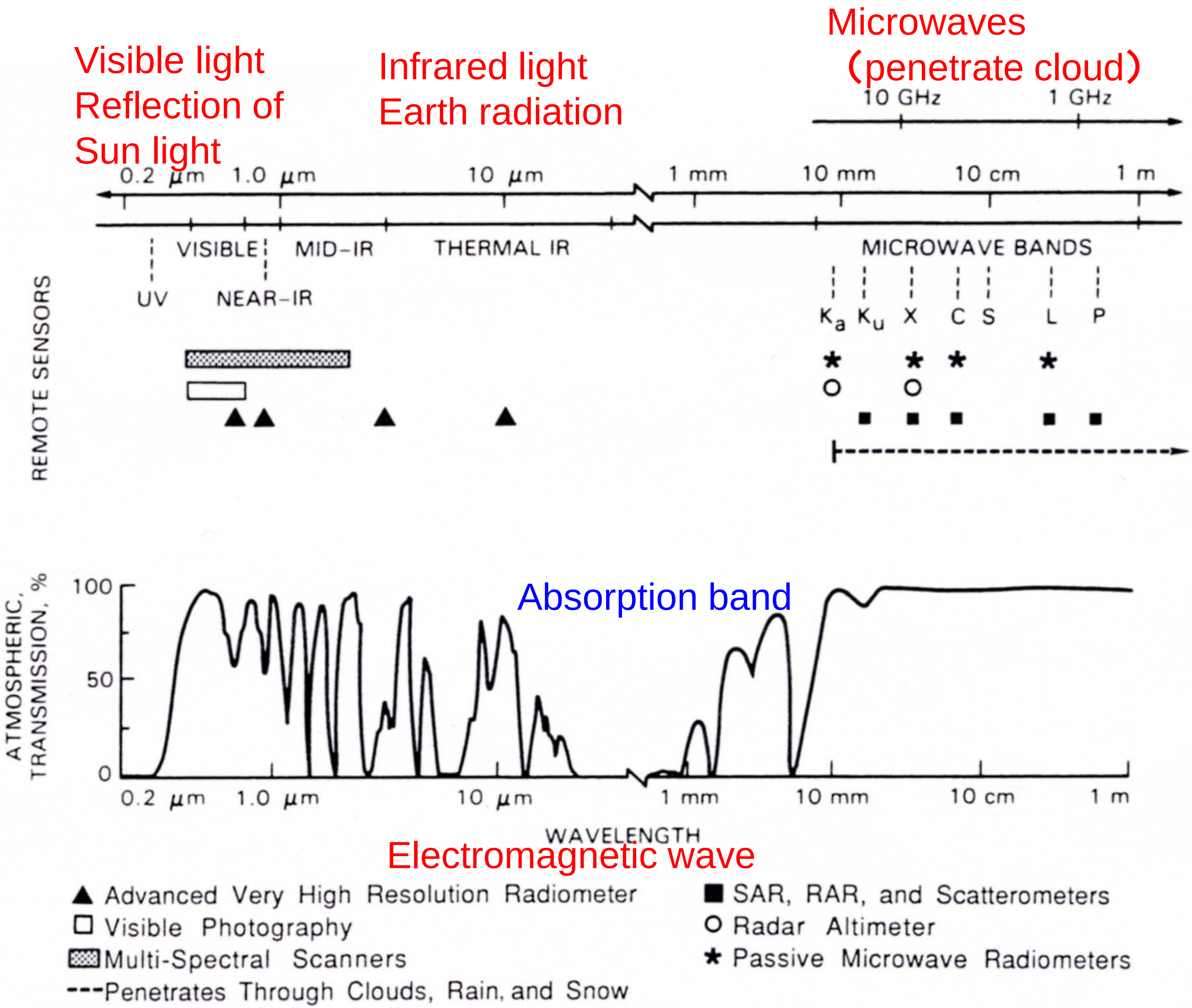
  - SAR (Synthetic Aperture Radar)
  - Microwave scatterometer
  - Microwave altimeter

- Passive sensor; Radiometer : relatively weak power

  （measure the electromagnetic waves from objects）

  - Microwave radiometer（SSM/I, AMSR）
  - Visible, infrared radiometer (MODIS, GMS)

(Geostationary Meteorological Satellite)



Visible light
Reflection of
Sun light
Infrared light
Earth radiation
Microwaves
（penetrate cloud）
10 GHz
1 GHz
0.2 μm
1.0 μm
10 μm
1 mm
10 mm
10 cm
1 m
UV
VISIBLE
NEAR-IR
MID-IR
THERMAL IR
MICROWAVE BANDS
Ka
Ku
X
C
S
L
P
REMOTE SENSORS
ATMOSPHERIC, TRANSMISSION, %
100
50
0
Absorption band
WAVELENGTH
Electromagnetic wave
Advanced Very High Resolution Radiometer
Visible Photography
Multi-Spectral Scanners
---Penetrates Through Clouds, Rain, and Snow
SAR, RAR, and Scatterometers
Radar Altimeter
Passive Microwave Radiometers

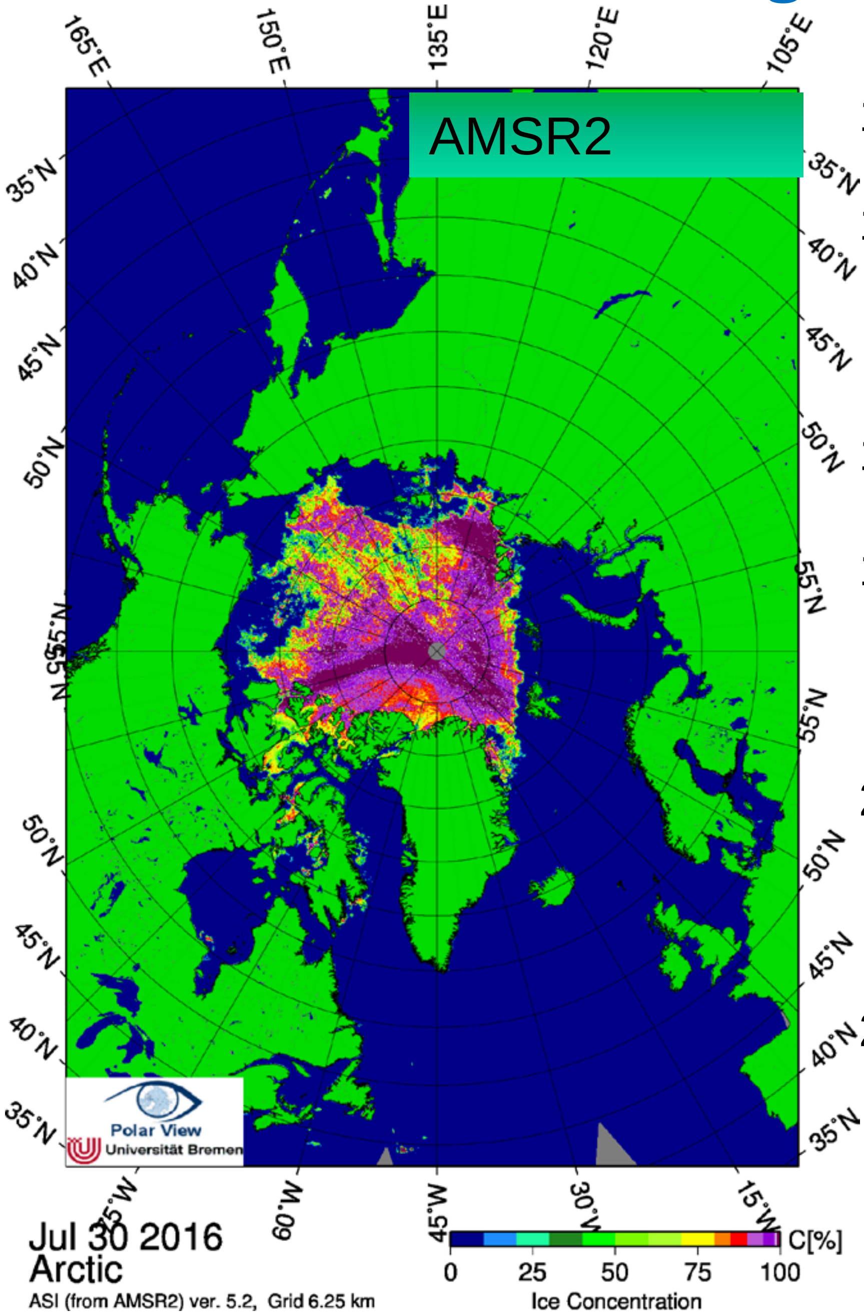
How many year has passed since global sea ice distribution can be known from satellite?

1. 80 yr
2. 60 yr
3. 40 yr
4. 20 yt

We can monitor the whole earth surface only for 40-50 years

Drastic change in the earth has likely occurred for recent 40-50 years

Satellite remote sensing: Life line of sea ice study



1972No satellite data for ice-covered area

1972 **ESMR**

The first global observation of sea ice from satellite microwaves

1978 **SMMR**

1987 **SSM/I**

resolution of 25km

2002 **AMSR, AMSR-E**

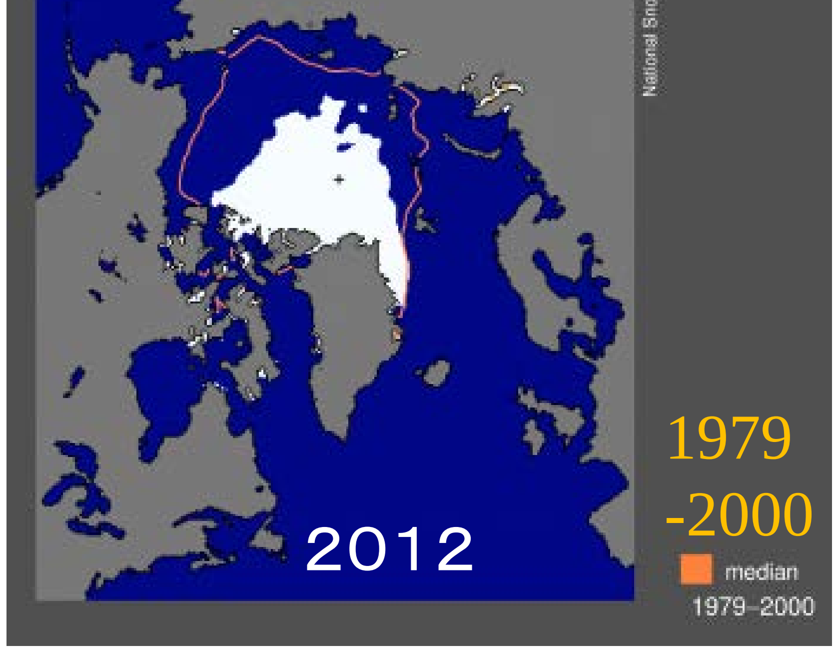
Japanese sensor

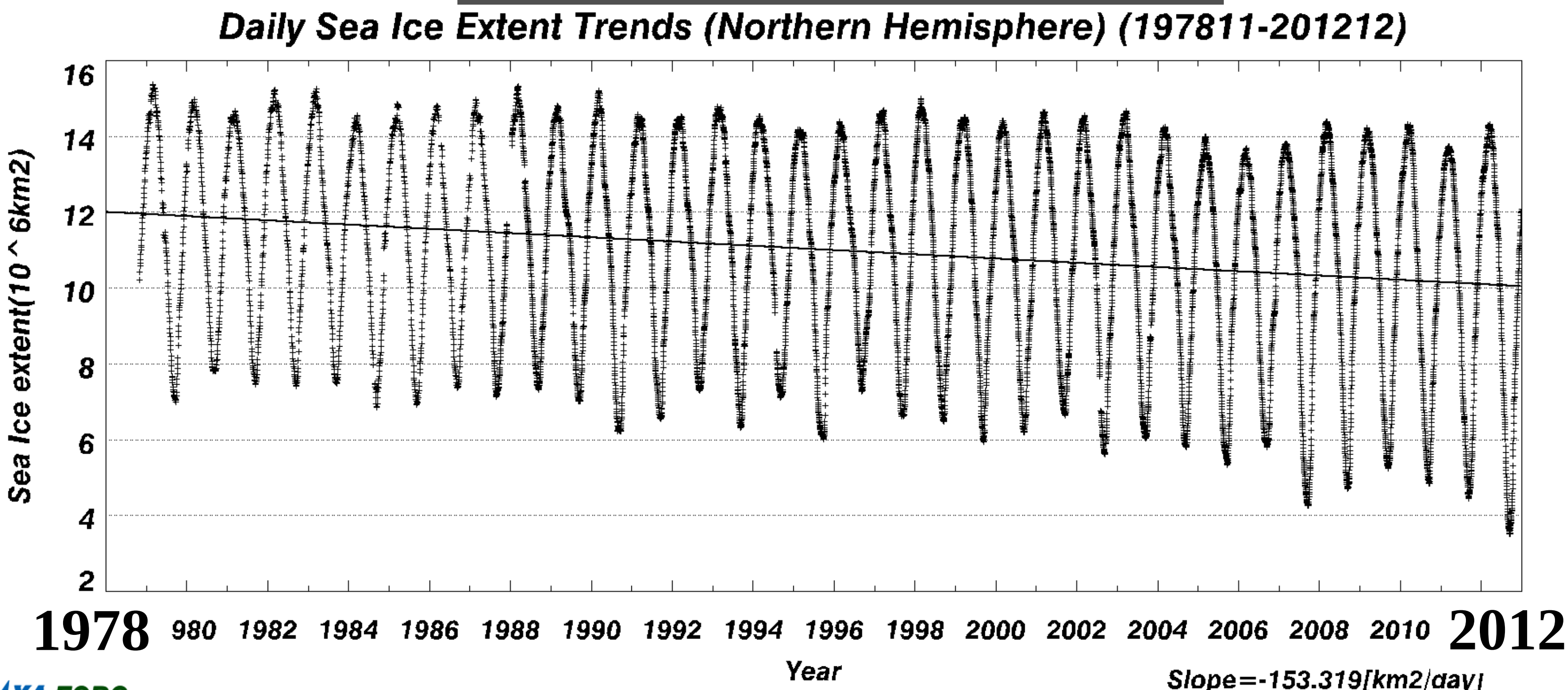
resolution of 6.3－12.5km

2012 **AMSR2**

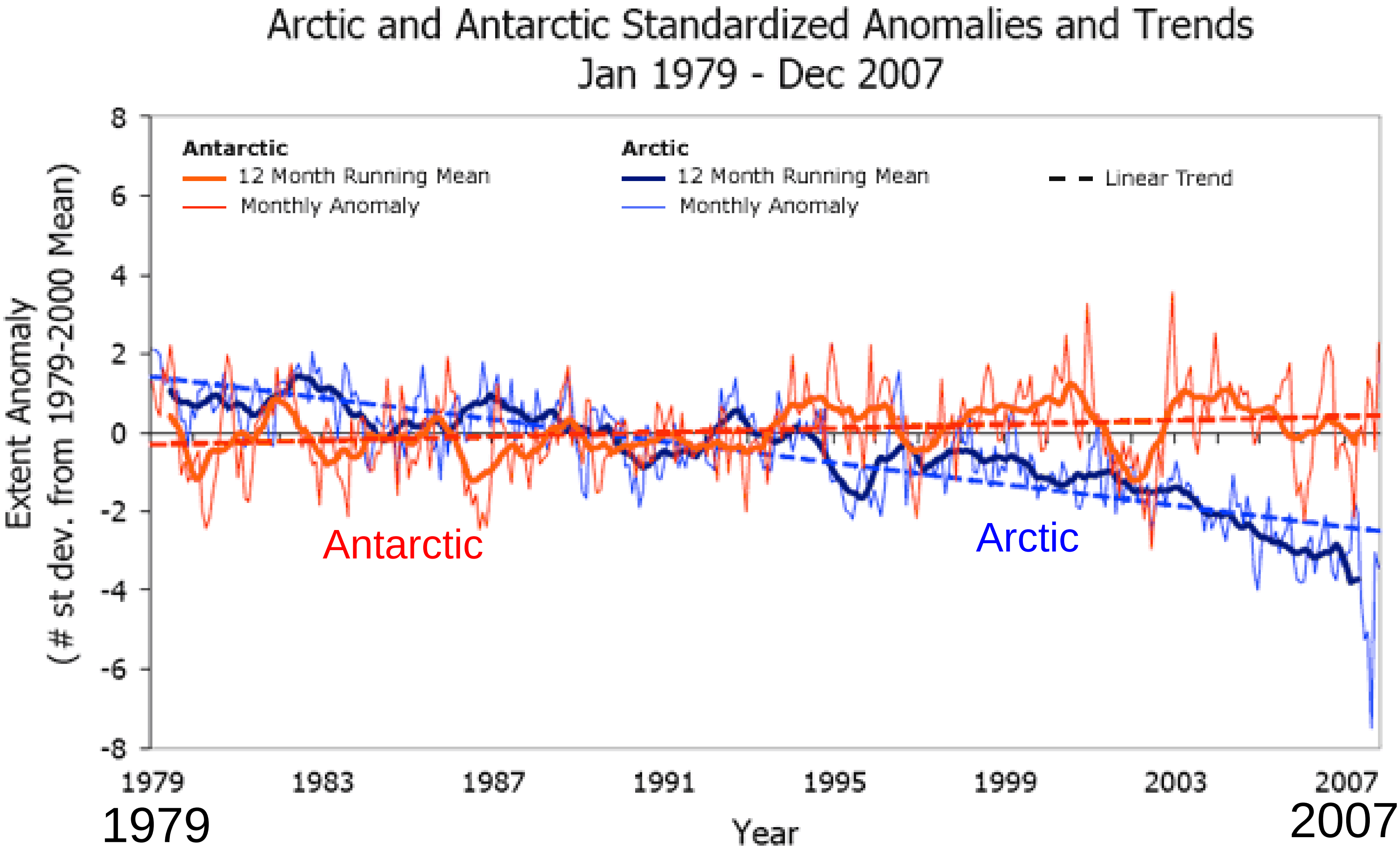
Successor of AMSR2？

Sea ice area
in the Northern
Hemisphere

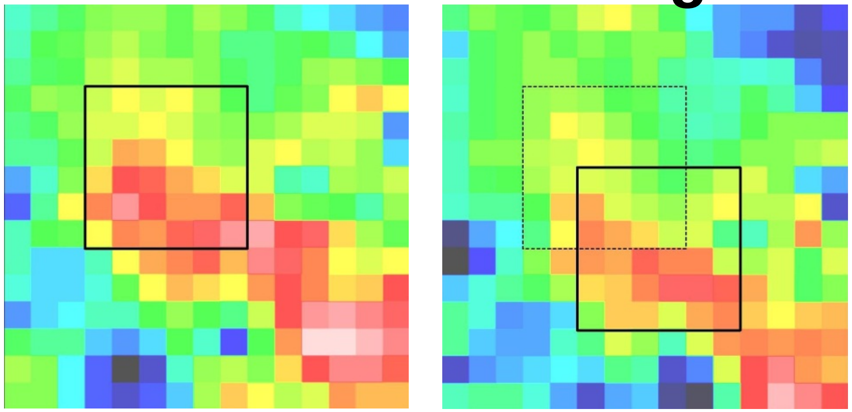


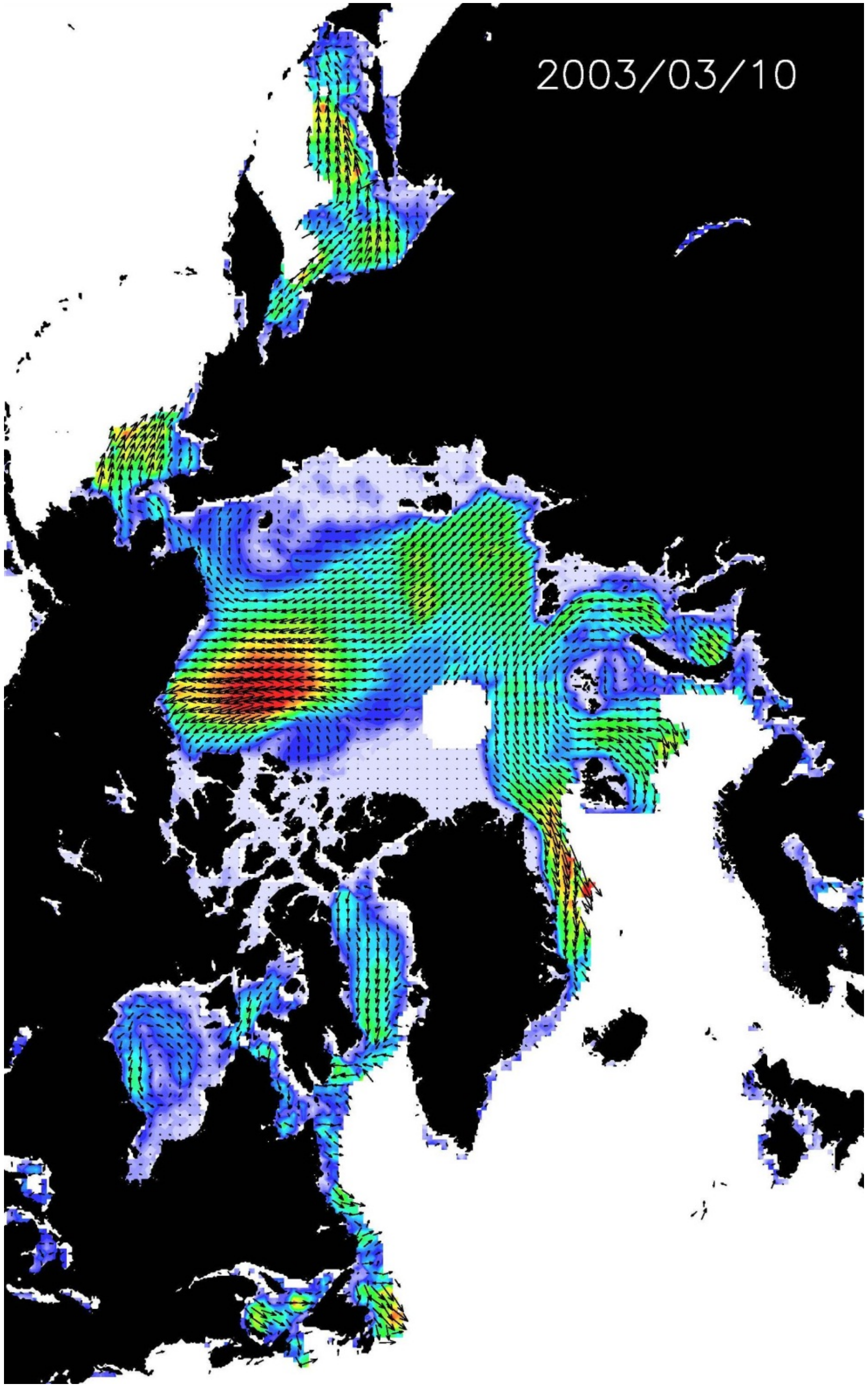


Trends of sea ice area from satellite microwaves



Calculation of sea ice drift from satellite image





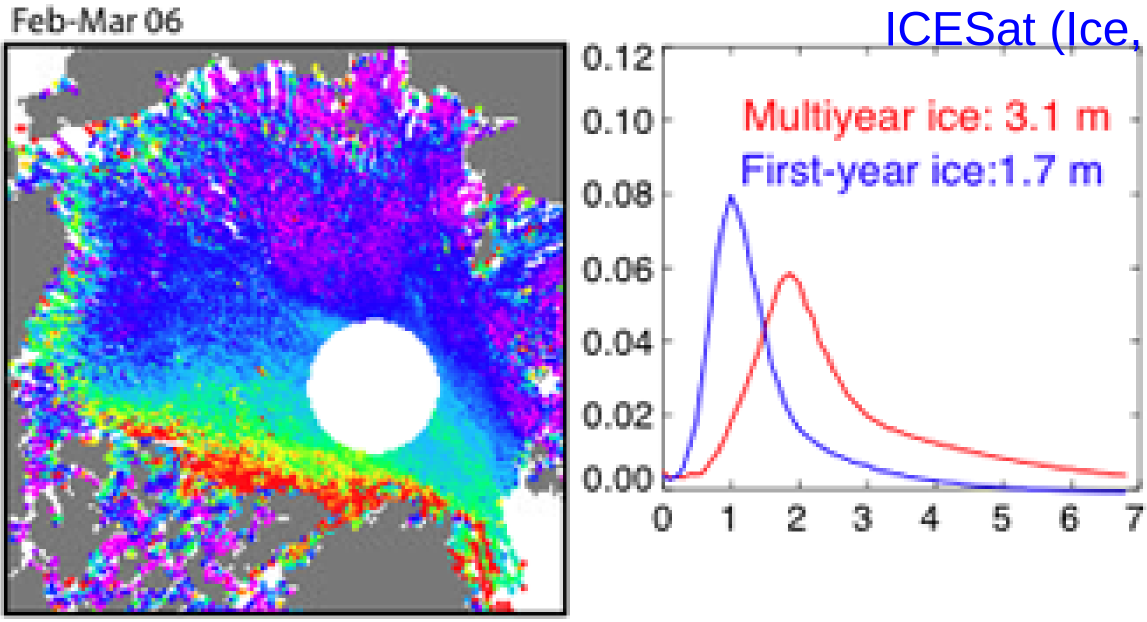
Maximum cross-correlation method

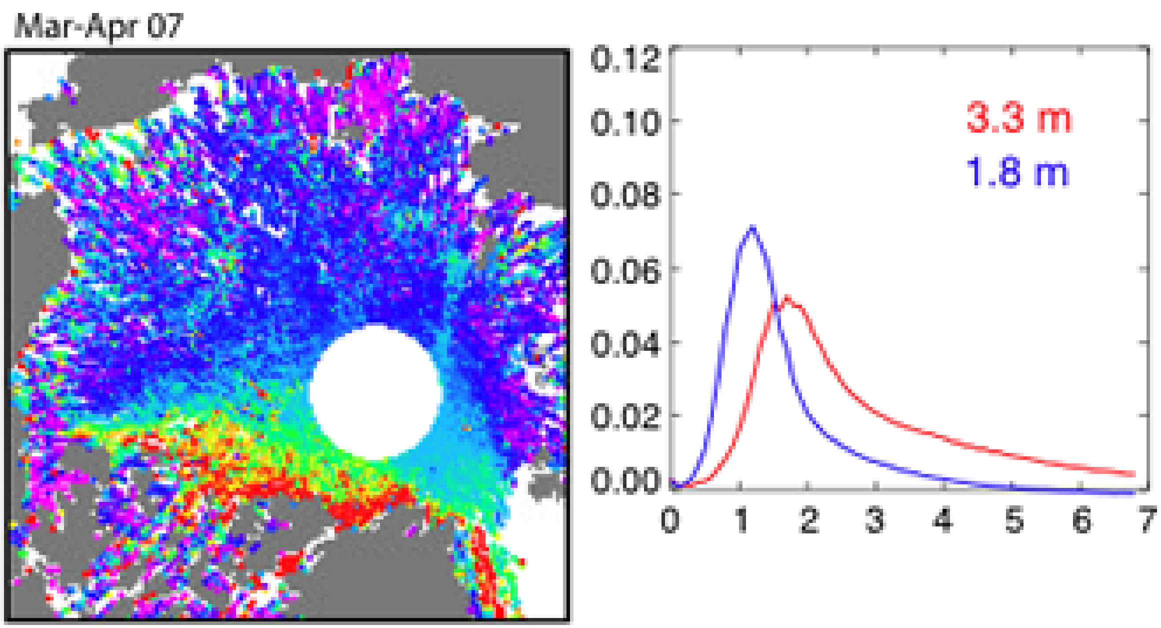
Resolution: **37.5×37.5km**

Daily ice drift data are obtained globally

Sea ice thickness measured by satellite

ICESat (Ice, Cloud, and Land Elevation Satellite)

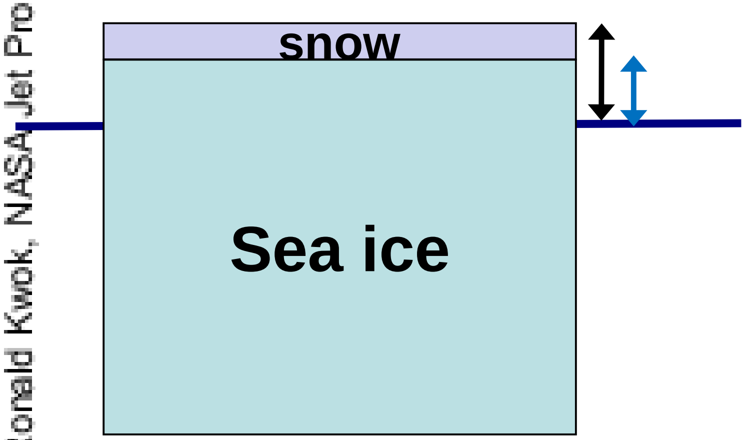




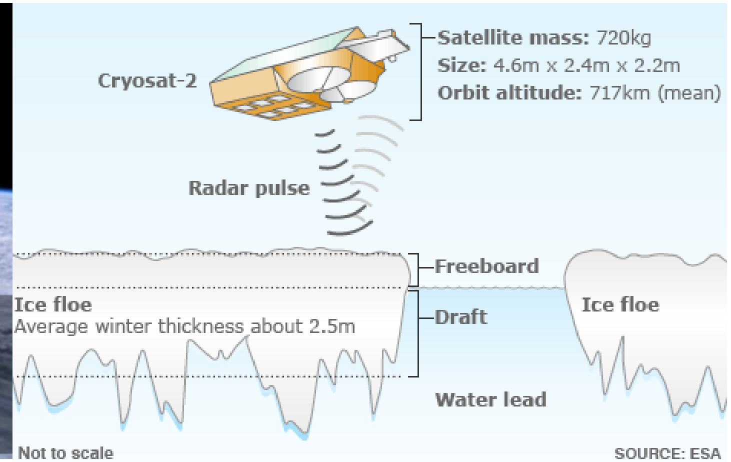
ter courtesy Ronald Kwok, NASA Jet Propulsion Laboratory

ICESat (2003-2009）
Laser altimeter

Assumption of Isostasy
Density of ice and snow
Thickness of snow



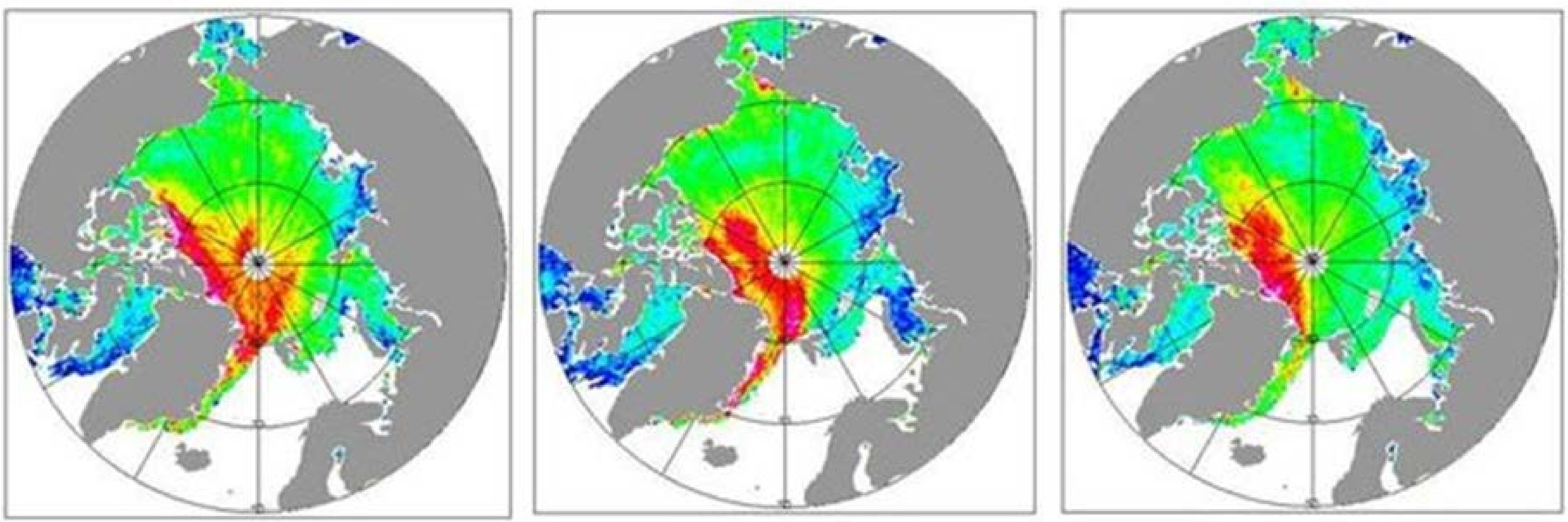
CryoSat-2(Radar altimeter)
(2010～)



Spring (April) Ice thickness

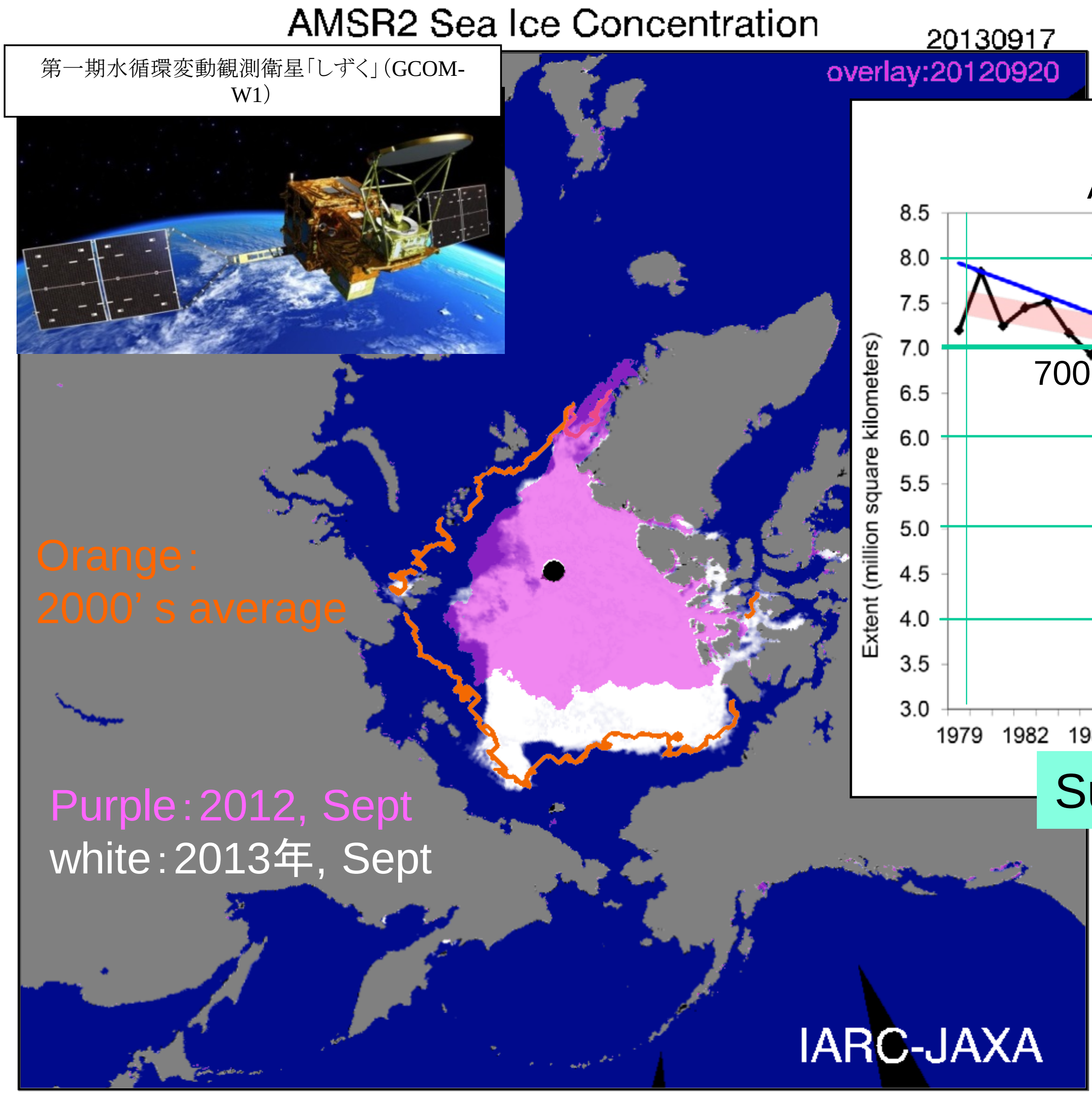
http://www.bbc.co.uk/news/science-environment-2396437

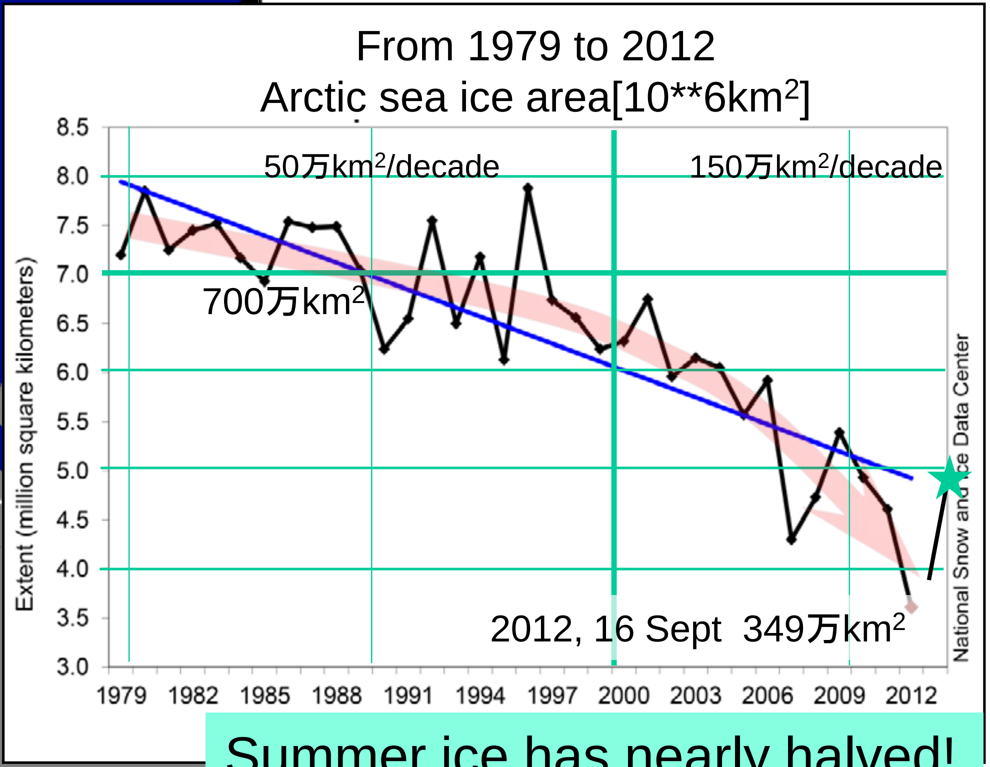
2011 2012 2013



http://www.esa.int/Our_Activities/Observing_the_Earth/
Living_Planet_Symposium_2013/New_dimensions_o

Rapid reduction of Arctic sea ice in summer



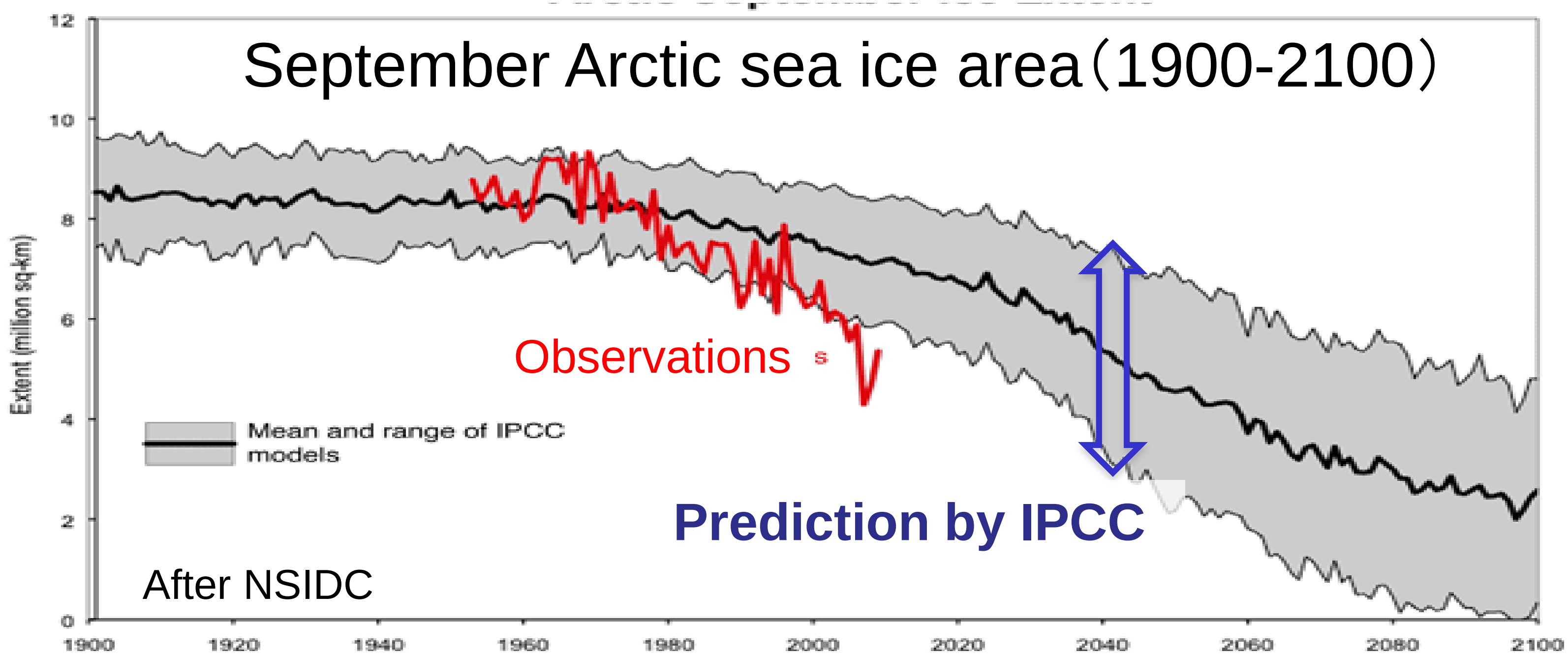


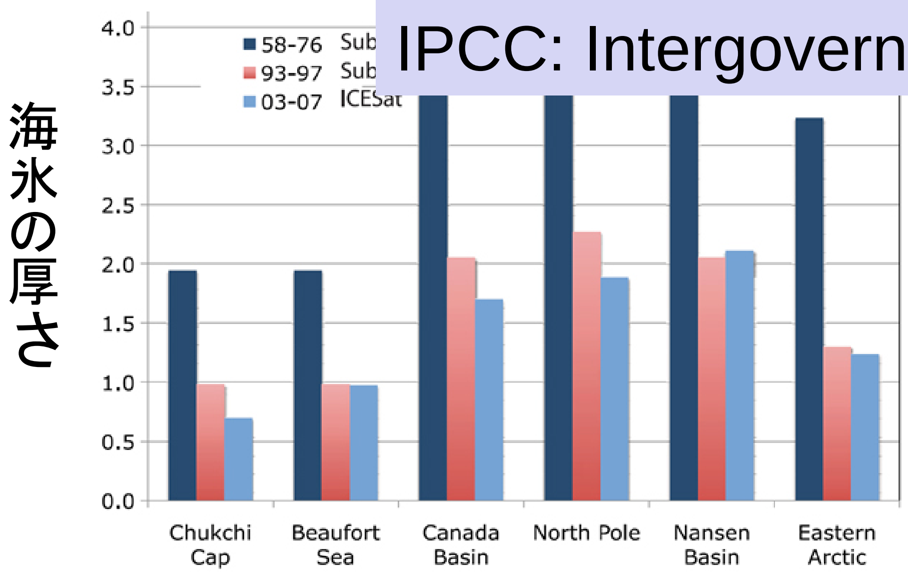
Summer ice has nearly halved!

AMSR2
JAXA
Japanese sensor

http://www.ijis.iarc.uaf.edu/cgi-bin/seaice-monitor.cgi?lang=e

Summer Arctic sea ice is declining more rapidly than prediction





Sea ice thickness for three decades

IPCC: Intergovernmental Panel on Climate Change

Ice area decreases by 10% per 10 years

Arctic Research Center has been established in Hokkaido Univ. last year.

What degree has surface air temperature increased in a global average for recent 50 years？

1．5.2 ℃

2．2.6 ℃

3．1.3 ℃

4．0.65℃

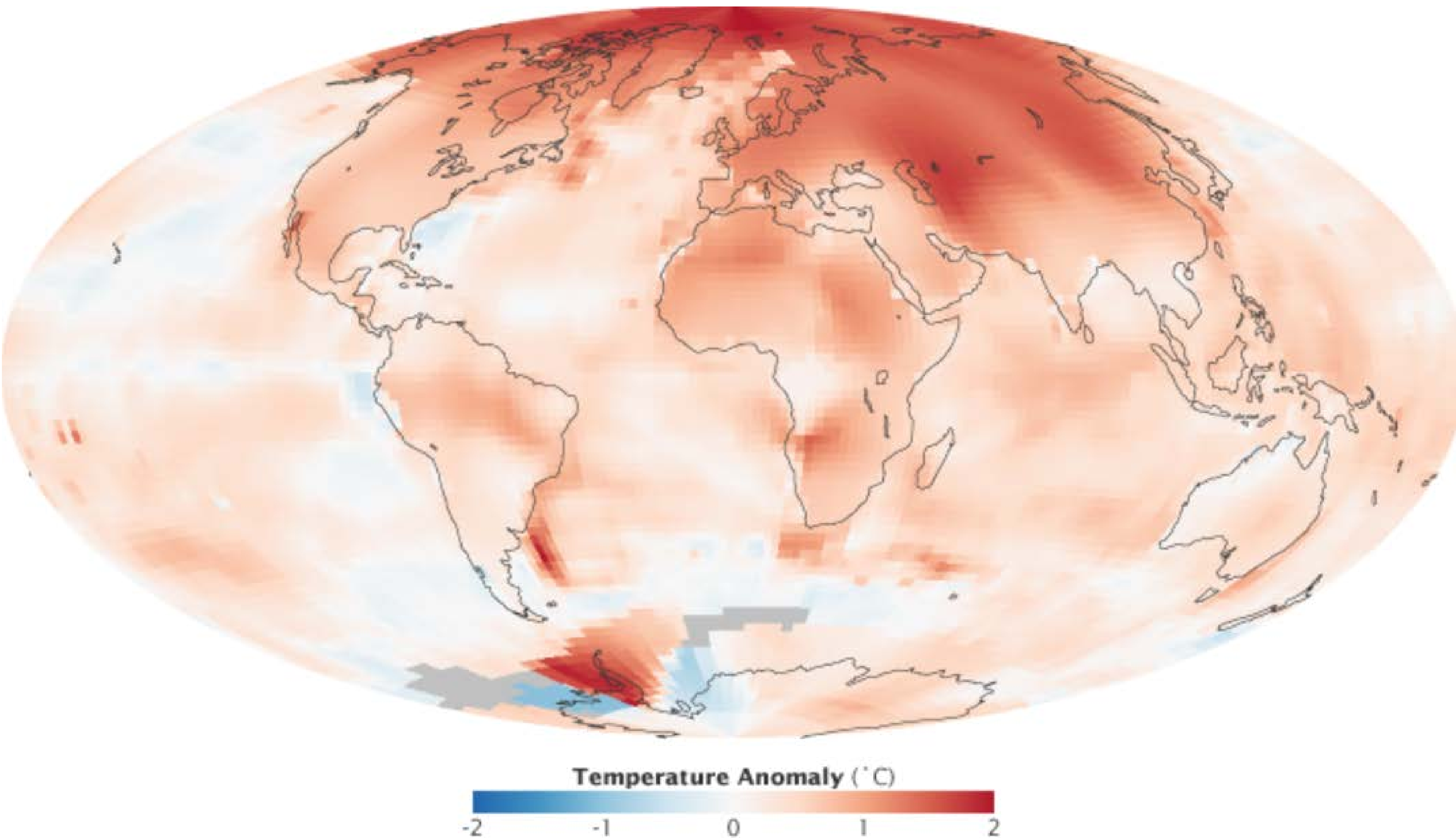
5．0.32℃

Warming by 0.65 ℃ for recent 50 years

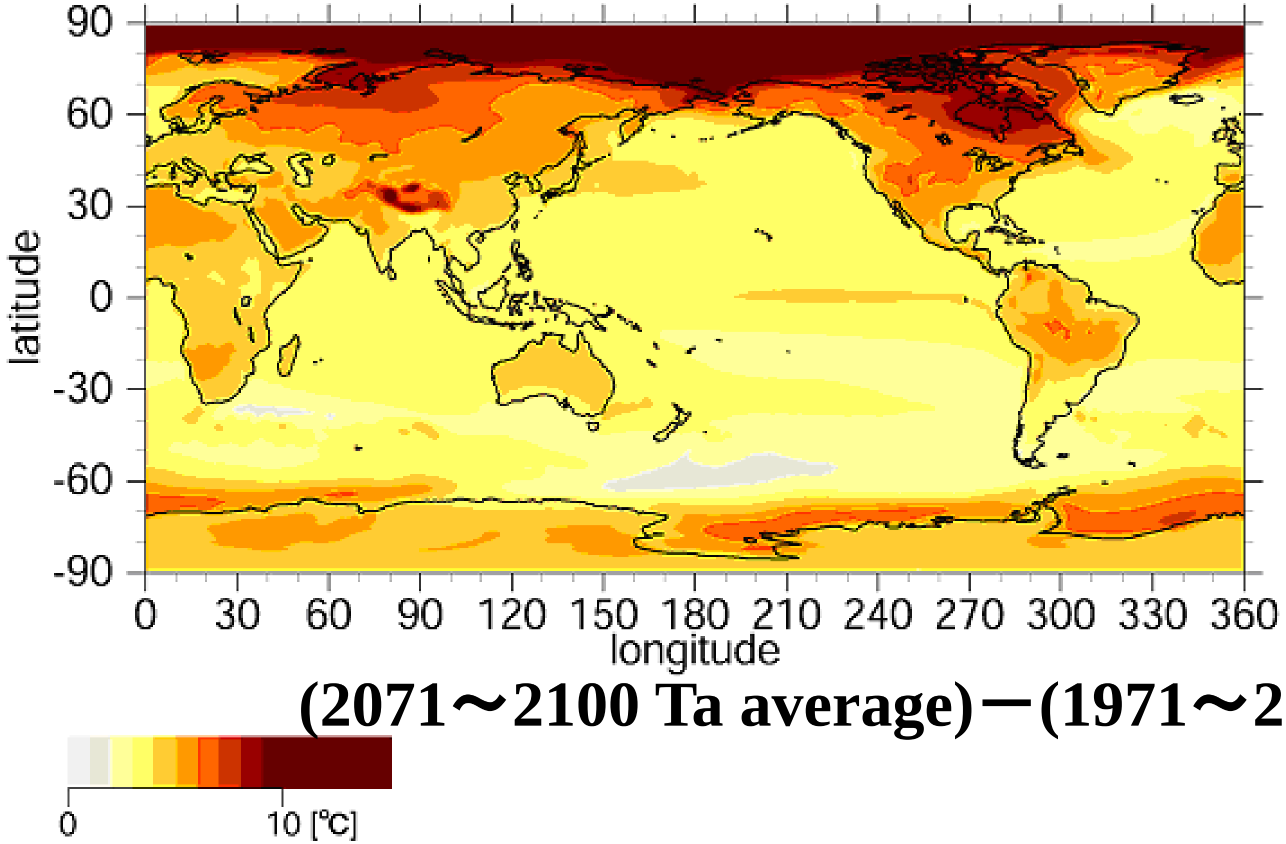
Warming by 0.74 ℃ for recent 100 years

Global warming Polar amplification

Air temperature anomalies for recent 10 years



Prediction of global warming by climate model with Earth Simulator



(2071～2100 Ta average)－(1971～2000 average)

Amplification in the Arctic　　positive feedback

Decline of Arctic sea ice

→decrease of albedo→increased absorption of solar radiation

→further decrease of sea ice

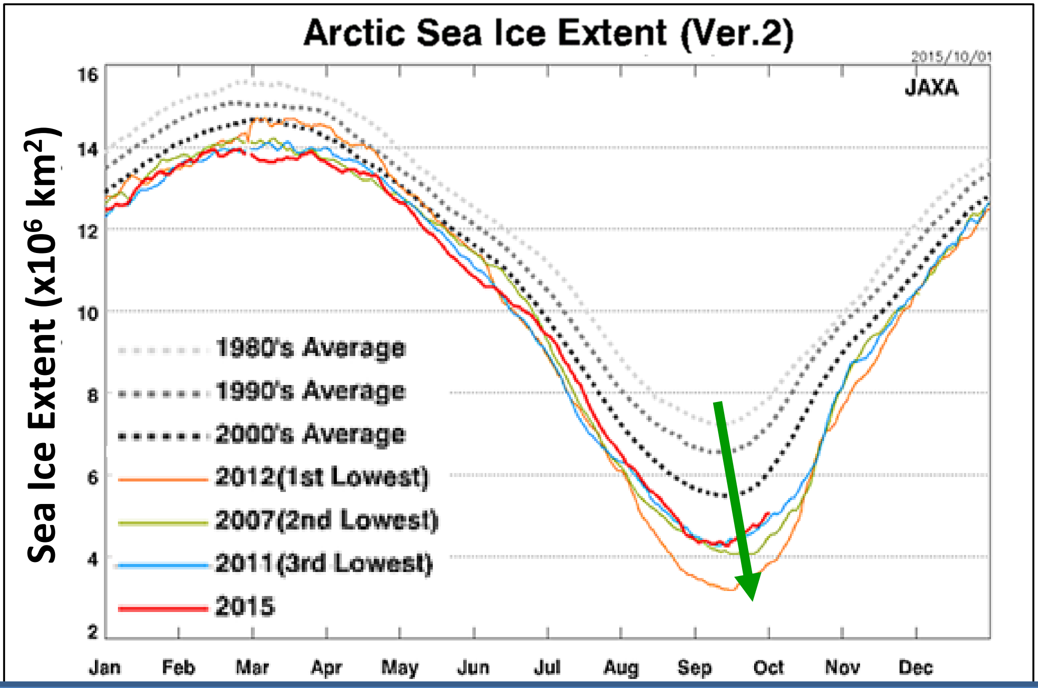
→reduction of heat insulation by sea ice

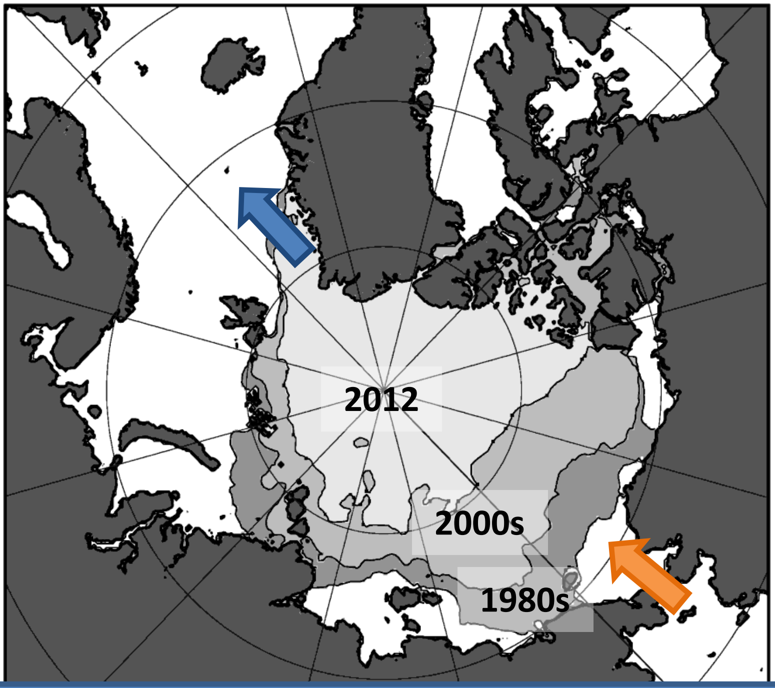
→enhanced oceanic heat flow→warming of air

Change in the Arctic sea ice associated with recent global warming

- Reduction in summer sea ice extent particularly after the 2000s. [e.g. Comiso et al., 2008]
- Thinning of sea ice. [e.g. Rothrock et al., 2008]
- Reduction of multi-year sea ice. (shift to the seasonal ice zone) [Comiso, 2012]

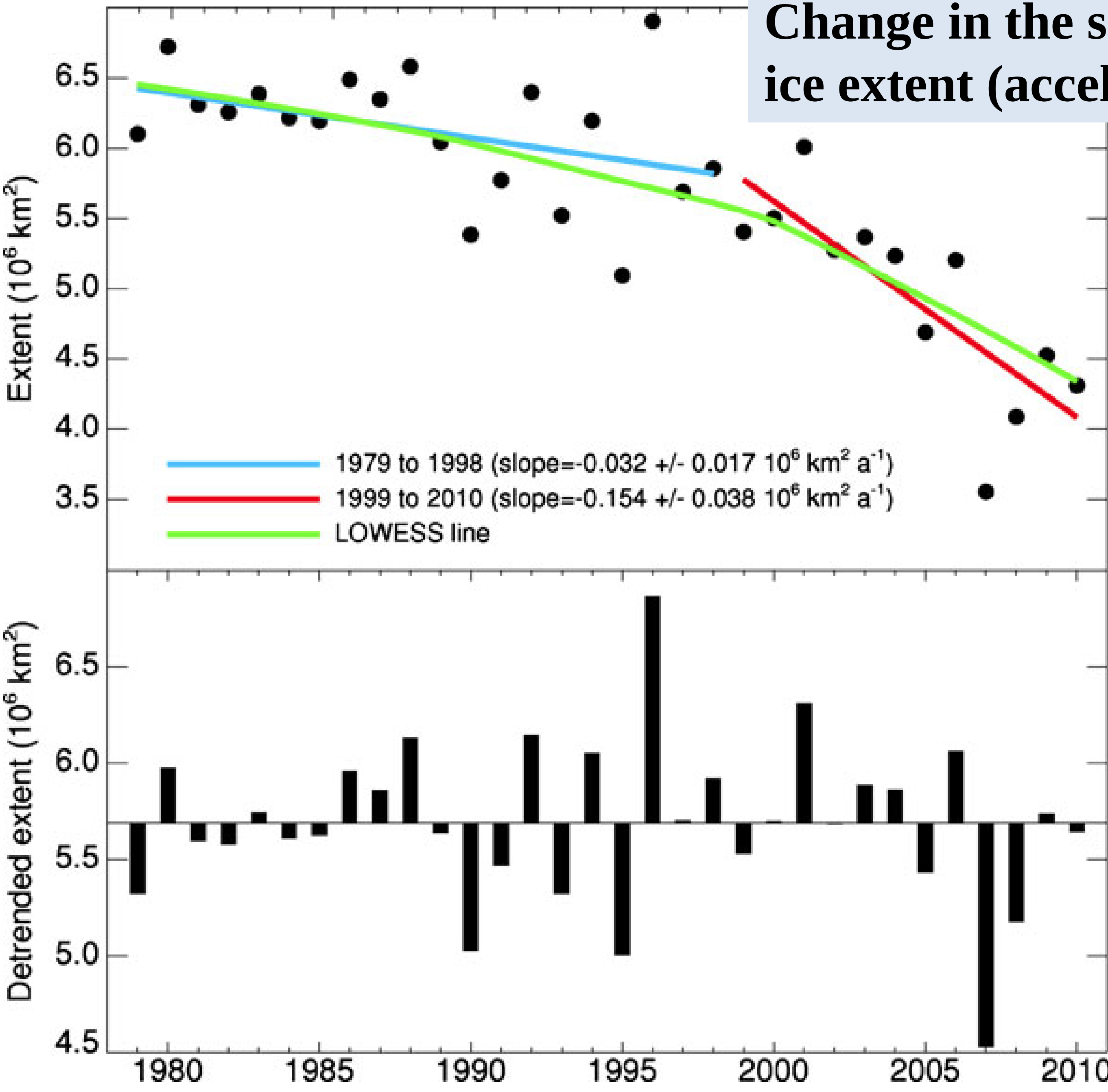
Drastic Ice reduction is explained by the combined effect of various factors.
(prolonged melting season, increased sea ice export, increased heat inflow, etc.)



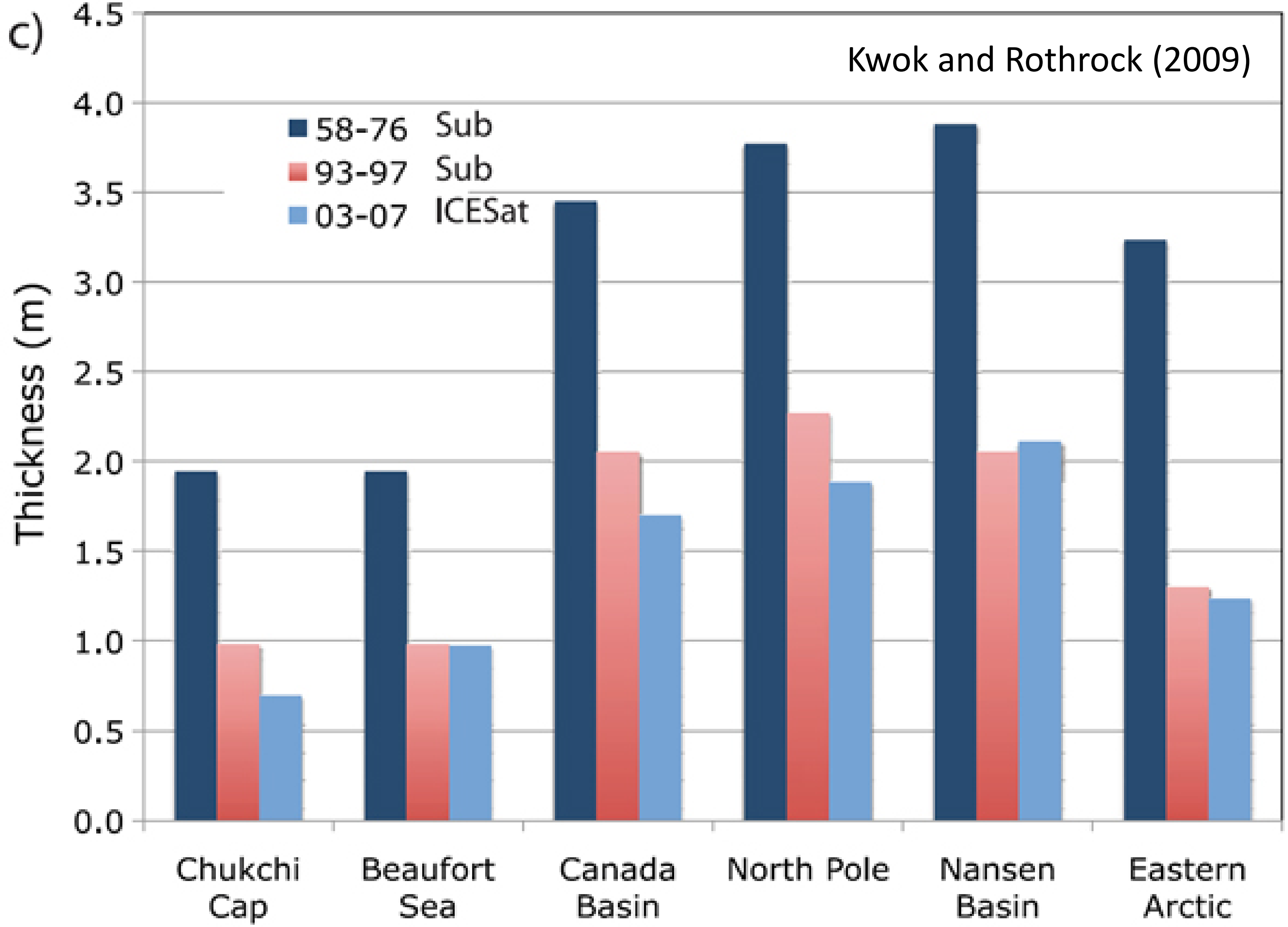


Ice-ocean albedo feedback becomes increasingly important for the Arctic Ocean shifting to the seasonal sea ice cover

Change in the summer Arctic ice extent (accelerated after 2000)

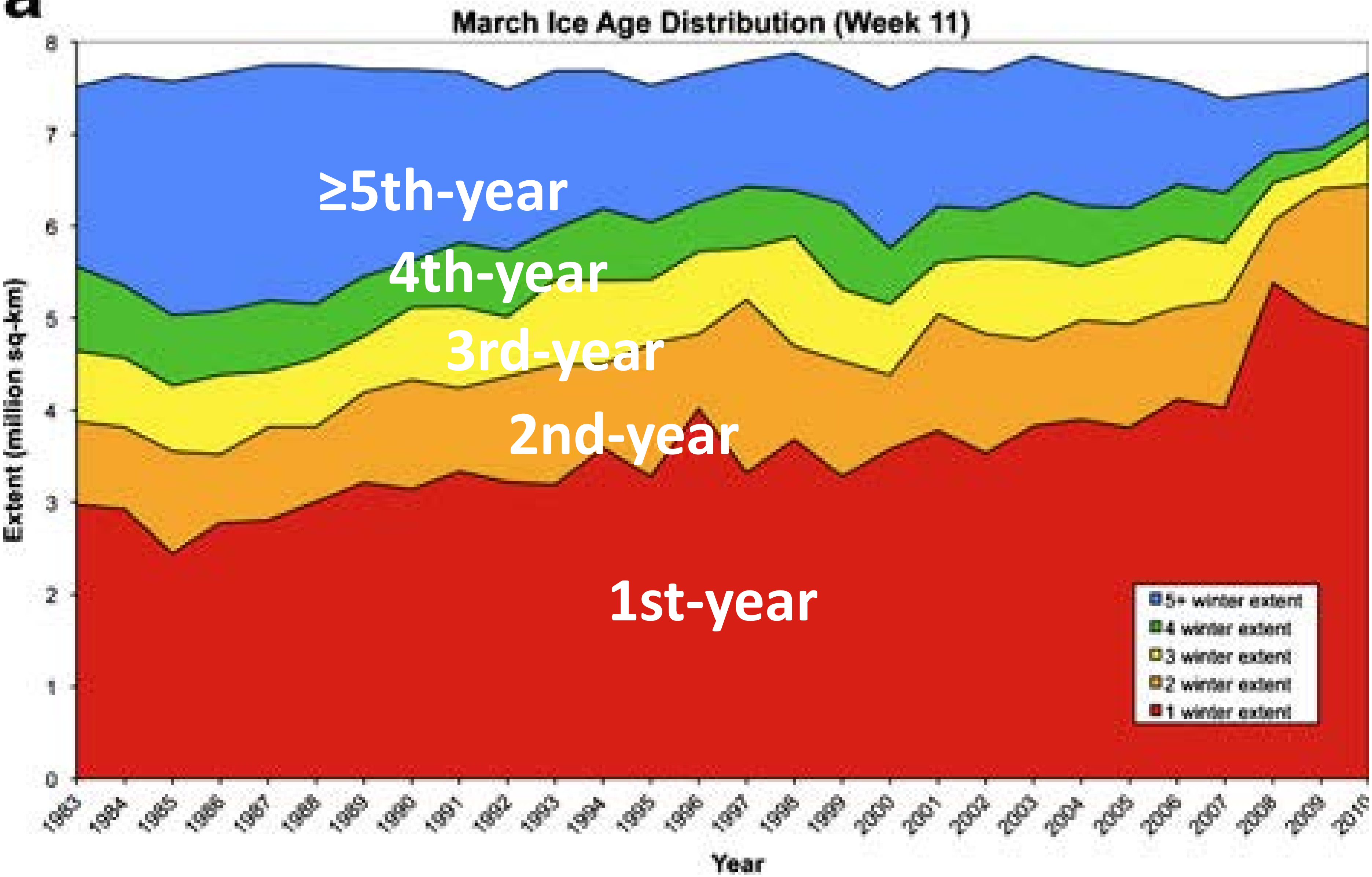


Stroeve et al. (2012)



Mean sea ice thickness obtained from submarine and ICESat observations（comparison for three time periods）

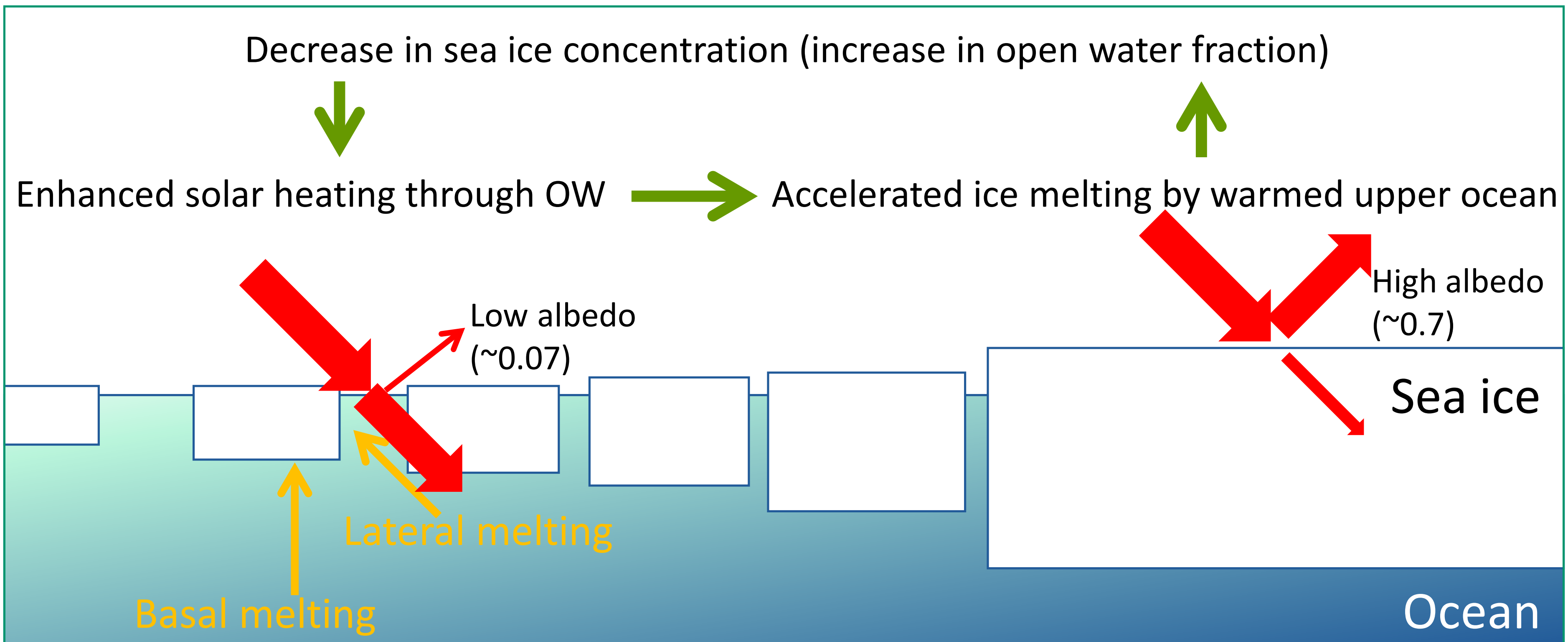
Change in sea ice age in the Arctic Ocean (decrease in MYI)



Stroeve et al. (2012)

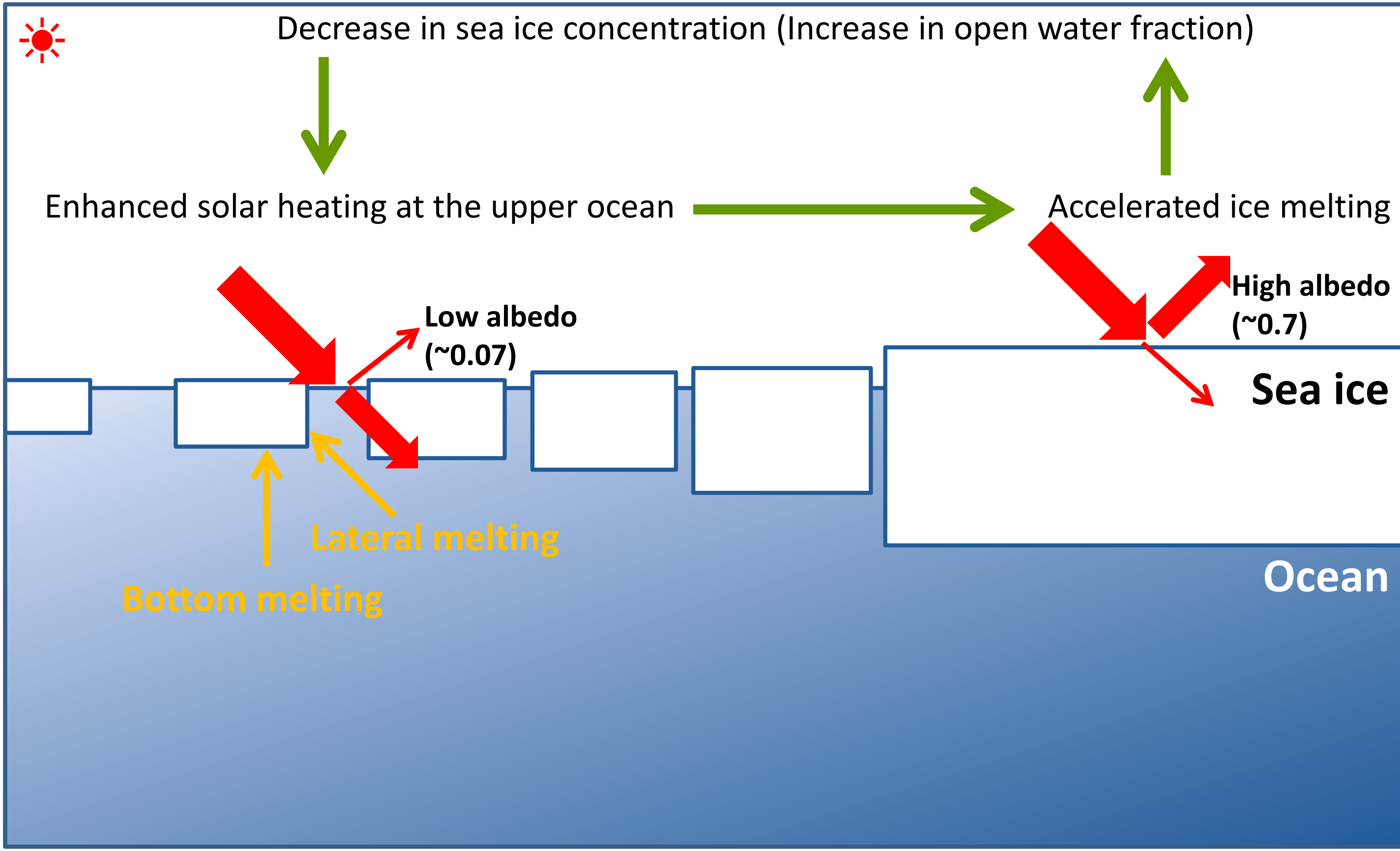
What is the (ice–ocean) albedo feedback effect?

- Albedo is the ratio of reflection to the solar radiation.
- Sea ice (commonly covered with the **white** snow) reflects 60–70 % of the solar radiation, while the **black** open water fraction reflects only less than 10 %.
- Once the ice concentration has reduced, the heat input into the upper ocean is intensified because of its lower albedo. Then, the accelerated ice melt by warmed ocean results more open water fraction and more sea ice melt.
- Such positive feedback is assumed as a key factor of the **"polar amplification"** of global waring. (Note that the quantitative evaluation is still insufficient)



- **In seasonal sea ice zones (Antarctic Ocean and Sea of Okhotsk)**

Ice-ocean albedo feedback triggered by offshore-ward wind (divergent ice motion) controls the seasonal/interannual variation in sea ice melt.



In the Arctic Ocean,

- Is the **necessary condition** for the feedback satisfied?
- What is the **physical process triggering and translating** the feedback?

Focusing on the **Pacific Arctic** where the summer ice extent is drastically reduced.

Data (analysis period: 36 years from 1979 to 2014)

・**Satellite Microwave Radiometer (SMMR, SSM/I)** **Heat Budget**, **Ice Melt Volume**, **Ice Divergence**

Sea ice concentration (Bootstrap algorithm)

Melt onset date（Markus et al., 2009）

Spatial resolution: 25km×25km polar-stereo graphic grid

Temporal resolution: 1day (2days for SMMR)

・**NSIDC Ice Motion Vector** **Ice Melt Volume**, **Ice Divergence**

(based on satellite/buoy observations and meteorological reanalysis)

Spatial resolution: 25km×25km EASE grid

Temporal resolution: 1day

・**NSIDC Sea Ice Age** **Heat Budget (estimation of albedo/pond fraction)**

Spatial resolution: 12.5km×12.5km EASE grid

Temporal resolution: 1week

・**ICESat Sea Ice Thickness** (2003–2008) **Ice Melt Volume**

Spatial resolution: 10m

Temporal resolution: 1season (from Feb to May)

・Meteorological Reanalysis (ERA-interim) **Heat Budget**

Spatial resolution: $1.5^{o}\times1.5^{o}$

Temporal resolution: 1/4day

Overview of the heat budget analysis

- **Heat input into the upper ocean through OW**

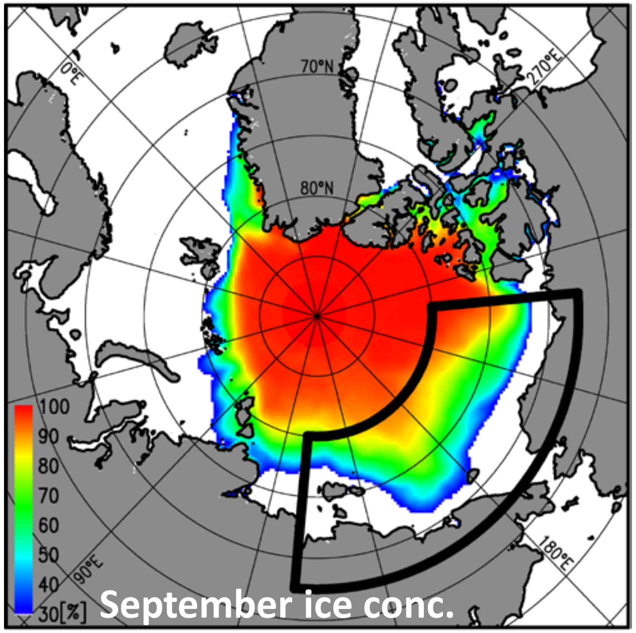
$$Qw = (\sum_n[(1 - C_n)Fw_n\, Sg_n])/Se$$

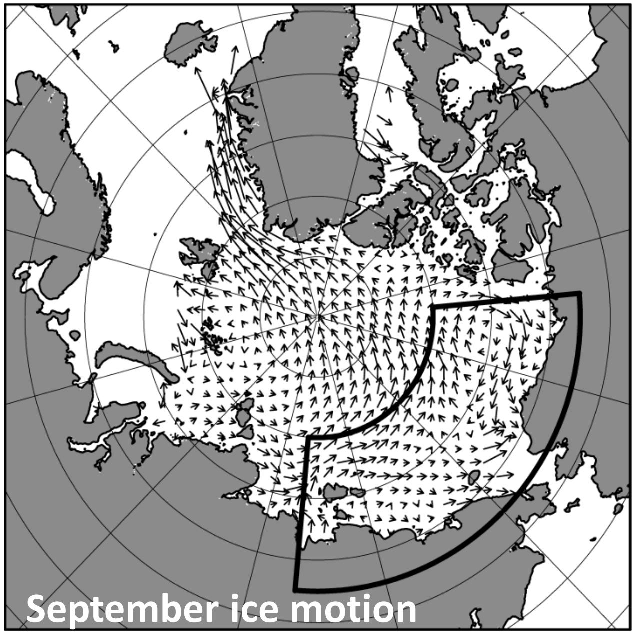
C: Ice concentration
Fw: Net heat flux at the water surface
Sg: Unit grid cell area (≈ 25km × 25km)
Se: Sea ice extent (= $\sum_n Sg_n$)

- **Ice Melt Volume (converted to the equivalent heat)**

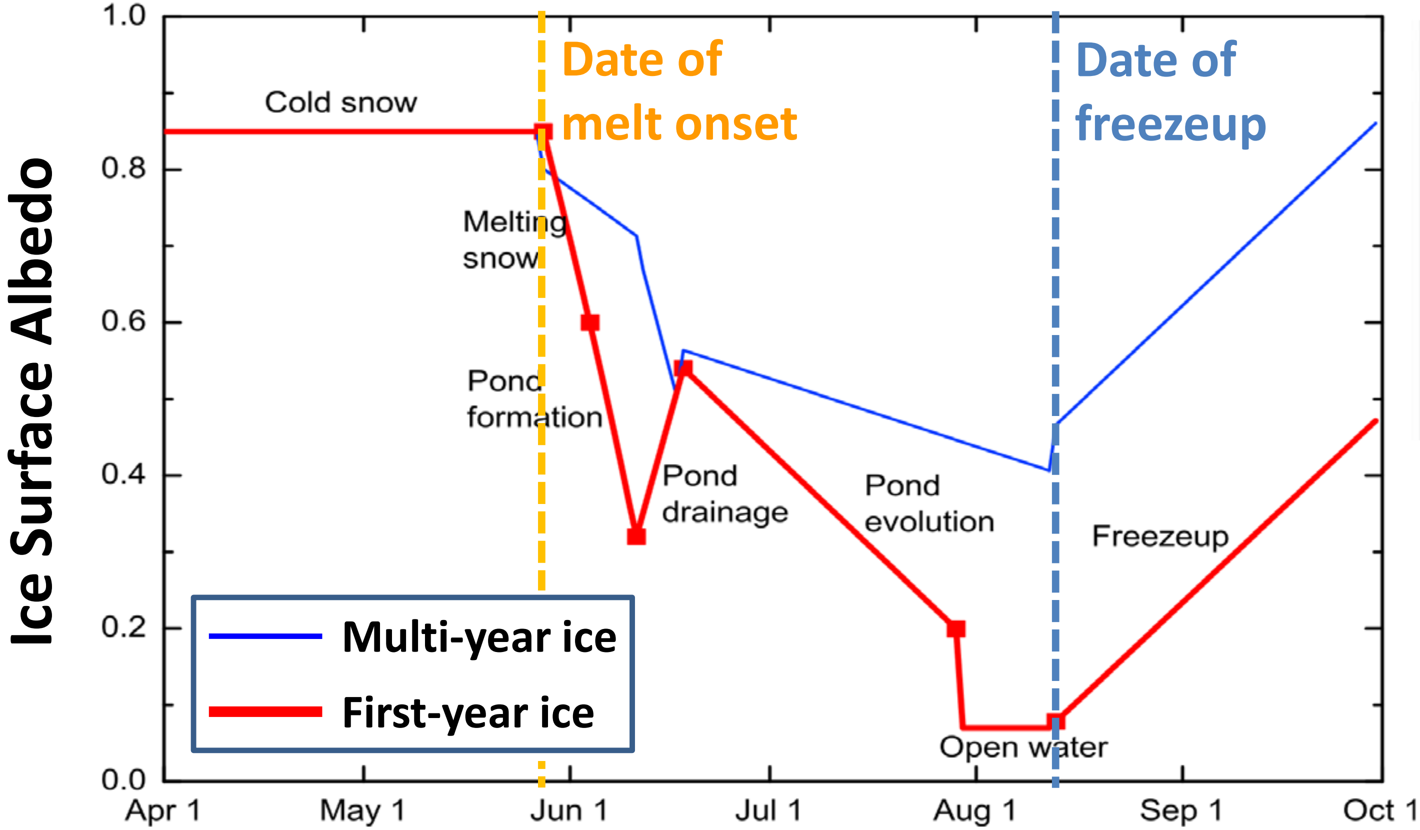
$$Qm = (\rho_i\, Lf\, h_i\, dSa/dt)/Se$$

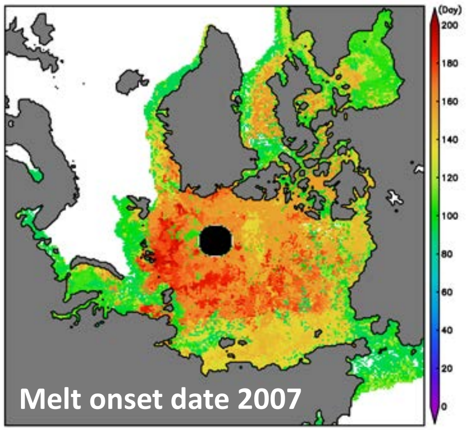
ρ_i: Ice concentration
Lf: Latent heat of sea ice for fusion
h_i: Mean ice thickness (assume a constant thickness of **1m**)
Sa: Sea ice area (= $\sum_n C_n Sg_n$)
dSa/dt: Decrease of ice area (ice export is removed)





◇Parameterization of ice surface albedo





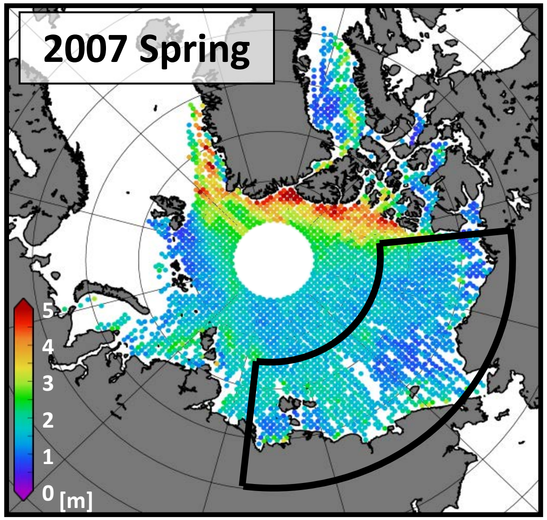
Markus et al. (2009)

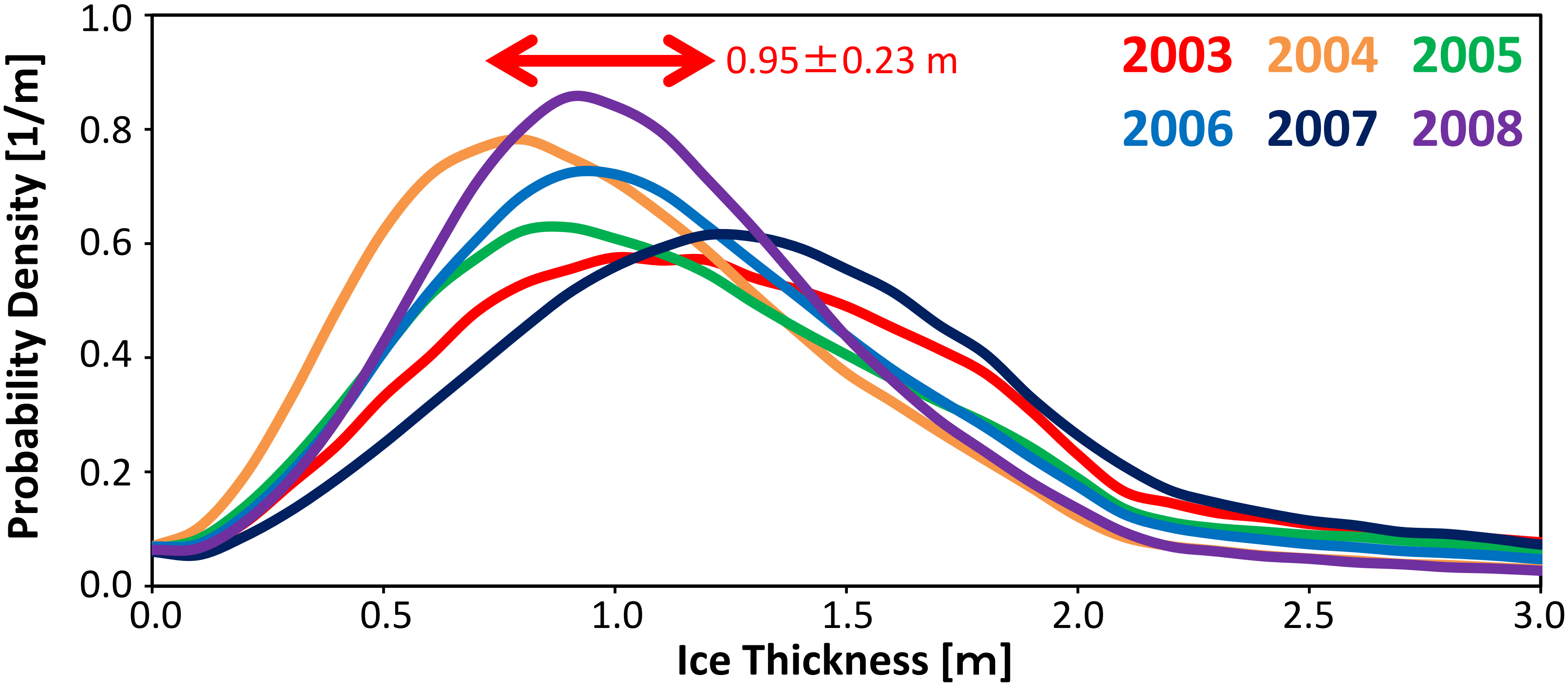
Perovich et al. (2012)

Ice thickness (h_i) from the ICESat observation

- Mean ice thickness in the analysis area is 1.5m.
  However, in fact, approx. 1m-thick sea ice is dominant.
- Assuming that a reduction in ice extent through melt is confined to FYI only.

→Here the value of <u>1m</u> is used as the typical ice thickness for calculation of ice melt volume.





☆Results of heat and ice budget analysis in the ice covered area (ice conc. ≥ 30%)

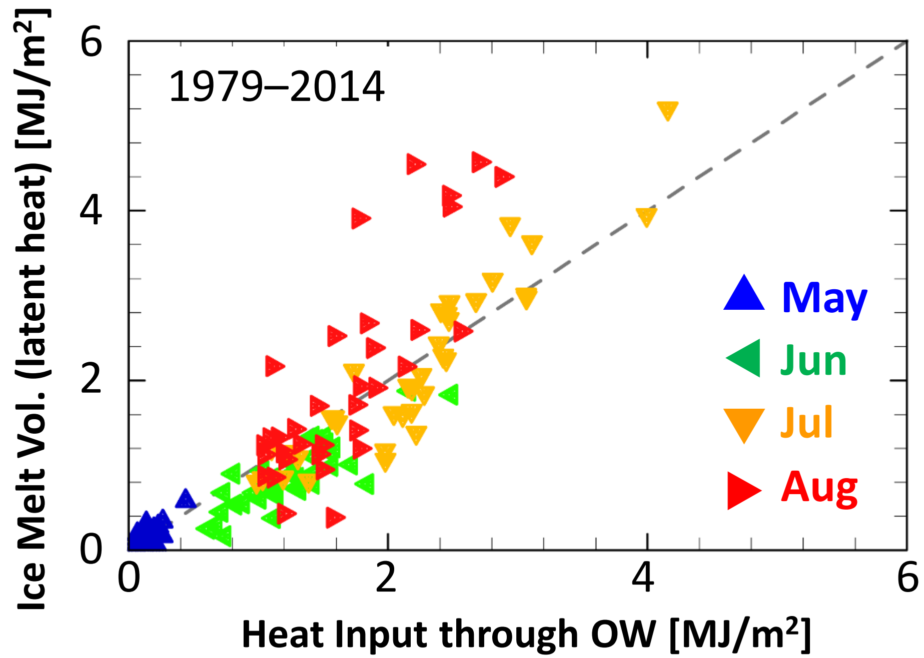
- **Heat input through the open water fraction** corresponds well with the **ice melt volume**.

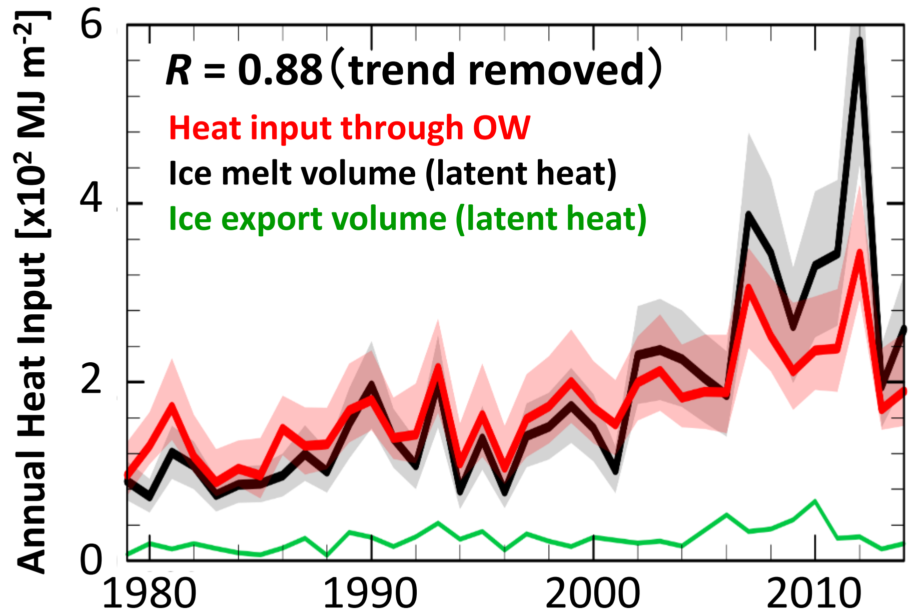
- Ice retreat is mainly explained by the **melting**, and the impact of **ice export** is much smaller.

- The effect of melt ponds is up to ~20 % of the **heat input through OW**.

→**Melting** caused by **heat input through OW** (mainly due to the solar radiation) controls sea ice retreat.

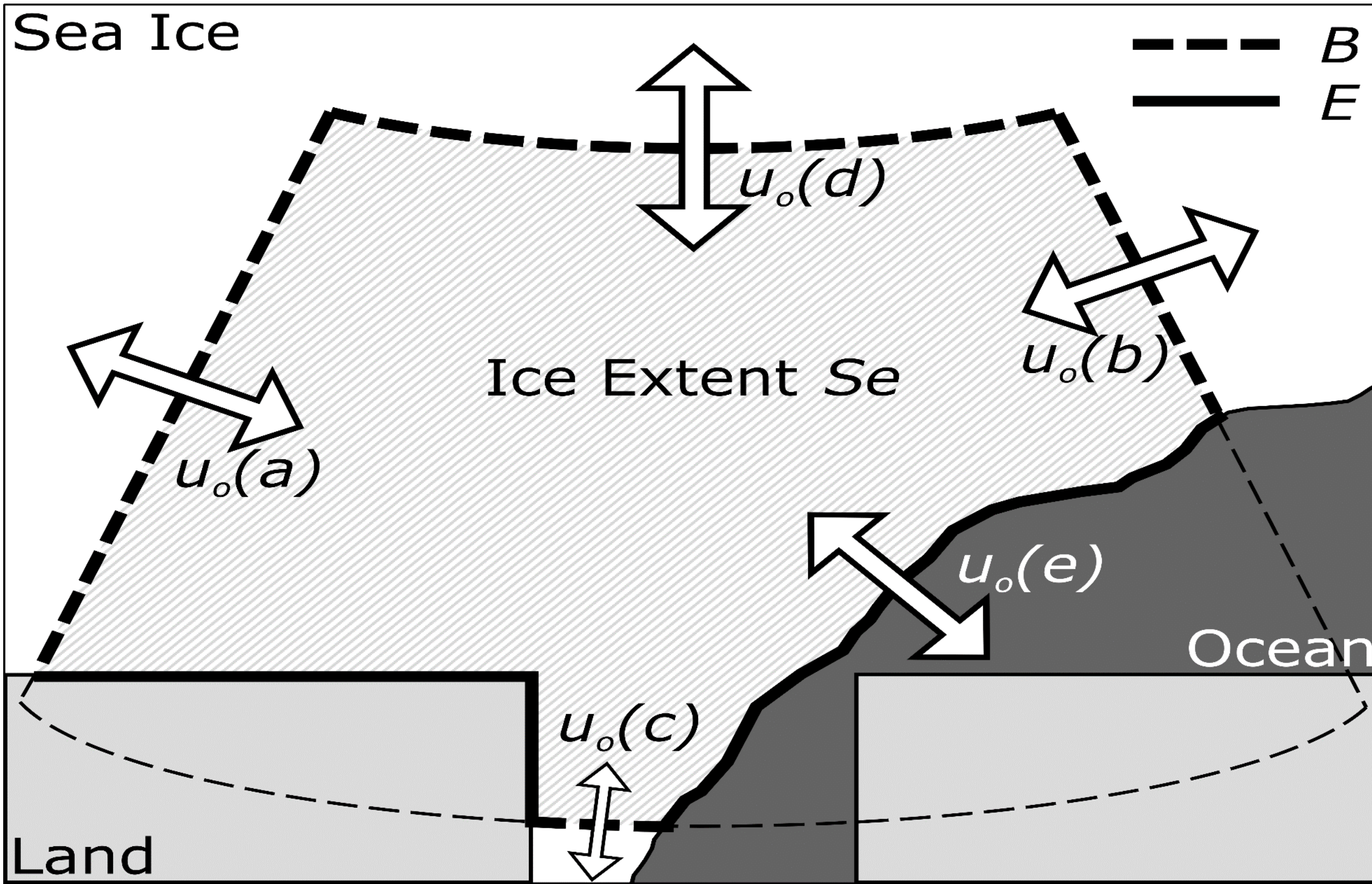
⇒**Necessary condition for the ice-ocean albedo feedback is satisfied!**





- To explore the specific trigger of the feedback effect, **sea ice divergence (*Div*)** is determined as the ice area export from the boundary (*B*) and ice edge (*E*) divided by ice extent (*Se*).

$$Div = (\int_B C\, u_o\, dl + \int_B C\, u_o\, dl)/Se$$

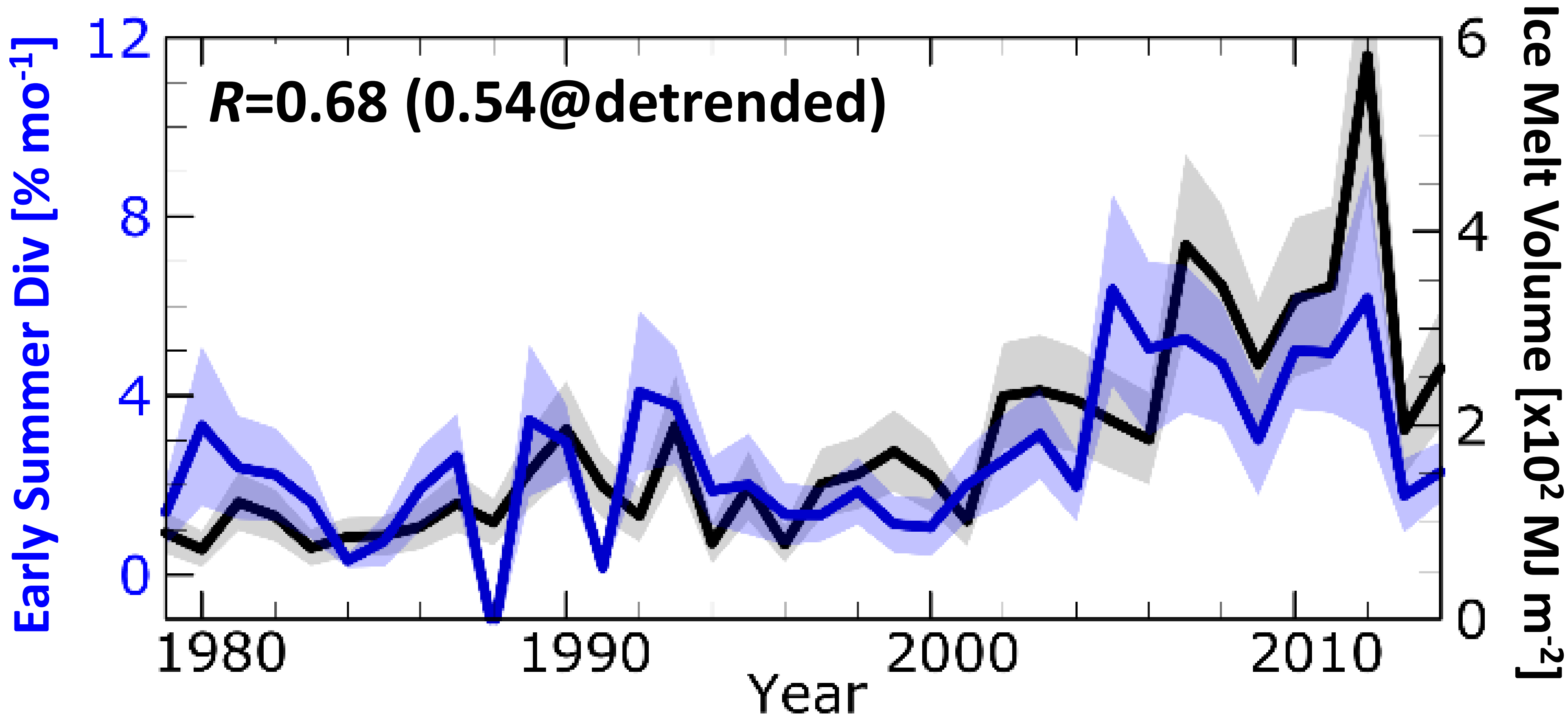


Early Summer *Div* (mid-May to early-Jun) vs. Ice Melt Volume

- ***Div* in the early summer** corresponds well with the 1-2 months lagged ice melt volume and thus the **annual value of *Qm***.

The albedo feedback enhances the subsequent ice melt within a couple of months.

※An increasing trend is apparent after the 2000s.

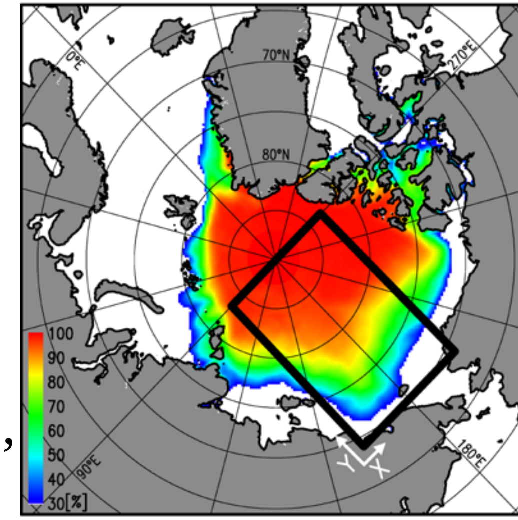


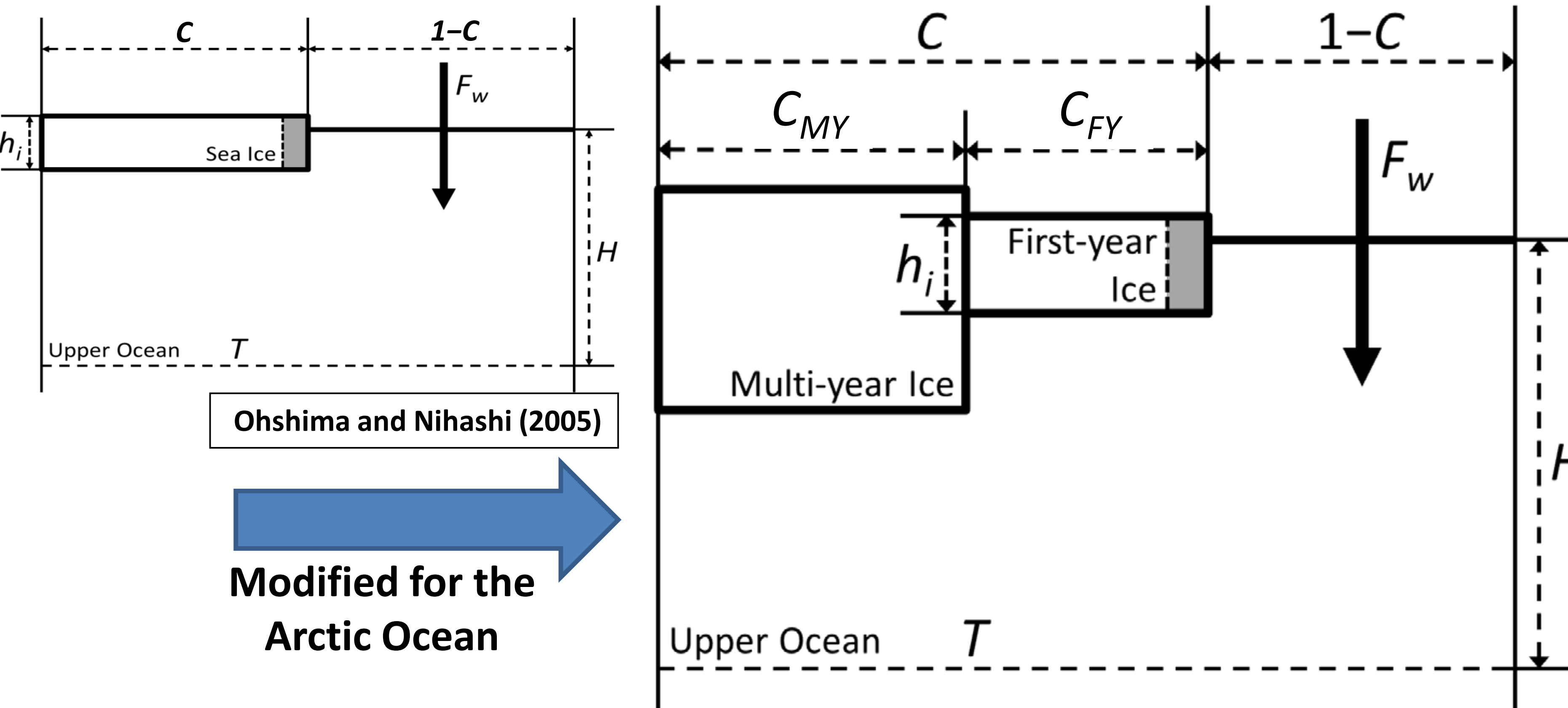
Representation of the feedback using a simplified model

- Y-axis–Time evolution of ice retreat is reproduced by a simplified ice-ocean coupled model.

→Quantifying the enhancement of ice melt by divergent ice motion through the feedback effect.

※Based on the model used by Ohshima and Nihashi (2005), **MYI distribution** is introduced to represent the Arctic Ocean.

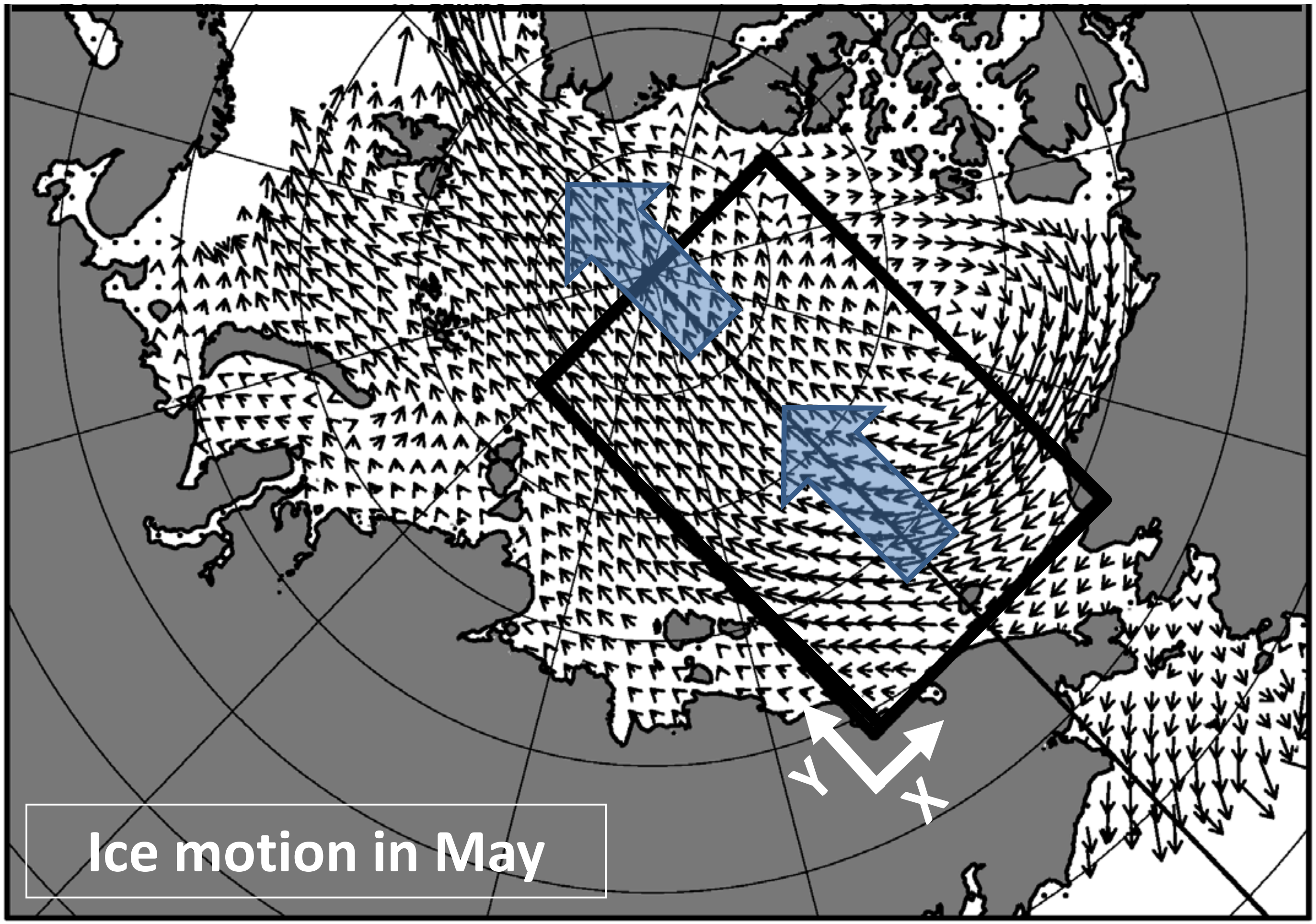


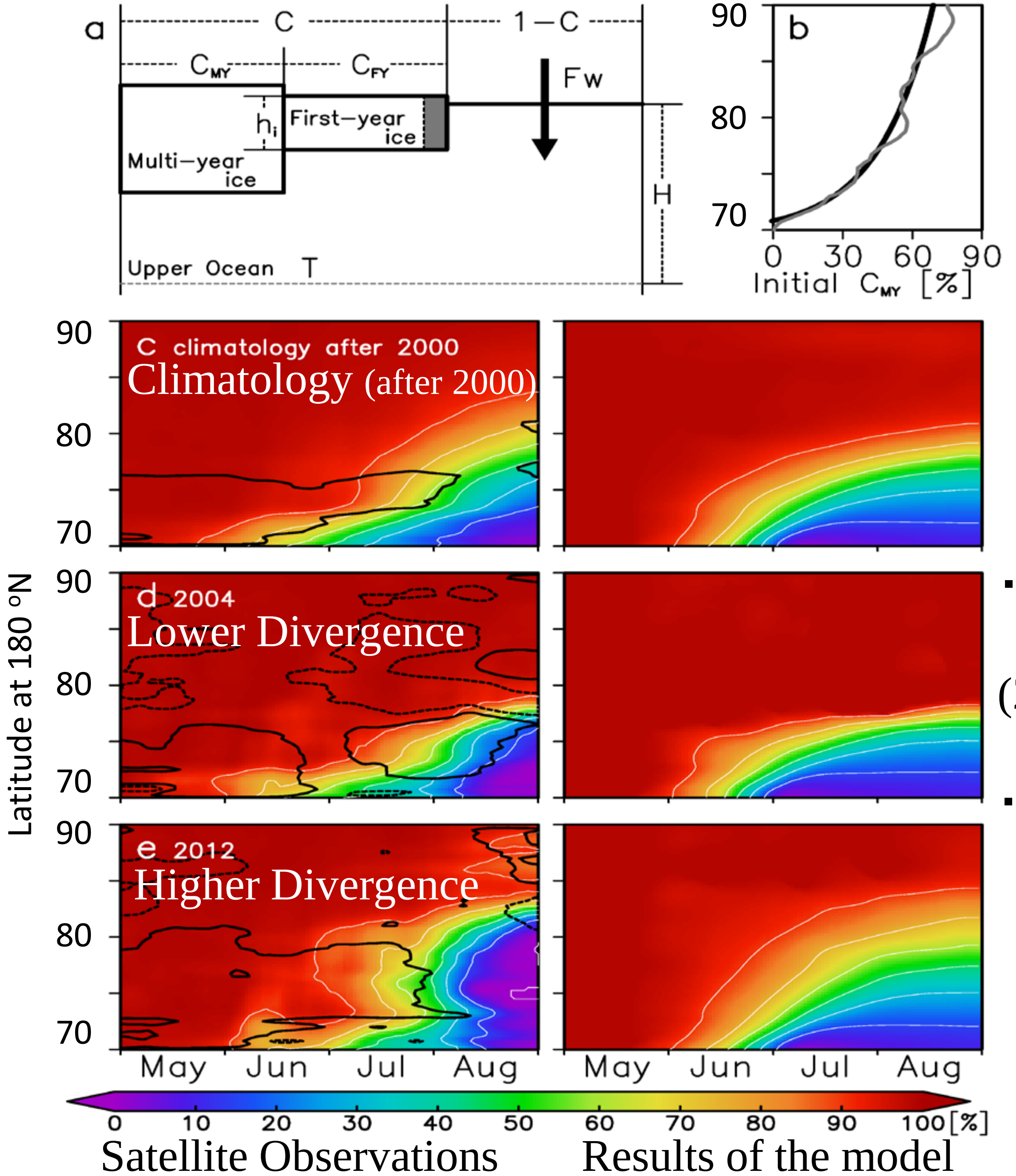


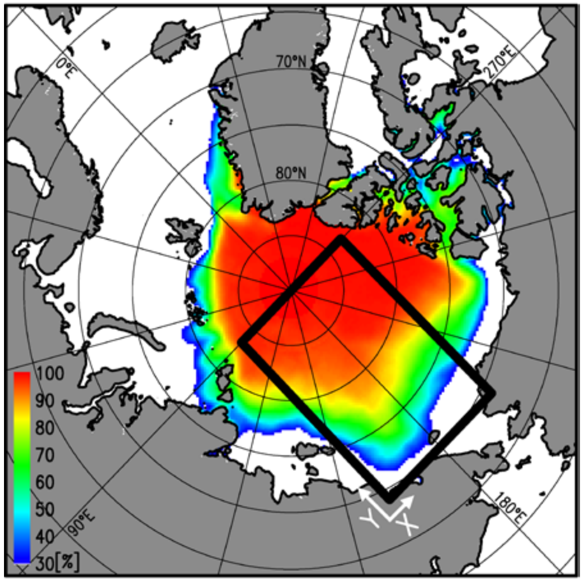
- The effect of ice motion is introduced to the model as,

$$dC/dt = -a_0\, C_{FY}\, (T - T_f)/h_i - U\, \partial C/\partial y + A_H\, \partial^2 C/\partial y^2 + \psi_C$$

Melting of ice | **Advection of ice** | **Horizontal diffusion** | **Ice resistance (internal stress)**

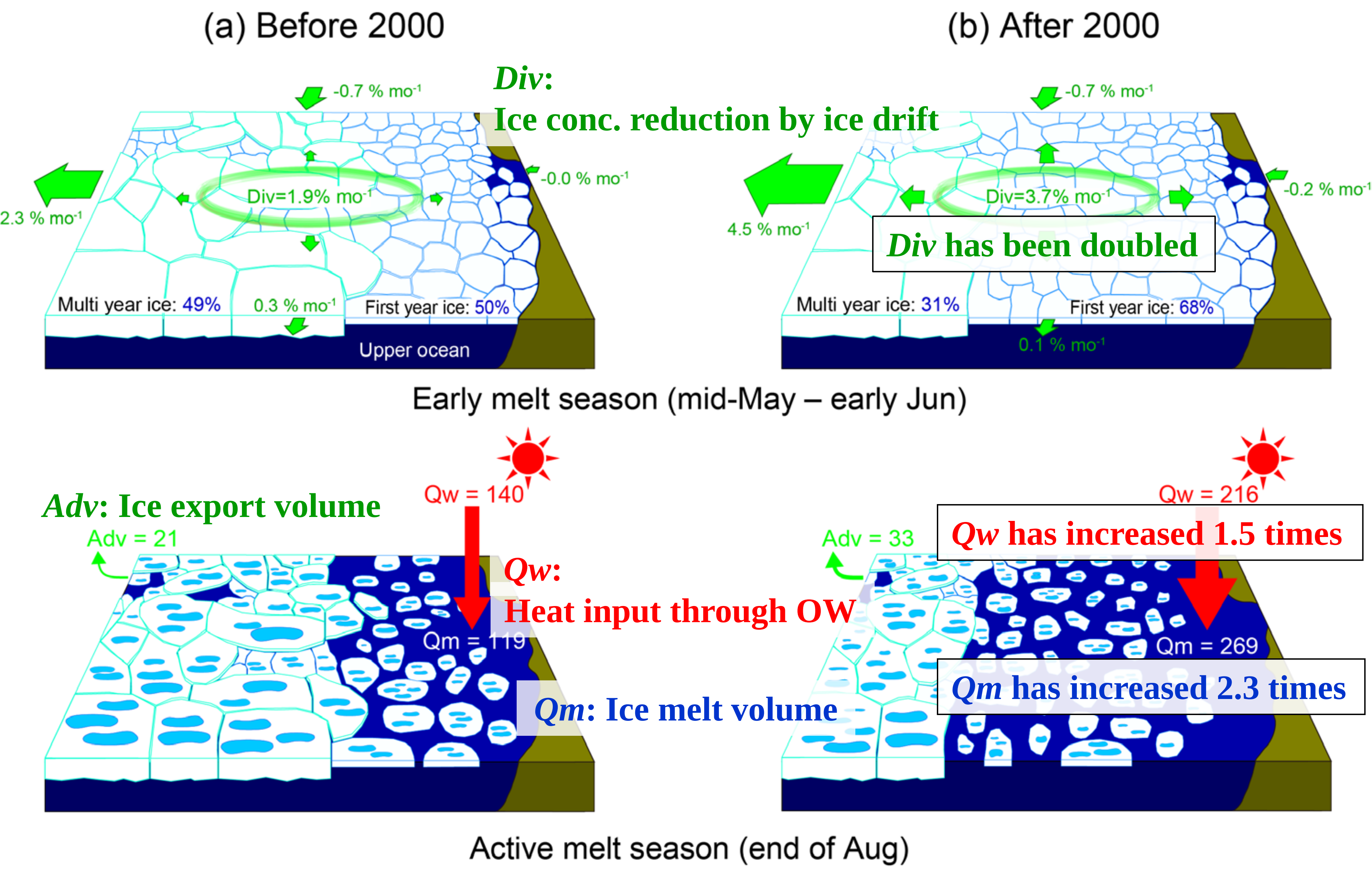






- **<u>Heat input through OW</u>** is the only heat source for **<u>ice melt</u>**. (2-dimensional ice retreat model)

- **<u>Effect of *Div*</u>** is introduced by using ice drift data obtained from satellite observations.



Drastic reduction of summer Arctic sea ice

Summary

○Ice-ocean albedo feedback has received increasing attention in the context of drastic sea ice reduction in the Arctic Ocean shifting to a seasonal ice cover.

○Heat budget analysis shows that the ice retreat is mainly explained by ice melting, and it corresponds well with the heat input through the open water fraction.

→**Heat input through OW is the primary driver of seasonal and interannual variations in Arctic ice retreat.**

○Divergent ice motion in the early melt season indicates a significant correlation with ice retreat lagged by 1-2 months and also the annual value of ice melt volume.

○A simplified model indicates that divergent ice motion accelerates the ice retreat through the enhanced ice melting.

→**Divergent ice motion can be a trigger of ice retreat through the ice-ocean albedo feedback.**

○From the comparison between before and after 2000, increased heat input through OW (through a doubled ice divergence) explains roughly 70 % of the observed 2.3-fold increase in sea ice melt volume.