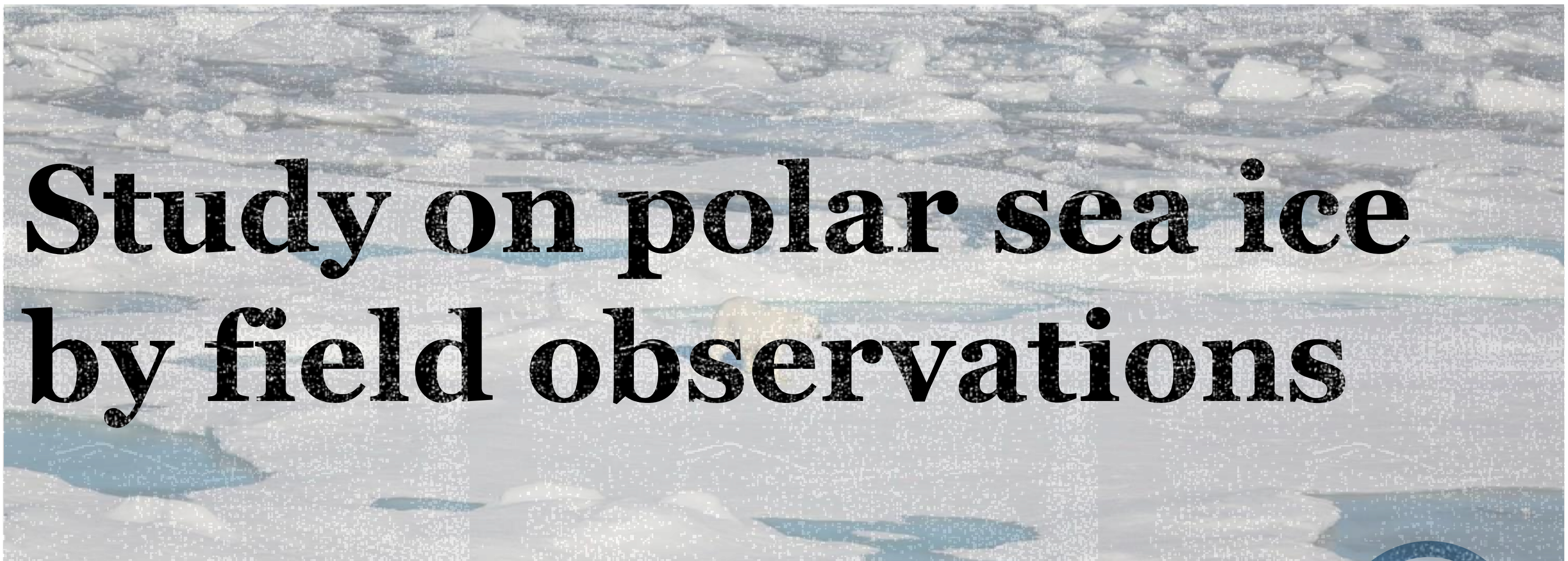

Study on polar sea ice by field observations

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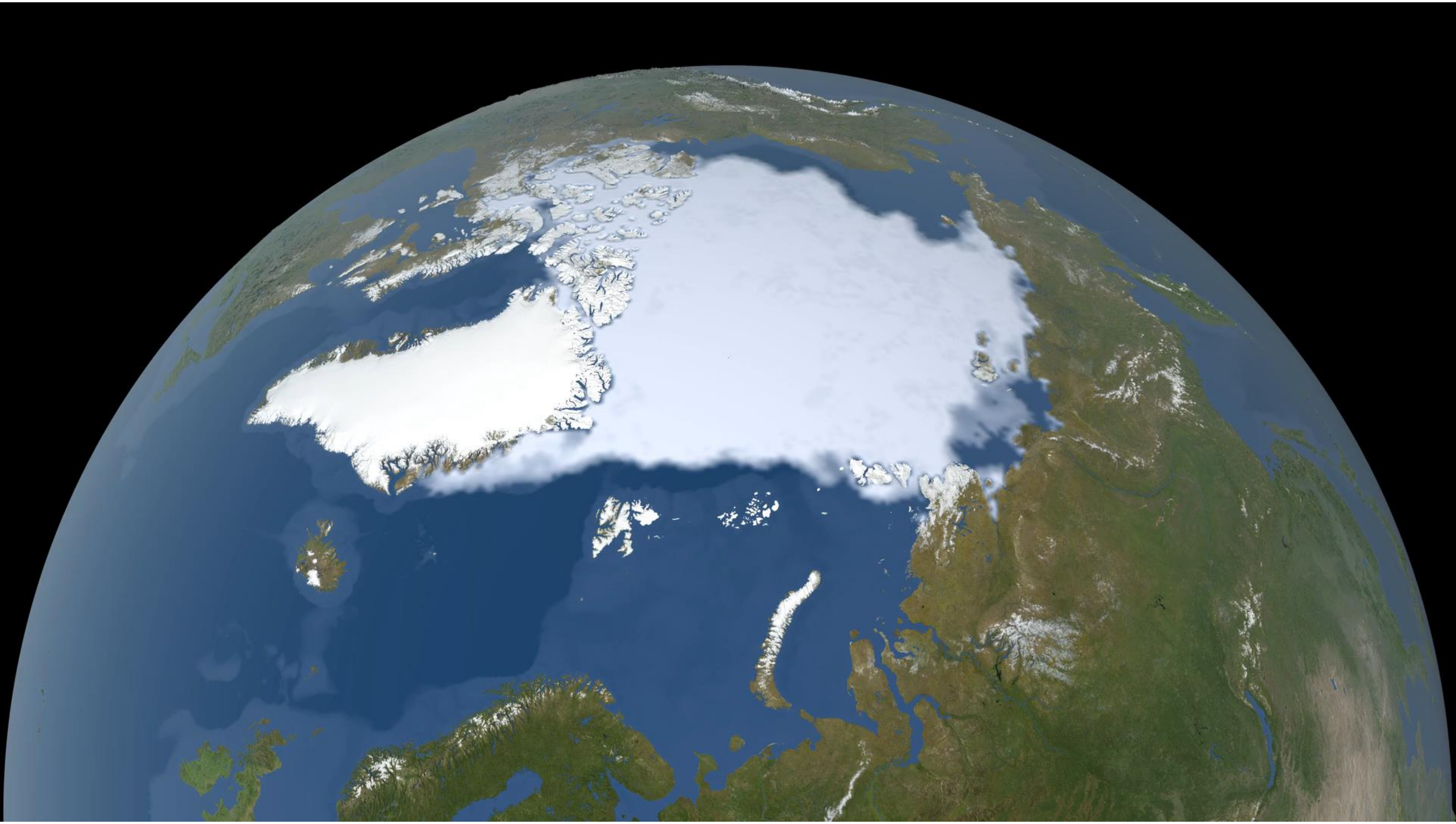
2024.08.16

Contents

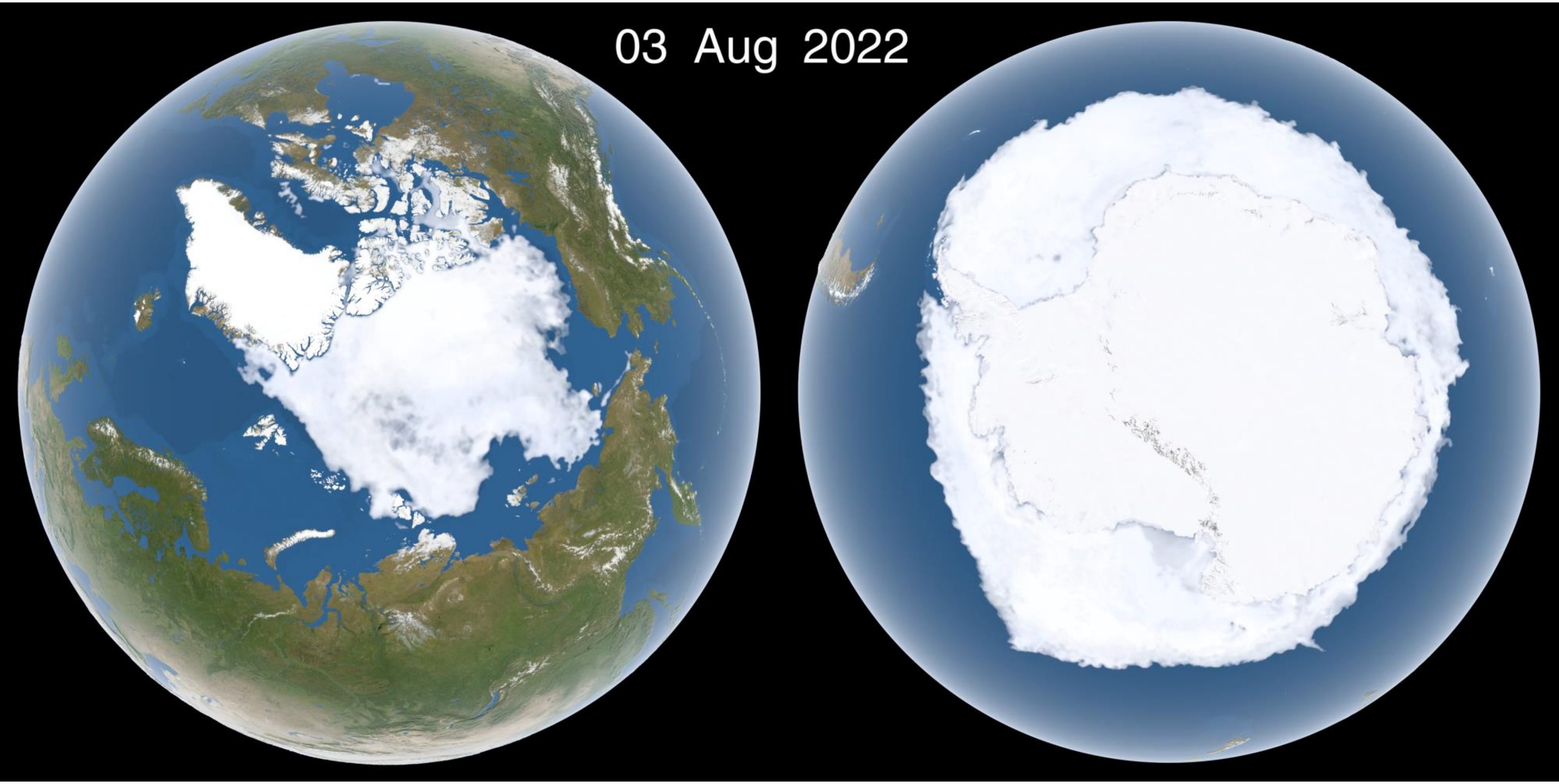
- Scientific background
- Airborne and shipborne observations
  - Sea ice distribution
- Sea ice physics observations
  - Sea ice microstructure
- Melt pond observations
  - Melt pond optics
- Sea ice mechanical observations
  - Sea ice engineering
- Discussions

1. Background

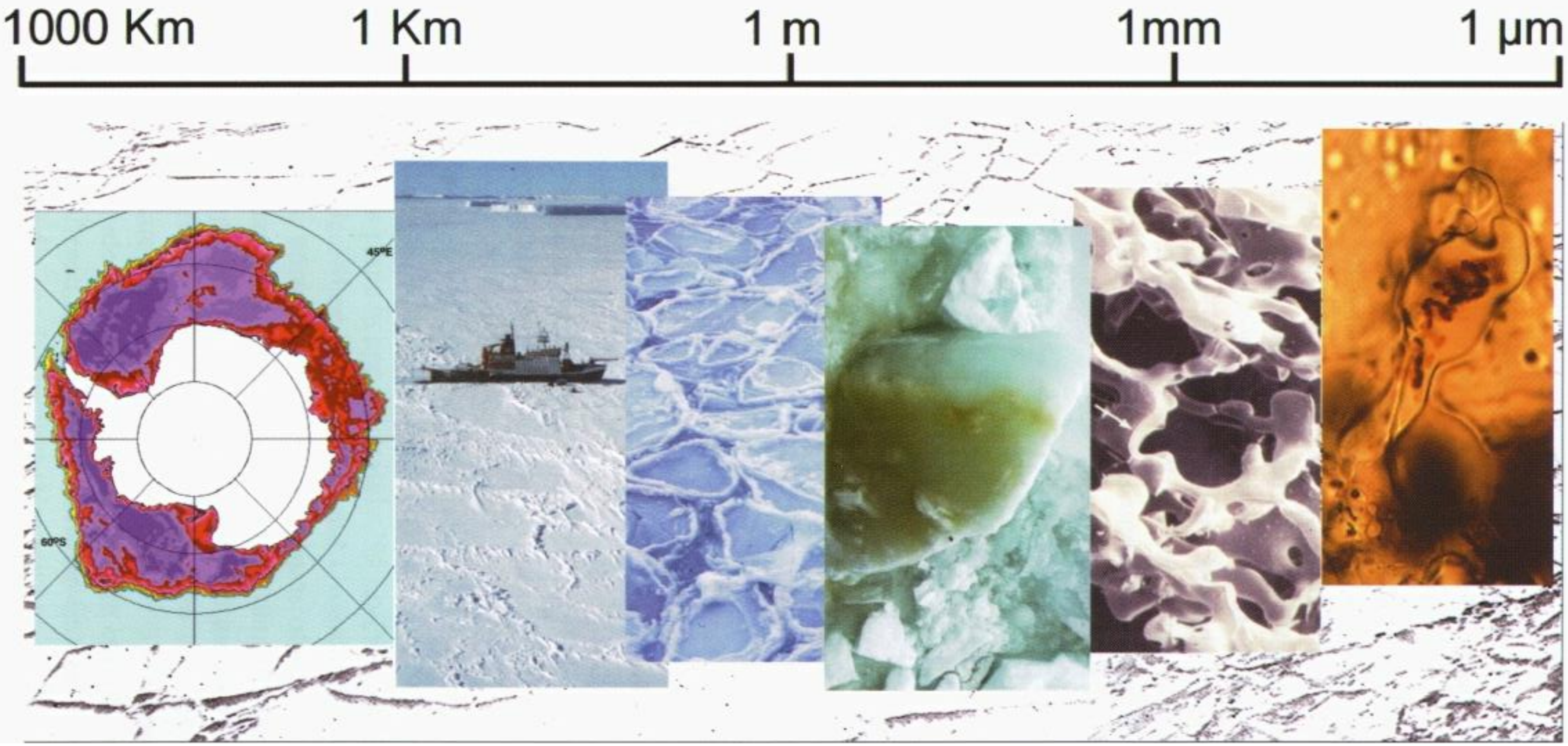


Arctic sea ice change from NASA

Arctic vs Antarctic sea ice



Spatial scale of sea ice

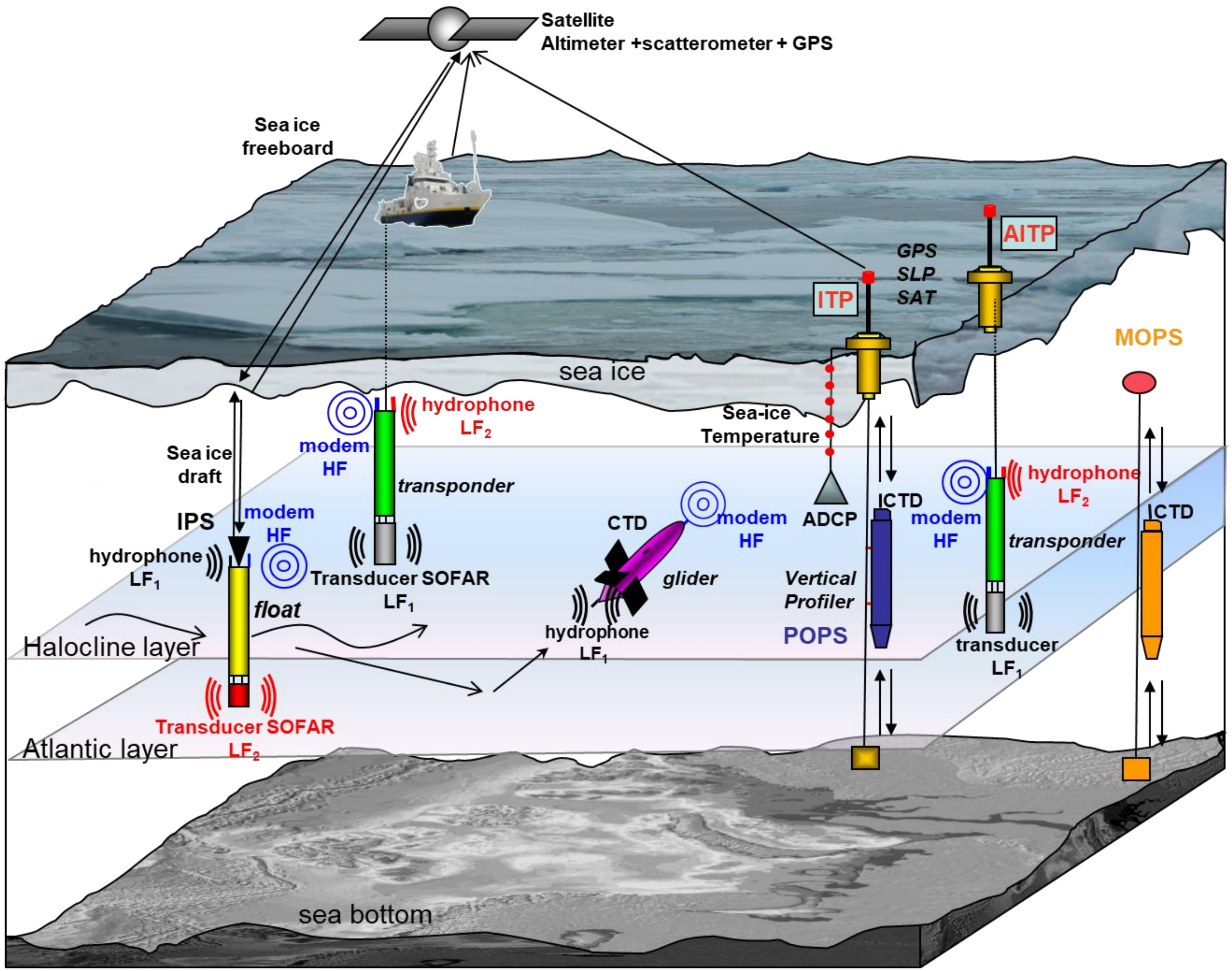


Research on sea ice spans several orders of magnitude, from the molecular and microscopic level to satellite images taken from space.

Shown from right to left are diatoms, a diatom chain in a brine pocket, cast of brine channel system, sea ice floe tainted brown by diatoms, pancake ice, the ice breaker in a pack ice field and satellite image of Antarctic sea ice.

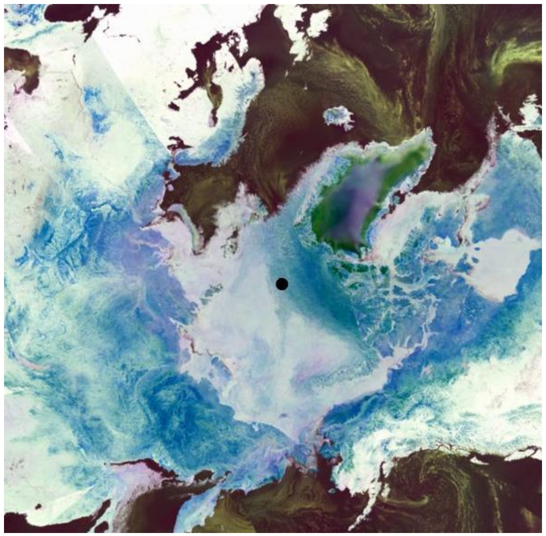
From Hajo Eicken, “Geophysics of Sea Ice”

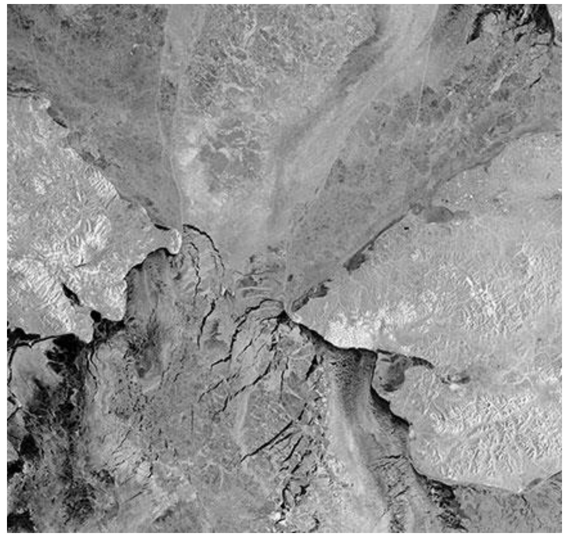
Method: Field observations

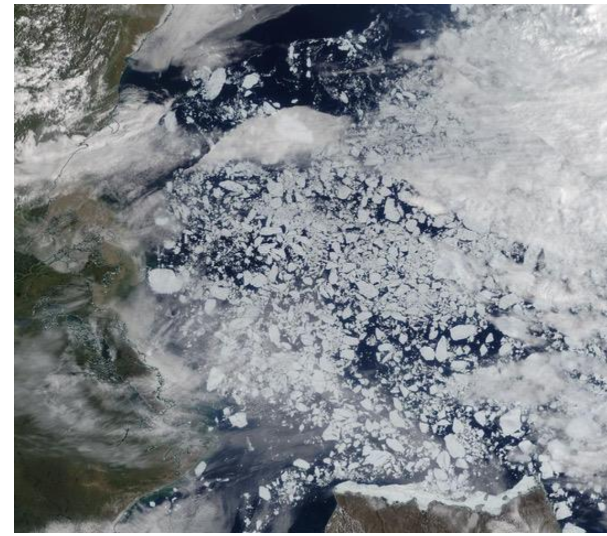


Sea ice in-situ observation system

Method: Remote sensing







Passive microwave RS

- ✓ Low resolution
- ✓ Long time series
- ➢ Ice concentration
- ➢ Thin ice thickness

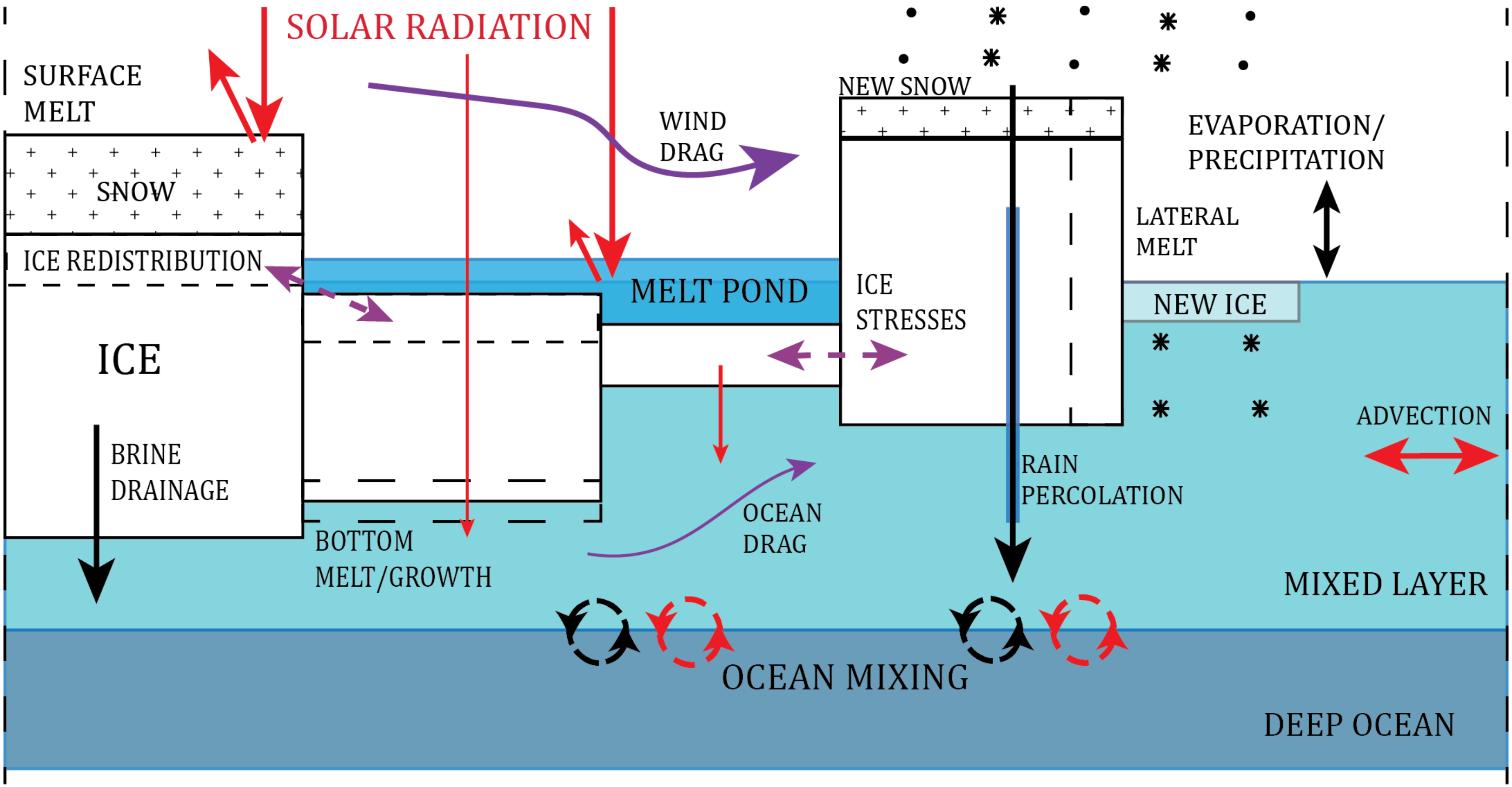
Synthetic Aperture Radar RS

- ✓ High resolution
- ✓ High cost
- ➢ Ice thickness
- ➢ Ice drift velocity

Visible light RS

- ✓ Moderate resolution
- ✓ Weather affect
- ➢ Ice concentration
- ➢ Surface melt pond

Method: Numerical modeling



Air-ice-ocean interactions in numerical models

Method: Laboratory experiment

Ice loads on offshore structure

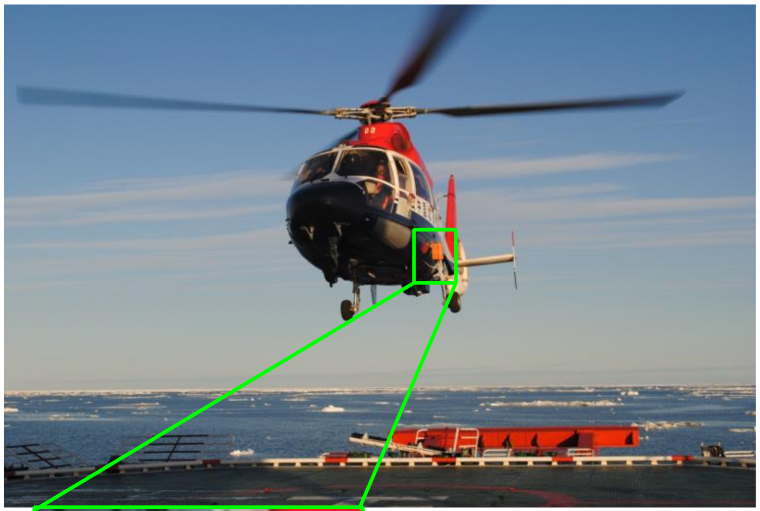
Ice-ship interaction

- Model ice
  - Non-breakable ice
  - Breakable ice
    - Frozen ice
      - Columnar ice
      - Granular ice
    - Non-frozen ice

Field observations on sea ice

- Airborne photography
- Shipborne observations
- Ice physics observations
- Melt pond observations
- Ice mechanical observations

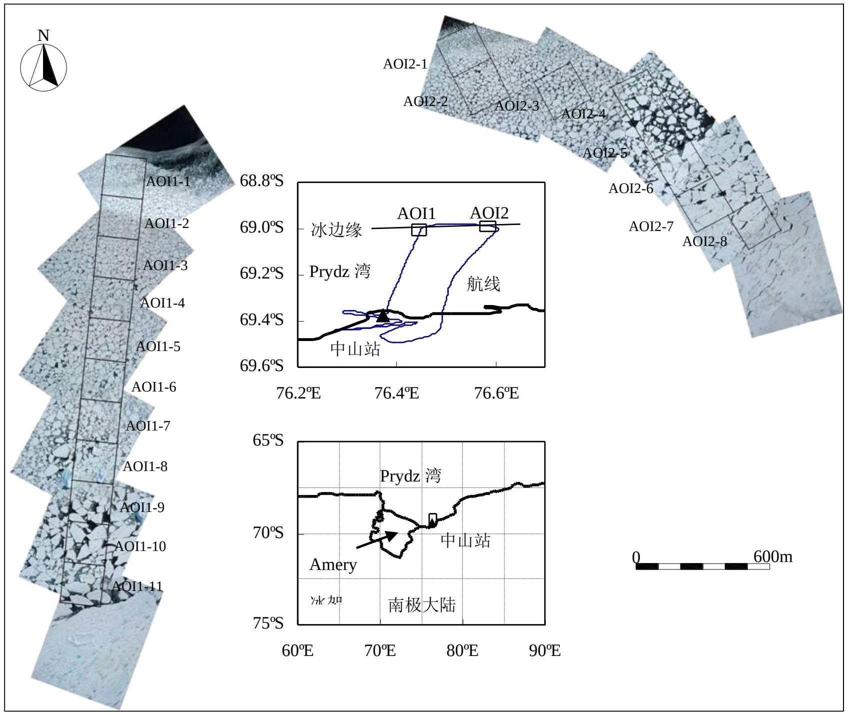
2. Airborne photography



Digital camera
onboard helicopter

Unmanned aerial
vehicle (UAV)

Example 1: Floe size distribution in MIZ



Aerial photographs of sea ice in the MIZ. The areas of interest are the squares in the two merged transects of the MIZ near the Zhongshan Station, Antarctica

Lu and Li, et al. 2008. JGR

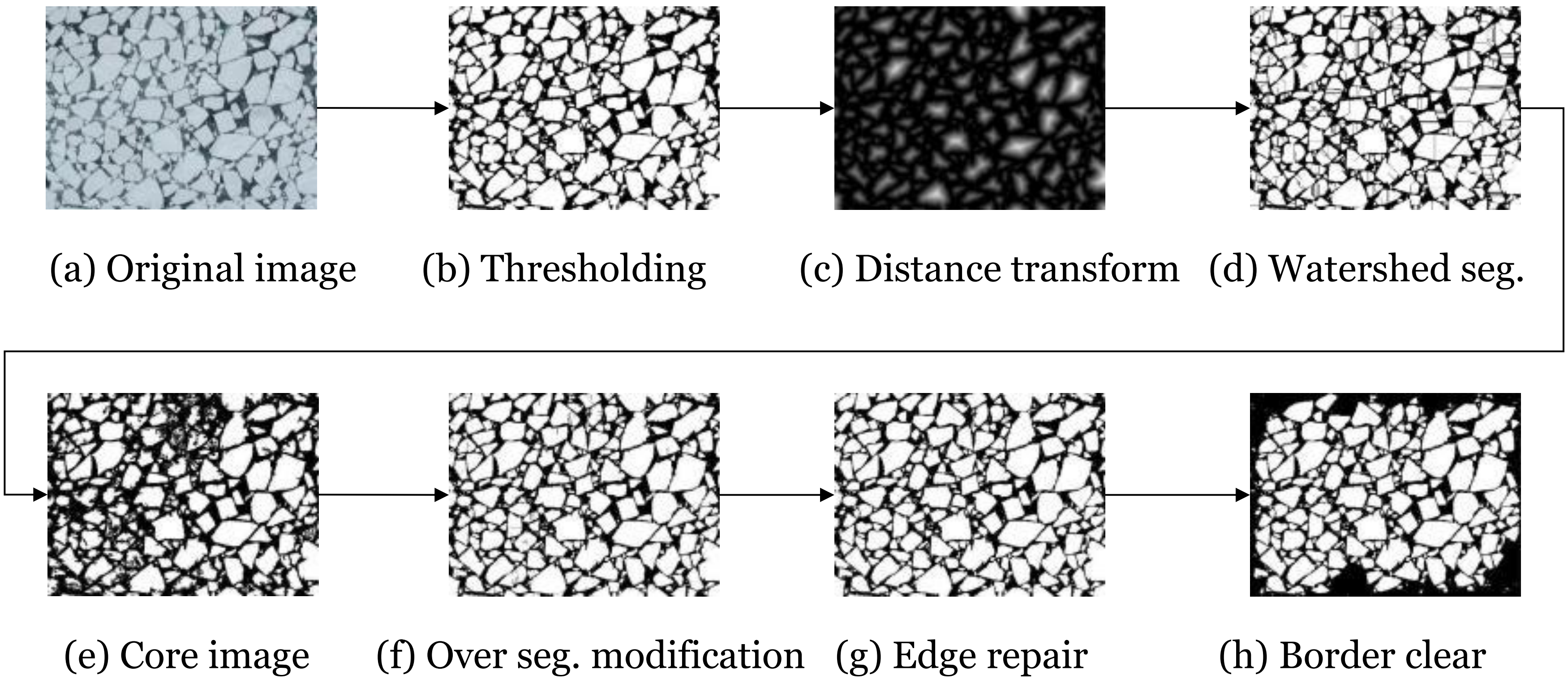
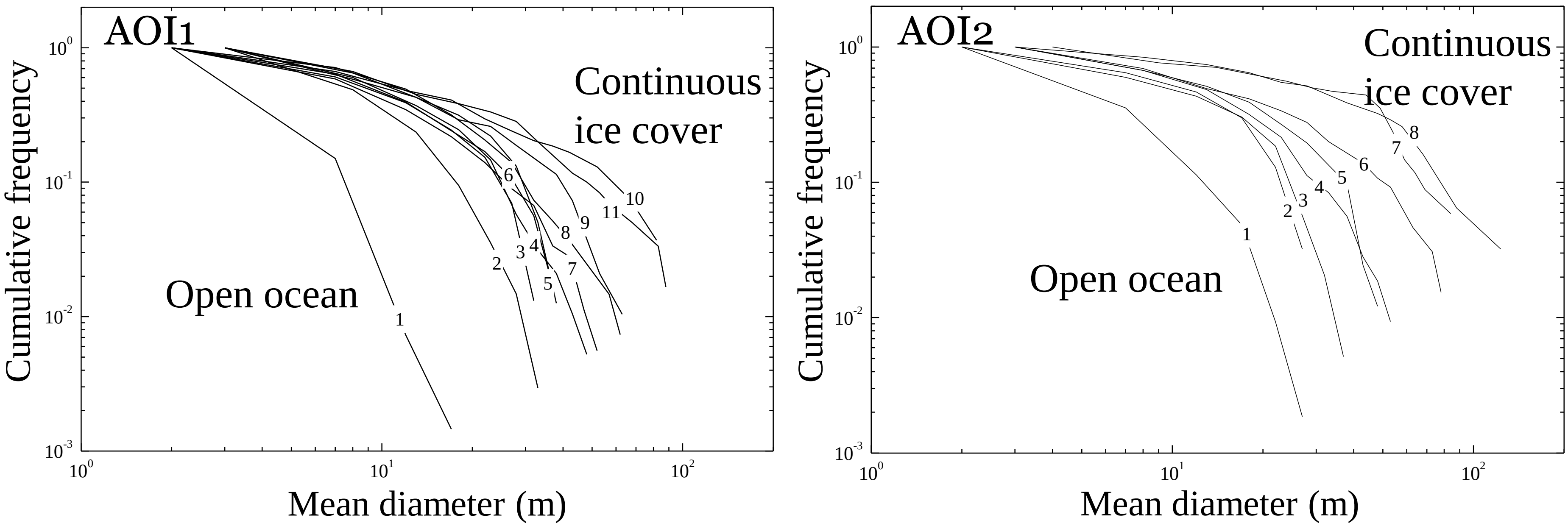


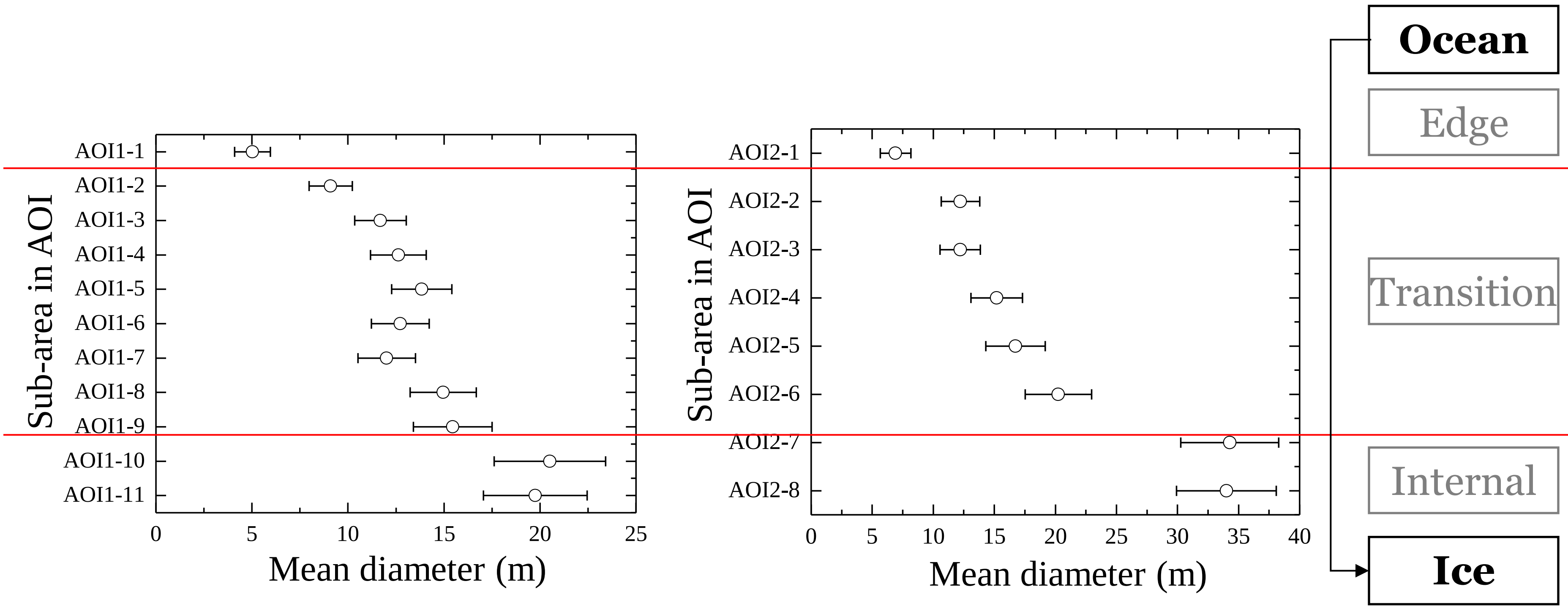
Image processing steps to obtain floe size distribution



Floe size distribution in the marginal ice zone

☞In each AOI, the minimum size of ice floe is basically the same, but the maximum size increases with the distance from open water.

☞The cumulative frequency distribution function shows a regular deviation from open water to continuous ice layers.



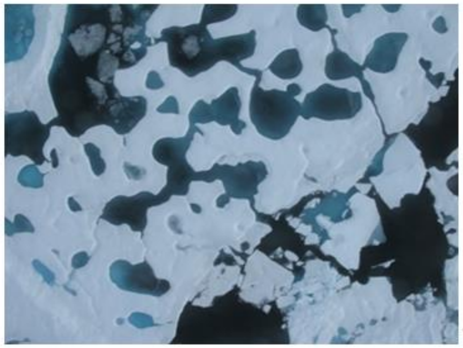
Zonal Structure of the MIZ revealed by a multiple comparison procedure

☞Wave energy in the edge zone is large, the sea ice is broken strongly, and the size is small.

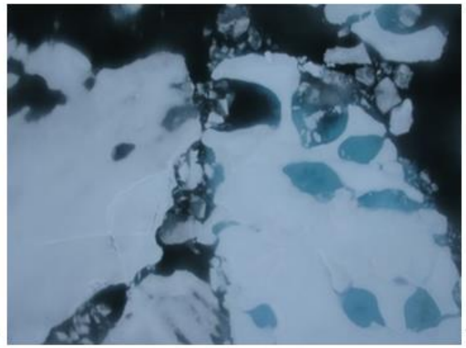
☞The wave energy in the transition zone has been greatly consumed, and the size is moderate. Ice friction becomes an important factor.

☞Most of the wave energy within the internal band has dissipated completely, leaving behind long-period waves. Large sea ice size.

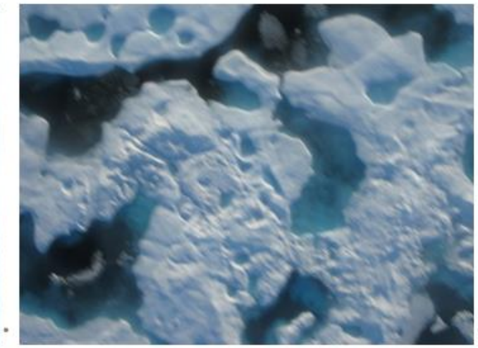
Example 2: Arctic sea ice distribution



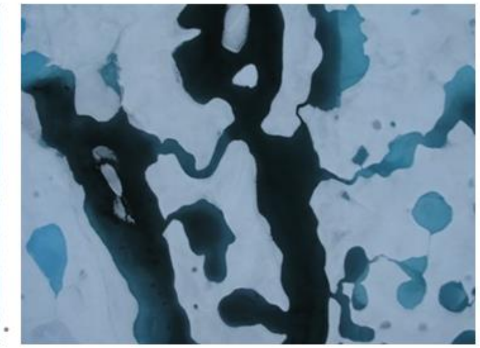
(a) 17 August, 113m



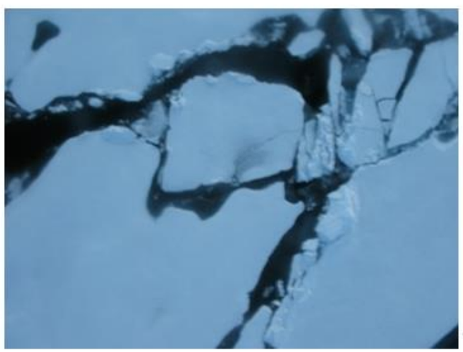
(b) 18 August, 72m



(c) 19 August, 87m

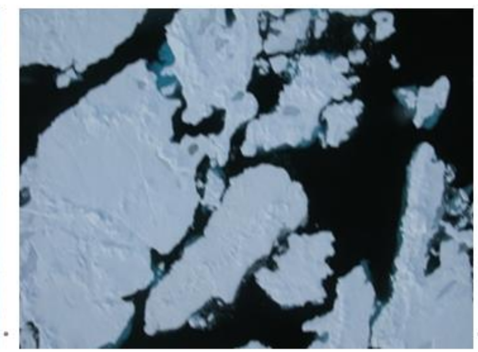


(d) 20 August, 94m

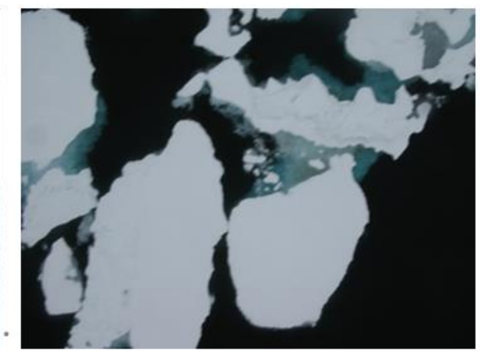


(e) 30 August, 71m

(f) 31 August, 25m



(g) 4 September, 123m



(h) 5 September, 62m

Aerial sea ice photographs selected from each flight during CHINARE2008. Capture dates and altitudes are assigned for each photo.

Lu and Li, et al. 2010. RSE

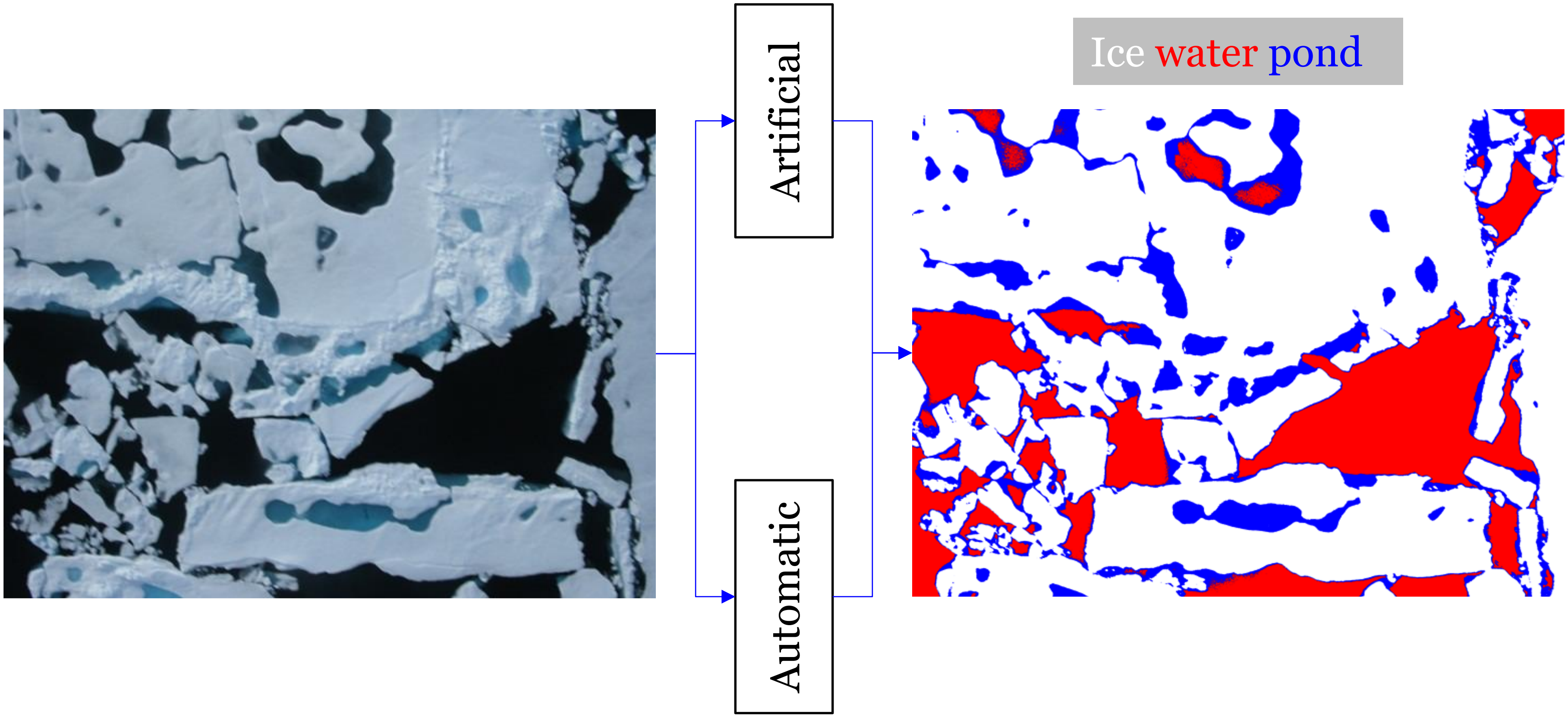
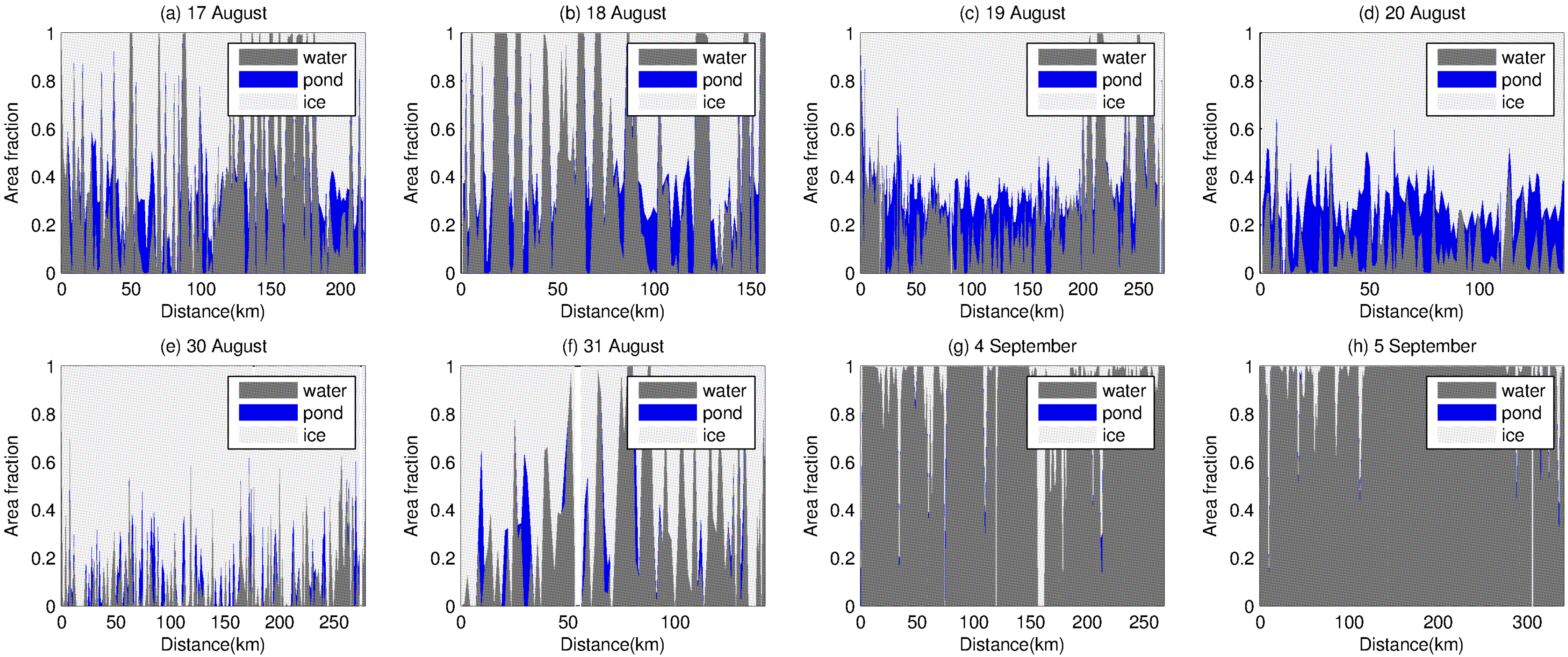
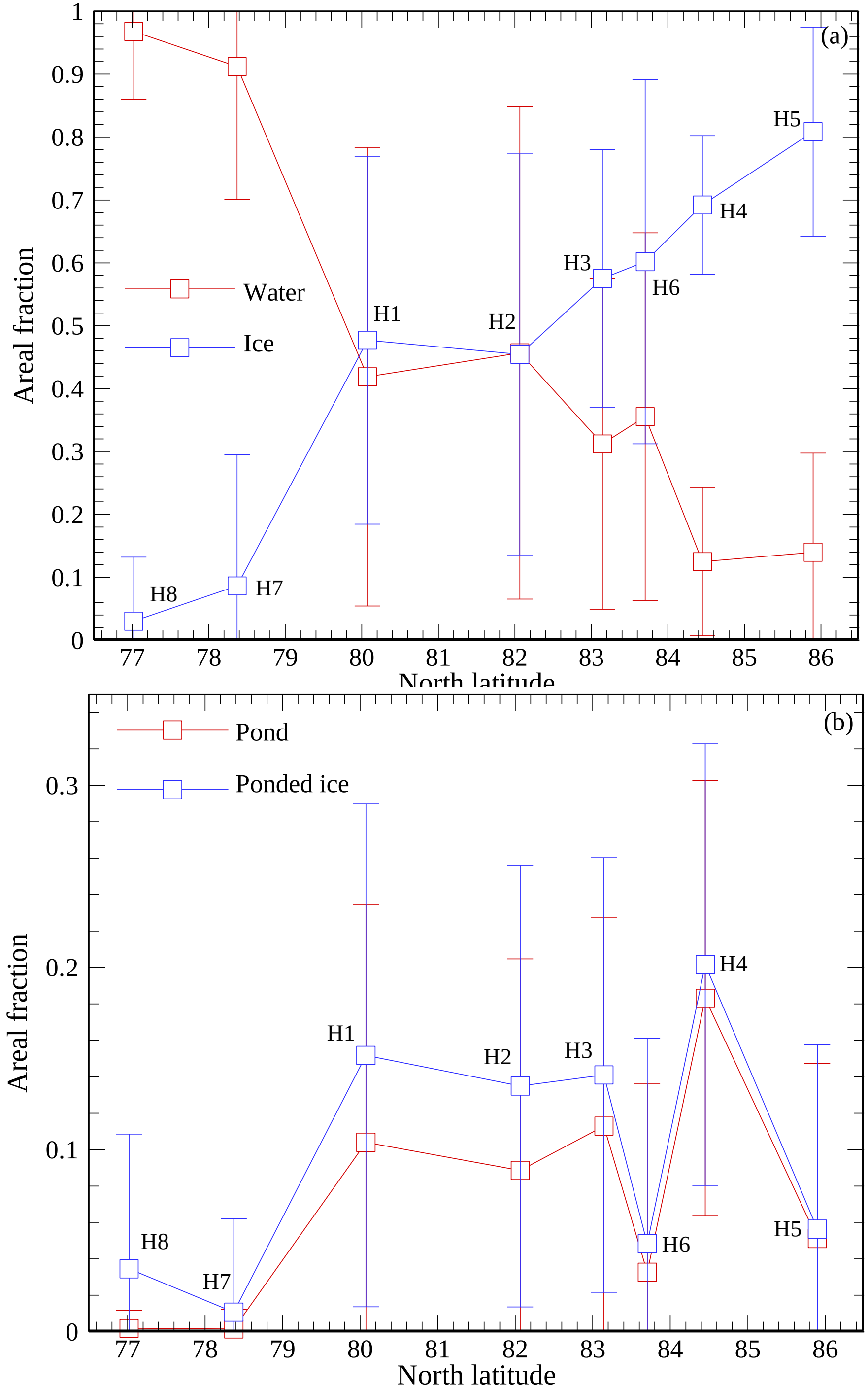
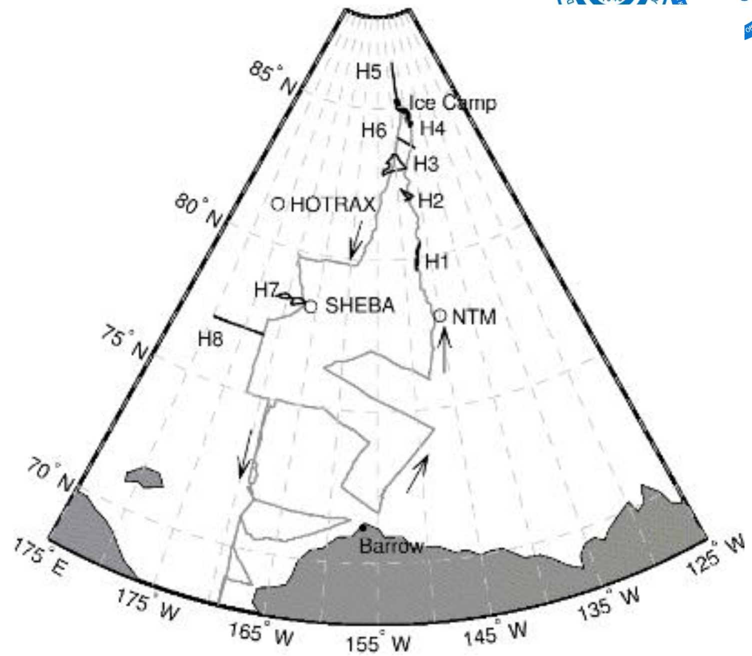


Image processing for photos with melt ponds on ice surface

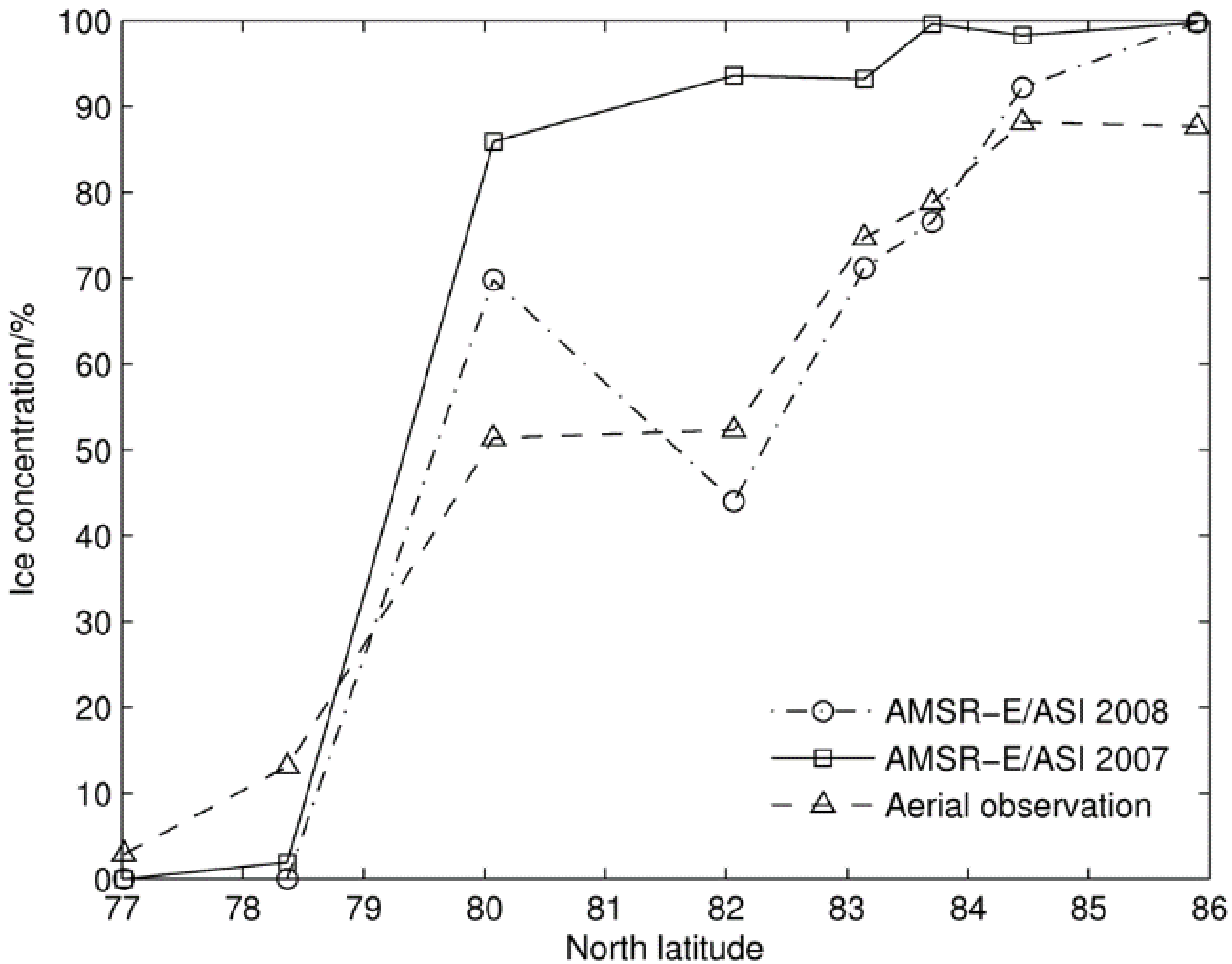


Area fractions of water, pond, and ice along the aerial survey flight path during CHINARE2008. The x-axis refers to the total distance of each flight



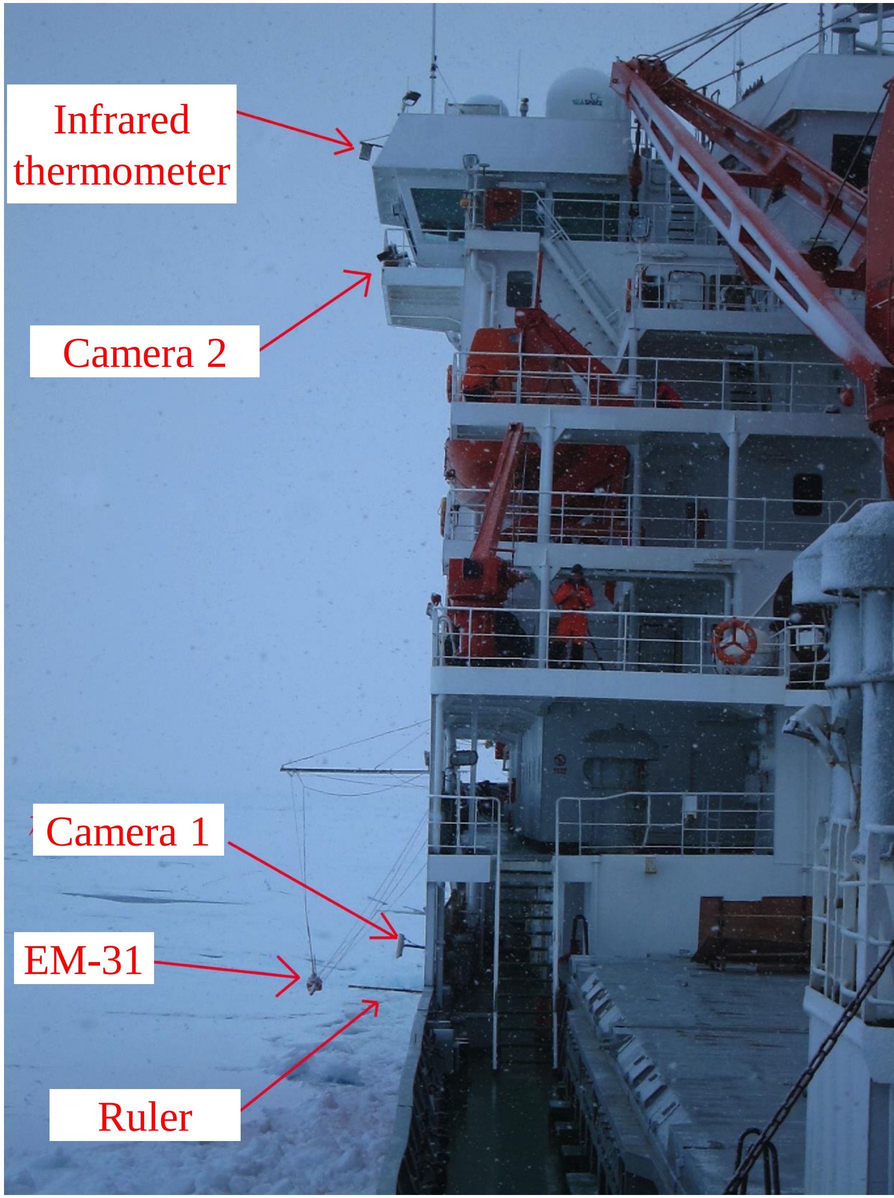


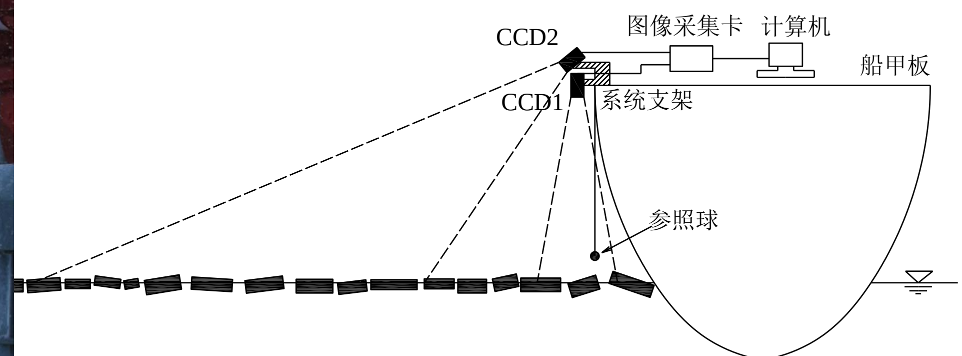
The average fractions of open water, ice cover, melt pond, and ponded ice cover during each flight, and variations along latitude.



The average ice concentration derived from the aerial images for each flight and the corresponding AMSR-E/ASI ice concentration at the same locations in 2007 and 2008. Note that the Arctic sea ice extent has a record low in summer of 2007 before 2012.

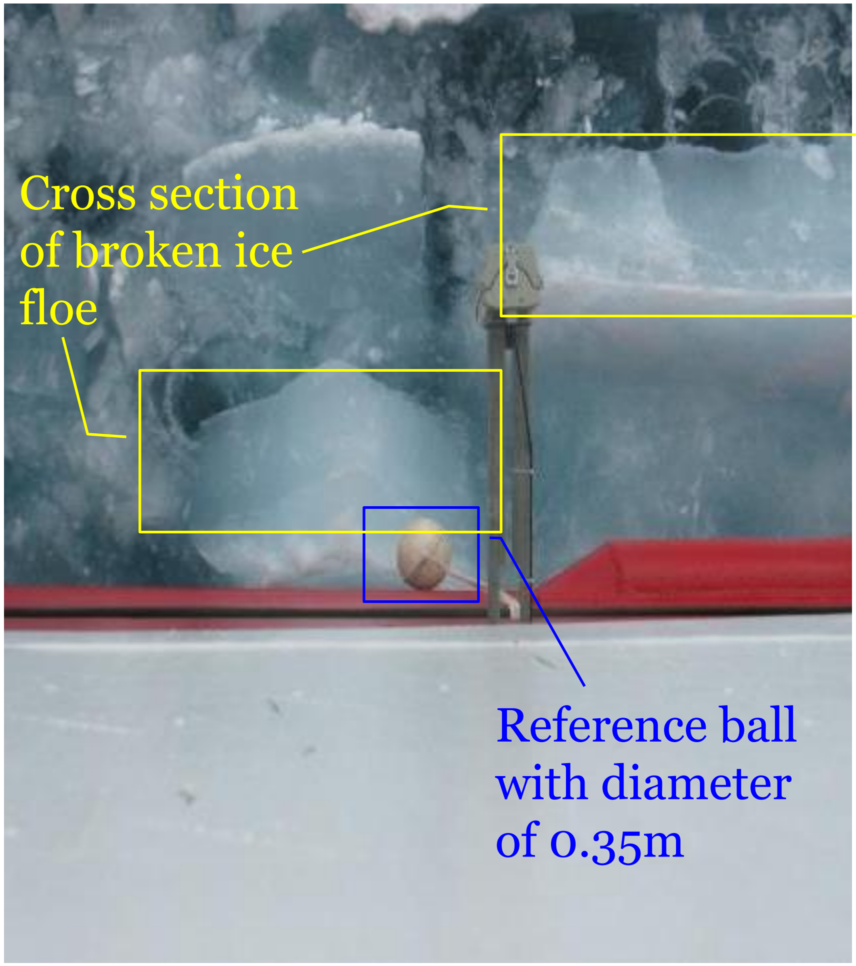
3. Shipborne photography

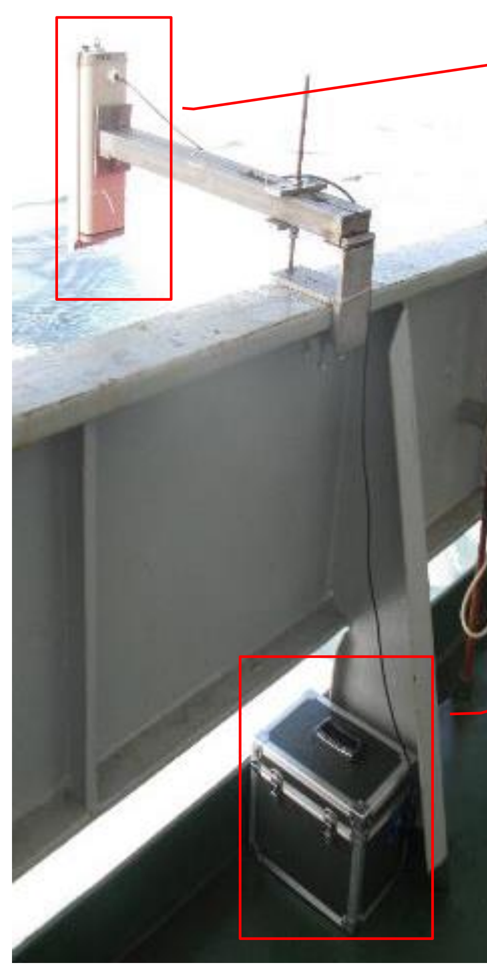




The observation system during navigation onboard R/V Xuelong

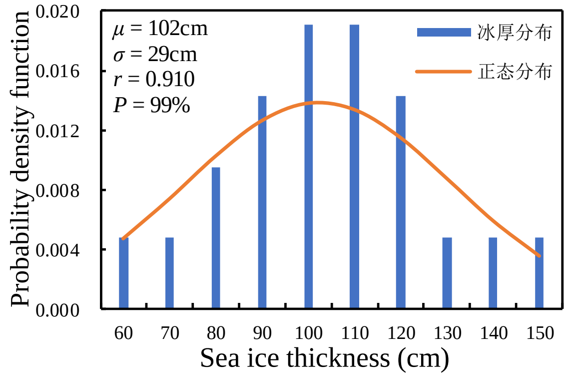
Ice thickness observations



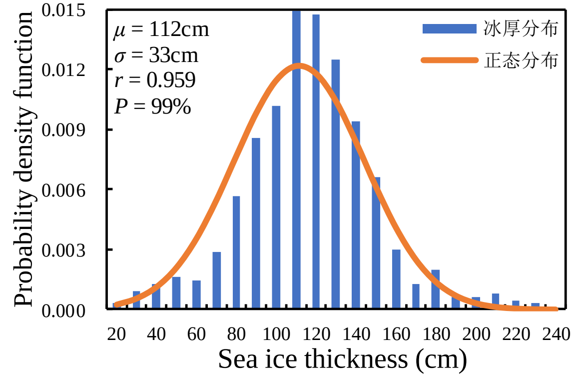


Sea ice thickness video monitoring system during navigation

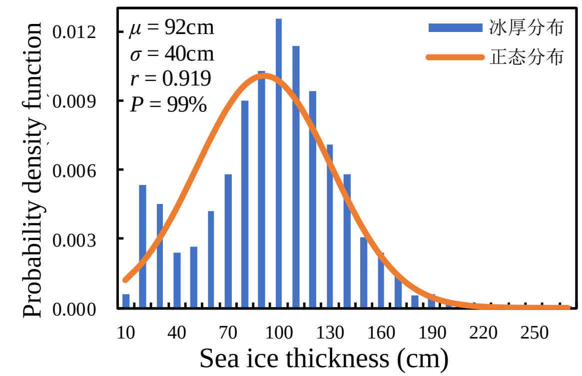
Example 3： Arctic sea ice thickness



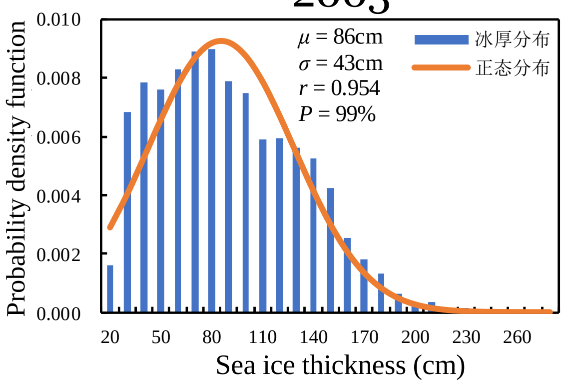
2003



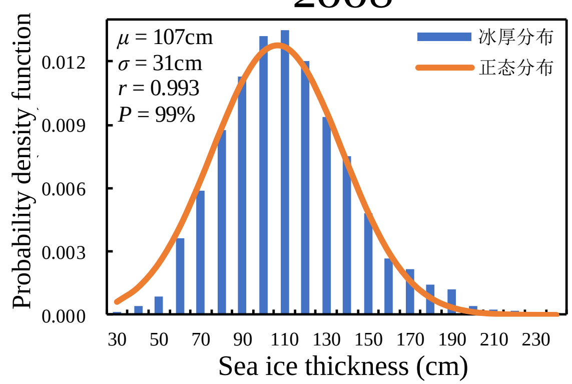
2008



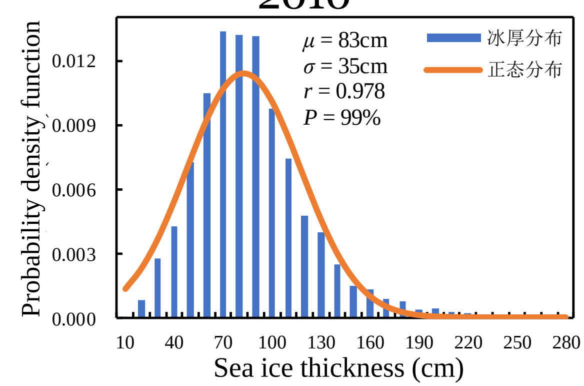
2010



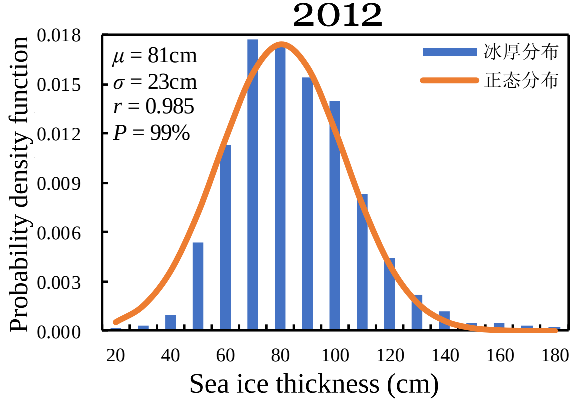
2012



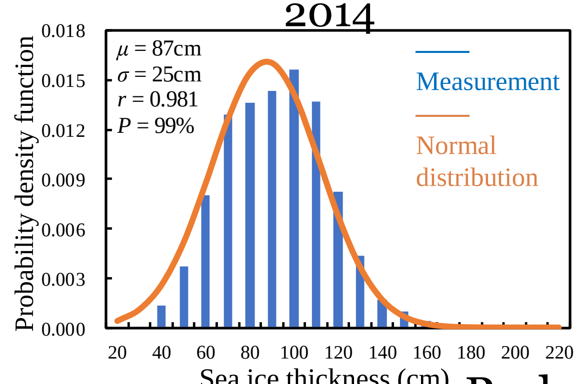
2014



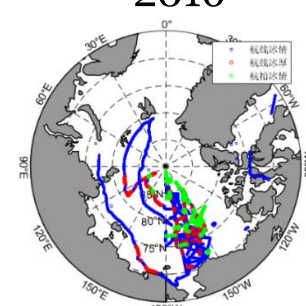
2016



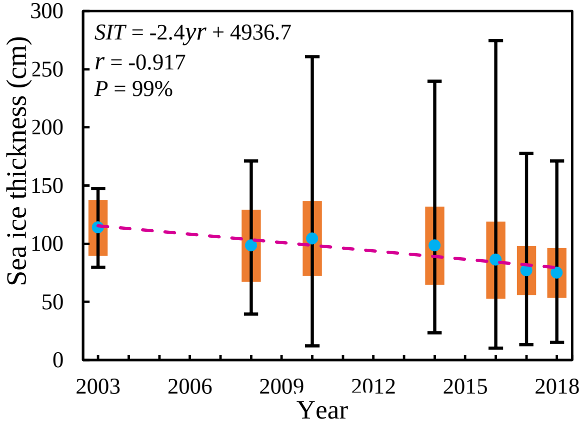
2017



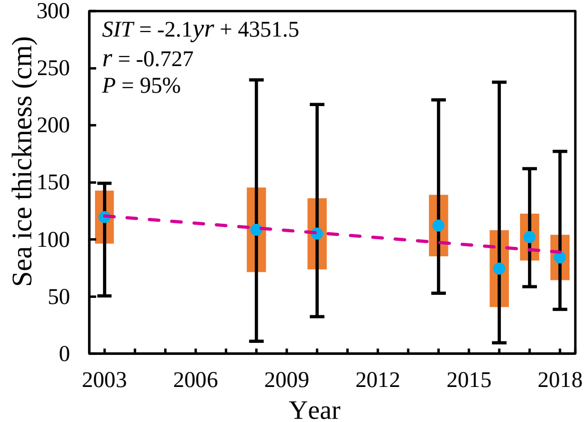
2018



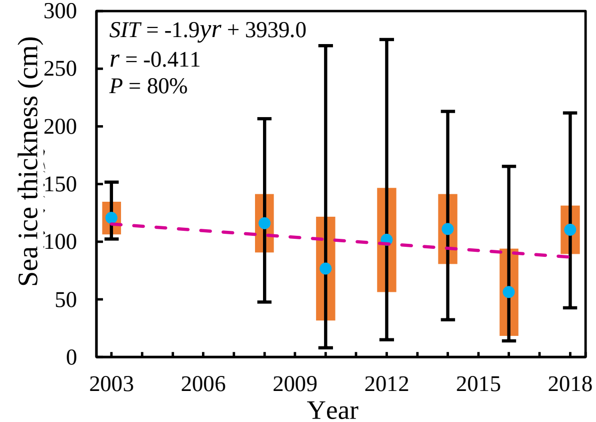
Probability density distribution of sea ice thickness during each cruise



Early August

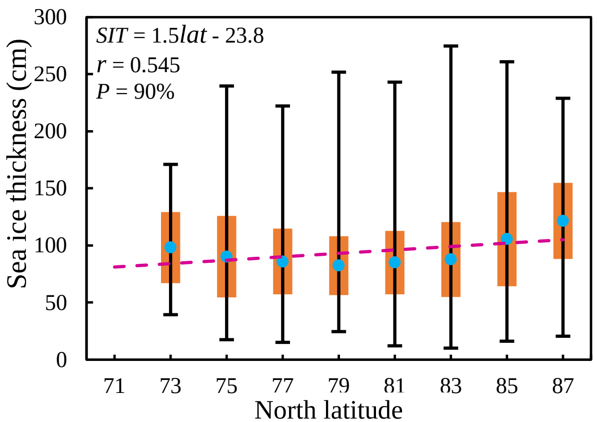


Mid August

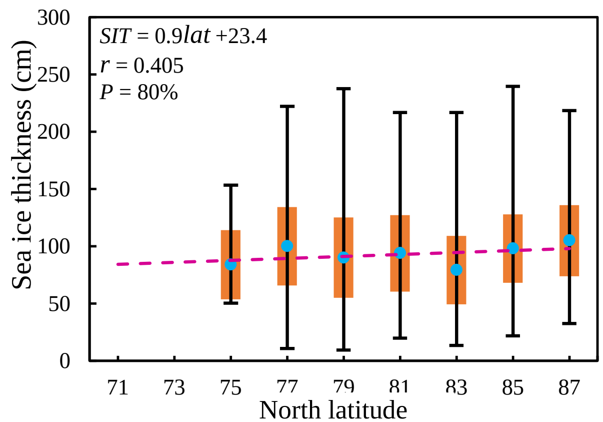


Late August

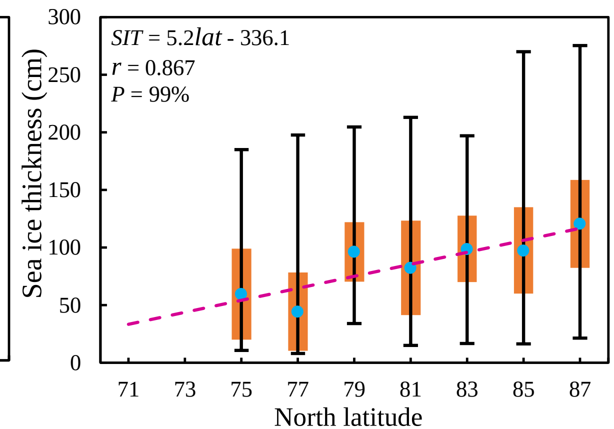
Interannual variation of ice thickness during navigation



Early August



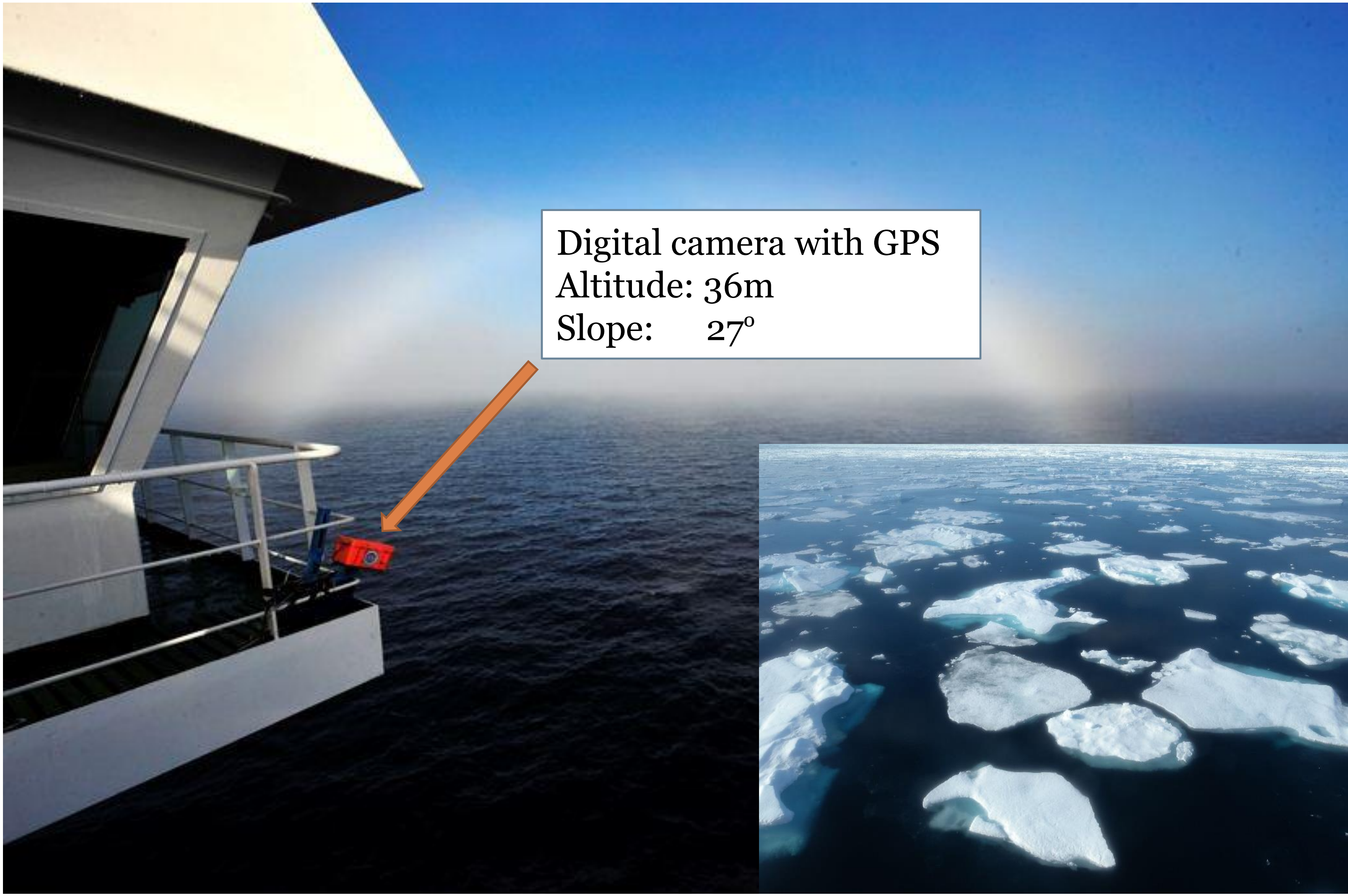
Mid August



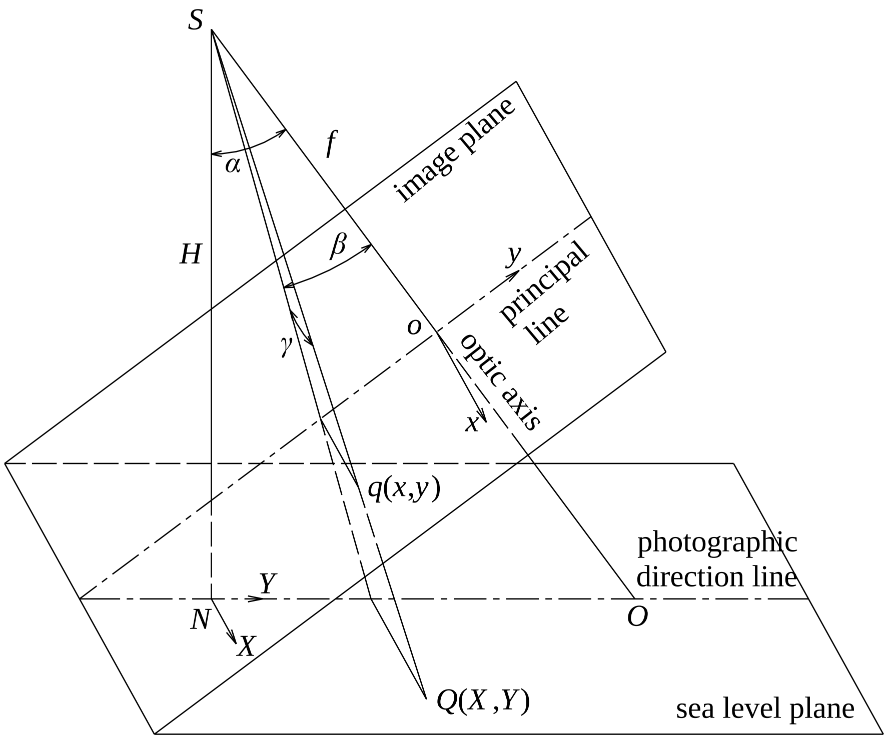
Late August

Variation of ice thickness with latitude during navigation

Shipside oblique photography



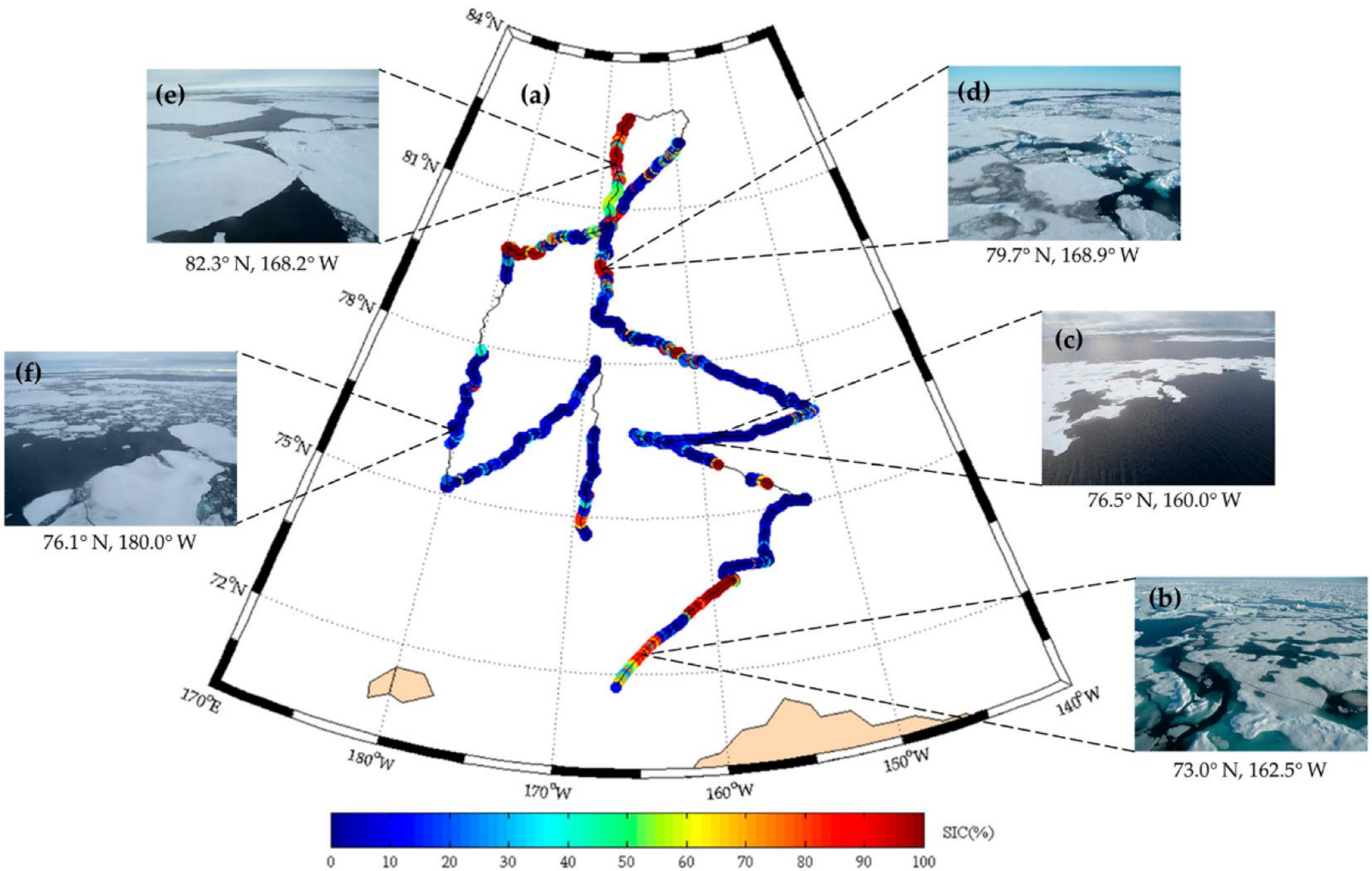
Correction of geometry distortion



$$\begin{cases} Y = H \tan\left[\alpha + \arctan\left(\dfrac{y}{f}\right)\right] \\ X = x\sqrt{\dfrac{H^2 + Y^2}{f^2 + y^2}} \end{cases}$$

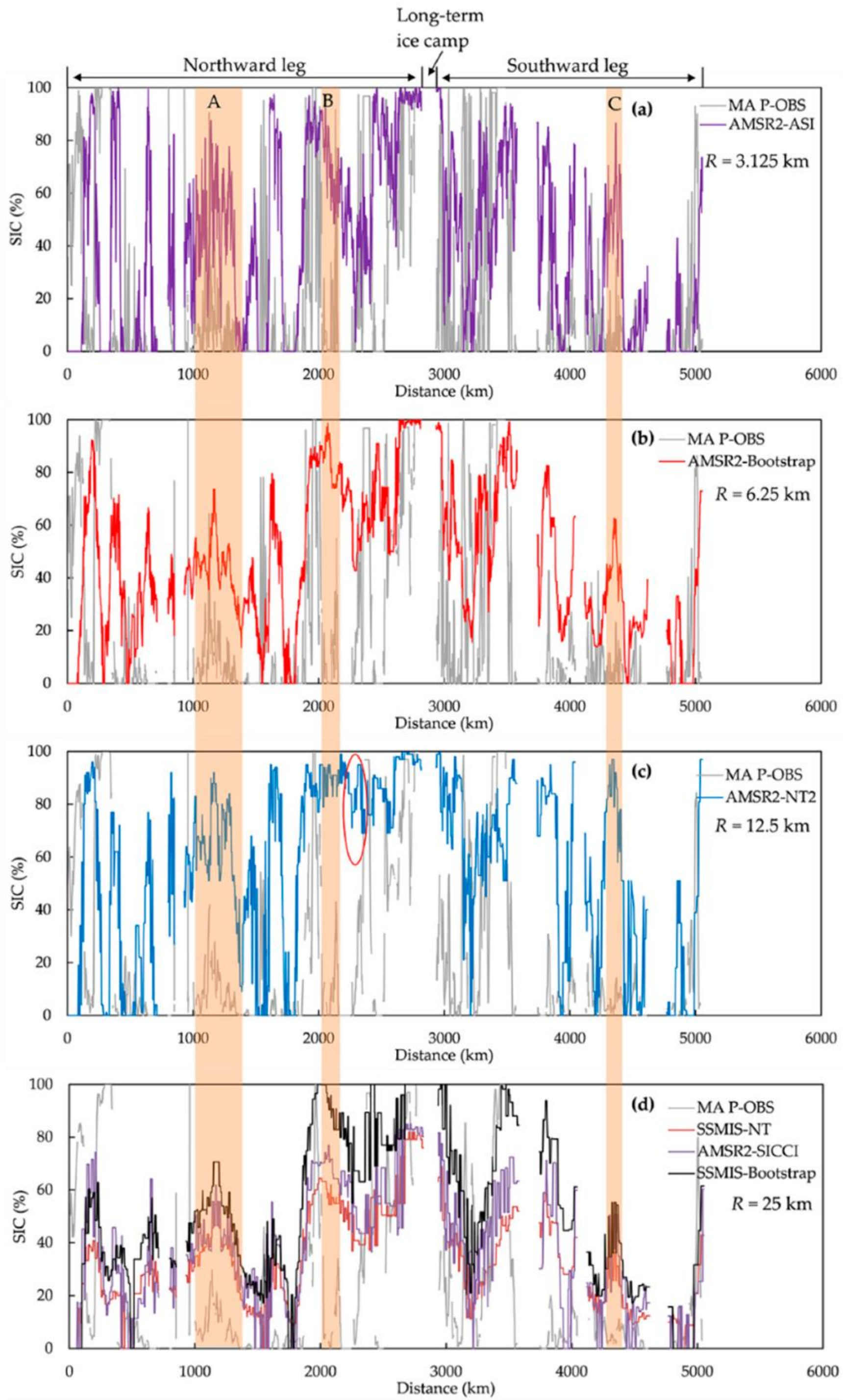
Lu and Li. 2010. IEEE TGRS

Example 4: Sea ice concentration



The distribution of sea ice concentration (colored points) derived from shipborne photographic observation along the cruise track (black line) in CHINARE-2016 (a) with photographs of typical ice conditions and corresponding locations (b–f).

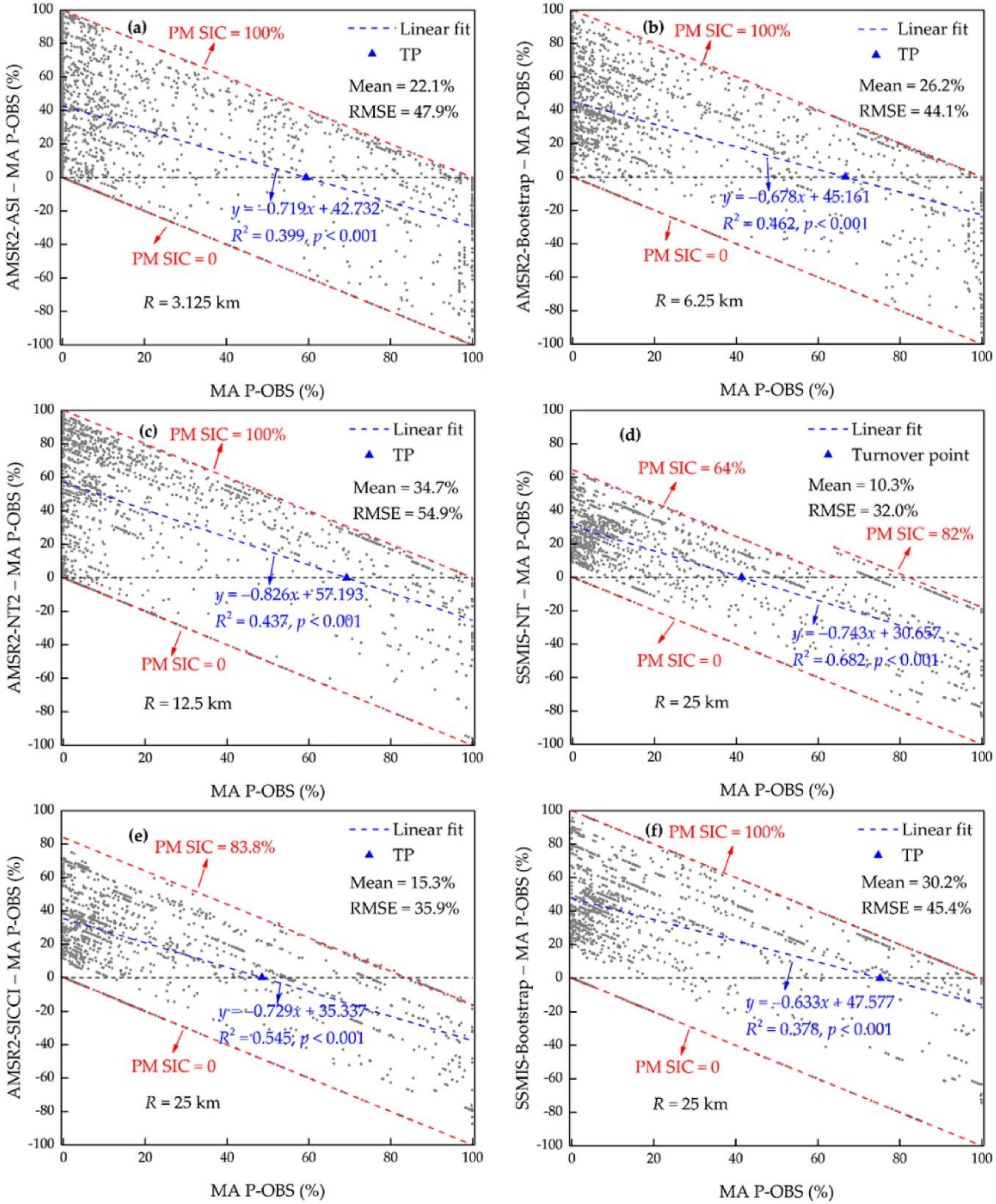
Wang and Lu, et al, 2019. Remote Sensing



Comparison between passive microwave (PM) sea ice concentration (SIC) and moving average (MA) photographic observation (P-OBS) SIC along the cruise path for each algorithm (a–d). The orange columns represent the regions with a large difference between PM SIC and MA P-OBS SIC, and R denotes the spatial resolution.

R = 3.125 km (a),
R = 6.25 km (b),
R = 12.5 km (c), and
R = 25 km (d).

The orange display indicates areas with significant differences, while the on-site display shows large open water areas.

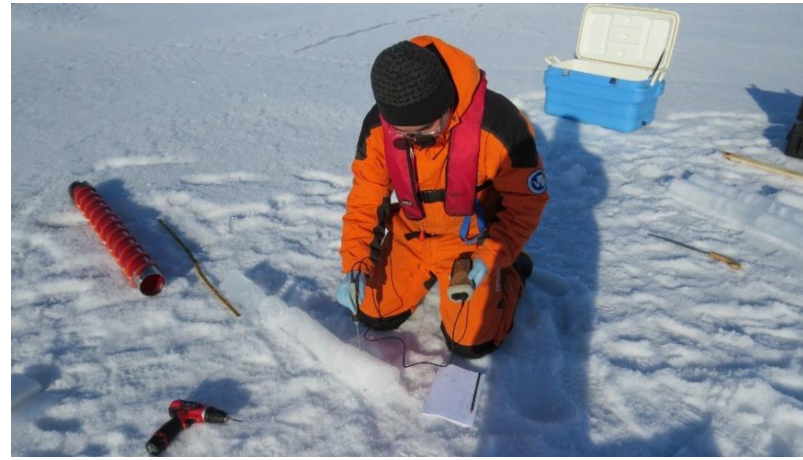


The difference in passive microwave (PM) sea ice concentration (SIC) with respect to moving average (MA) photographic observation (P-OBS) SIC for each algorithm (a–f).

(a) AMSR2-ASI
(b) AMSR2-Bootstrap
(c) AMSR2-NT2
(d) SSMIS-NT
(e) AMSR2-SICCI
(f) SSMIS-Bootstrap

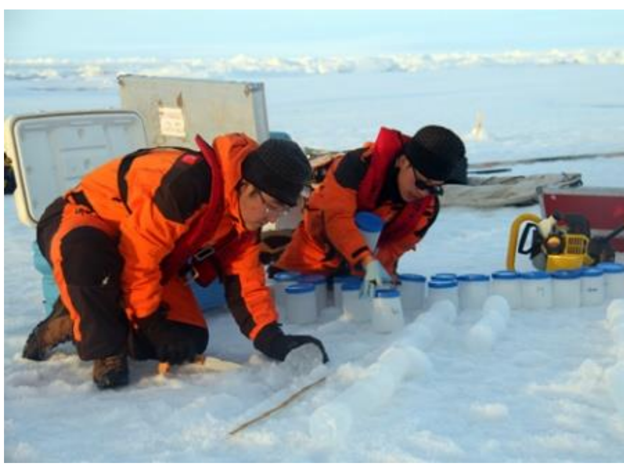
4. Observations on ice cores

Ice core drilling



Ice core temperature

Ice sample

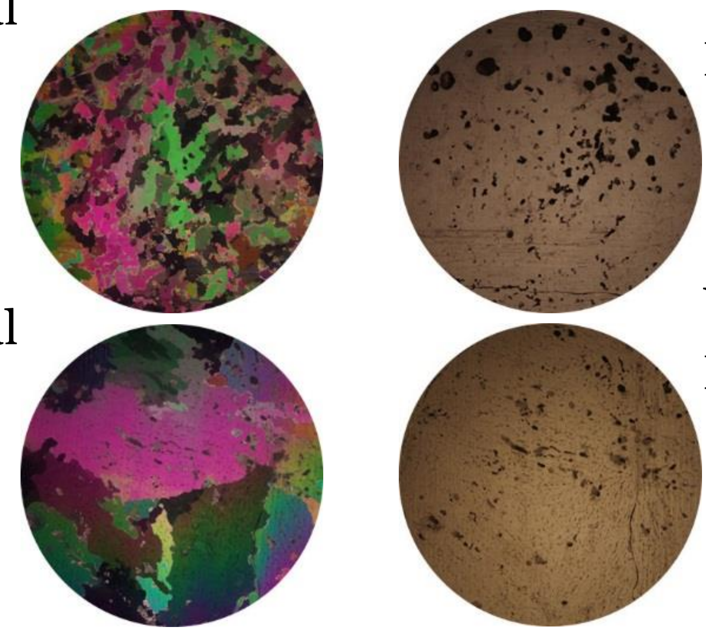


Ice density measurement

Polarized light | Natural light

Horizontal profile at 5 cm

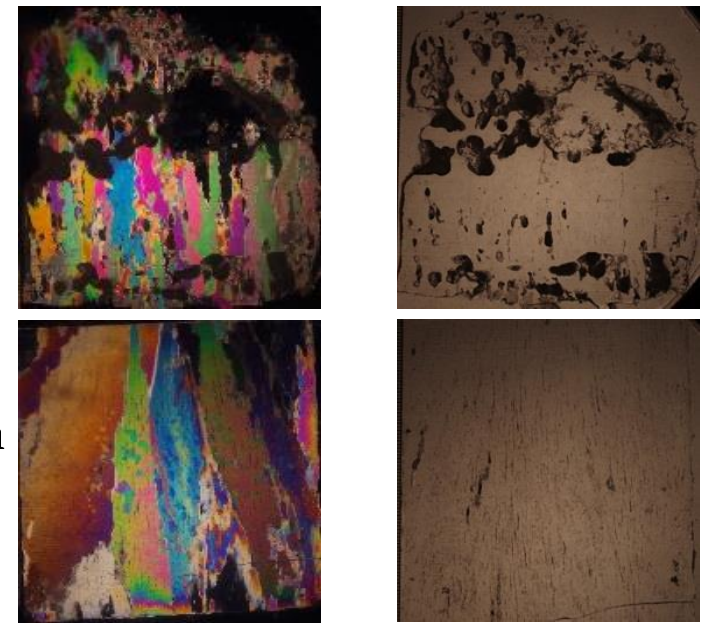
Horizontal profile at 80 cm



Polarized light | Natural light

Vertical profile at 0~5 cm

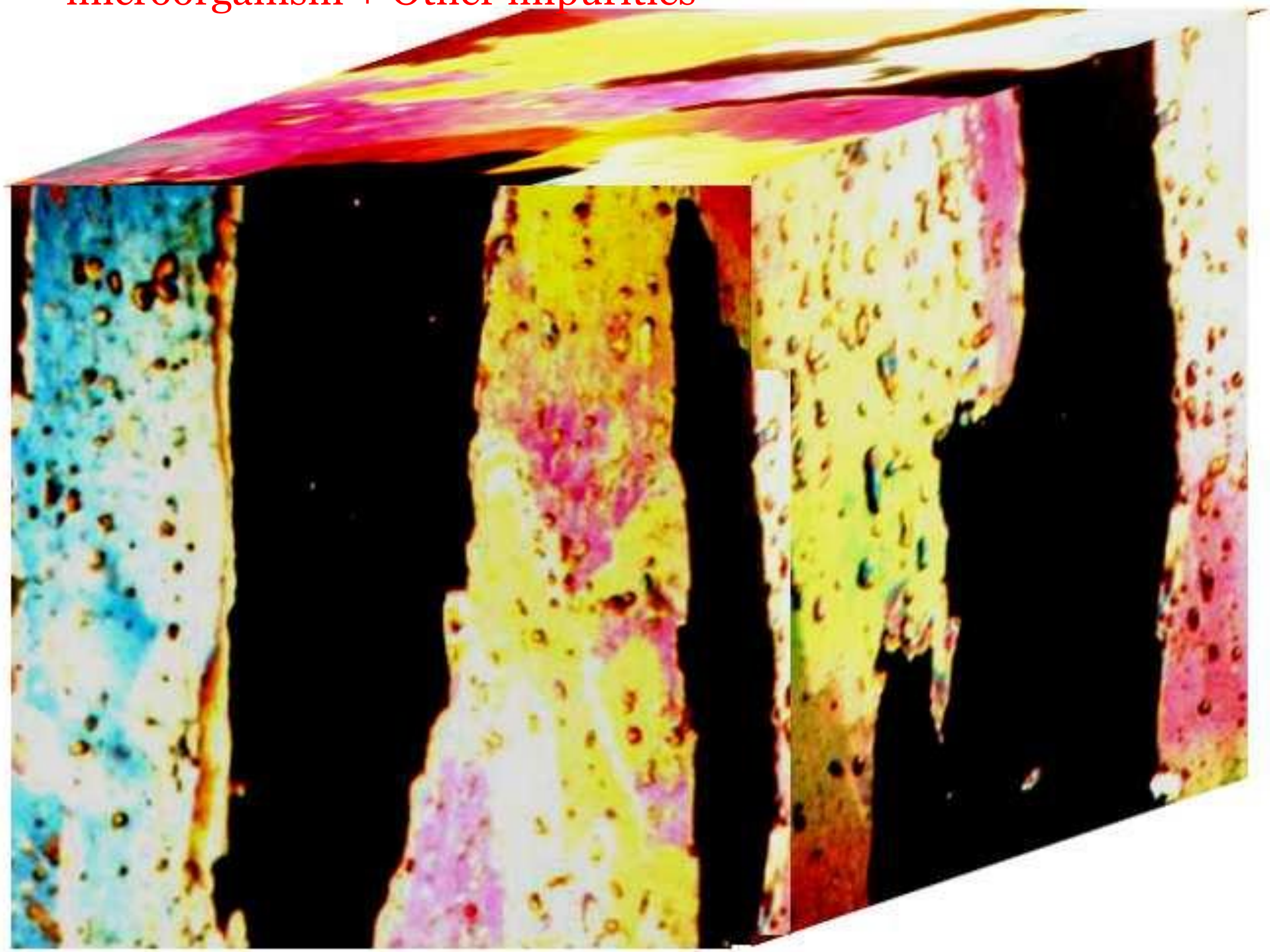
Vertical profile at 80~85 cm



Ice crystal structure observation buring CHINARE-2018

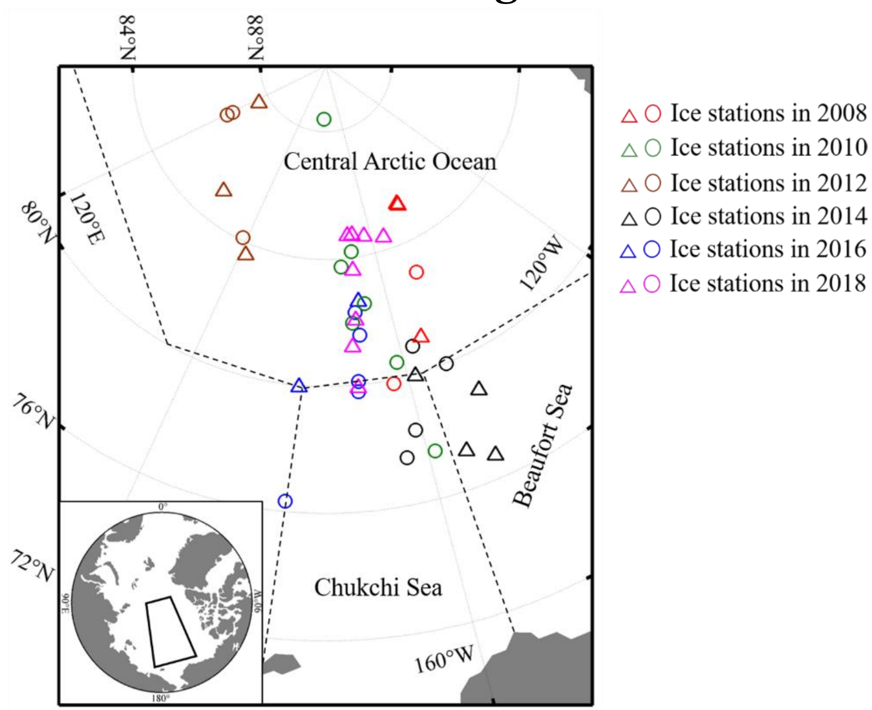
Sea ice microstructure

Sea ice = ice crystal + air bubbles + brine pockets +crystallized salt + microorganism + Other impurities

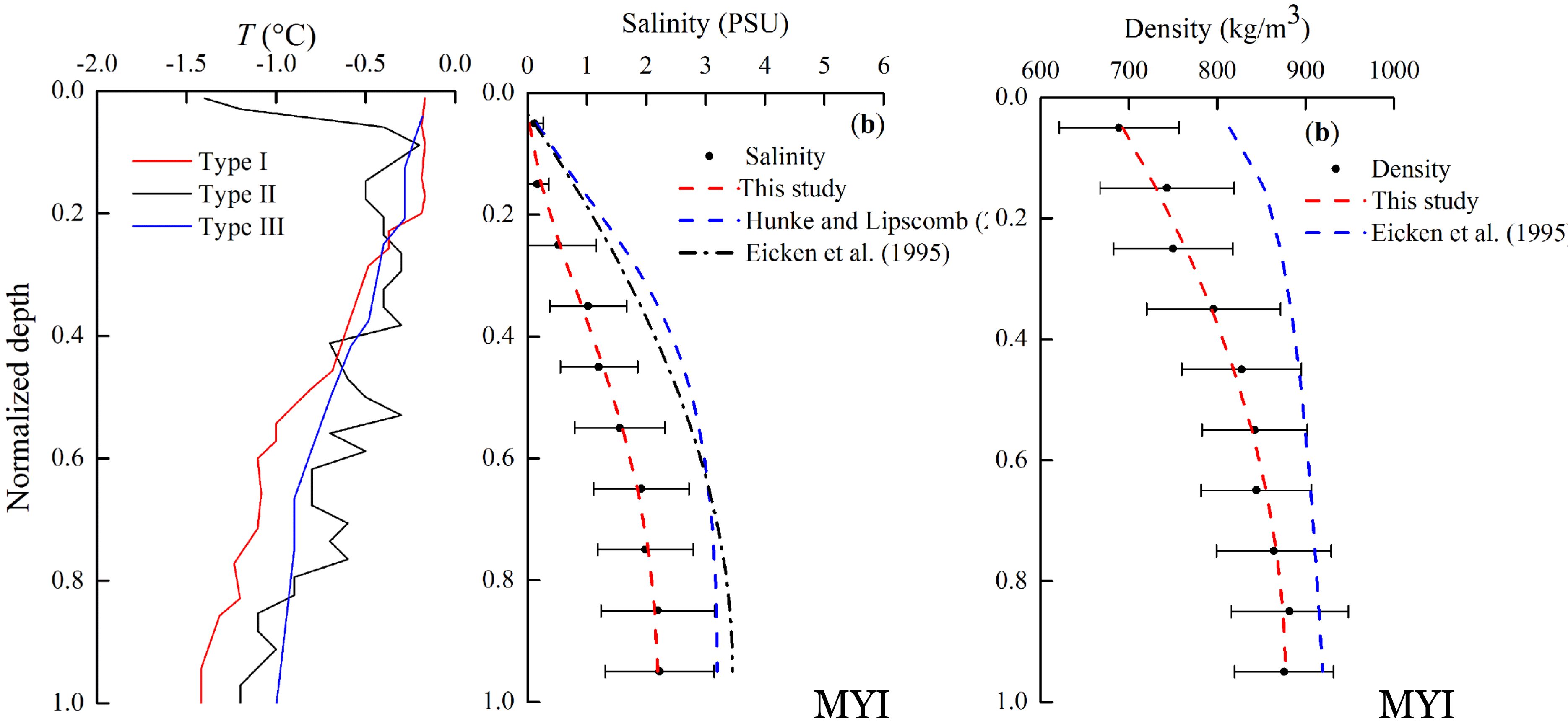


Example 5: Ice cores in CHINARE 2008-2018

- The rapid decay Arctic sea ice in summer have become a fact. However, it is still unclear how the physics of Arctic summer sea ice respond.
- Most numerical models are still based on physical observations of sea ice from many years ago, and our knowledge needs to be updated.
- Physical observations on Arctic sea ice from 2008 to 2018 can help improve the accuracy of sea ice model forecasting.



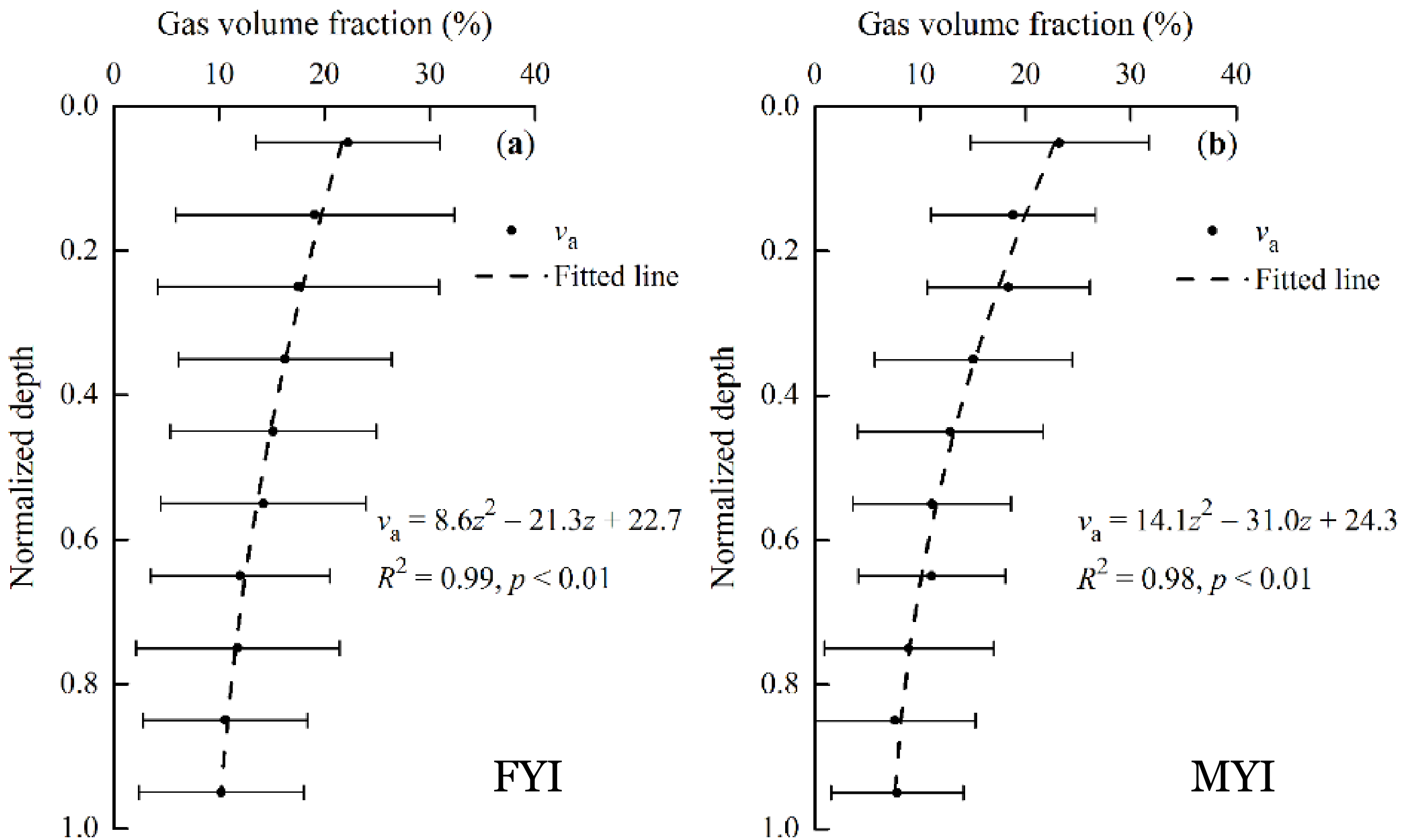
Sea ice physics



Mean sea ice physics including temperature, salinity and density versus normalized depth for Arctic sea ice during the melt season.

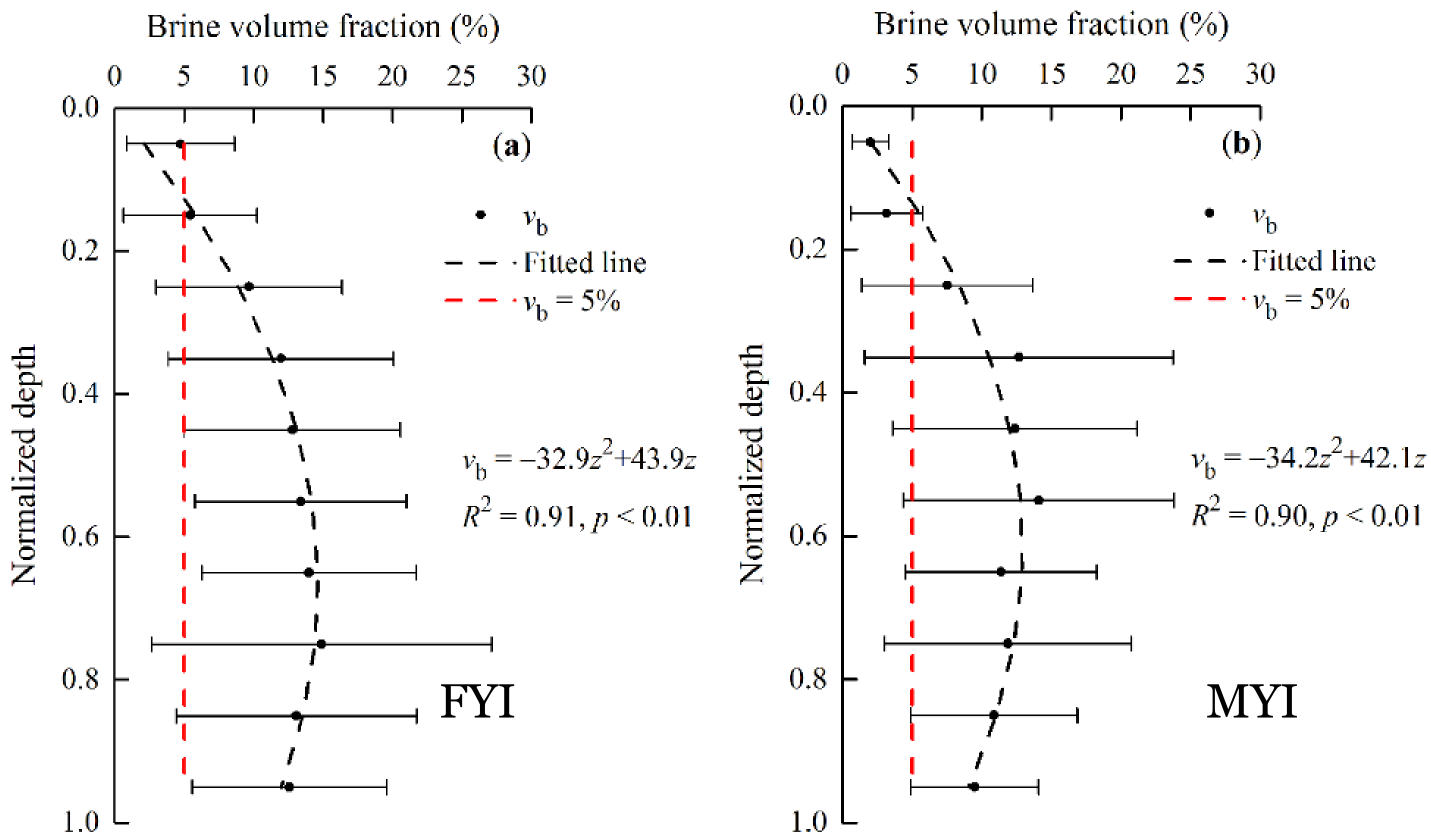
Wang et al., 2020. JGR-Oceans.

Gas bubbles in sea ice



Variations in volume fraction of gas bubbles Va within sea ice along depth

Brine pockets in sea ice

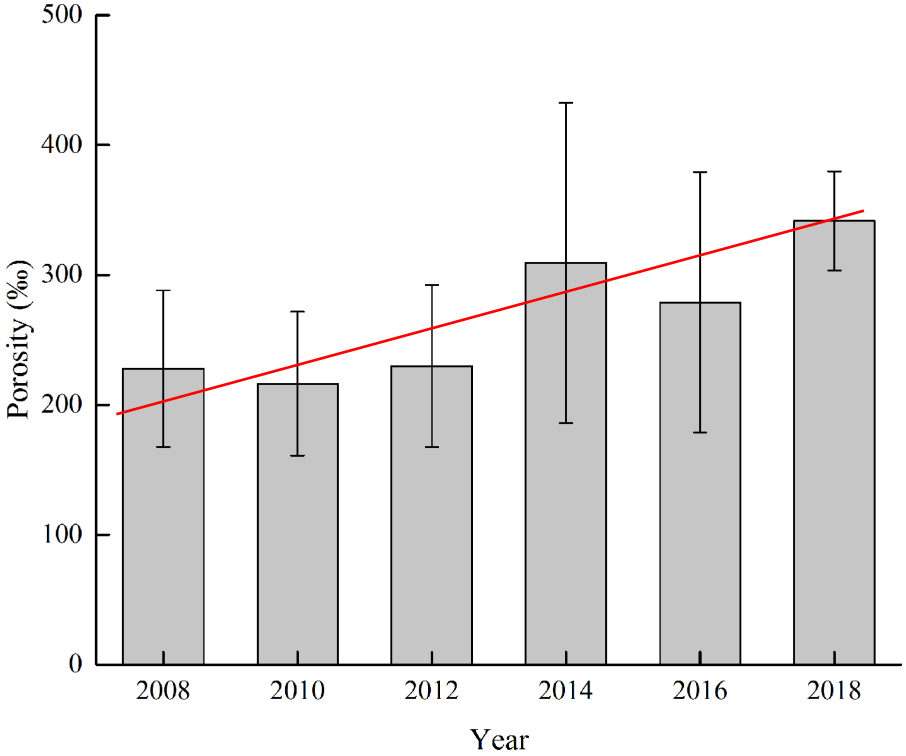


Variations in volume fraction of brine pockets Vb within sea ice along depth

Arctic sea ice is fully permeable in summer！

Sea ice porosity

Porosity = $V_a + V_b$



Increases by 10% in ten years.

Changes in sea ice porosity during 2008—2018

Is there any effects of such changes in sea ice microstructure?

Sea ice physics (T / s / ρ) are the basis for all other properties！

Thermal

$T/S/\rho$

Optical

Electromagnetic

Inherent optical properties of sea ice

From constants to variables of microstructure

Scattering coefficient of sea ice

$$\bar{\sigma} = \sigma_b + \sigma_a + \sigma_p = \int_{l_{min}}^{l_{max}} \pi r_b^2 Q_{sca}^b N_b(l) dl + \int_{r_{min}}^{r_{max}} \pi r_b^2 Q_{sca}^a N_a(r) dr + \pi r_p^2 Q_{sca}^p N_p$$

Absorption coefficient of sea ice

$$\bar{\kappa} = \kappa_i + \kappa_b + \kappa_p = k_i V_i + \int_{l_{min}}^{l_{max}} \pi r_b^2 Q_{abs}^b N_b(l) dl + \pi r_p^2 Q_{abs}^p N_p$$

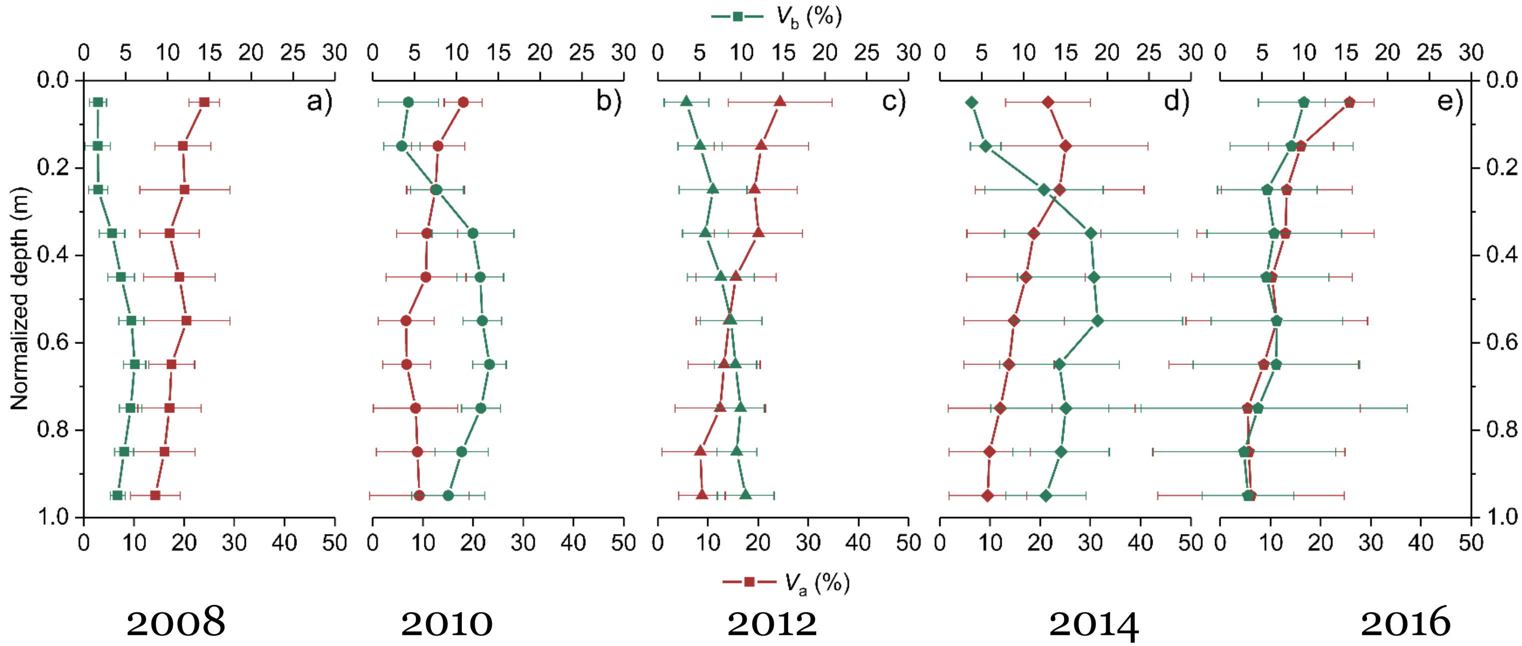
Asymmetric factor of scattering

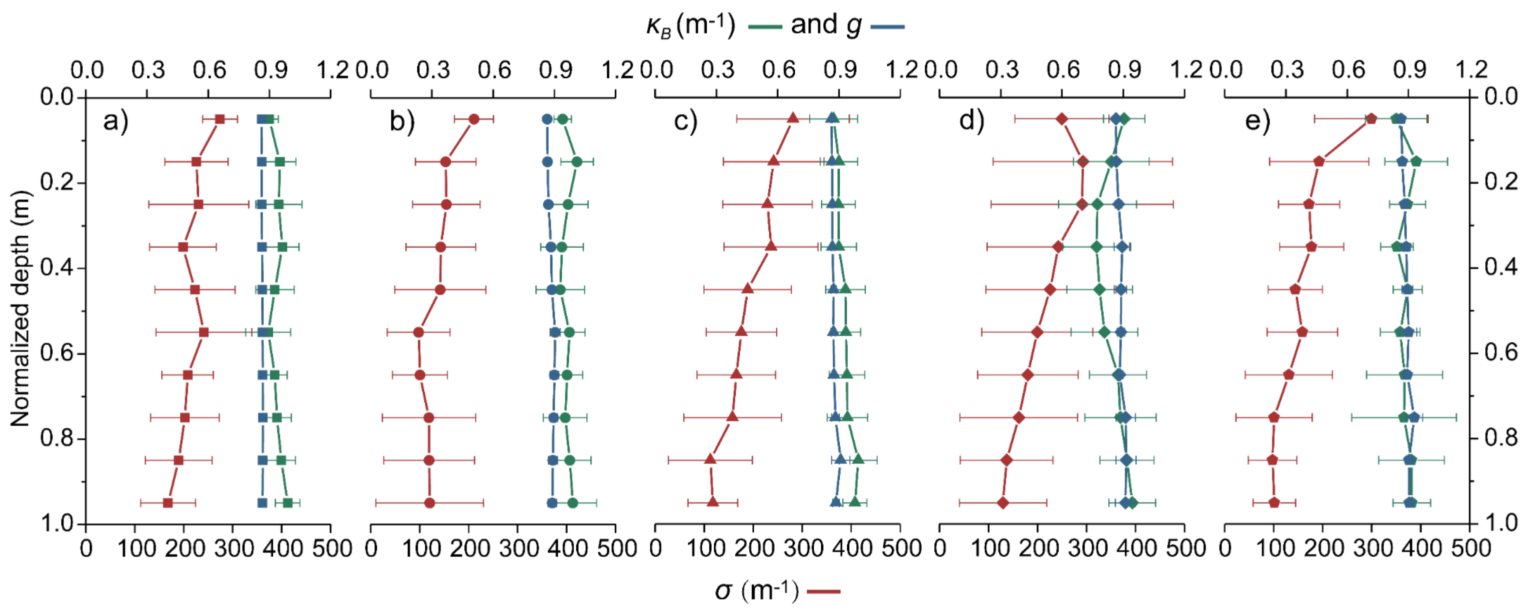
$$g = \frac{g_a \sigma_a + g_b \sigma_b + g_p \sigma_p}{\sum \sigma}$$

- Subscripts： i-ice、a-air、b-brine、p-particle
- Gas bubbles： V_a： volume fraction、r_a： bubble radius
- Brine pockets： V_b： volume fraction、l_b： pocket length
- Particle impurity： M_{pm}： concentration、r_{pm}： particle size

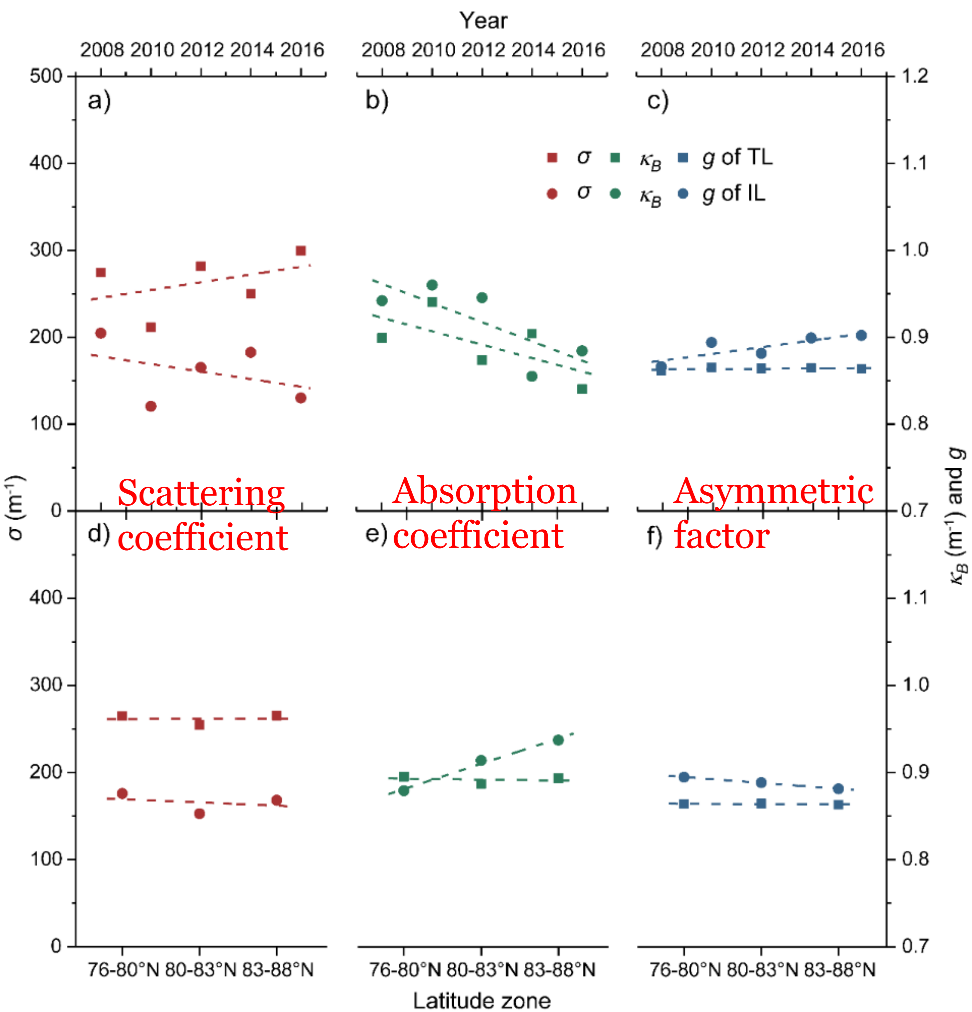
Yu et al., 2022. Frontiers in Marine Science.

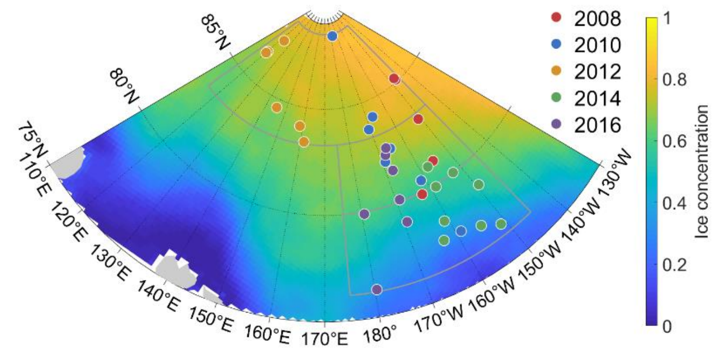
IOP variations along depth





Changes in IOP





- Changes with year

σ increases in top layer (TL)

σ decreases in internal layer (IL)

κ decreases in TL and IL

g keeps steady in TL

g increases in IL

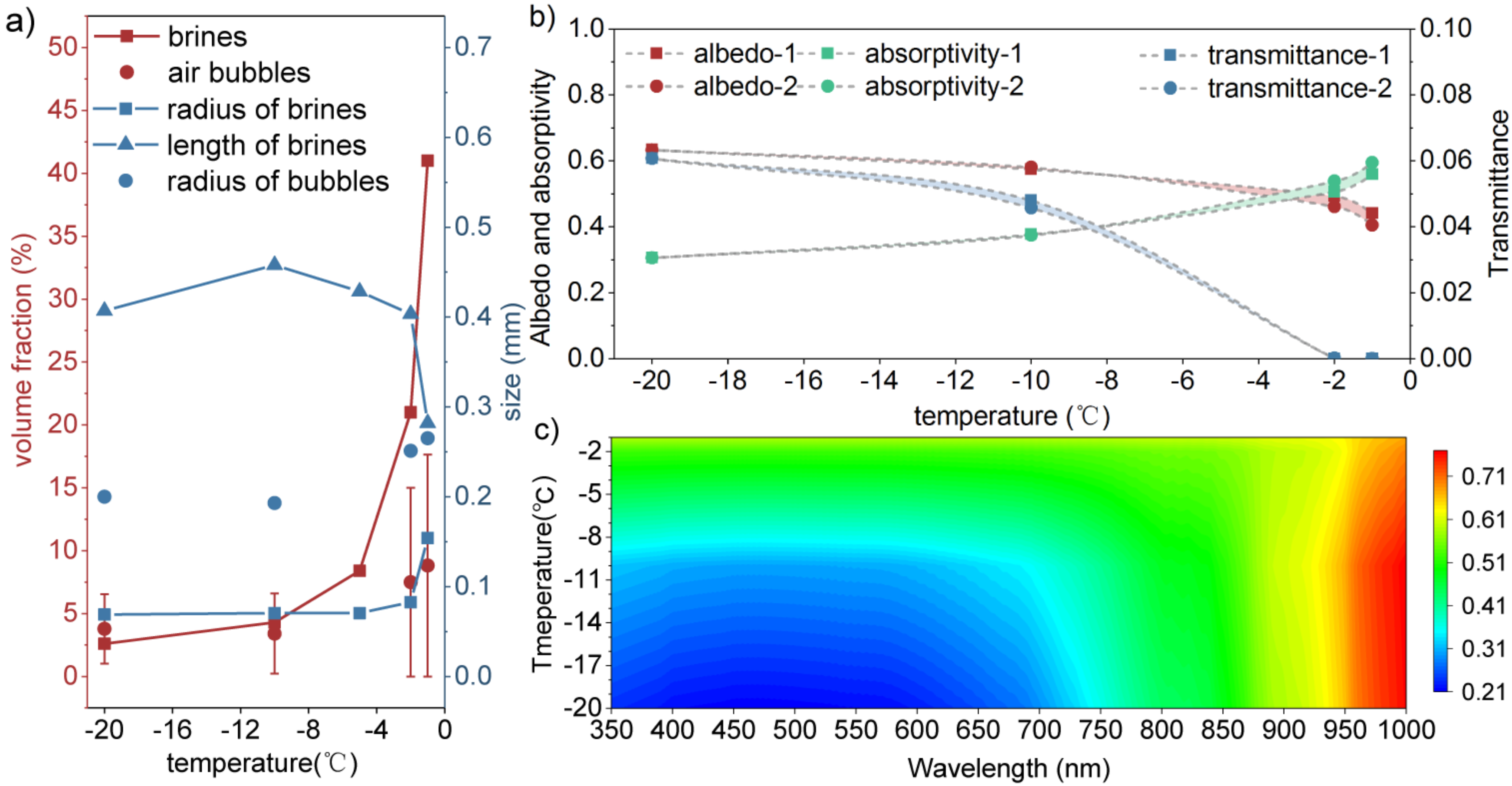
- Changes with latitude

No changes in TL

κ increase in IL

g decreases in IL

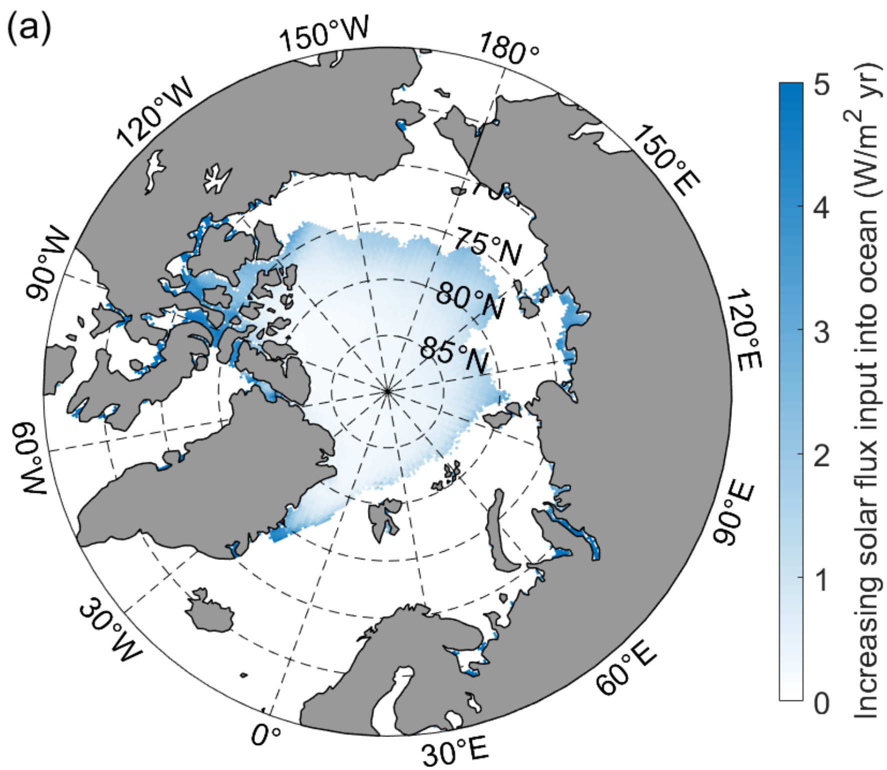
Changes in AOP



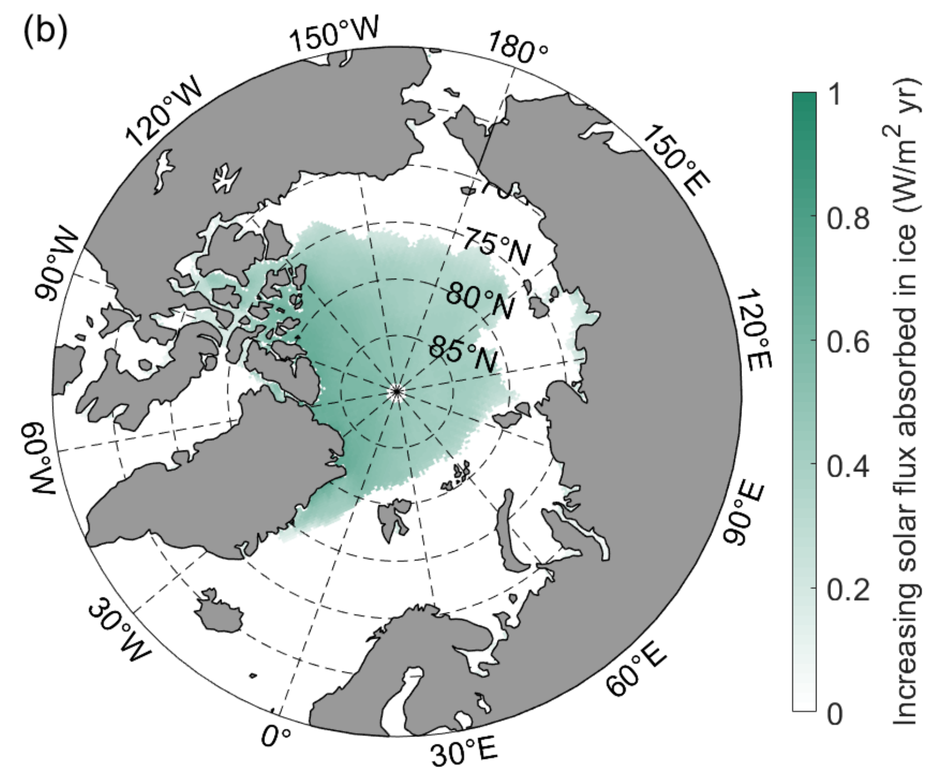
Changes in (a) air and brine parameters, (b) albedo, transmittance, absorption, and (c) spectral absorption during the heating of sea ice with thickness of 1m

The changes in air bubbles and brine during the high temperature stage (>-5◦C) are very obvious, leading to significant changes in AOP. The absorption rate changes are mainly concentrated in the range of<750nm.

Trends in Arctic energy budget



Trend in energy absorbed by ocean beneath ice

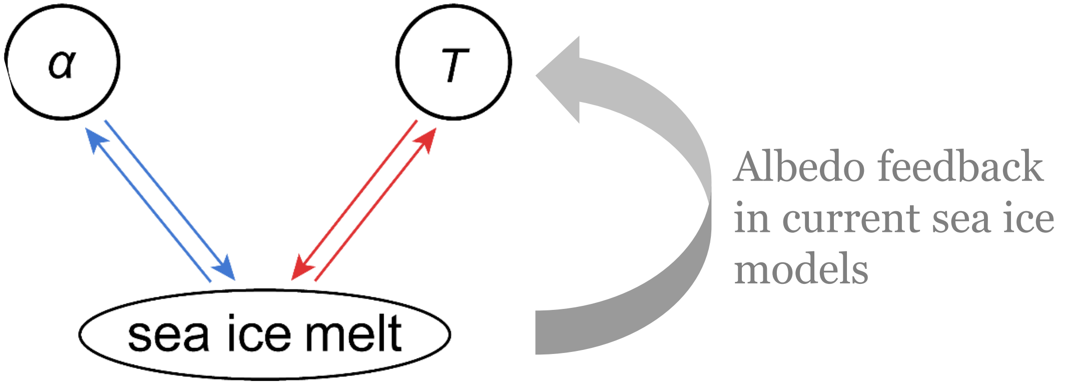


Trend in energy absorbed by sea ice

Variation trend of transmitted and absorbed solar radiation through sea ice from 2008 to 2016 when the sea ice thickness was set to a constant with changing IOPs.

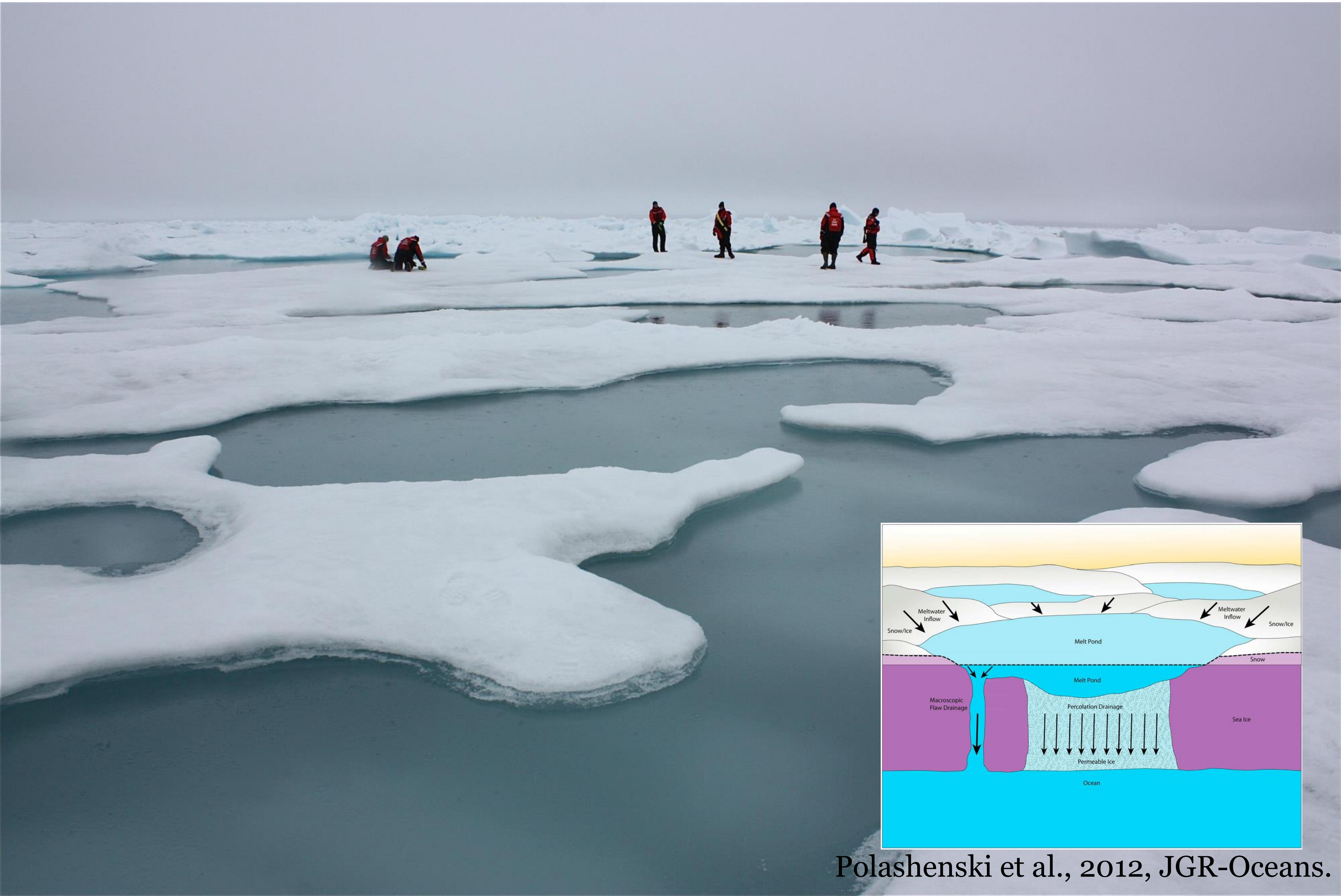
Yu et al., 2024. The Cryosphere.

Impact on sea ice melt



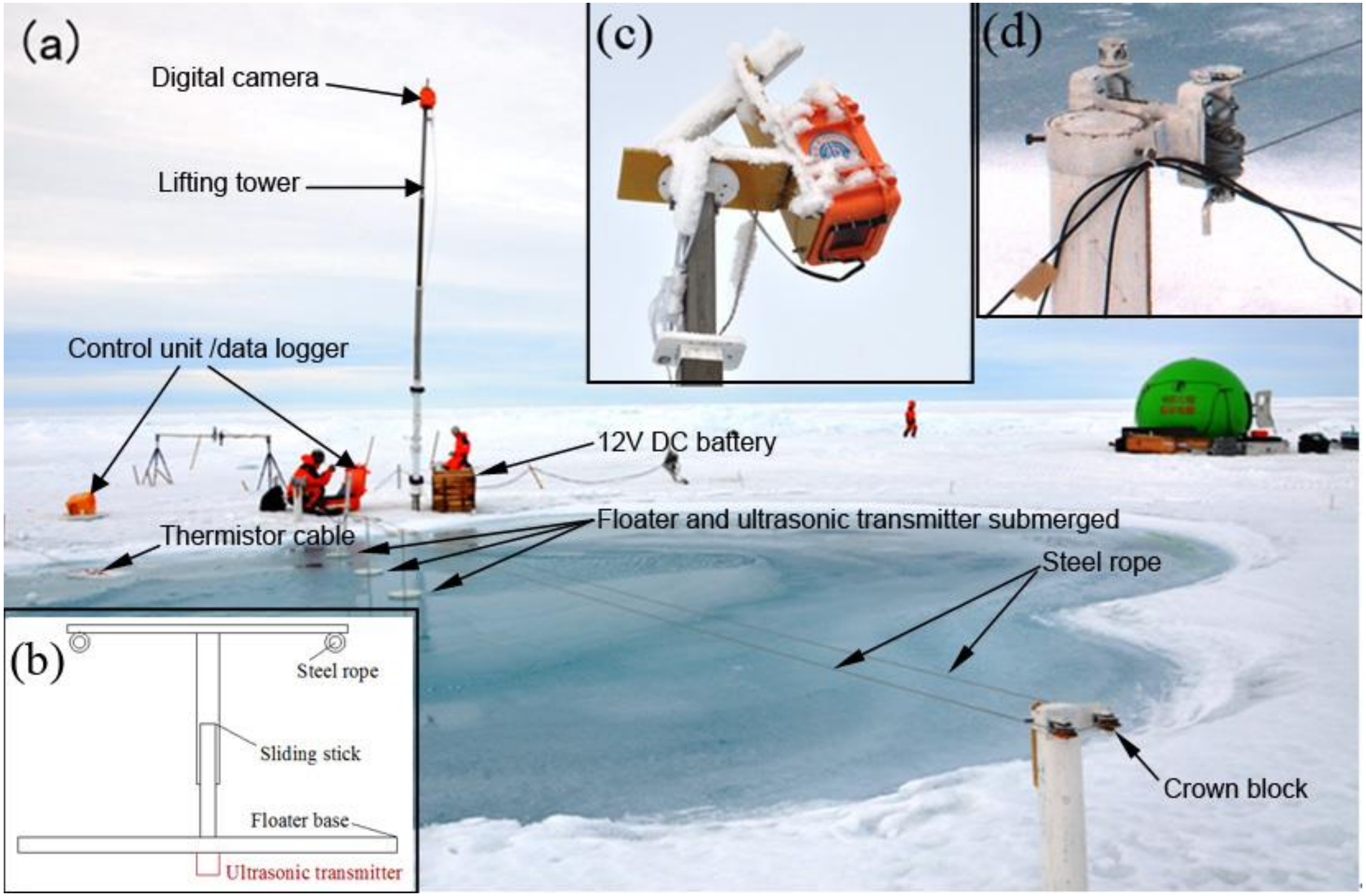
Changes in the microstructure of ice during melting alter the IOP and AOP of sea ice, which will further affect the process of sea ice melting.

5. Melt pond observations



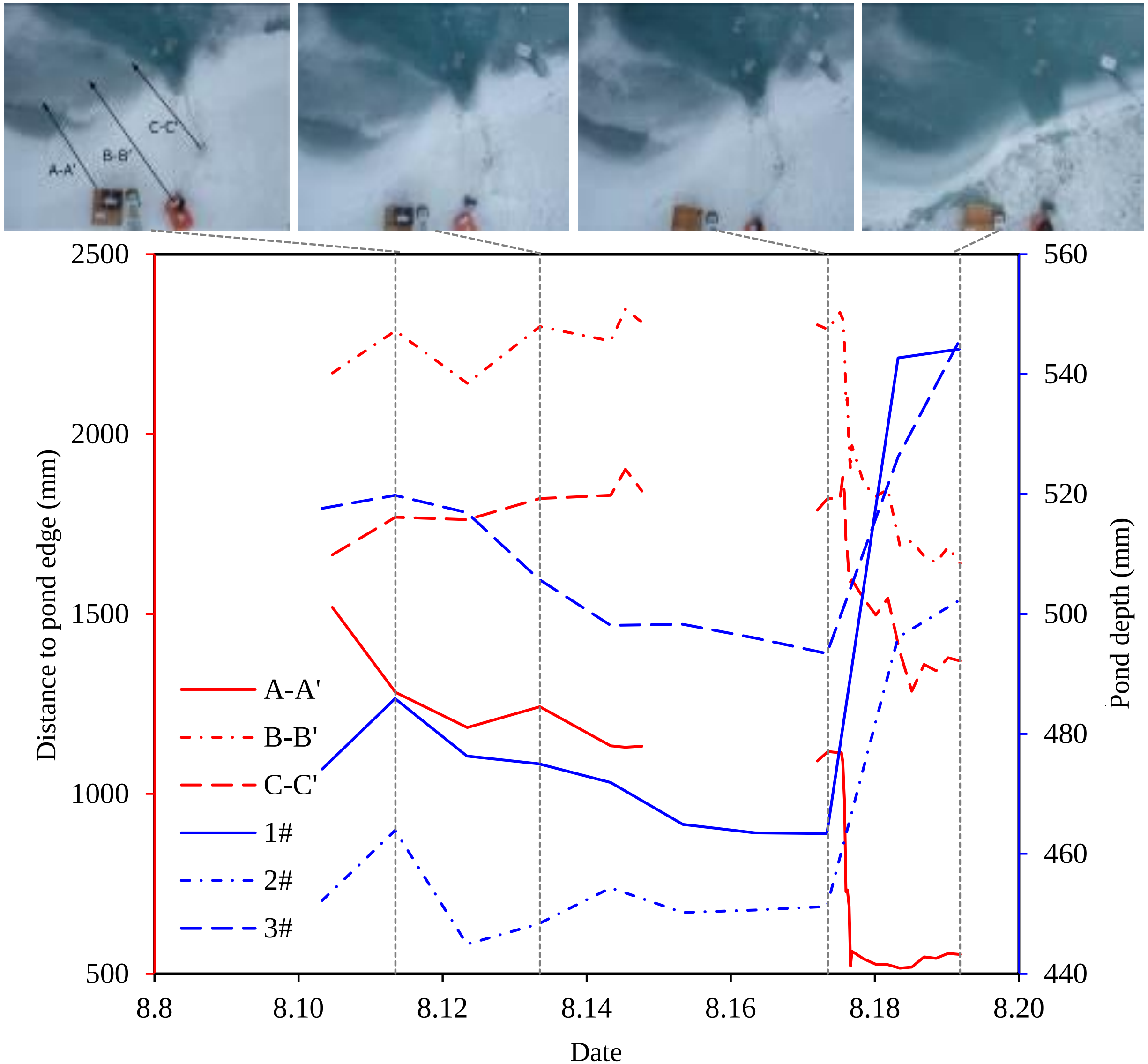
Polashenski et al., 2012, JGR-Oceans.

(1) Melt pond evolution



Monitoring of melt pond during ice camp period. a) In situ instrumentation; b) floater for ultrasonic transmitter; c) adjustable support and sealed box for digital camera; d) PRS unit.

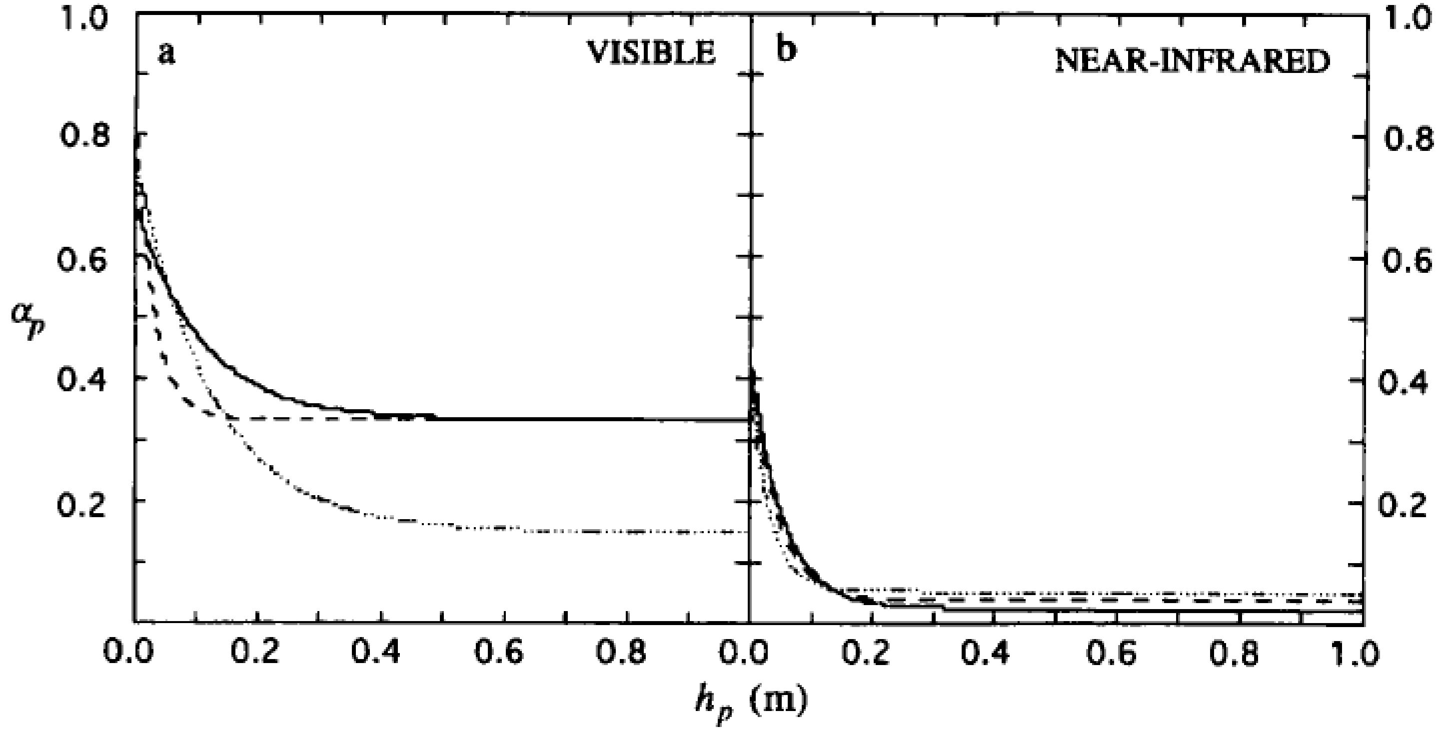
Huang and Li et al. 2012. APS.



Evolution of melt pond during long-term ice station of CHINARE-2010

(2) Melt pond optics

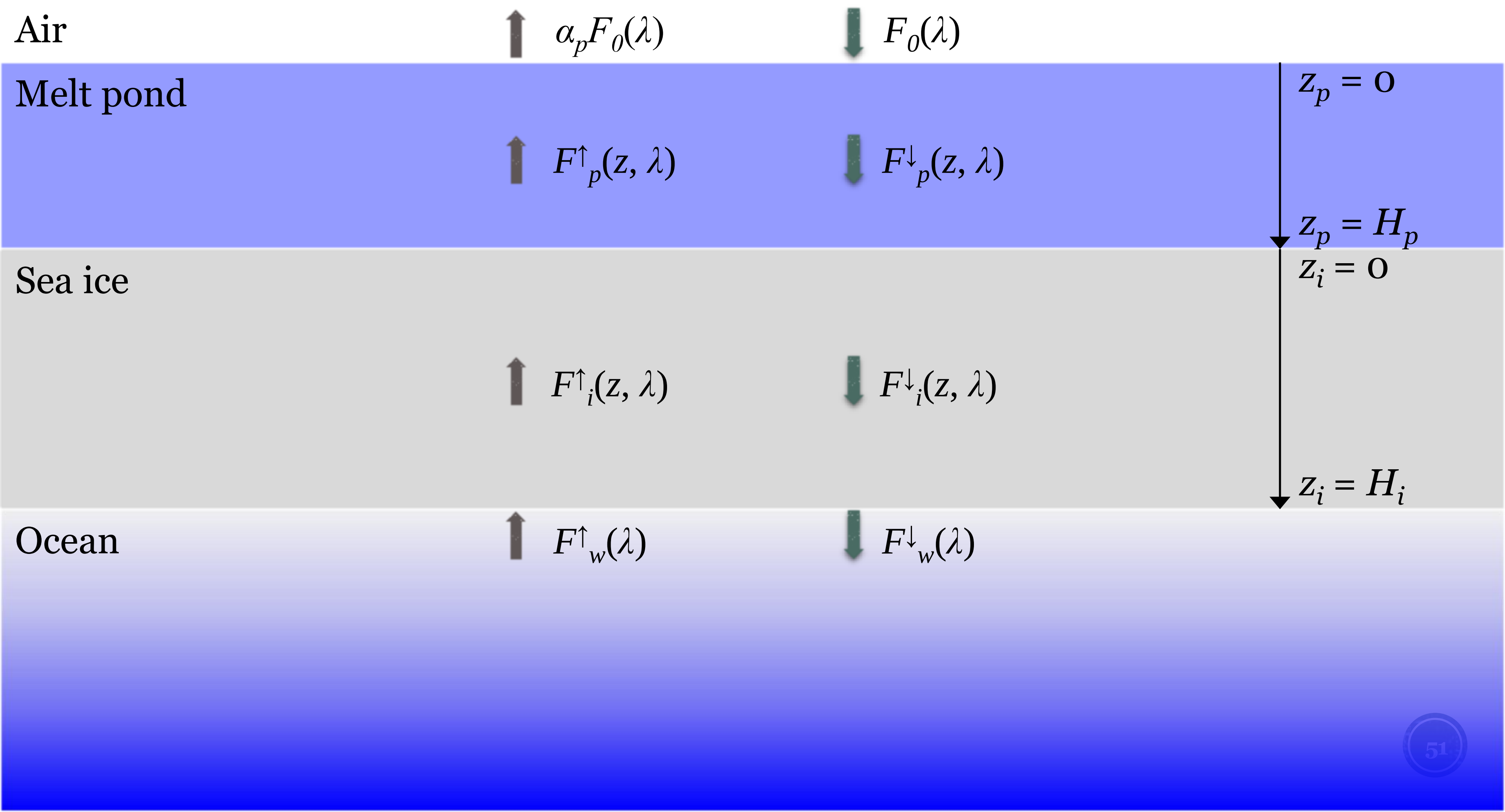
Albedo of melt pond



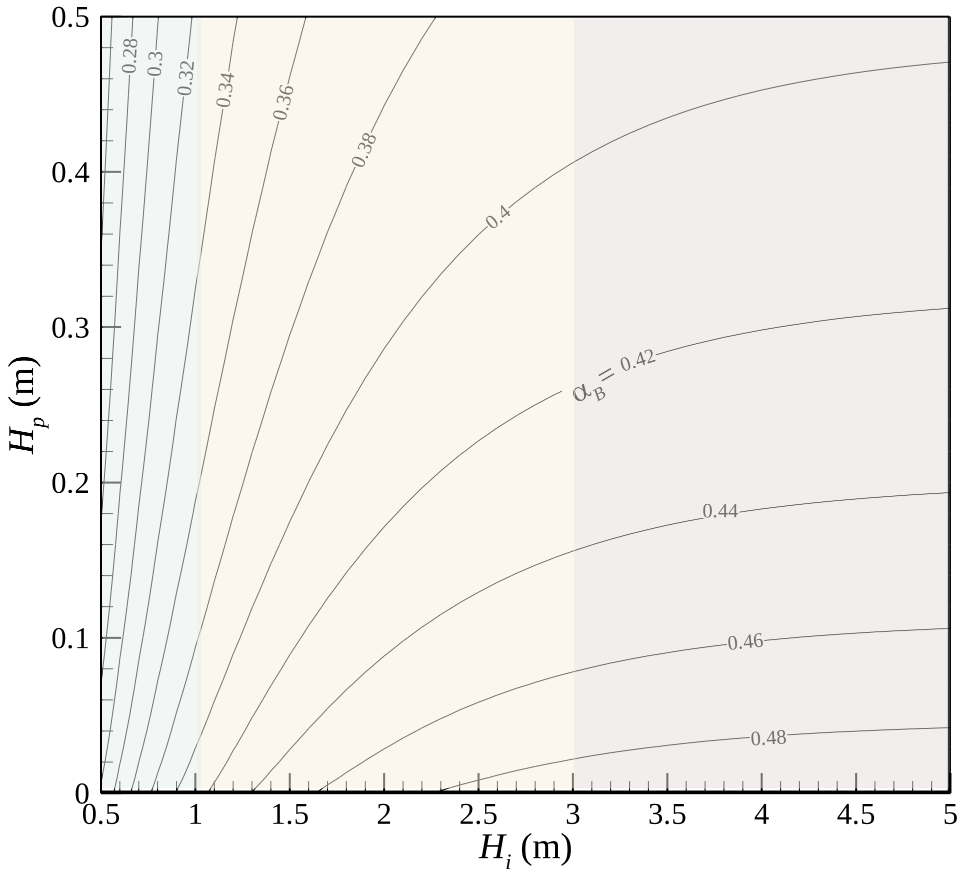
Parameterization on melt pond albedo， $\alpha_p = b + exp(-ch_p - d)$

Morassutti and Ledrew, 1996, IJC.

Radiative transfer in melt pond



Impact of H_i and H_p on α



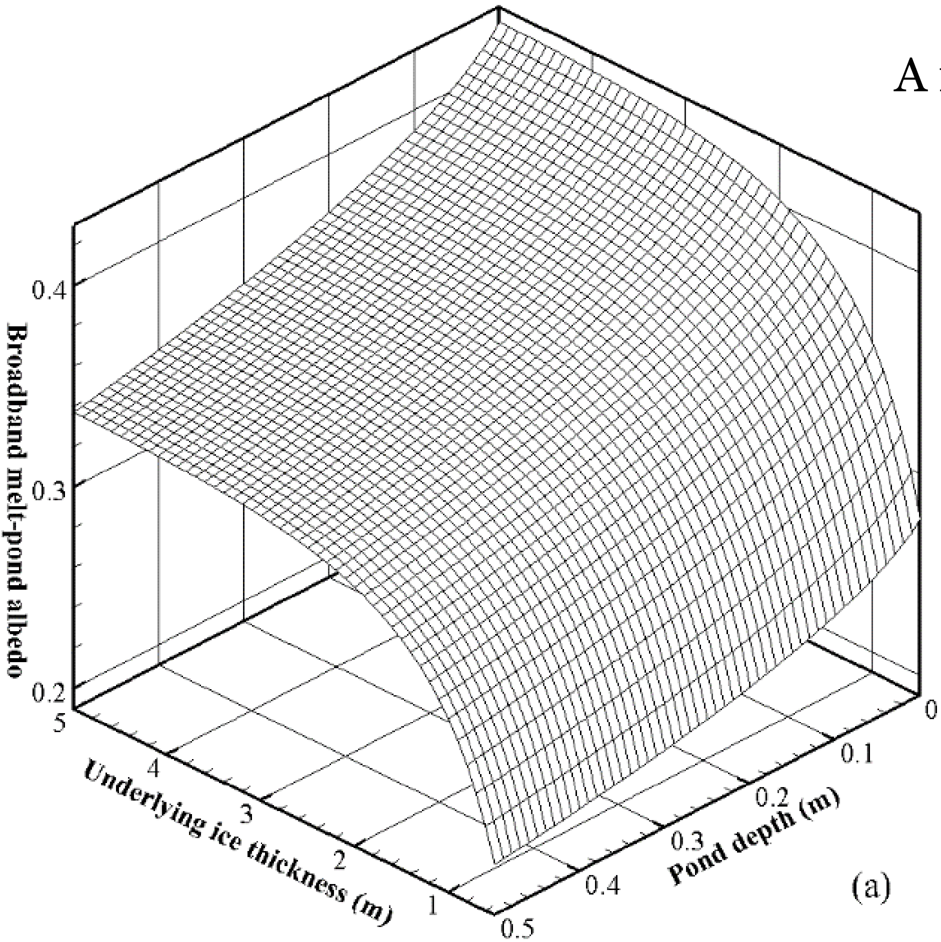
(a)

Melt-pond albedo is sensitive to:

- Hp for thick ice (Hi > 3m)
  - Morassutti and Ledrew (1996)
- Hp and Hi for middle ice (3m > Hi > 1m)
- Hi for thin ice (Hi < 1m)

Lu et al., 2016. CRST.

New parameterization



A new parametrization on melt pond albedo:

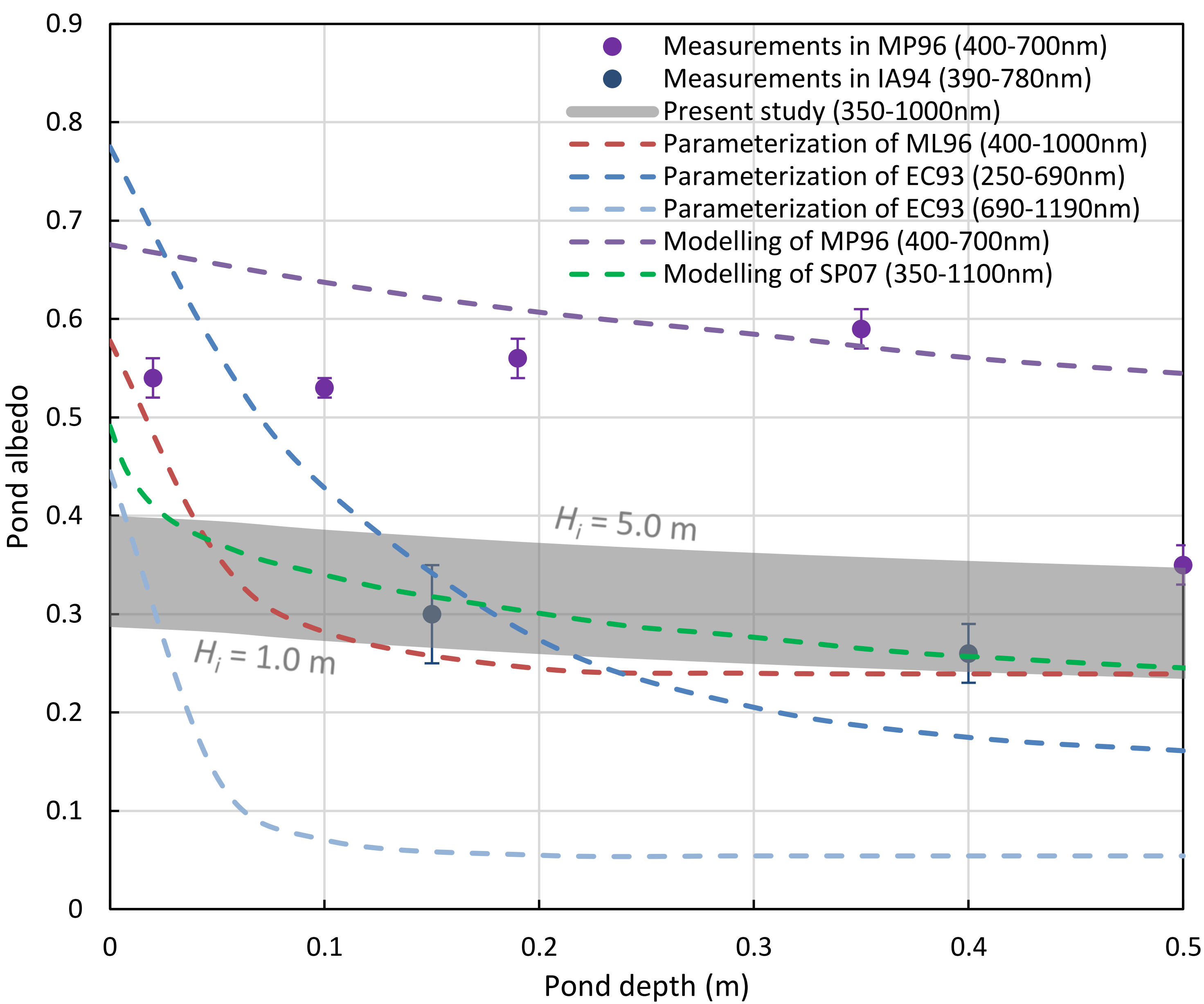
$$\alpha = \begin{cases} b \cdot H_i + c & H_i \leq 1\ \mathrm{m} \\ d \cdot H_i + e \cdot H_p + f & 1\ \mathrm{m} < H_i \leq 3\ \mathrm{m} \\ g \cdot H_p + h & 3\ \mathrm{m} < H_i \end{cases}$$

b, c, d, e, f, g, h are constants based on the wavelength band.

For 350-2500 nm:
b = 0.1341; *c* = 0.1840;
d = 0.0248; *e* = -0.1486; *f* = 0.3322;
g = -0.1534; *h* = 0.4045.

R > 0.9

Comparisons with others

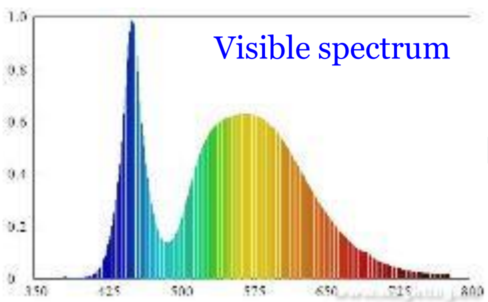


Ebert and Curry (1993) (EC93)
Ivanov and Alexandrov (1994) (IA94)
Morassutti and Ledrew (1996) (ML96)
Skyllingstad and Paulson (2007) (SP07)
Makshtas and Podgorny (1996) (MP96)

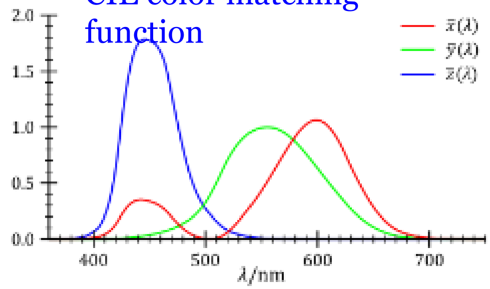
(3) Melt pond color

- Why is there such a big difference in the color of ice surface?

Spectrum→RGB



CIE color matching function



XYZ Color Space

$$X = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\,\overline{x}(\lambda)\,d\lambda,$$

$$Y = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\,\overline{y}(\lambda)\,d\lambda,$$

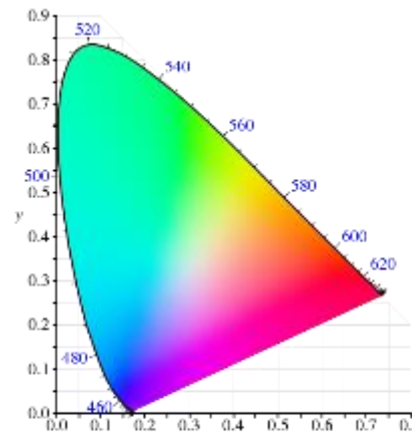
$$Z = \int_{\lambda} L_{e,\Omega,\lambda}(\lambda)\,\overline{z}(\lambda)\,d\lambda.$$

xyY Color Space

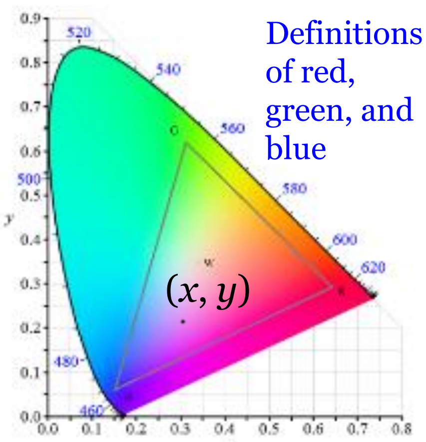
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$



CIE color space chromaticity diagram

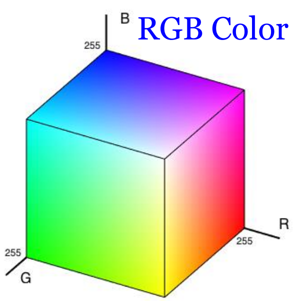


Definitions of red, green, and blue

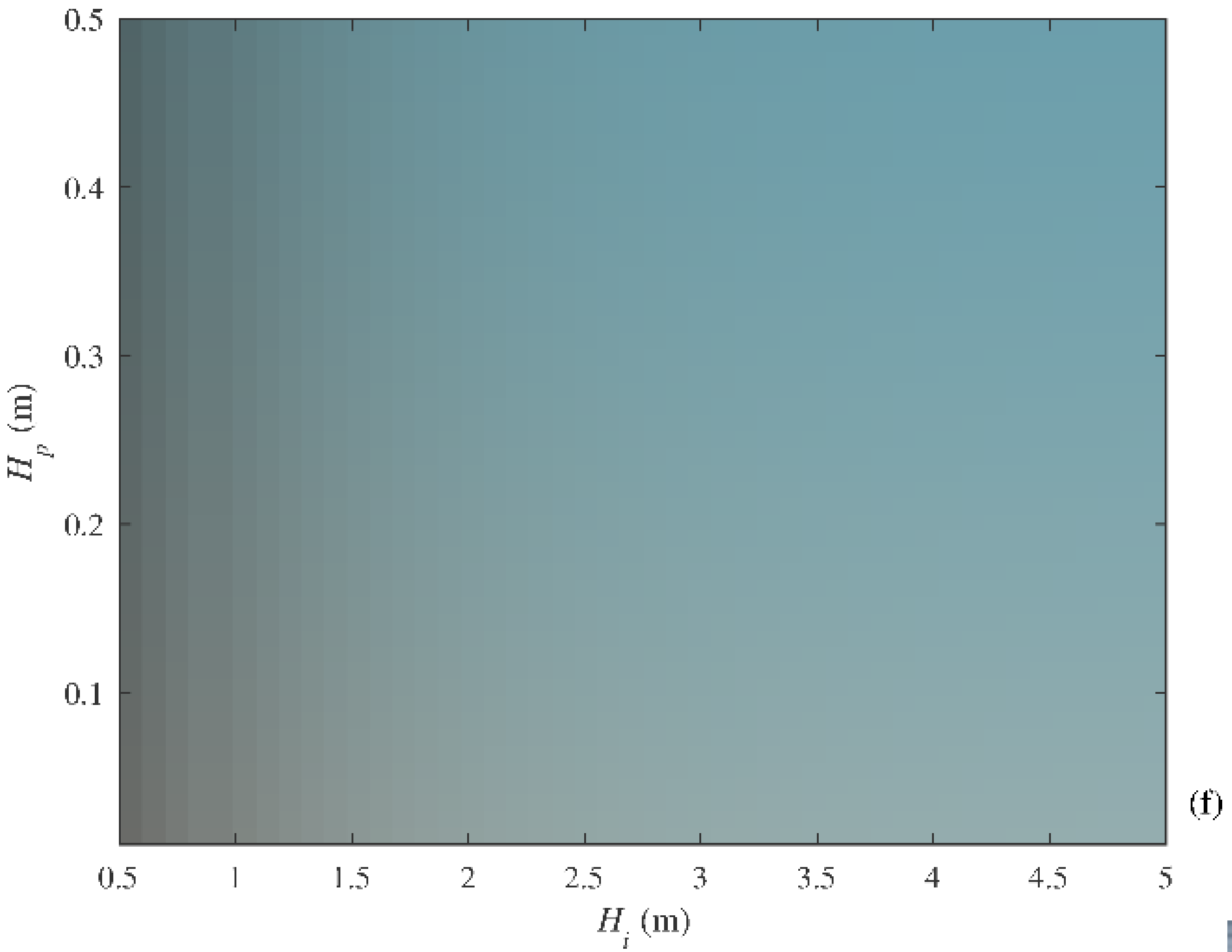
Spectrum

$[r, g, b]$

RGB Color Space



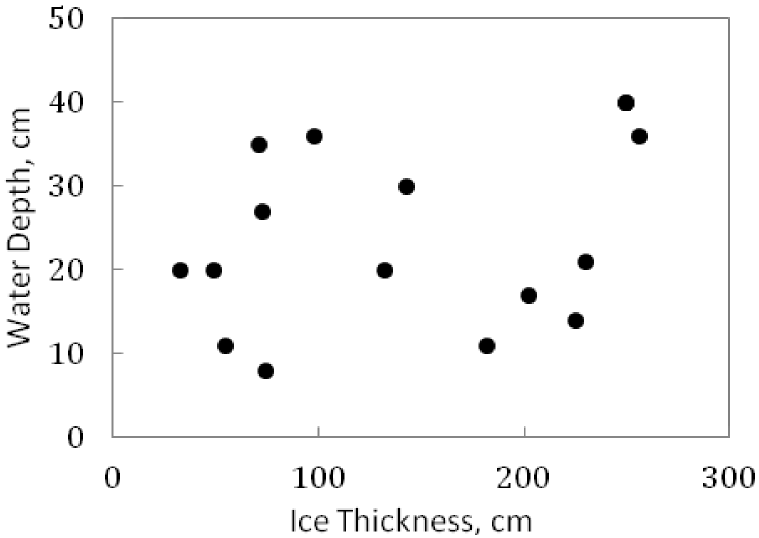
Lu and Leppäranta, et al. 2018. The Cryosphere.



Gray on FYI.
Blue on MYI.

Variation of RGB color of melt pool simulated by RTM with pool depth Hp and ice thickness Hi

Observations on pond color

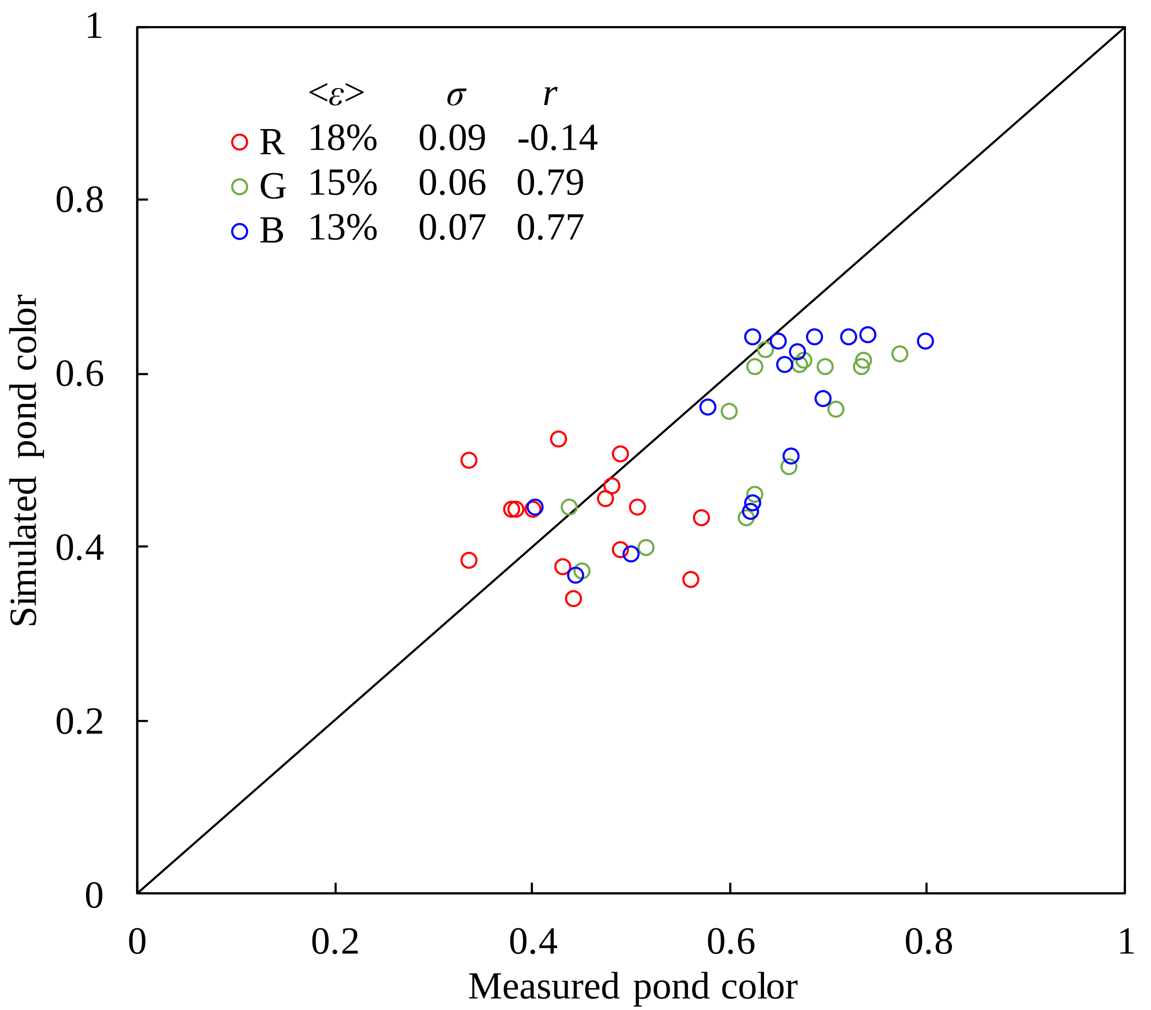


Water depth and SIT in melt ponds during ARK27/3

Table 1. SIT, water depth (WD) and HSL of melt ponds measured during ARK 27/3.

Pond tag	SIT,	WD, cm	H	S	L
1008_N3	55	11	120	23	121
1008_N4	98	36	128	52	147
1008_P1	74	8	126	17	153
1008_P2	230	21	130	137	145
1008_P3	225	14	129	94	121
1508_N7	73	27	113	33	99
1608_P1	250	40	127	59	131
1608_P12	250	40	126	102	142
1608_P13	250	40	126	87	138
1608_P3	71	35	131	19	151
2208_P1	182	11	125	69	140
2208_P2	202	17	126	57	149
2208_P3	143	30	125	65	155
2208_P4	132	20	120	33	138
2208_P5	33	20	40	3	160
2608_P1	256	36	128	86	155
2608_P3	49	20	100	2	114

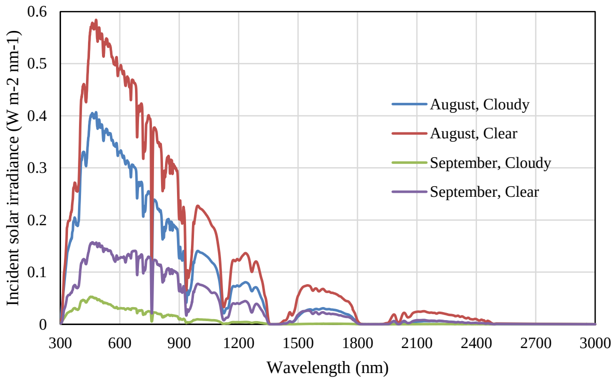
Istomina, L., et al., 2016. IGARSS 2016, Beijing, 7678–7681.



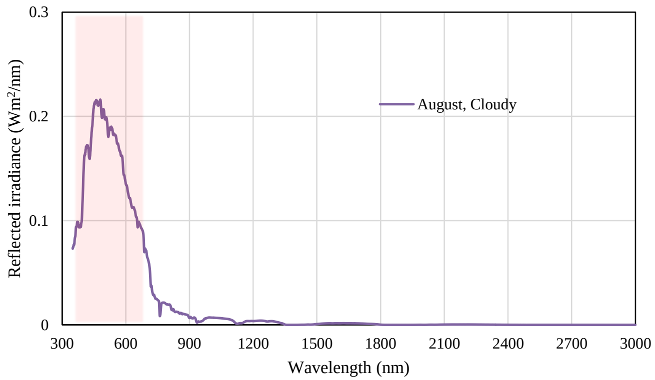
Comparison of simulated pond color with in-situ observations in Istomina et al. (2016)

What the color means?

Incident solar radiation

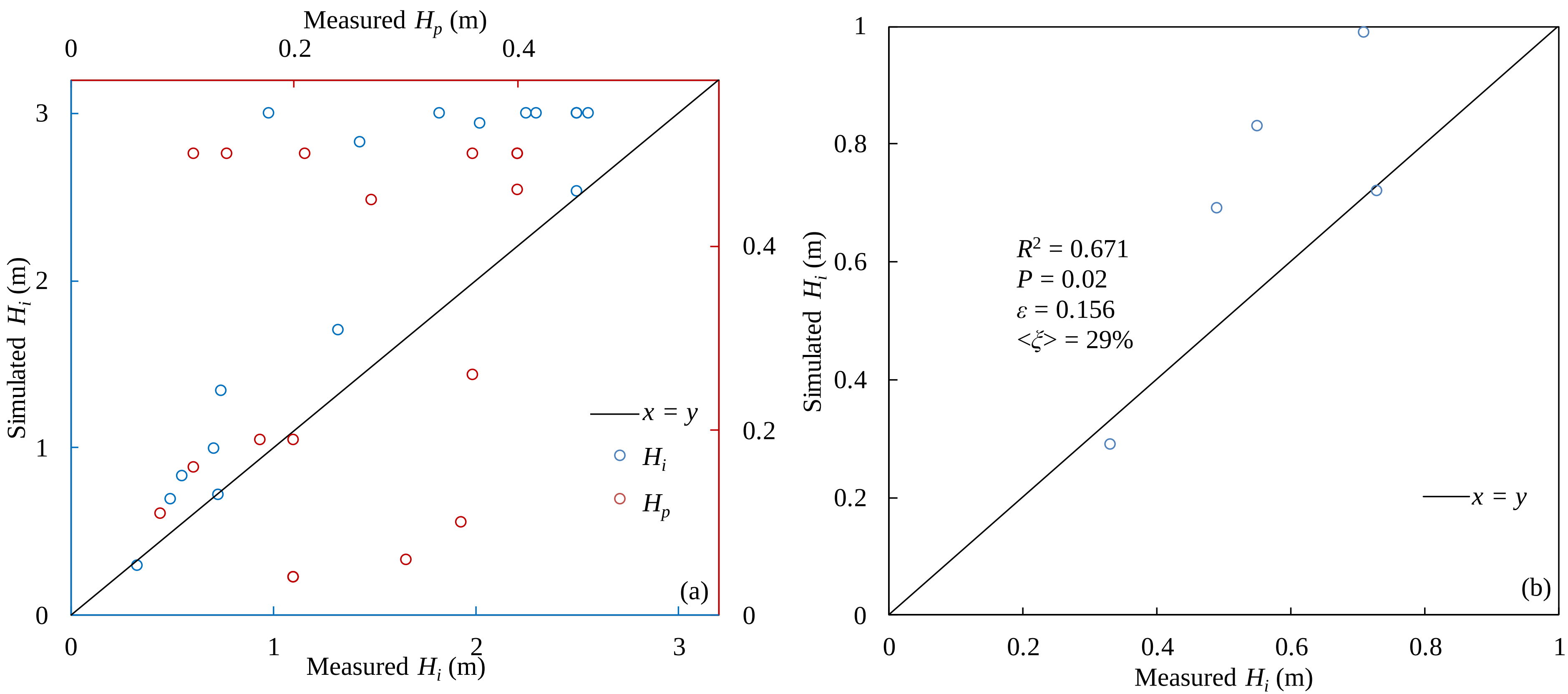


Reflected solar radiation



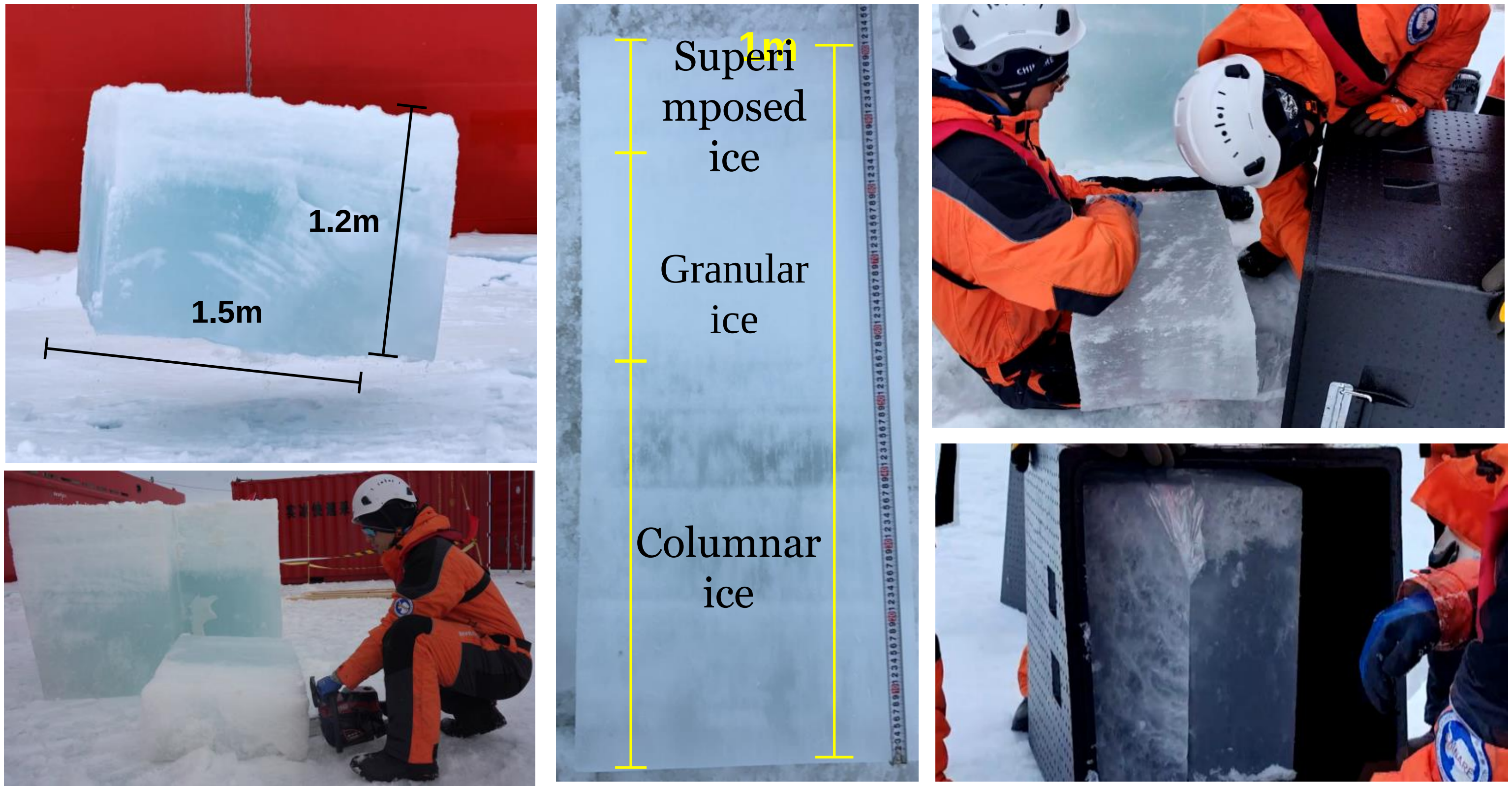
The reflection spectrum includes the influence of the pond water and bottom ice, so it is possible to separate the melt pond depth and sea ice thickness from it!

A possible new method for estimating Arctic summer sea ice thickness!



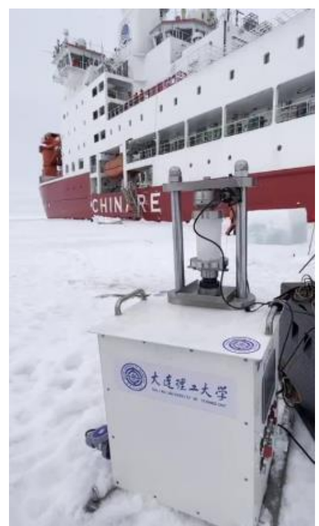
(a) Retrievals of underlying ice thickness and pond depth using measured pond colors in Istomina et al. (2016).
(b) Is a subset of panel (a) for Hi < 1 m.

6. Observations on sea ice mechanics

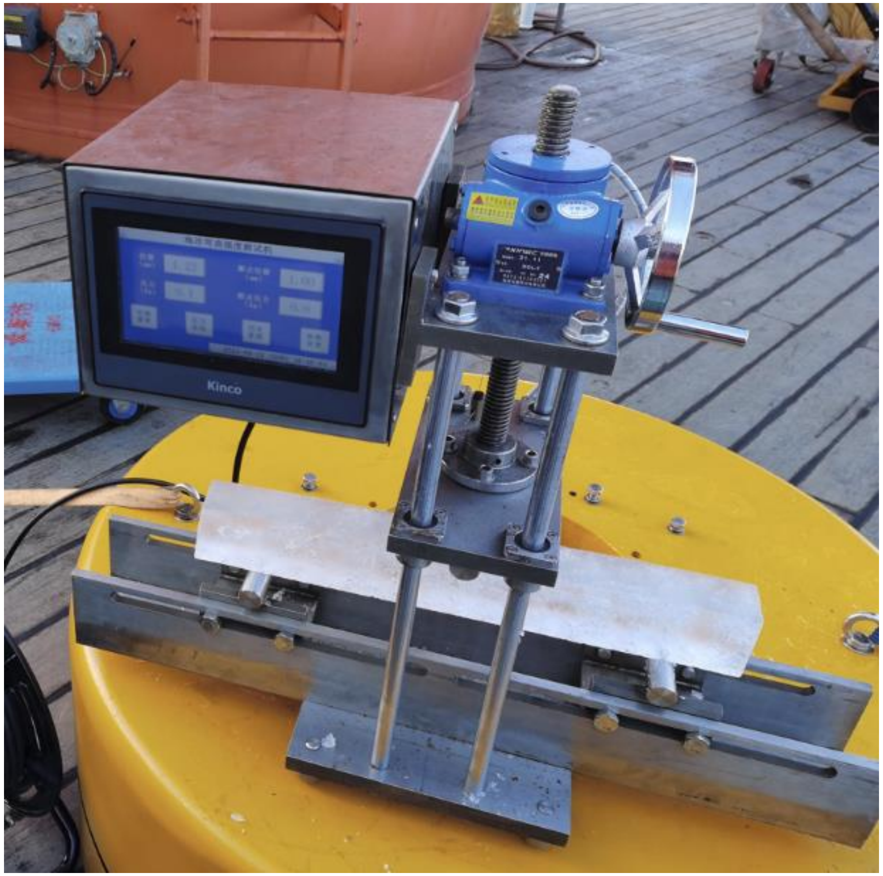


Sea ice sampling during CHINARE-2023

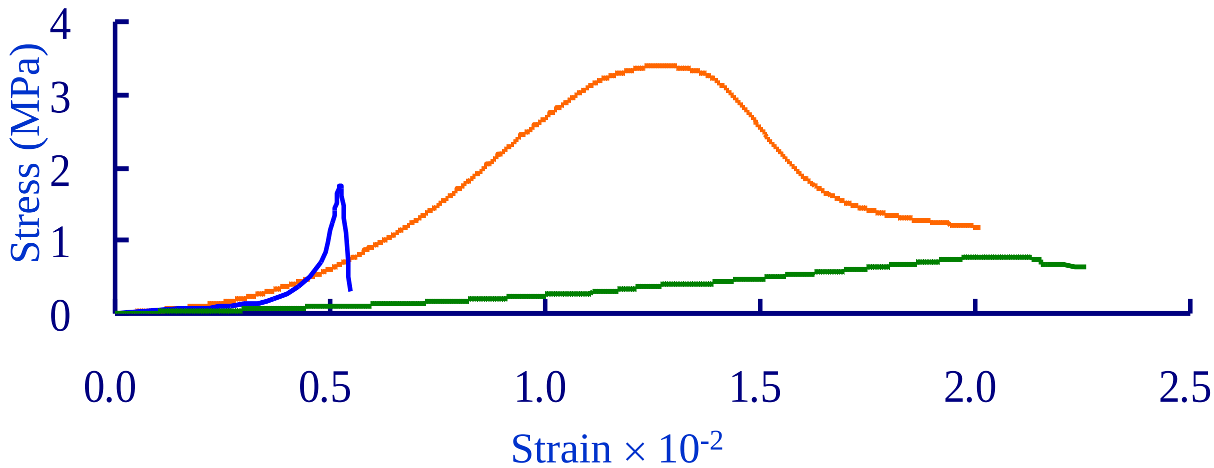
Mechanical test samples



Mechanical test samples



Uniaxial compression test



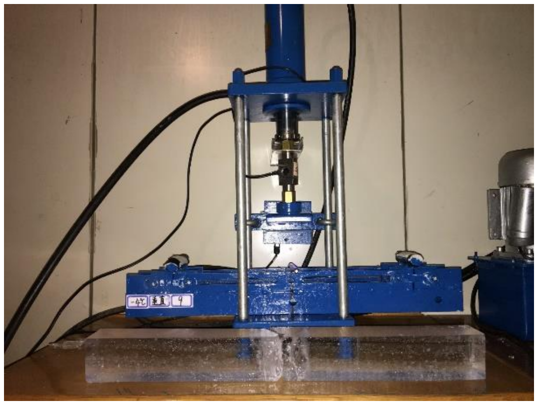
Shear failure
brittle

Splitting failure
Elastoplastic

Swelling failure
Viscoplastic

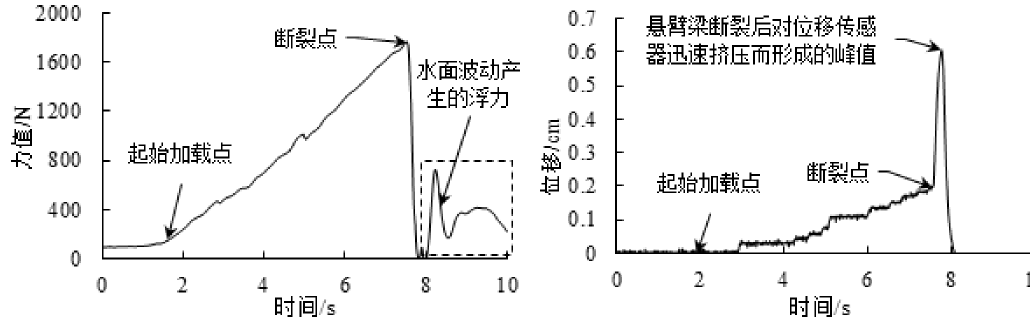
Different failure modes in uniaxial compression test of sea ice

Flexural strength test



Laboratory three-point flexural test

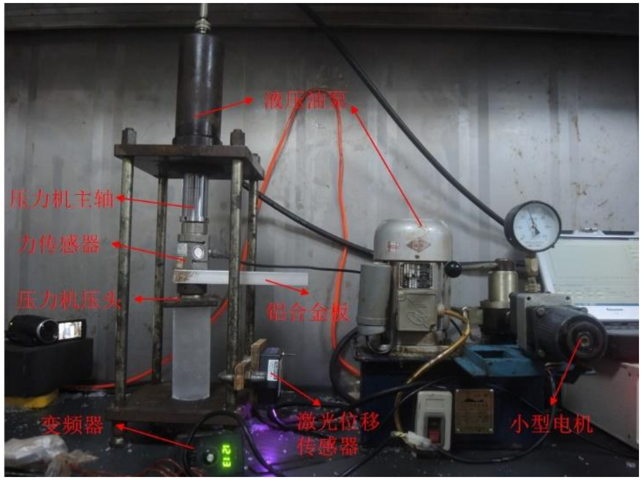
In-situ cantilever beam test



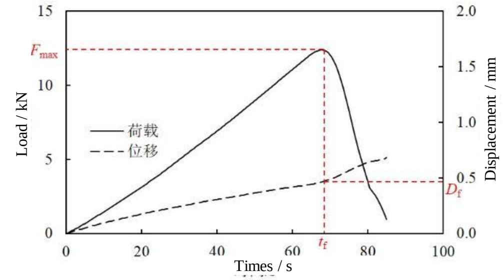
Time series of force (a) and displacement (b) in a cantilever beam test

- The ice flexural strength measured by different methods varies, so when discussing bending strength, it is necessary to explain the measurement method.
- The ratio of uniaxial compression strength to bending strength of sea ice is close to a constant value.

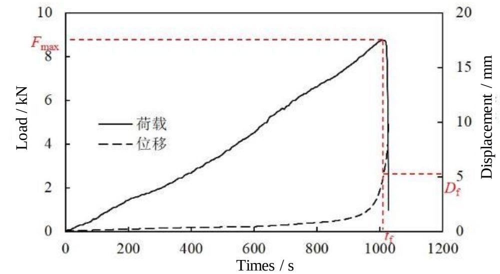
Example 6: Arctic sea ice 2012-2018



Equipment for ice uniaxial compression test

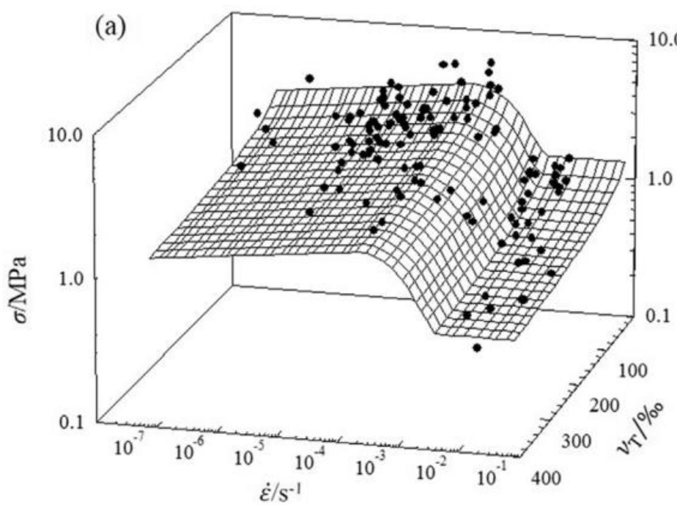


$\dot{\varepsilon} = 5.71 \times 10^{-3}$ 1/s

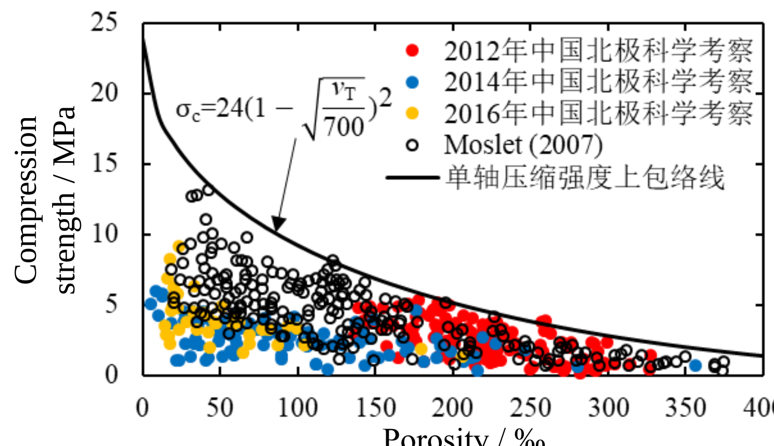


$\dot{\varepsilon} = 4.39 \times 10^{-6}$ 1/s

Time series of force and displacement in a uniaxial compression test

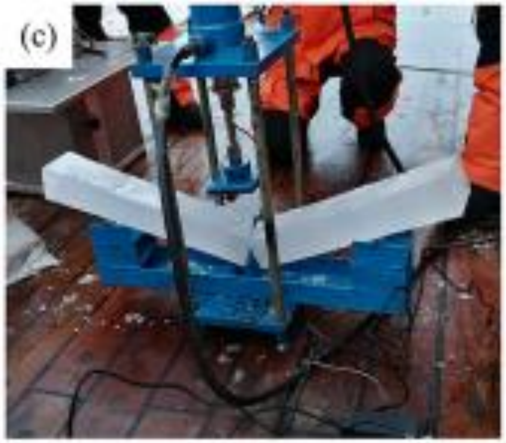


Relationship between uniaxial compressive strength, porosity, and strain rate

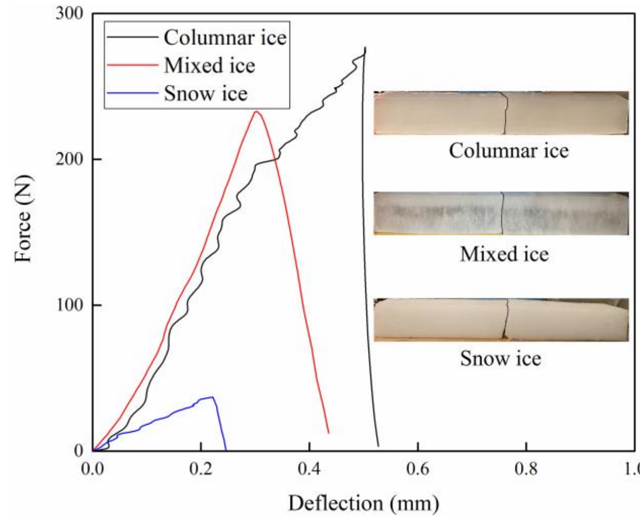


Upper limit of uniaxial compression strength of summer Arctic sea ice

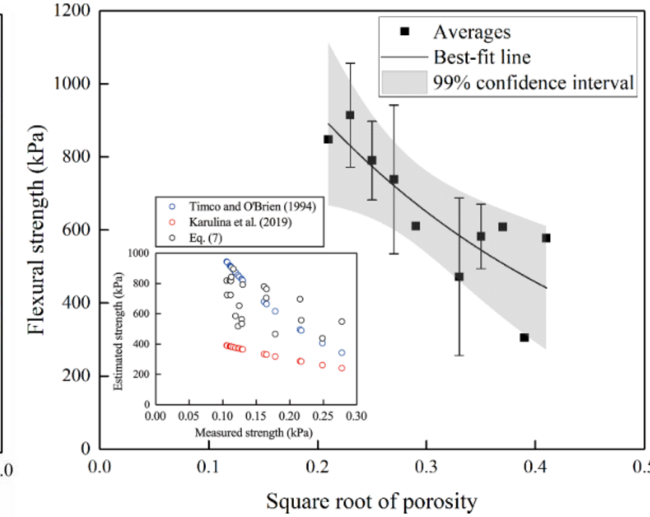
Example 7: Antarctic sea ice 2019



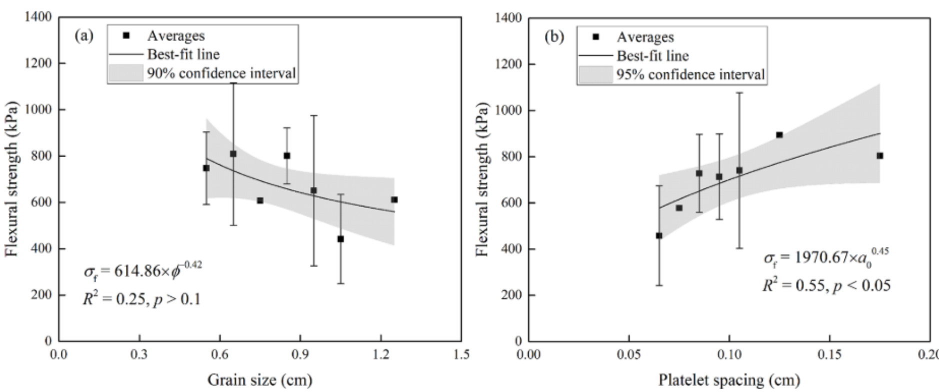
Three point test equipment

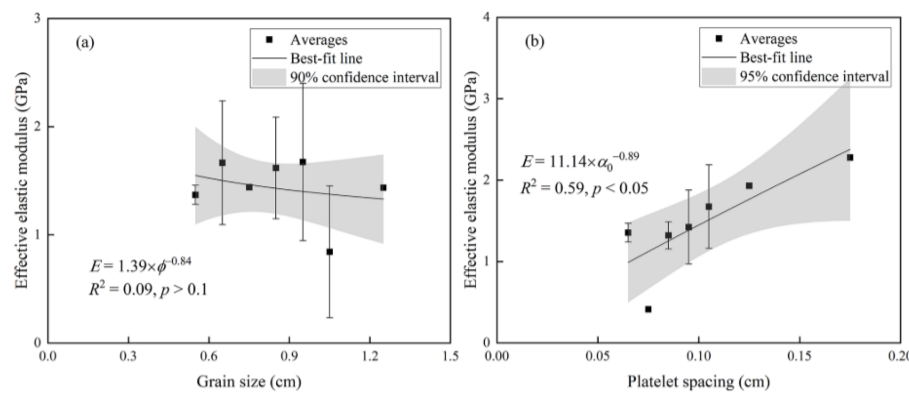


Loading process and failure modes of sea ice with different crystal types



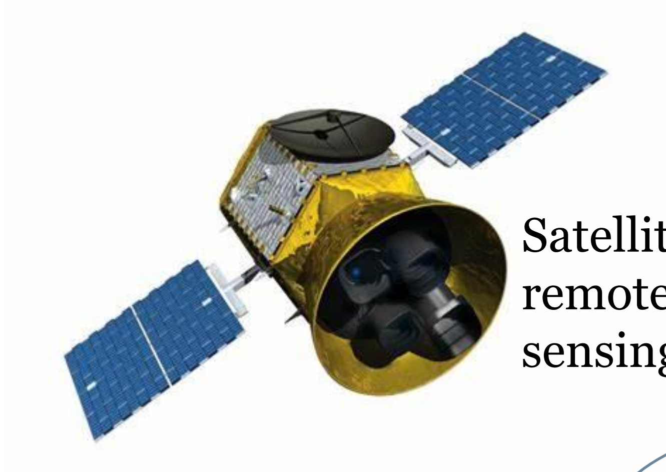
Flexural strength .vs. porosity





Relationship between flexural strength and crystal size and spacing of sea ice

7. Discussions



Satellite remote sensing

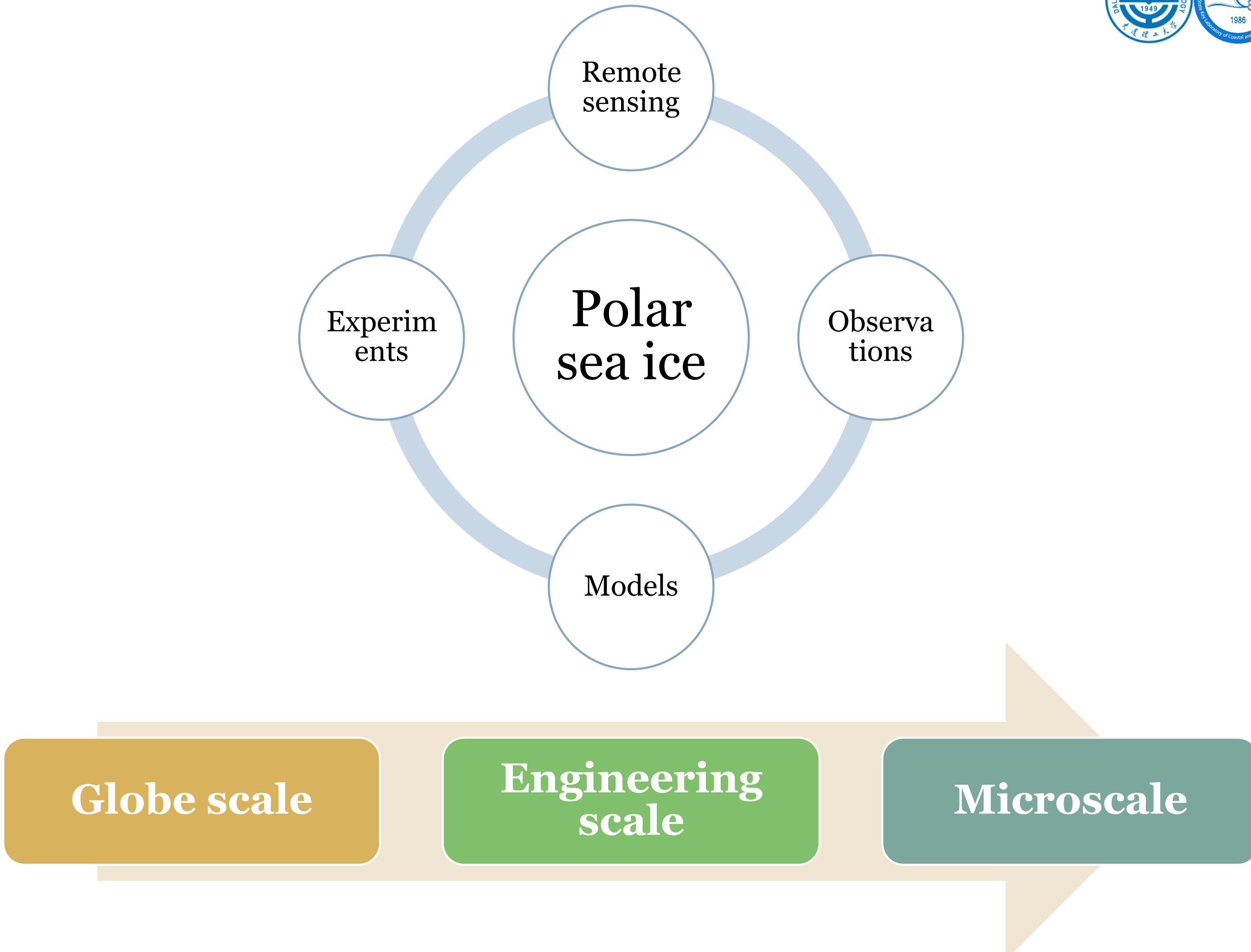
Numerical forecast

Highly associated with ice properties

Polar sea ice change

Smaller size! More pores!

Impacts of dynamic and thermodynamic processes will be more active.


Remote sensing
Experim ents
Polar sea ice
Observa tions
Models
Globe scale
Engineering scale
Microscale

Thank you！