Overview of Sea Ice Earth Observation - Altimetry, Extent, Concentration, Drift

Lecturer: Dr. Sinéad Louise Farrell

[1] Earth System Science Interdisciplinary Center (ESSIC), University of Maryland, USA
[2] NOAA Laboratory for Satellite Altimetry, NOAA Center for Weather and Climate Prediction, USA

Email: sineadf@umd.edu • Twitter: @sineadlfarrell •
www.star.nesdis.noaa.gov/sod/lsa/

1st ESA Advanced Training Course on Remote Sensing of the Cryosphere
University of Leeds, United Kingdom
12-16 September 2016

Photo Credit: Sinéad L. Farrell

Overview

- **Introduction to sea ice**
  - Sea ice characteristics
  - Role in the climate system
- **Measuring and Monitoring Sea Ice**
  - Review of remote sensing methods and sensors
  - Review of observations with satellite altimetry
- **Research Goals for Sea Ice Mapping**
- **Key Sea Ice Parameters**
  - Sea Ice Area/Extent/Concentration
  - Sea Ice Drift and Age
  - Sea Ice Thickness and Volume
- **Handy links to available data sets and further reading**

The Frozen Ocean

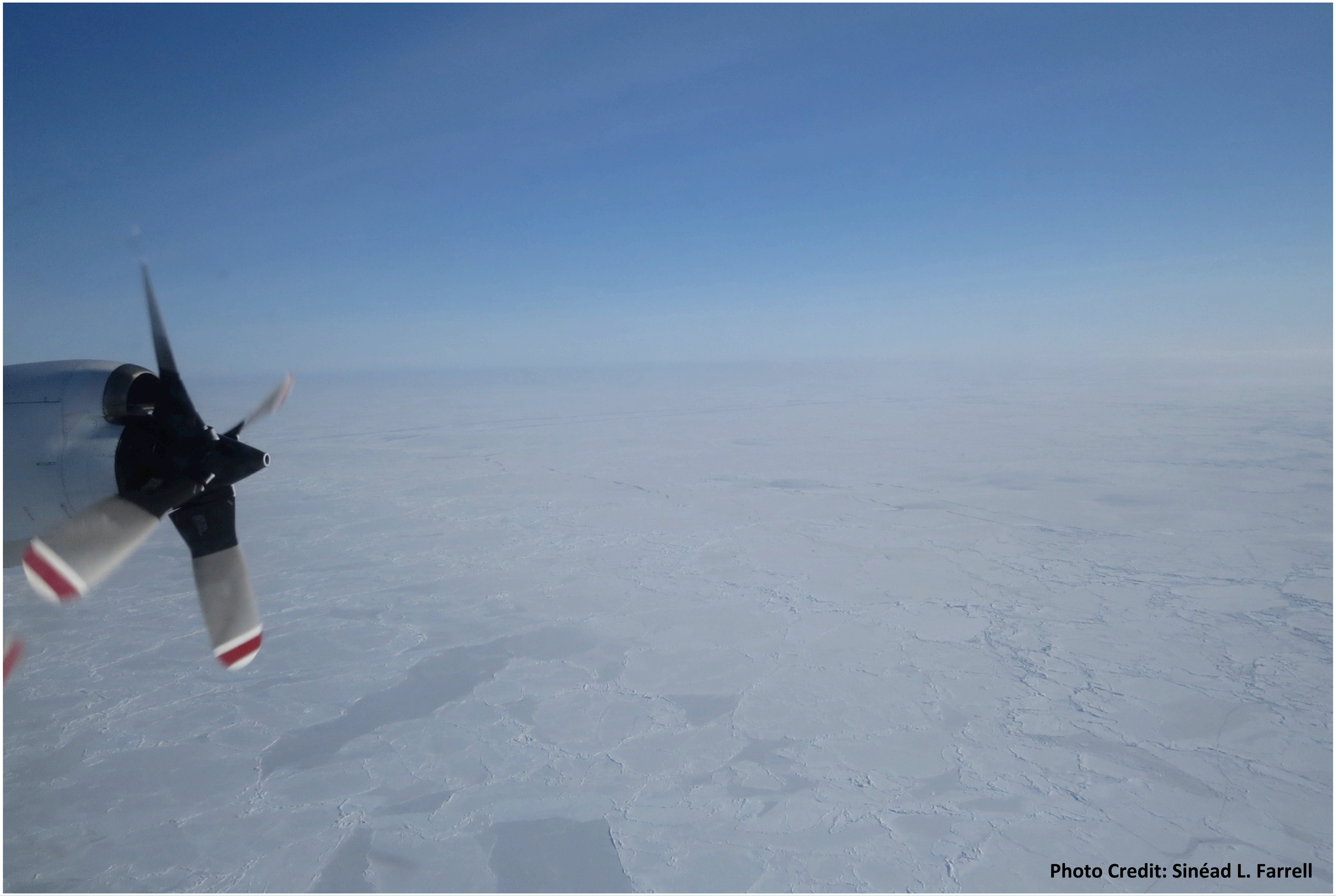
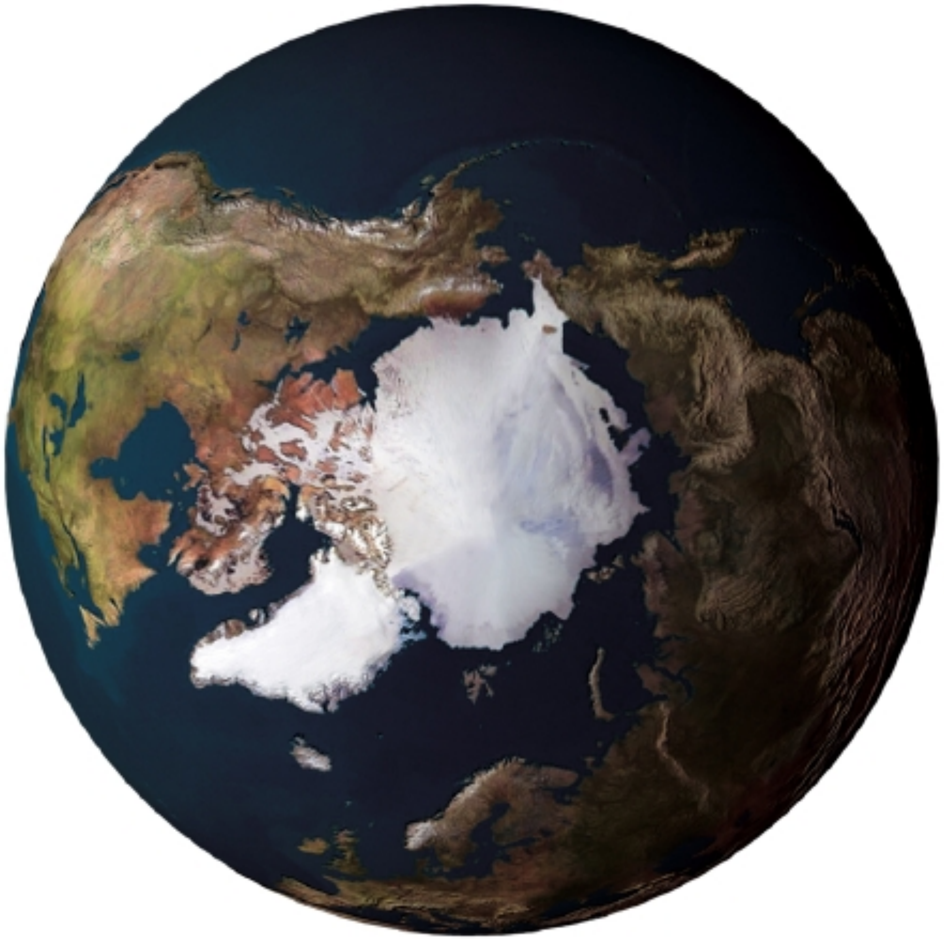


Photo Credit: Sinéad L. Farrell

The Frozen Ocean

Arctic Ocean



Southern Ocean

Global coverage: ~ 20 – 25 x 10^6 km^2 !

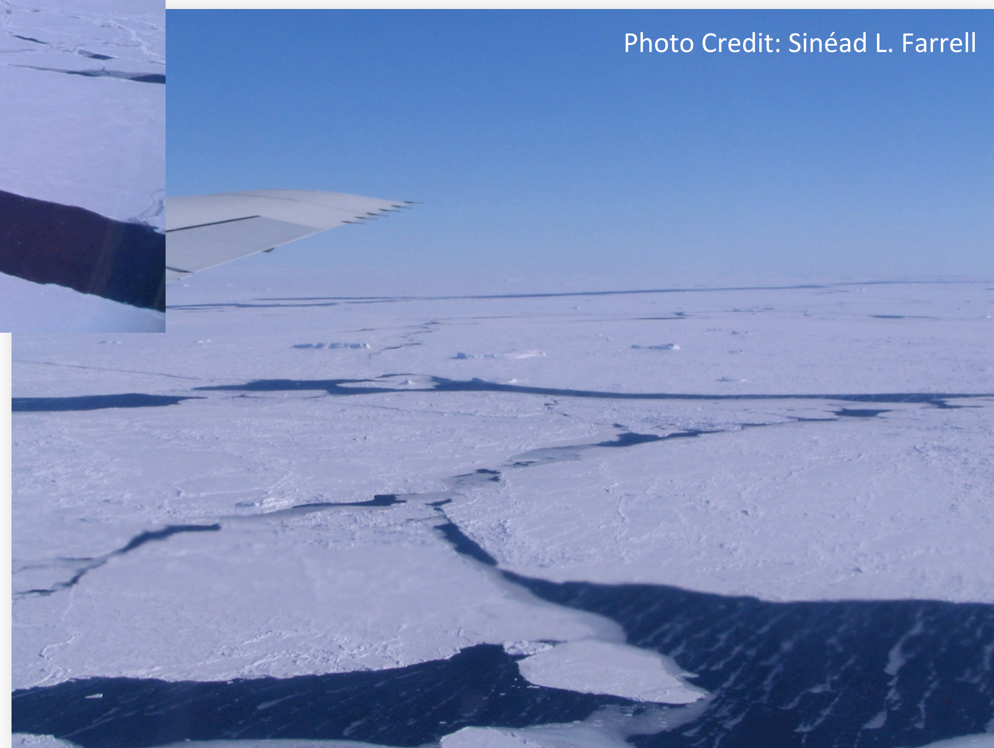
A Complex Matrix

$$\begin{pmatrix} 1 & i & -i & 0 \\ -i & 0 & 0 & 1 \\ i & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

A Complex Matrix

The sea ice pack is a complex system of smooth, level sea ice floes, deformed ice and pressure ridges, open water areas including linear leads and polynyas, and new areas of thin ice. Snow cover atop the sea ice increases the albedo.

Sea Ice Morphology: Leads



Sea Ice Morphology: Pressure Ridges

Photo Credit: Sinéad L. Farrell

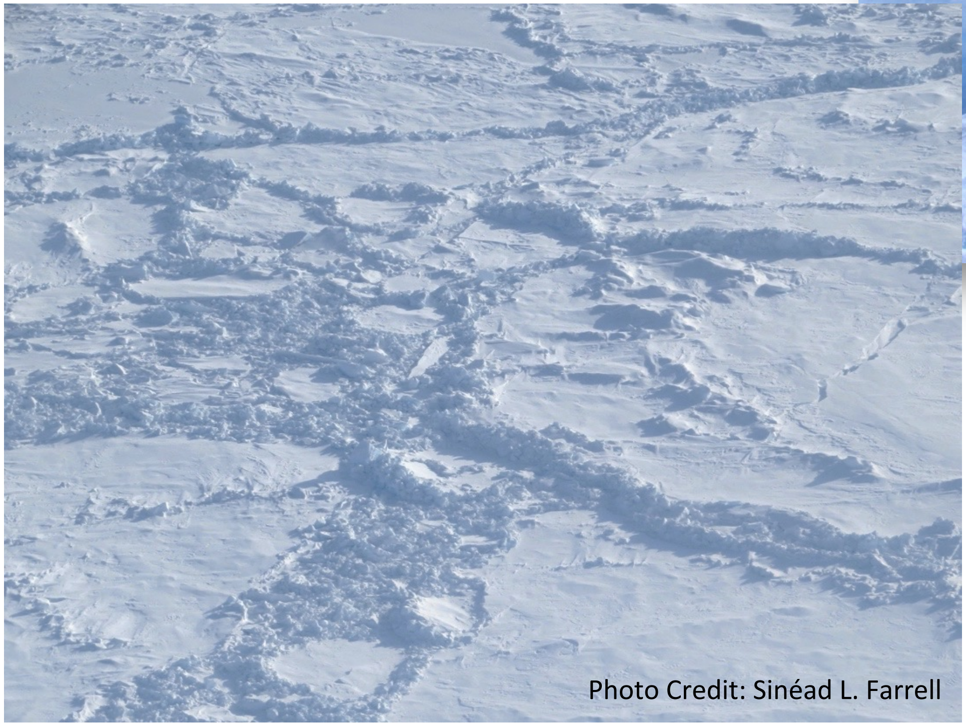


Photo Credit: Sinéad L. Farrell

Sea Ice Morphology: Melt Ponds & Polynyas

Photo Credit: Sinéad L. Farrell

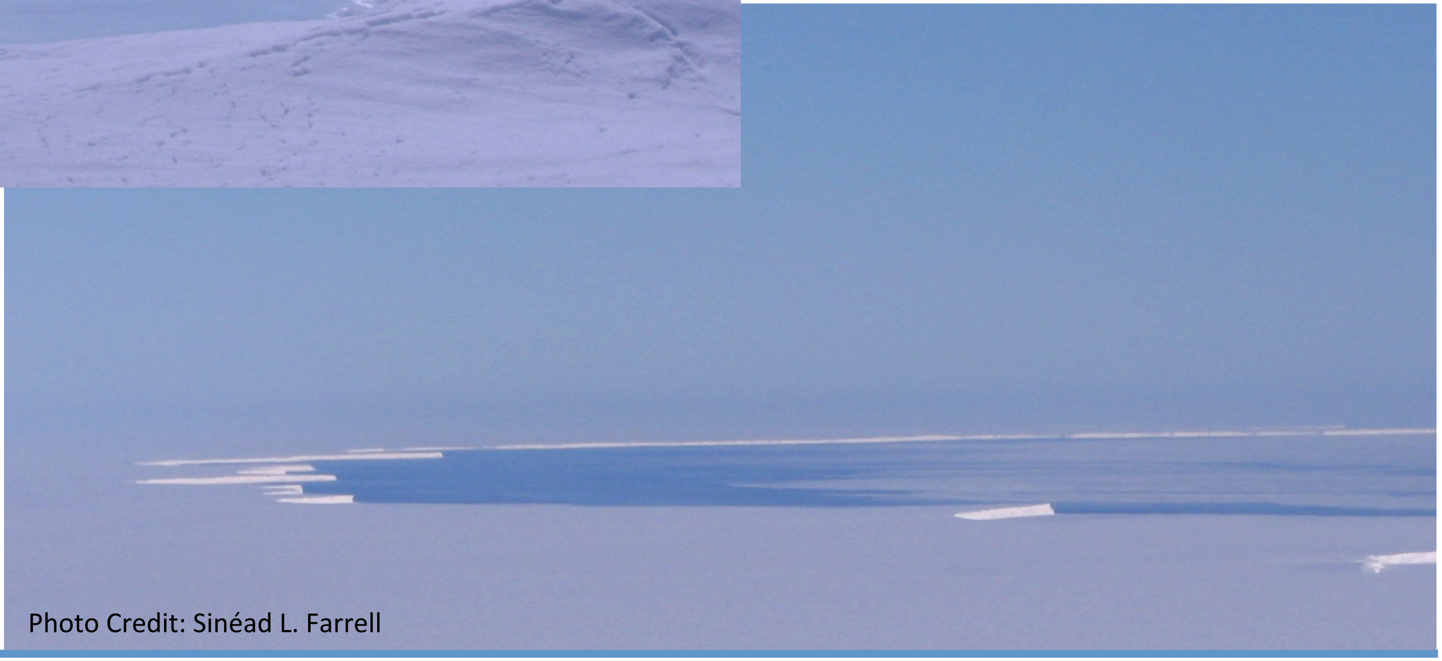
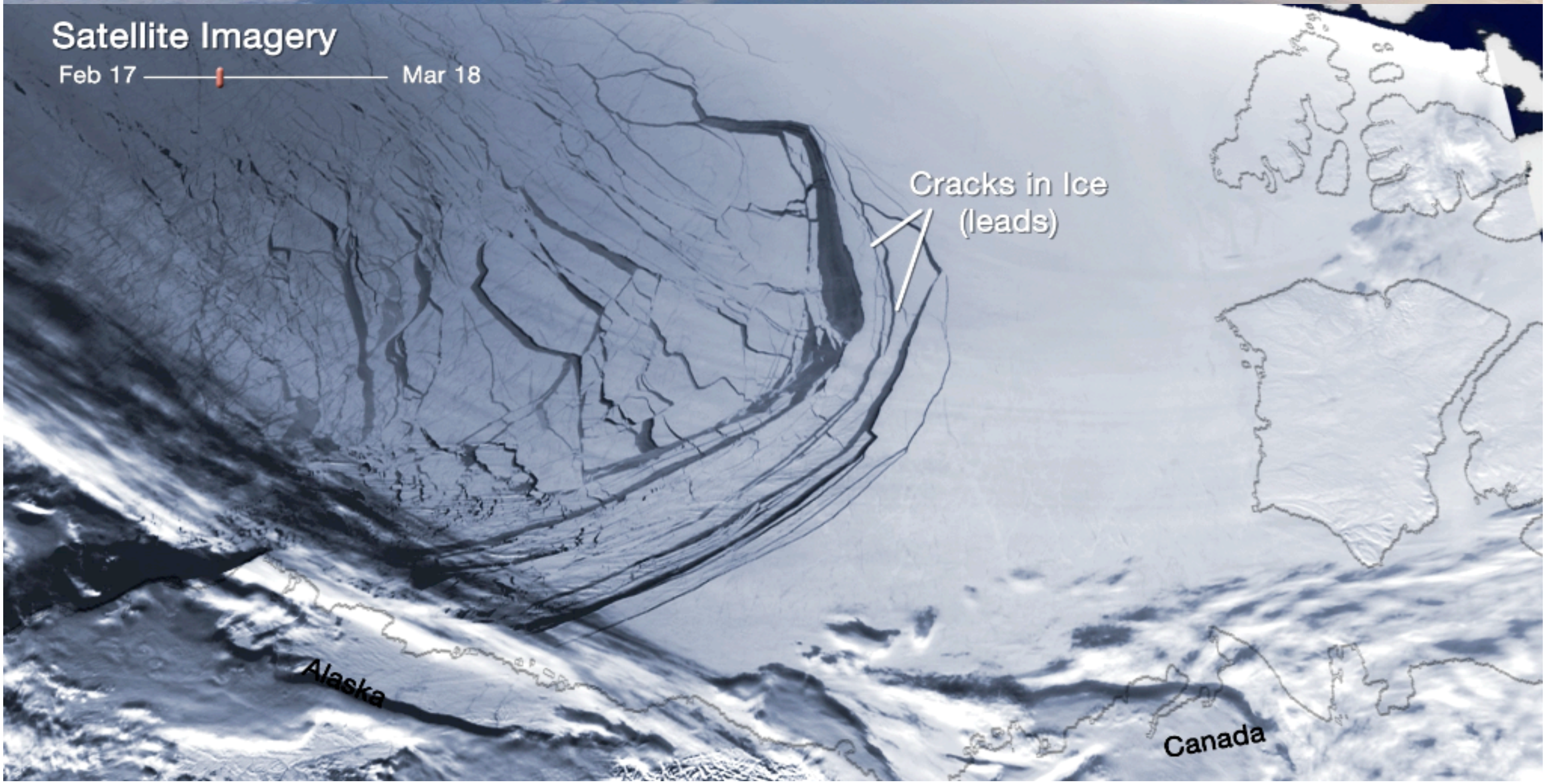


Photo Credit: Sinéad L. Farrell

A Dynamic Ice Cover



Sea ice is almost continually in motion!

5 principal forces acting on sea ice: wind (primary forcing factor over days to weeks, via surface drag), ocean currents, coriolis force, internal ice stress, sea surface slope/ tilt (sea level changes due to uneven heating and gravity forces across Arctic Basin).

Sea Ice in the Climate System

- **Albedo Feedback**:

Increasing global temperatures, together with Arctic amplification, cause a decrease in the Earth's snow and ice cover. This decreases overall albedo of region, which in turn increases the absorption of solar radiation, amplifying the warming: a positive feedback loop!

Albedo Feedback

Sea Ice in the Climate System

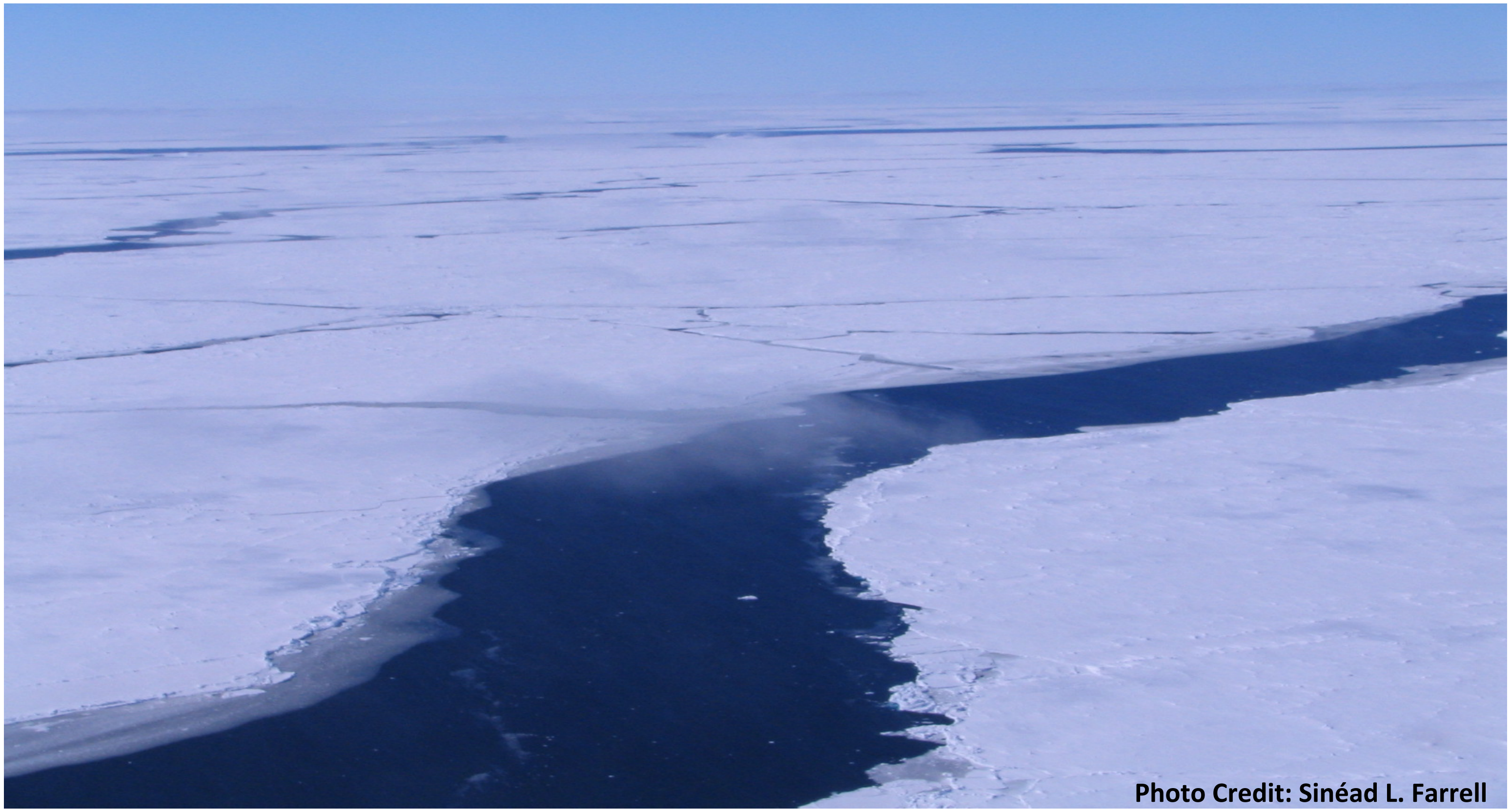
- **Albedo Feedback**:

Increasing global temperatures, together with Arctic amplification, cause a decrease in the Earth's snow and ice cover. This decreases overall albedo of region, which in turn increases the absorption of solar radiation, amplifying the warming: a positive feedback loop!

- **Heat and Moisture Flux Feedback**:

Diminishing Arctic sea ice increases ocean heat flux to atmosphere, amplifying warming. It also increases vapor flux to the atmosphere, which may enhance cloud cover. This could potentially either cool or warm the planet.

Ocean-Atmosphere Heat Flux



- Approximately 50 % of the total exchange of heat between the Arctic Ocean and the atmosphere occurs through leads and polynyas.
- As the areal fraction of open water, leads, polynyas, or thinner ice increases in the Arctic, the sea ice will no longer efficiently insulate the ocean from the atmosphere.

Sea Ice in the Climate System

- **Albedo Feedback**:

Increasing global temperatures, together with Arctic amplification, cause a decrease in the Earth's snow and ice cover. This decreases overall albedo of region, which in turn increases the absorption of solar radiation, amplifying the warming: a positive feedback loop!

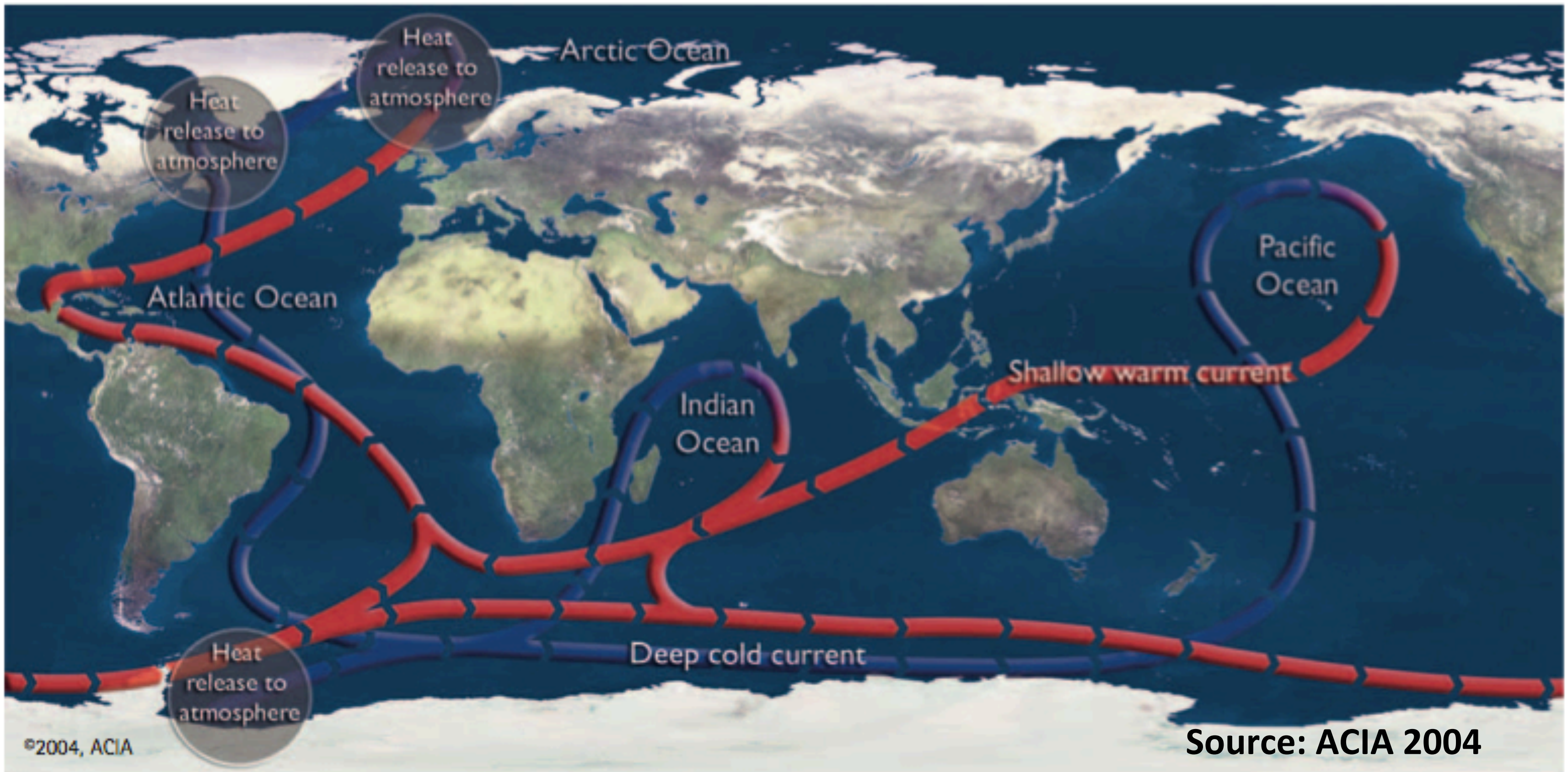
- **Heat and Moisture Flux Feedback**:

Diminishing Arctic sea ice pack increases ocean heat flux to atmosphere, amplifying the warming. It also increases vapor flux to the atmosphere, which may enhance cloud cover. Could potentially either cool or warm the planet.

- **Thermohaline Circulation (THC) feedback**:

Increased export of freshwater (sea ice flux) from Arctic Ocean could increase stratification of North Atlantic, which could slow THC.
A decrease in THC would then draw less Atlantic water into high latitudes, leading to a slowdown in global overturning cell & subsequent localized cooling

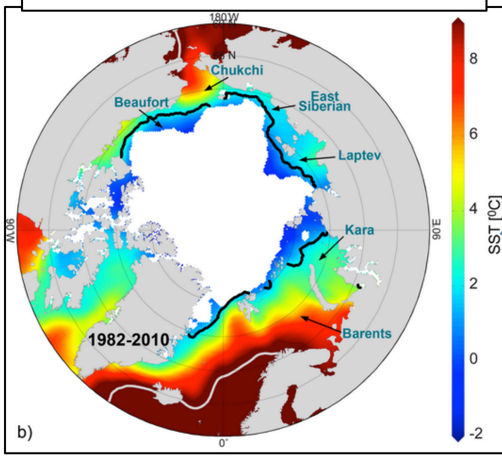
Global Thermohaline Circulation



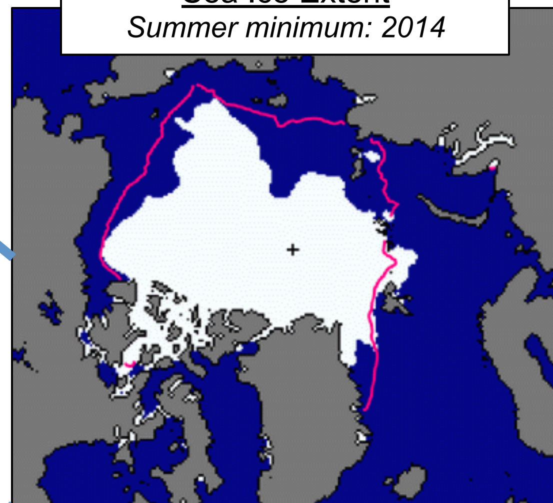
Ocean currents transport heat from the equator to the poles through a heat- and salt-driven process called ***thermohaline circulation***. As the water cools at the poles, it becomes dense and heavy, and sinks. This cold water moves south along the lower part of the ocean and rises near the equator to complete the cycle (Source: NSIDC).

Sea Ice in the Arctic System

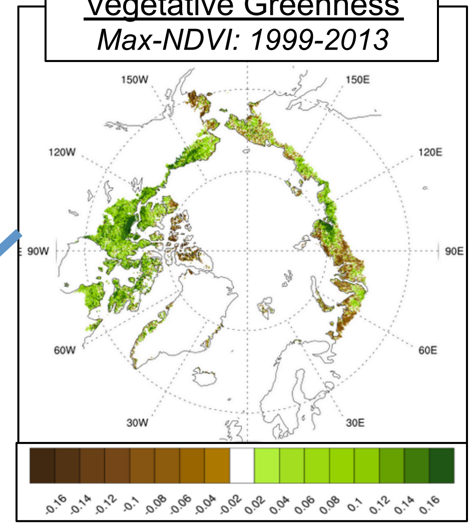
Ocean Surface Temperatures
Summer 1982-2010



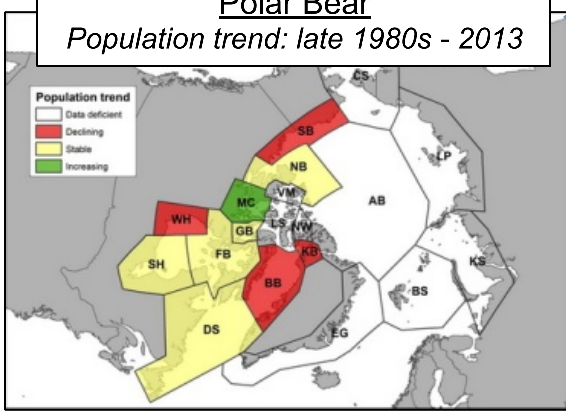
Sea Ice Extent
Summer minimum: 2014



Vegetative Greenness
Max-NDVI: 1999-2013

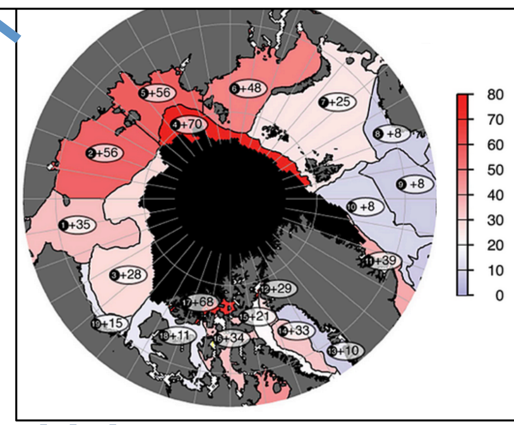


Polar Bear
Population trend: late 1980s - 2013



Loss of sea ice linked to:
- Increase in ocean temperatures
- Increase in vegetation
- Increase in primary productivity
- Decline of polar bear

Primary Productivity
Change in occurrence of double bloom (%)
1998-2001 versus 2007-2012



Impact of <u>persistent</u> ice loss in peripheral seas widely apparent
(source: Arctic Report Card)

Slide courtesy of J. Richter-Menge (Co-Editor, Arctic Report Card)

Measuring and Monitoring the Polar Oceans

- **Remote and harsh environment**
- **In situ** measurements provide detailed measurements in specific locations
- **Submarine** and **airborne** reconnaissance missions provide regional measurements
- **Remote sensing satellites** are one of the best ways to observe snow and ice-covered regions and their *variability*: good temporal and spatial coverage year-round, and at basin scales.

Photo Credit: Jennifer Hutchings

Photo Credit: Sinéad L. Farrell

Remote Sensing Observations of the Polar Oceans (1)

- **Visible and infrared sensors** provide high-resolution images under sunlit, cloud-free conditions by measuring the reflected radiation from the sun, or the emitted infra-red radiation

  - Challenges: polar darkness (long winters) and cloudy conditions

  - NOAA Advanced Very High Resolution Radiometer (AVHRR)

  - NASA Moderate Resolution Imaging Spectroradiometer (MODIS)

  - NOAA Visible Infrared Imager Radiometer Suite (VIIRS)

Remote Sensing Observations of the Polar Oceans (2)

- **Microwave sensors** provide coarse-resolution observations under ANY conditions — dark or light, cloudy or cloud-free

  - Challenges: Low resolution (6.25 km, 12.5 km, 25 km) due to low-levels of emitted microwave radiation from Earth's surface

  - NASA's Scanning Multichannel Microwave Radiometer (SMMR), 1978

  - DMSP Special Sensor Microwave/Imager (SSM/I), 1987 - date

  - Advanced Microwave Scanning Radiometer-Earth Obs. System (AMSR-E)

  - JAXA's Advanced Microwave Scanning Radiometer-2 (AMSR-2)

Remote Sensing Observations of the Polar Oceans (3)

- **Imaging Radar** provide high-resolution radar images of the polar ocean: sea ice reflects more radar energy than water

  - Challenges: interpretation of images provide complex details of sea ice structure (brine vs. air bubbles: older vs. younger sea ice)

  - Synthetic aperture radar (SAR) images e.g. from ASAR, RADARSAT, TerraSAR-X, Sentinel-1 SAR, etc.

- **Non-imaging Radar** measure radar backscatter from ice surface to provide medium-resolution regular coverage during day and night conditions

  - Challenges: interpretation of backscatter profiles requires knowledge of surface roughness at microwave λ. Lower resolution than SAR images

  - SeaWinds sensor aboard NASA's Quick Scatterometer (QuikSCAT)

  - Advanced Scatterometer (ASCAT) on METOP-A and -B

Remote Sensing Observations of the Polar Oceans (4)

- **Radar and LASER Altimeters** measure round-trip travel time between sensor and Earth's surface providing detailed measurements of the elevation of the ice sheets and polar oceans. Altimeters work in day/night conditions and Radar Altimetry (RA) works in cloudy/cloud-free conditions

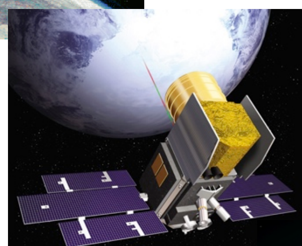
  - Challenges: Laser altimeters cannot penetrate cloud cover; RAs provide lower-resolution (~ km scale) sampling than laser altimeters (~ m scale)

Polar Altimetry Time Series

ERS-1 and -2: 1991- 2000, 1995 – 2003 RA-2 Radar Altimeter

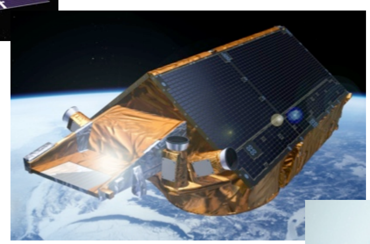
81.5 °N

Envisat: 2002 – 2012 RA-2 Radar Altimeter



ICESat: 2003 – 2009 GLAS Laser Altimeter

86 °N



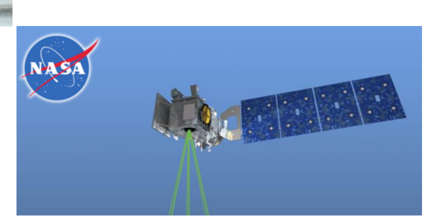
CryoSat-2: 2010 – present
SIRAL Radar Altimeter

88 °N

Operation IceBridge:
2009 - present

90 °N

ICESat-2
Due for launch: 2017/2018



88 °N

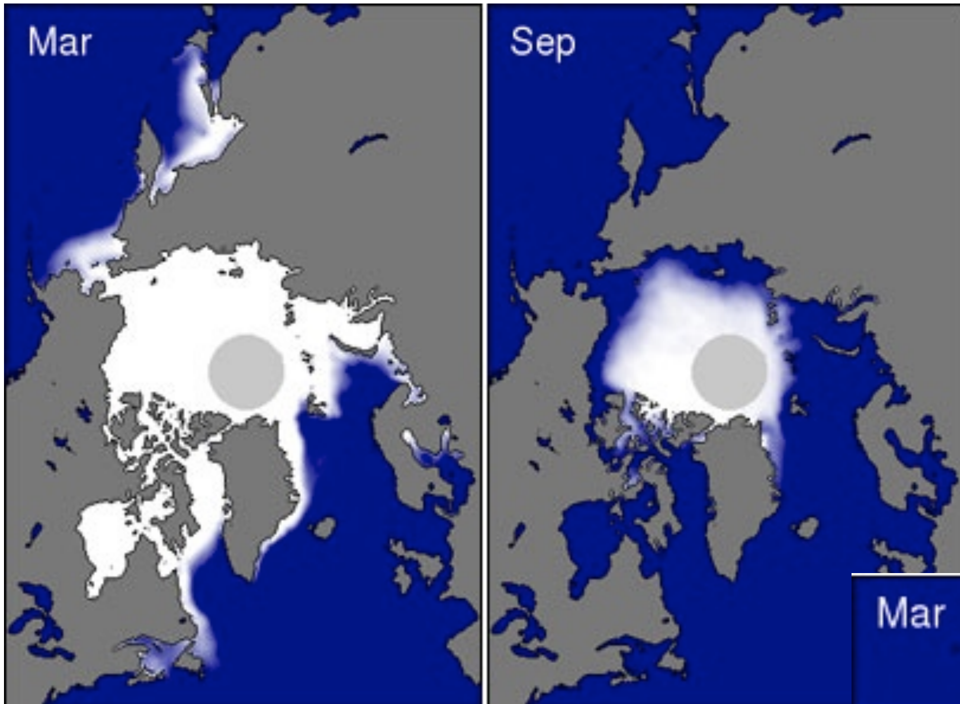
plus SARAL/AltiKa and
SRAL on Sentinel-3!

Key Sea Ice Remote-Sensing Research Goals

- **Measure, map and monitor** key sea ice parameters:

  (i) extent/concentration, (ii) drift, (iii) thickness and volume
- **Precisely determine** changes in key parameters:
  - annual/seasonal trends and inter-annual variability
- **Understand** nature of these changes:
  - assess thermodynamic and dynamic forcing, via process studies
- **Calibrate and Validate** satellite altimeter measurement accuracy:
  - via x-comparison with independent airborne / in situ data-sets
- **Improve remote sensing techniques** for inferring key parameters:
  - algorithm development for current/future missions
- **Advance** the predictability of Arctic sea ice:
  - improve model parameterizations on seasonal-decadal timescales

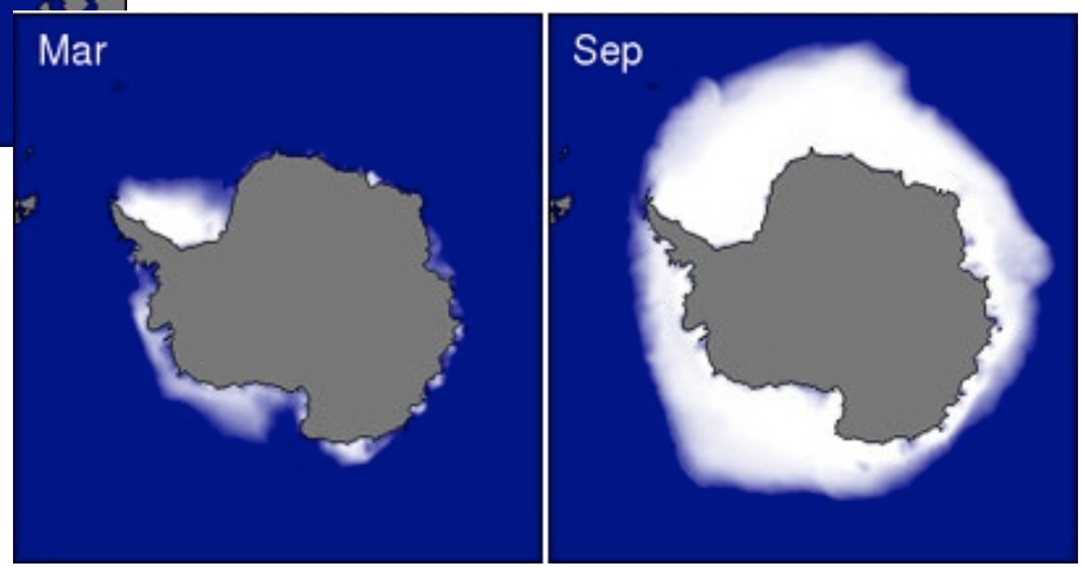
Climatology of Sea Ice Extent



Arctic Ocean

Maximum Extent (March):
14 - 16 million square km

Minimum Extent (September):
4 – 6 million square km



Southern Ocean

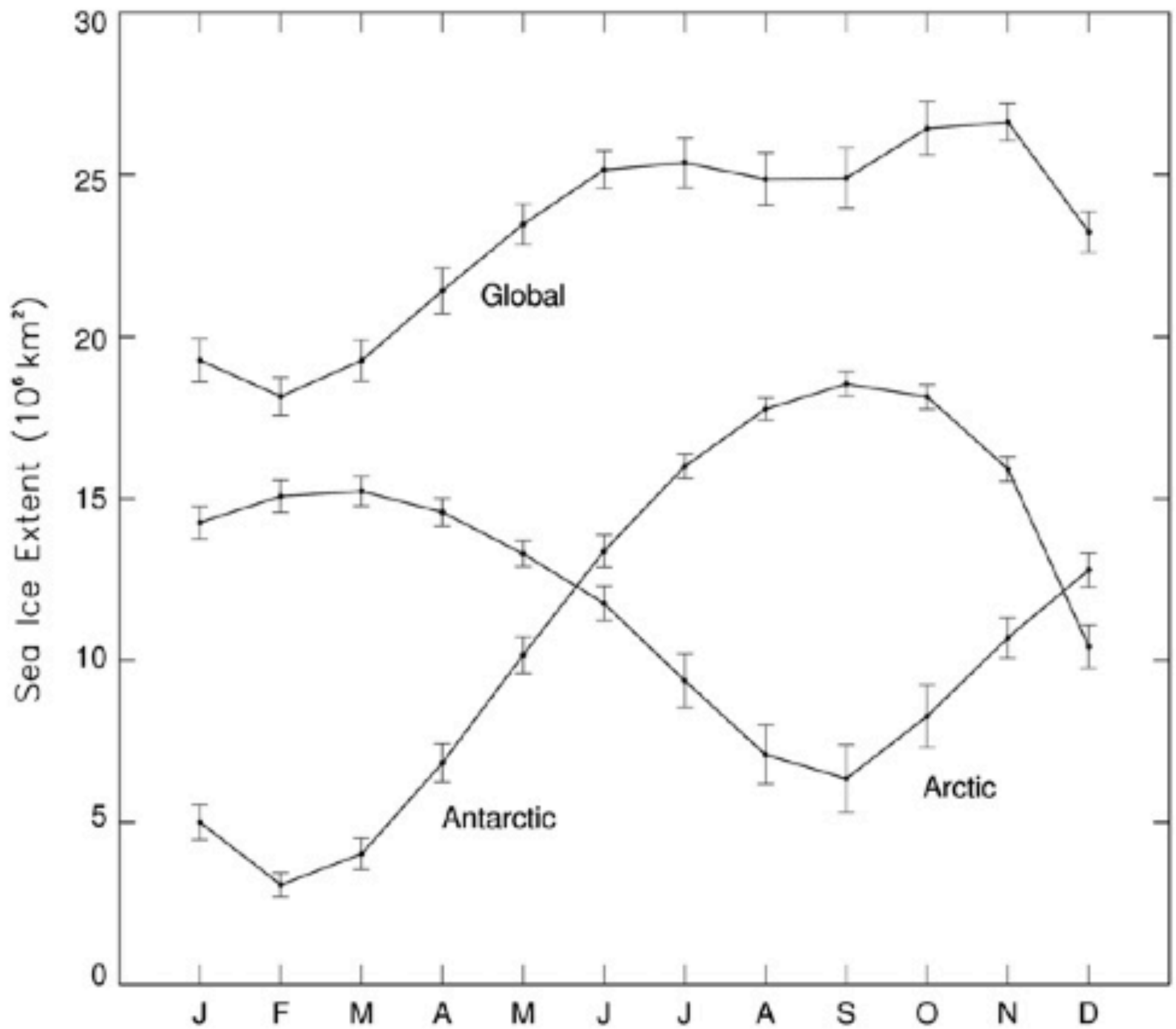
Maximum Extent (September):
17 - 20 million square km

Minimum Extent (March):
3 – 4 million square km

Maps: NSIDC

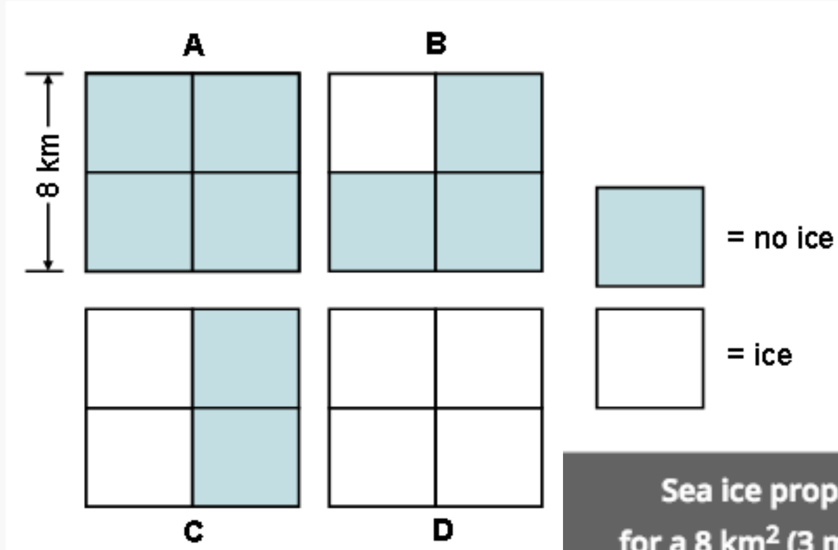
Annual Cycle of Sea Ice Extent

Annual average Arctic, Antarctic and Global sea ice extent (1979-2013)



***Source**:*
Parkinson, C., J. Climate, 2014

Sea Ice Area, Extent and Concentration



Area: region covered by sea ice (km^2)

Concentration: relative amount of area covered by sea ice (% or fraction)

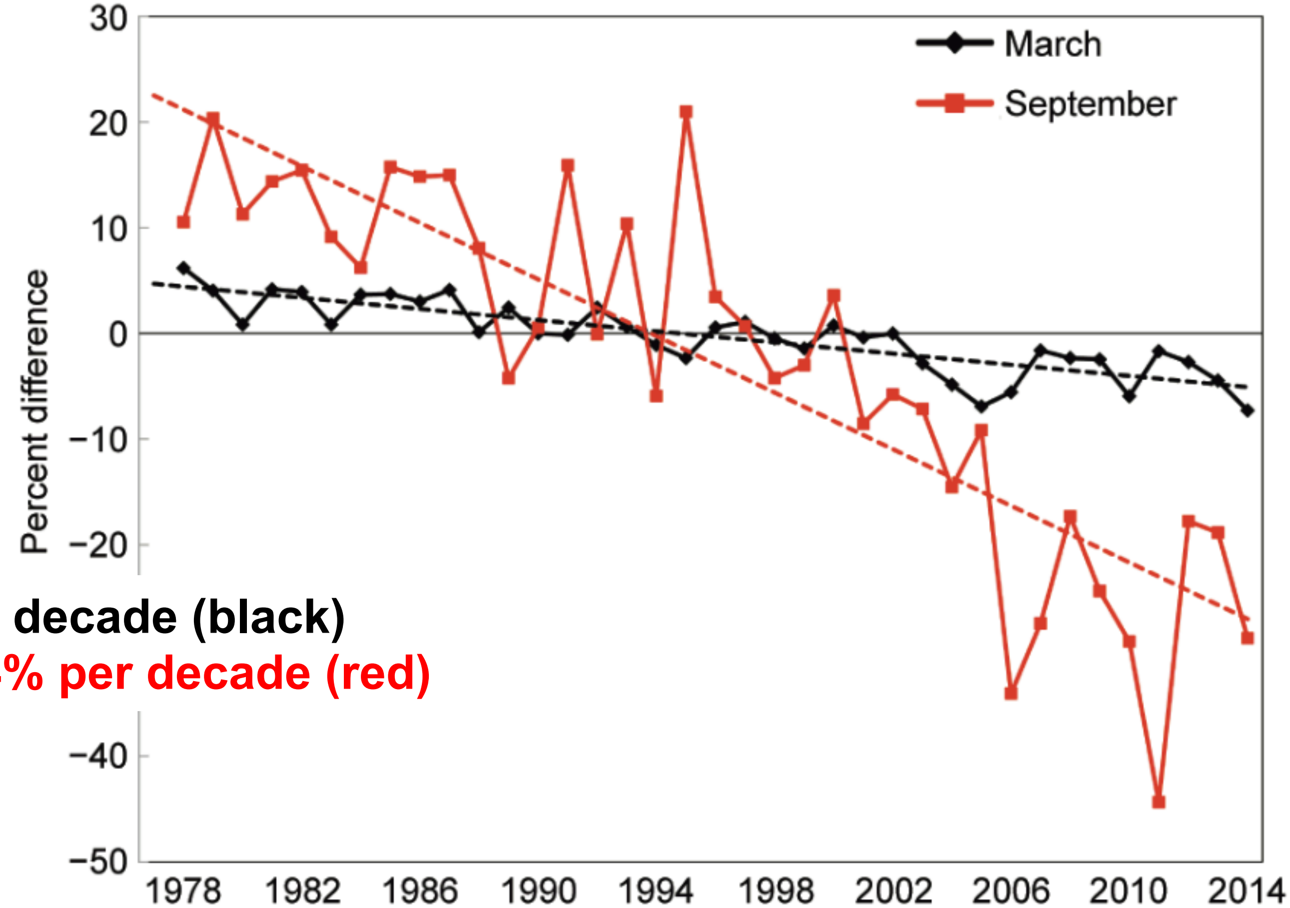
Extent: binary classification of ice/no ice, based on ice concentration threshold (0/1, then converted to km^2)

Sea ice property for a 8 km^2 (3 mi^2) cell	A	B	C	D
Ice-Covered Area	0 km^2	16.0 km^2 (6.2 mi^2)	32.0 km^2 (12.4 mi^2)	64.0 km^2 (24.7 mi^2)
Concentration (%)	0%	25%	50%	100%
Concentration (fraction)	0	0.25	0.5	1.0
Extent No units, 30% concentration threshold	0	0	1	1
Extent 30% concentration threshold	0 km^2	0 km^2	64.0 km^2 (24.7 mi^2)	64.0 km^2 (24.7 mi^2)

Source: NSIDC

Decadal Scale Trends in Arctic Sea Ice Extent

The diminishing Arctic sea ice cover is possibly the most striking environmental changes underway today



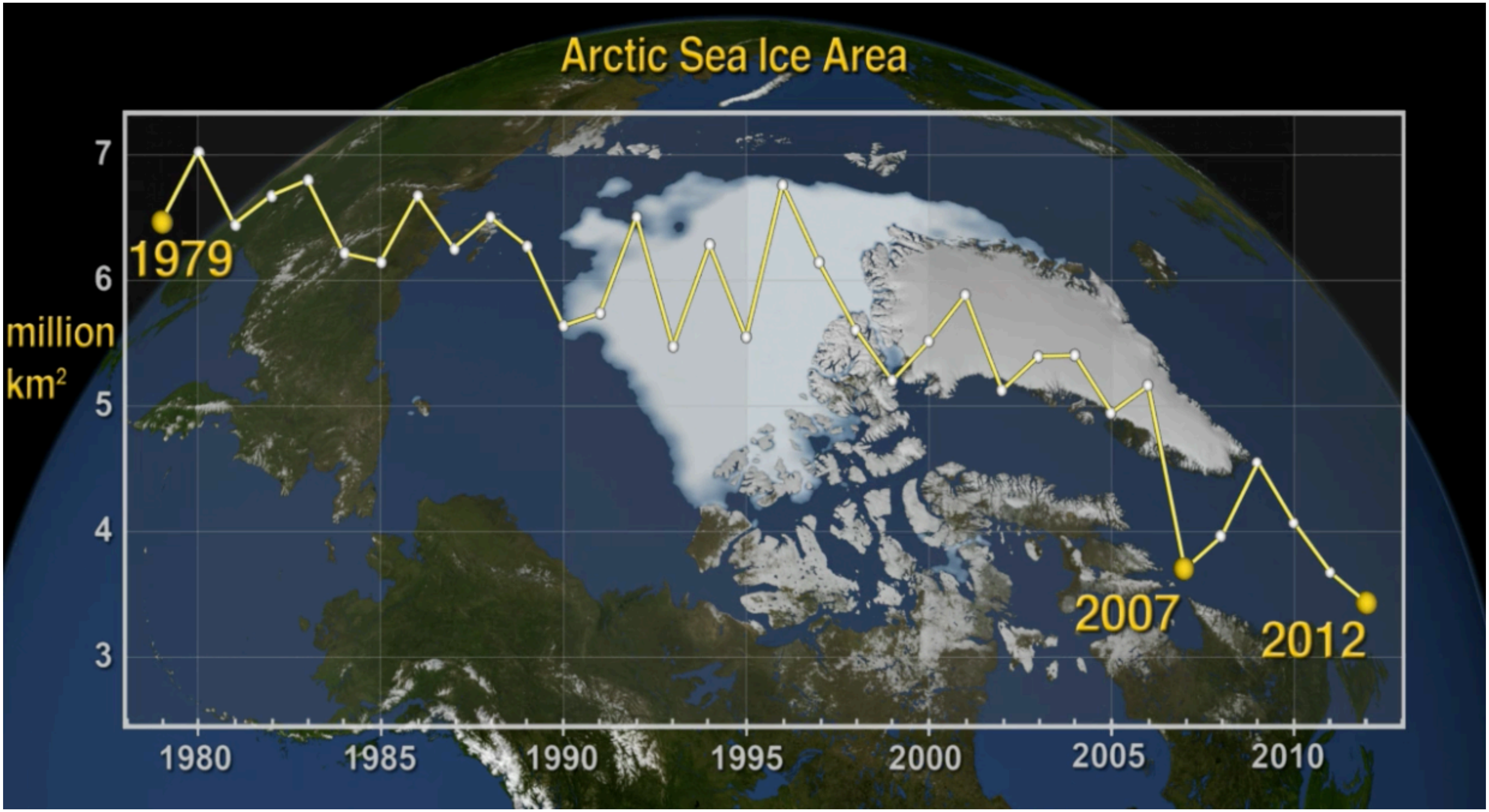
March ice loss: -2.6% per decade (black)

September ice loss: -13.4% per decade (red)

Source: *Perovich et al.* (2016),
Sea Ice Cover in Chapter 5
State of the Climate 2015, BAMS

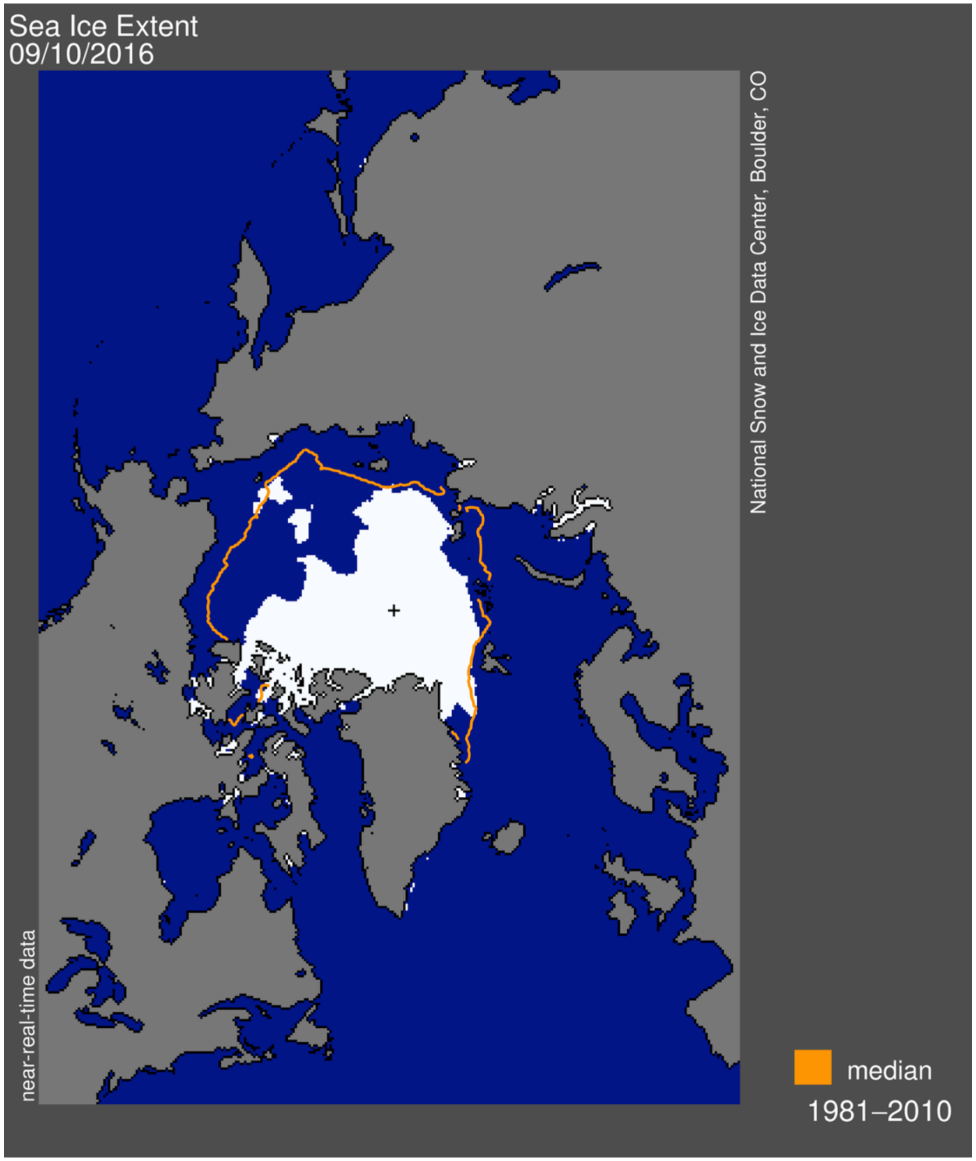
- Time series of Arctic sea ice extent anomalies in March and September, 1979 - 2015.
- Anomalies for each year: difference (in %) in ice extent relative to the mean for 1981-2010.

Arctic Sea Ice Extent: 1979-2012



Source: NASA Goddard Space Flight Center Visualization Studio

September 2016 Sea Ice Extent Minimum

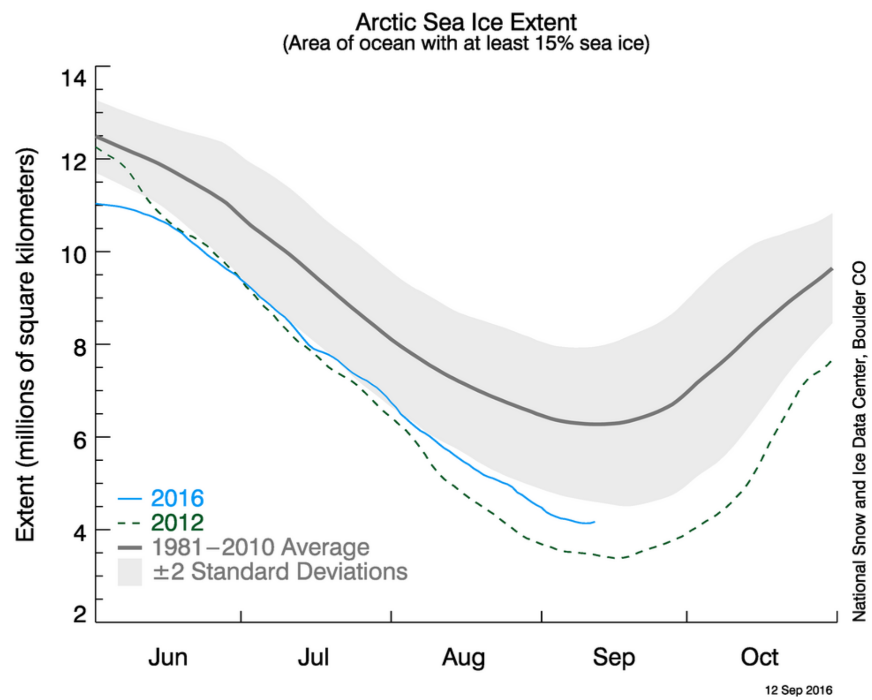


Graphics Credit: NSIDC

2016 Summer Minimum

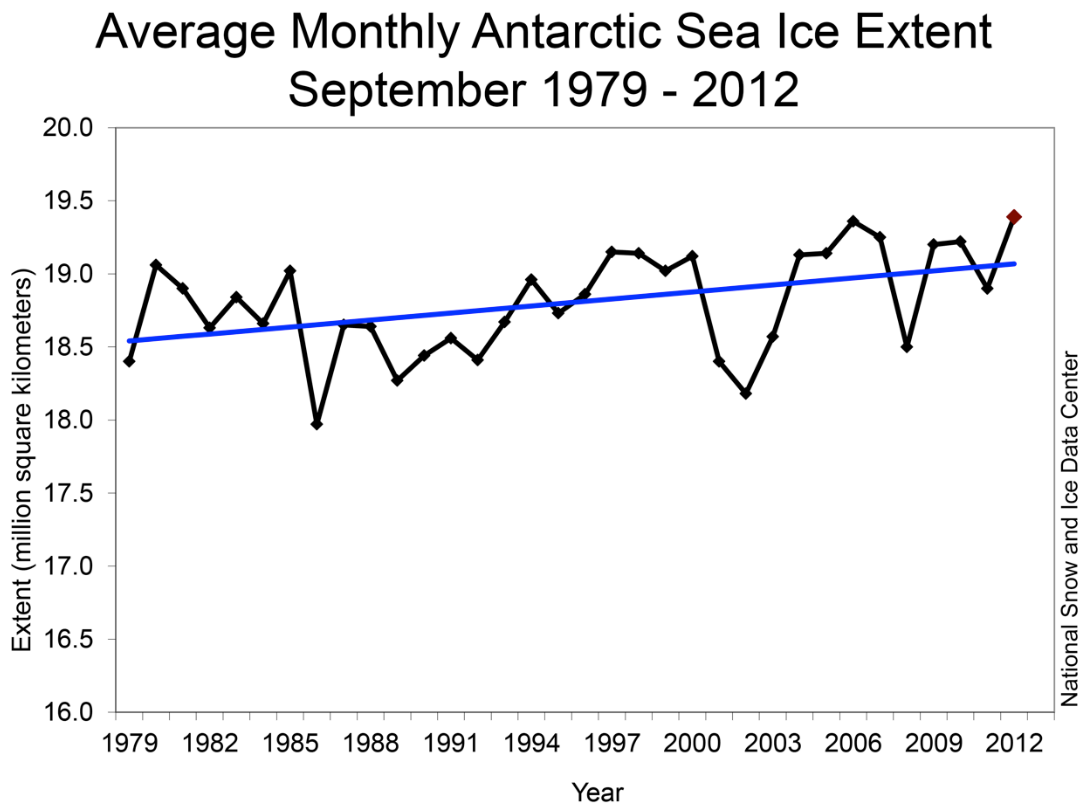
Preliminary data suggest that minimum extent was reached on **September 11th 2016, at ~ 4.1 – 4.2 million sq. km.**

This may tie for the 2nd lowest extent on record, and will be close to the 2007 minimum (4.13 million sq. km, 16 Sept. 2017)



Antarctic Sea Ice Extent: 1979 - 2012

September Antarctic extent trend for 1979 to 2012 is +0.9% per decade.
The ice growth likely results from a combination of forcings due to wind & ocean circulation.



Antarctic sea ice underwent a slight increase, although some regions of the Antarctic experienced strong declining trends in sea ice extent. Source: NSIDC

Antarctic Sea Ice Extent

The ice is decreasing in the Arctic but it's increasing in the Antarctic, so don't they cancel out?

The Washington Post

Search

Capital Weather Gang

Antarctic sea ice gains do not "cancel out" Arctic sea ice losses, NASA finds

By Jason Samenow February 11

Volume 27 Issue 24 (December 2014)

< Previous Next >

Current Issue
Available Issues
Early Online Releases
Author Index
Share this Article

< Previous Article | Volume 27, Issue 24 (December 2014) | Next Article >

Add to Favorites | Email | Download to Citation Manager | Track Citations | Glossary | Permissions

Full-text | PDF

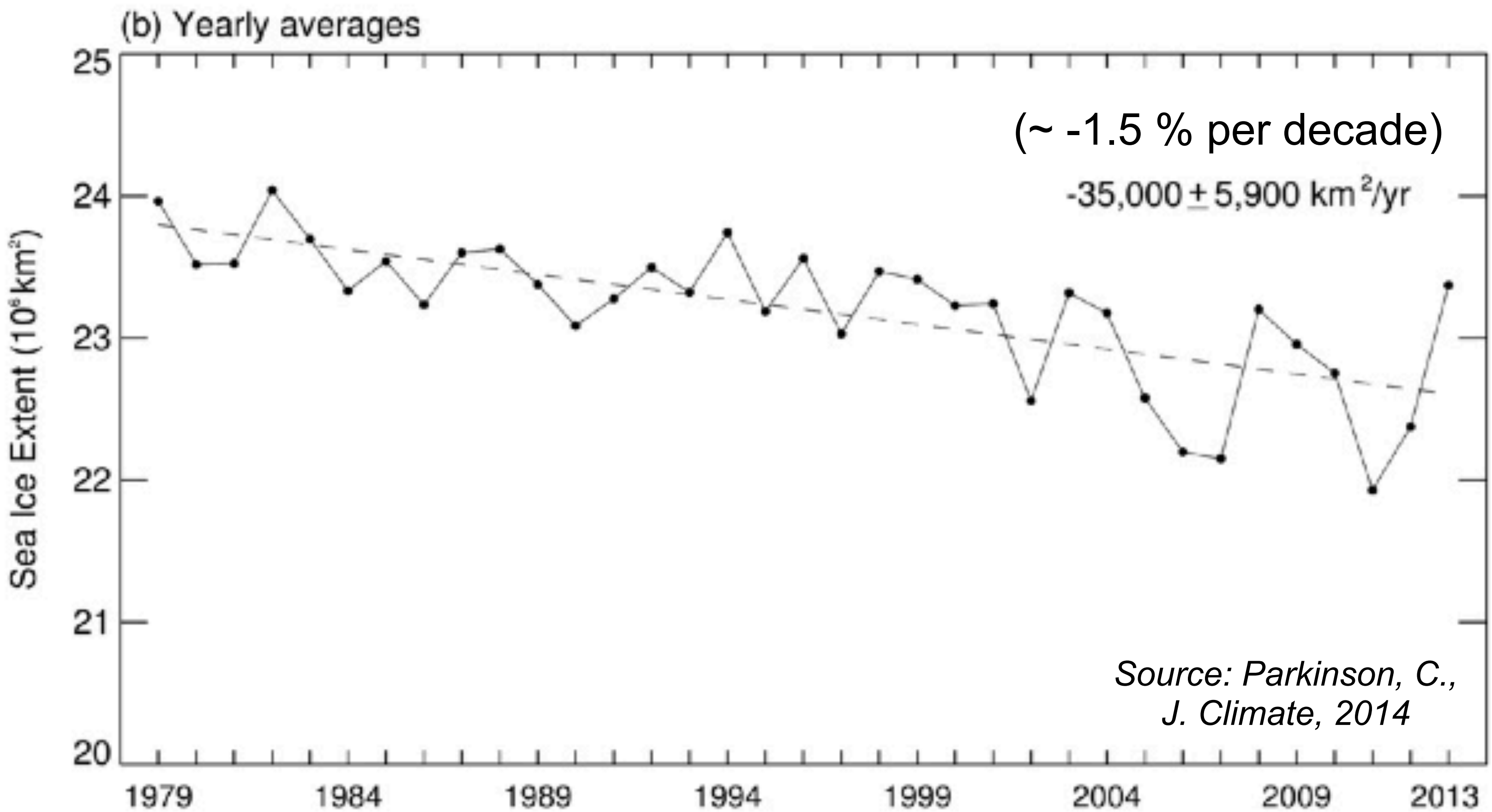
Claire L. Parkinson, 2014: Global Sea Ice Coverage from Satellite Data: Annual Cycle and 35-Yr Trends. *J. Climate*, **27**, 9377–9382.
doi: http://dx.doi.org/10.1175/JCLI-D-14-00605.1

Global Sea Ice Coverage from Satellite Data: Annual Cycle and 35-Yr Trends

Claire L. Parkinson

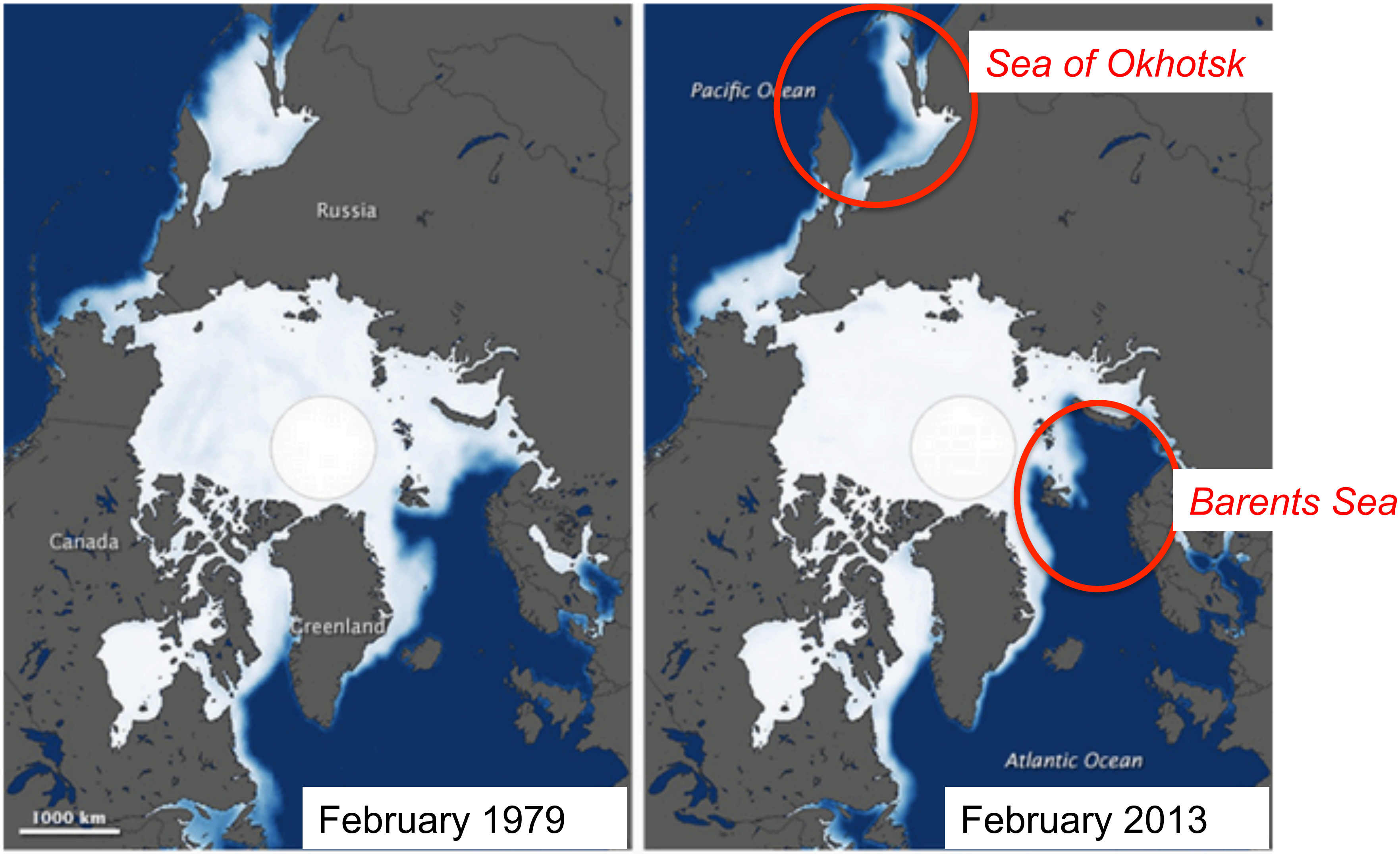
Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland

Global Sea Ice Extent 1979 - 2013



Yearly average global sea ice extents (1979–2013) and the line of linear least squares fit through the data points: Loss of ~ 35,000 km^2 ice extent per year!

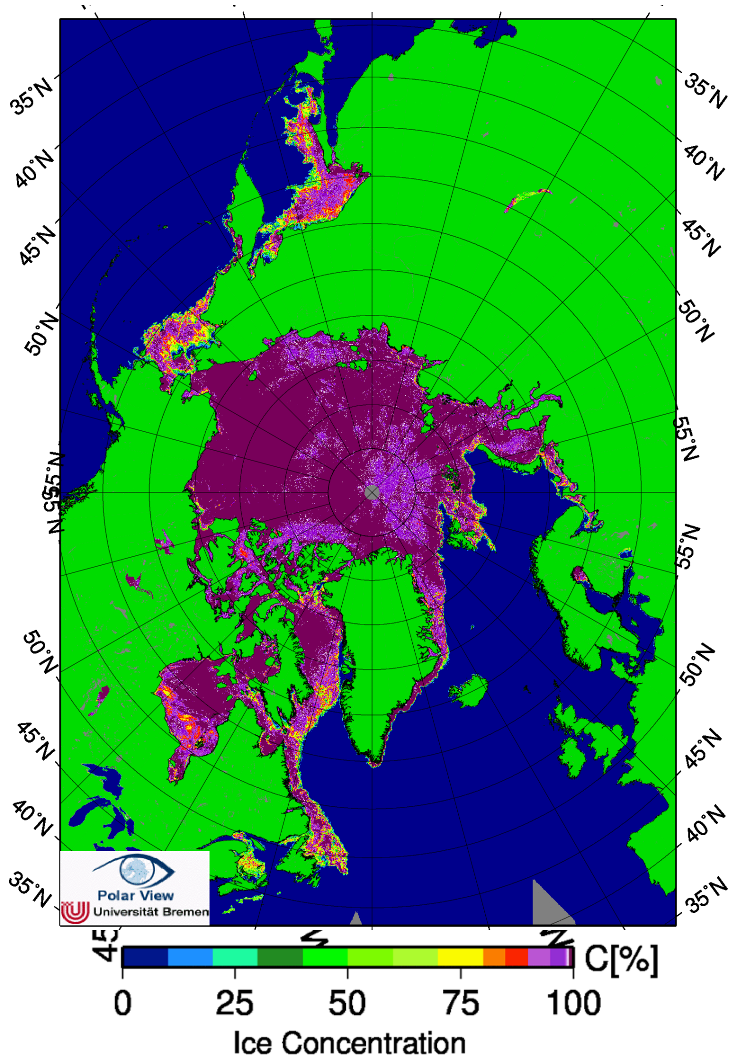
Arctic Winter Ice Extent: 1979 vs. 2013



Comparisons in Arctic sea ice extent between 1979 and 2013 in February. Source: NASA

Sea Ice Concentration

Winter Sea Ice Concentration
26 March 2016
ASI (AMSR2), v5.2, 6.25 km Grid



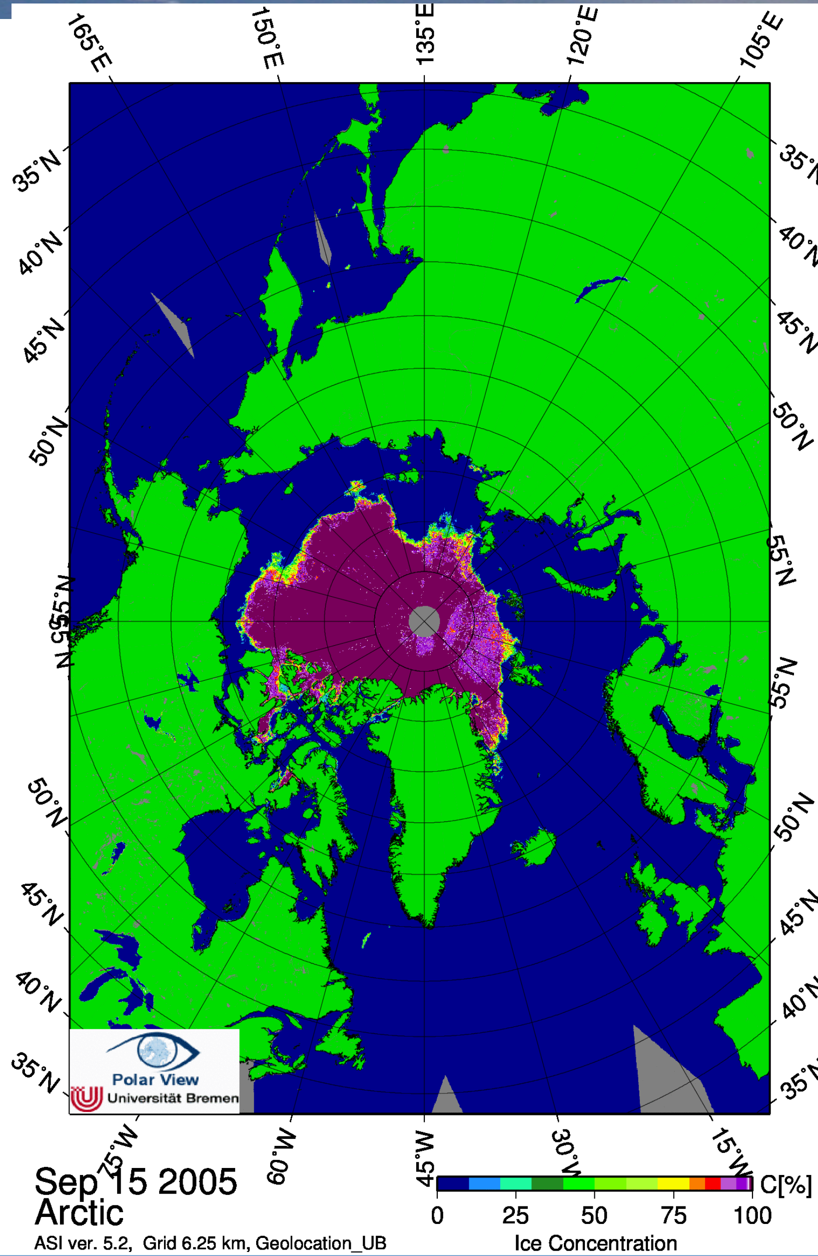
#	Period	Algorithm	Sensor, Frequencies, Source	Adapted to	Overlap period
1.	1972 - 2002	NASA Team	SMMR & SSM/I, 19 and 37 GHz from NSIDC(1)	#2.	1989 - 2002
2.	Oct 26, 1978 - Dec 2010	NASA Team	Sea ice concentrations from NIMBUS-7 SMMR and DMSP SSM/I-SSMIS passive microwave data, 19 and 37 GHz, from NSIDC(2)	reference only, but not part of the time series because of some gaps 1978 - 1988	
3.	2003 - Oct 4, 2011	ASI	AMSR-E, 89 GHz	#2.	2002 - 2007
4.	Oct 5, 2011 -Jul 2, 2012	ASI	SSMIS F-17, 91 GHz	#3.	Sep 2010 – Sep 2011 (using SSMIS F-17 data)
5.	Jul 3, 2012 to date	ASI	AMSR2, 89 GHz	#3. (same fit parameters used)	Jul 3, 2012 to date

(1): Merged ESMR, SMMR, and SSM/I-SSMIS Sea Ice Extent from NSIDC
(2): See information on this data set at NSIDC

- Arctic and Antarctic Sea Ice Concentration
  - Historical Archive
  - Near Real Time Data

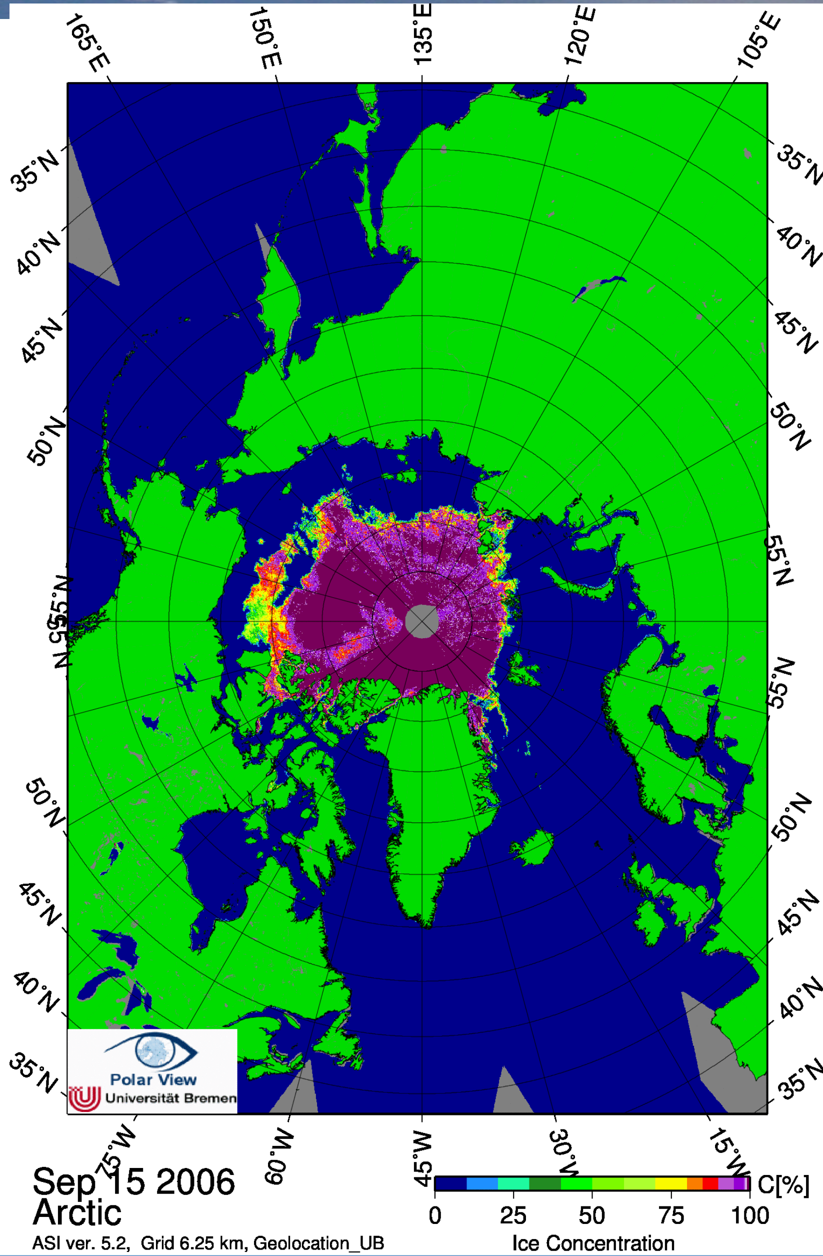
Source: IUP/Polar View, University of Bremen
and *Spreen et al.*, JGR, 2008

Arctic Sea Ice Concentration: Sept. 2005



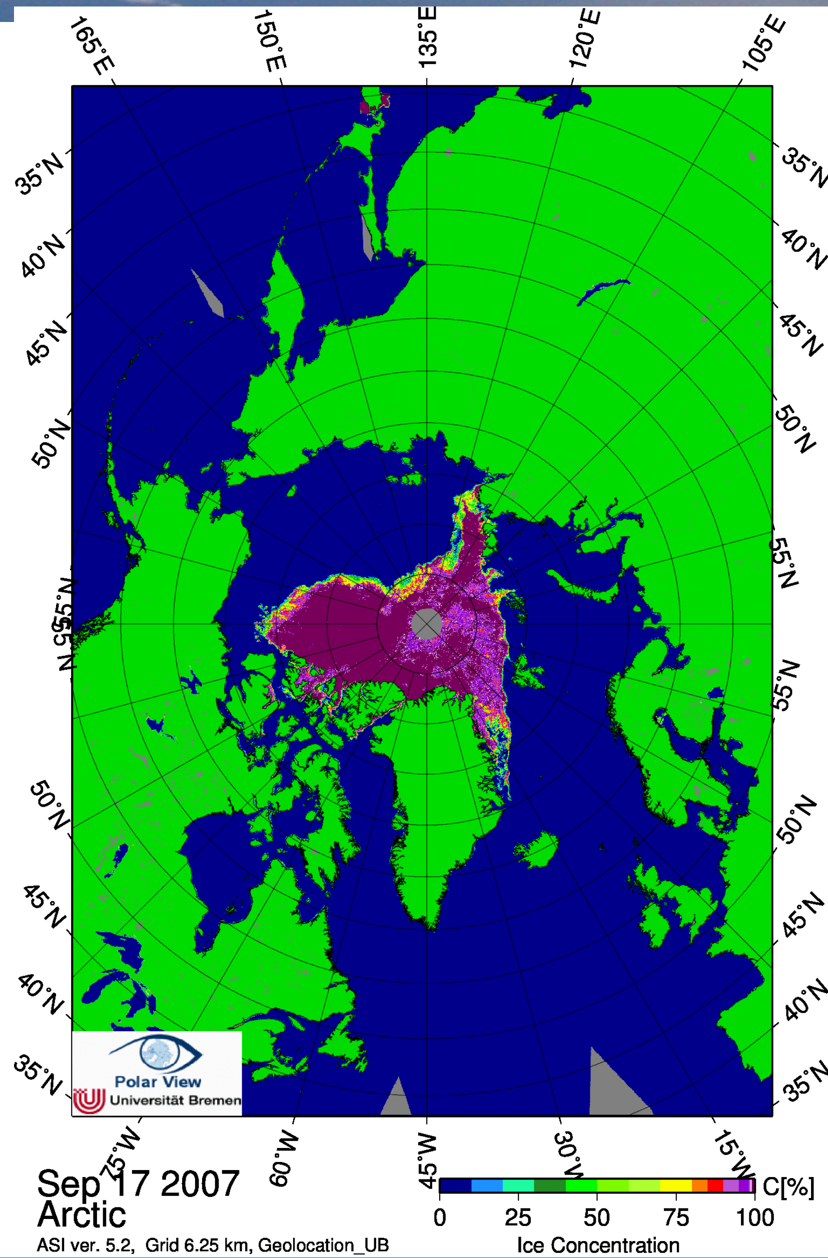
Source: IUP/Polar View, University of Bremen
Spreen et al., JGR, 2008

Arctic Sea Ice Concentration: Sept. 2006



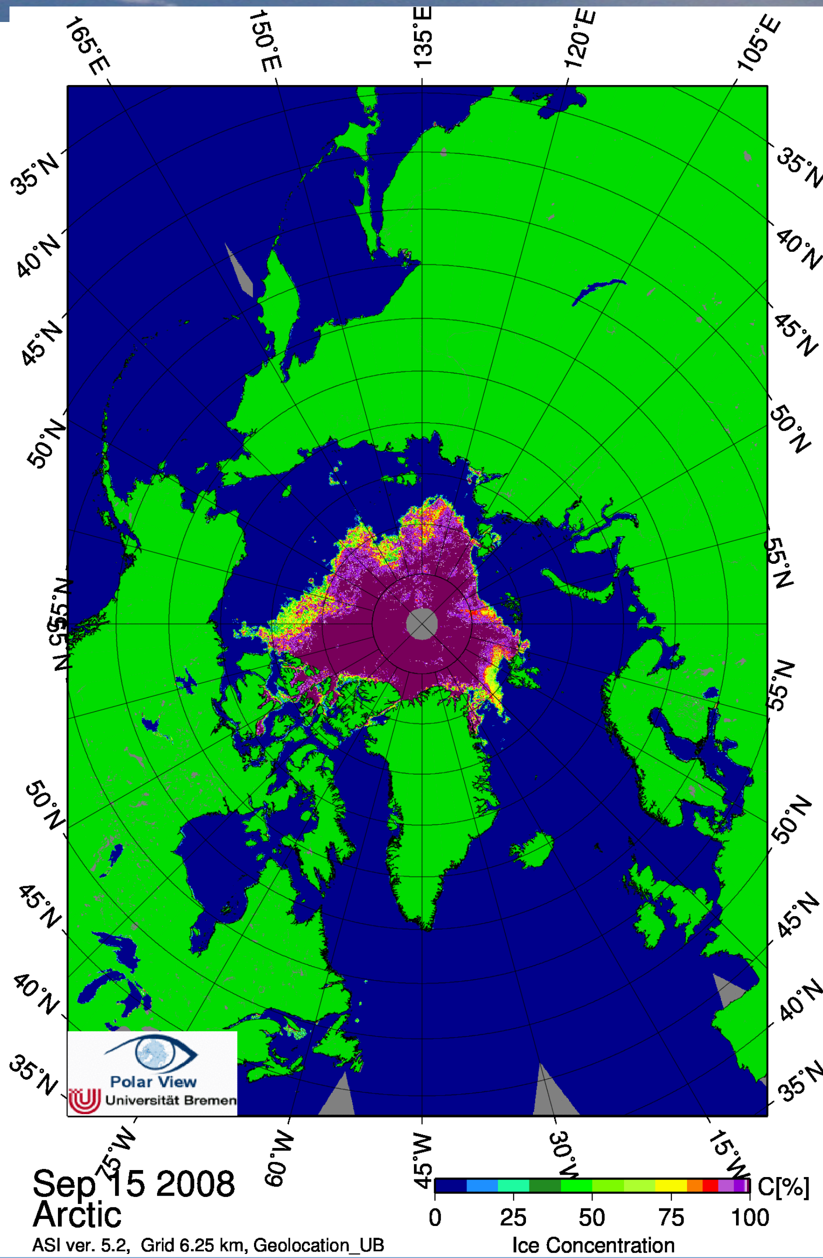
Source: IUP/Polar View, University of Bremen
Spreen et al., JGR, 2008

Arctic Sea Ice Concentration: Sept. 2007



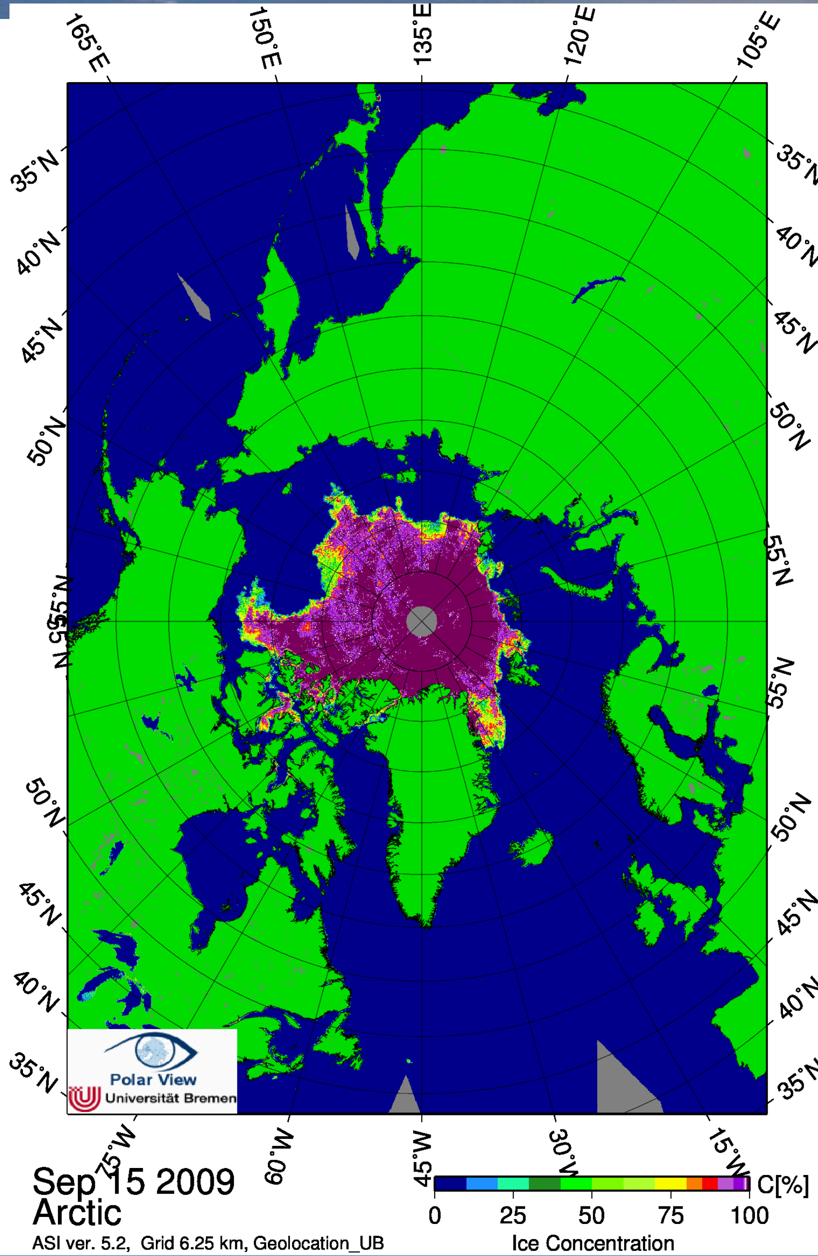
Source: IUP/Polar View, University of Bremen
Spreen et al., JGR, 2008

Arctic Sea Ice Concentration: Sept. 2008



Source: IUP/Polar View, University of Bremen
Spreen et al., JGR, 2008

Arctic Sea Ice Concentration: Sept. 2009



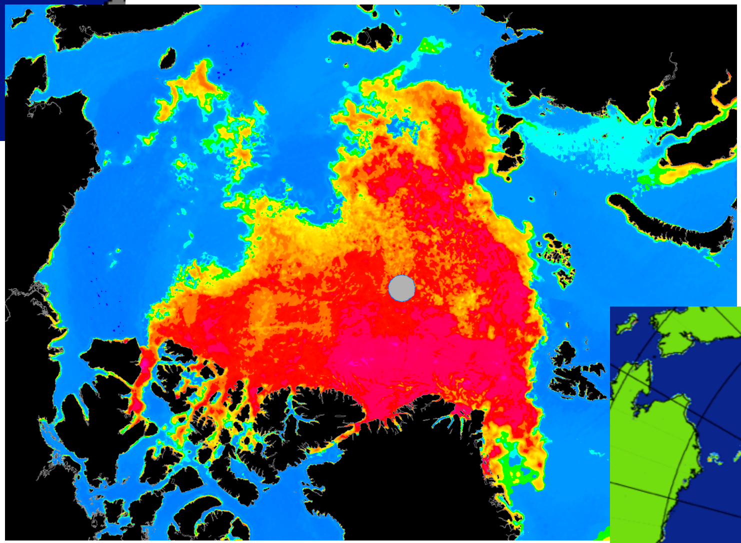
Source: IUP/Polar View, University of Bremen
Spreen et al., JGR, 2008

September 2016: Hierarchy of Observations

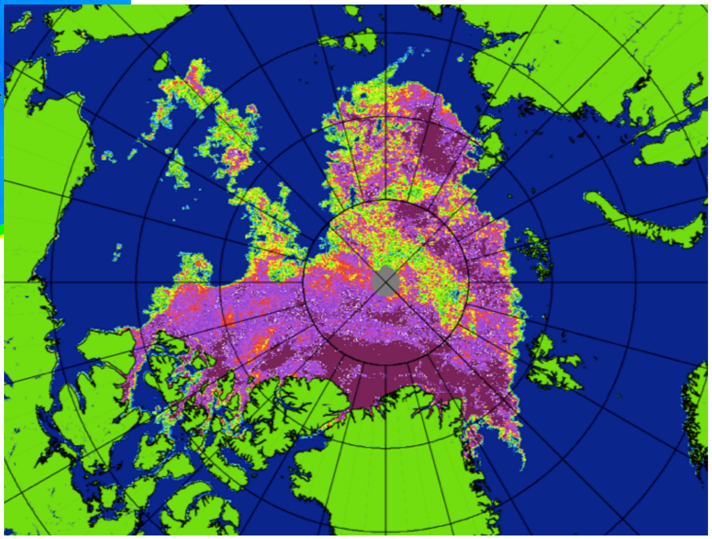
10 September 2016

NSIDC Sea Ice Extent

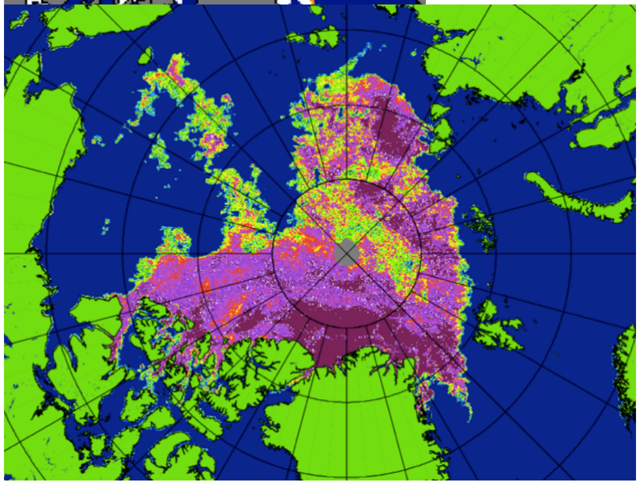
Sea Ice Concentration
DTU Space (seaice.dk)

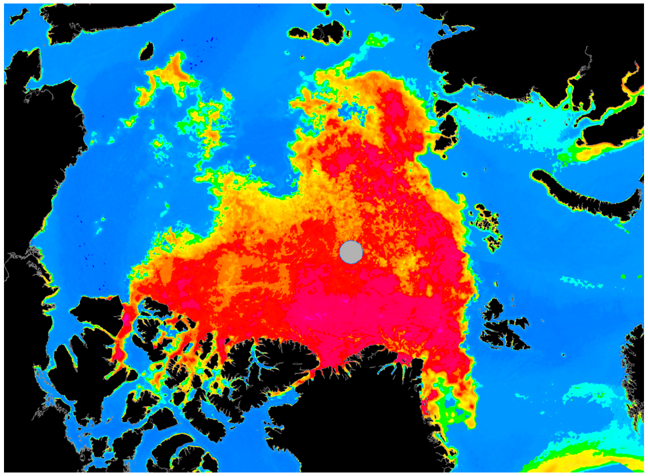


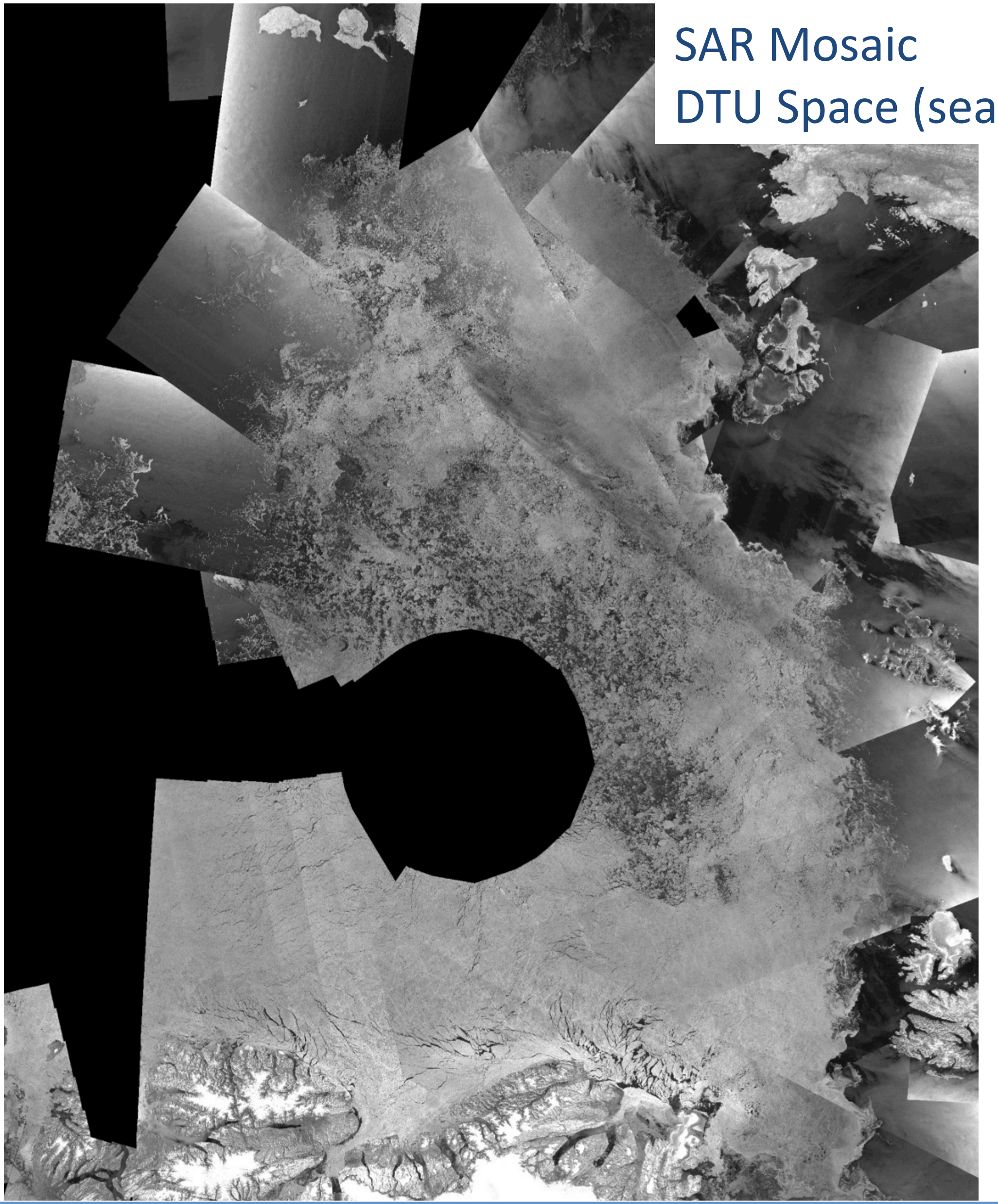
Sea Ice Concentration
IUP Uni Bremen



Passive Microwave vs. Sentinel-1 SAR

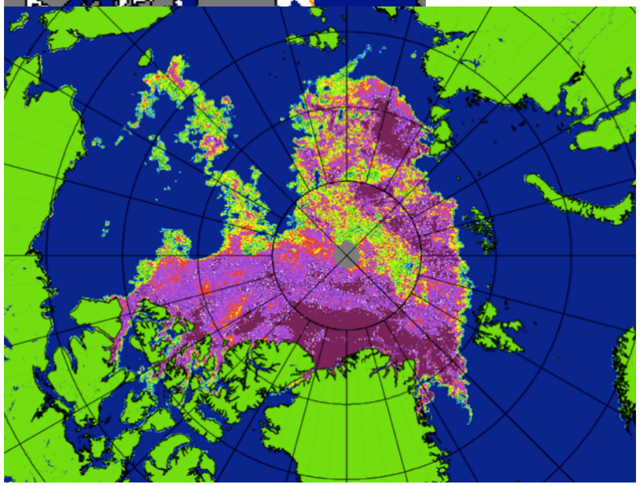


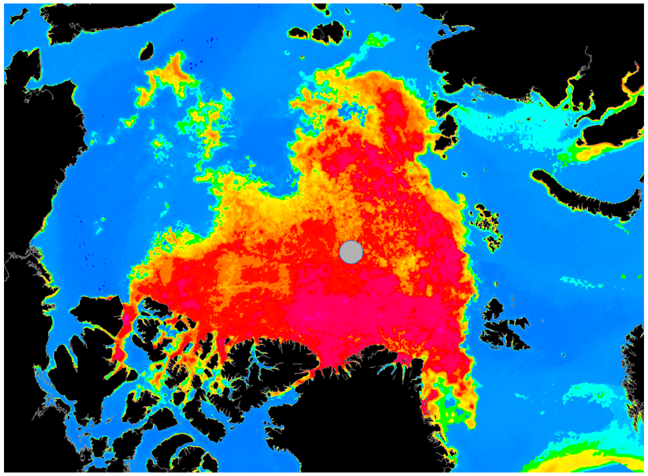




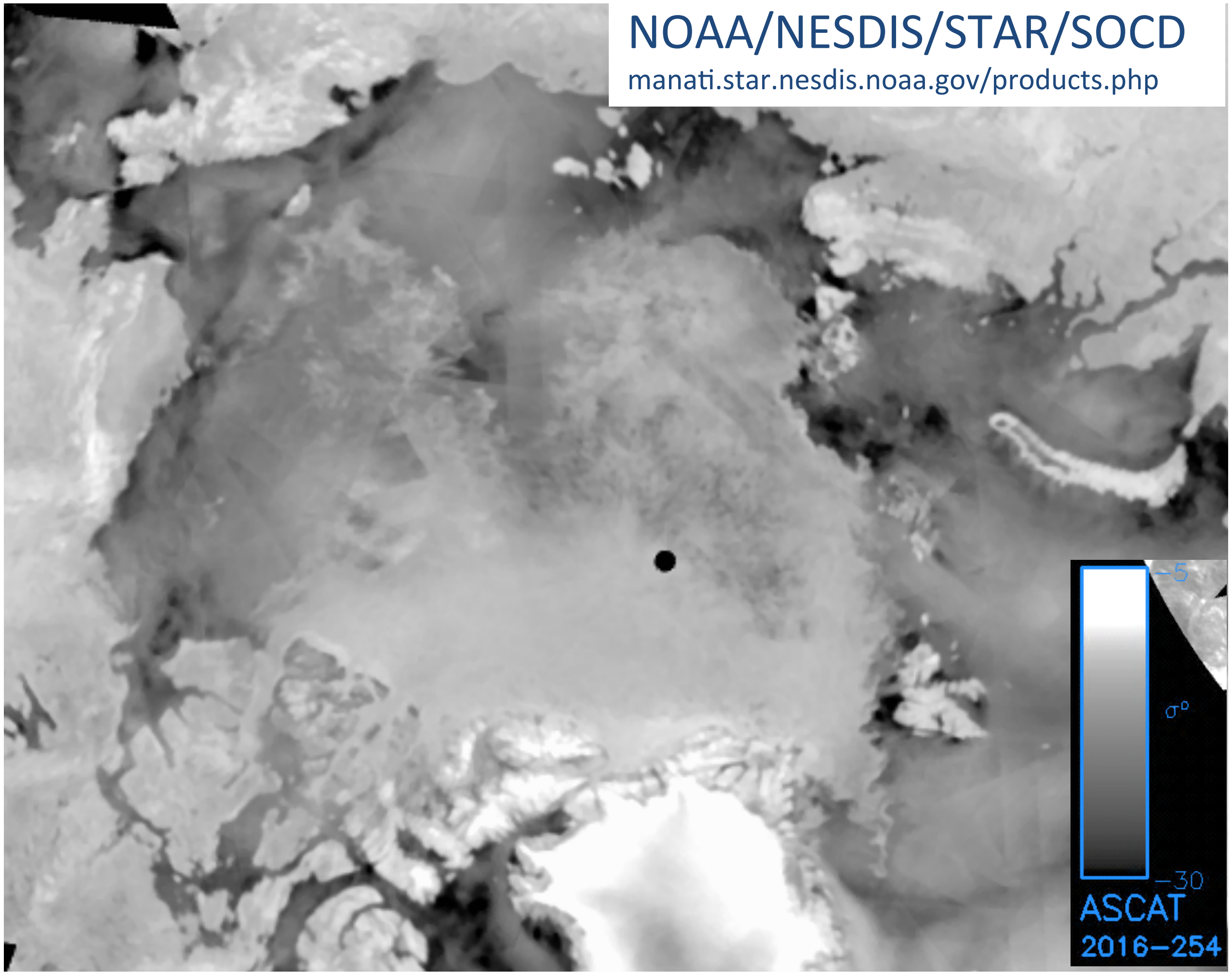
SAR Mosaic
DTU Space (seaice.dk)

Passive Microwave vs. Scatterometer backscatter





Radar Backscatter
NOAA/NESDIS/STAR/SOCD
manati.star.nesdis.noaa.gov/products.php



Circulation in the Arctic Ocean

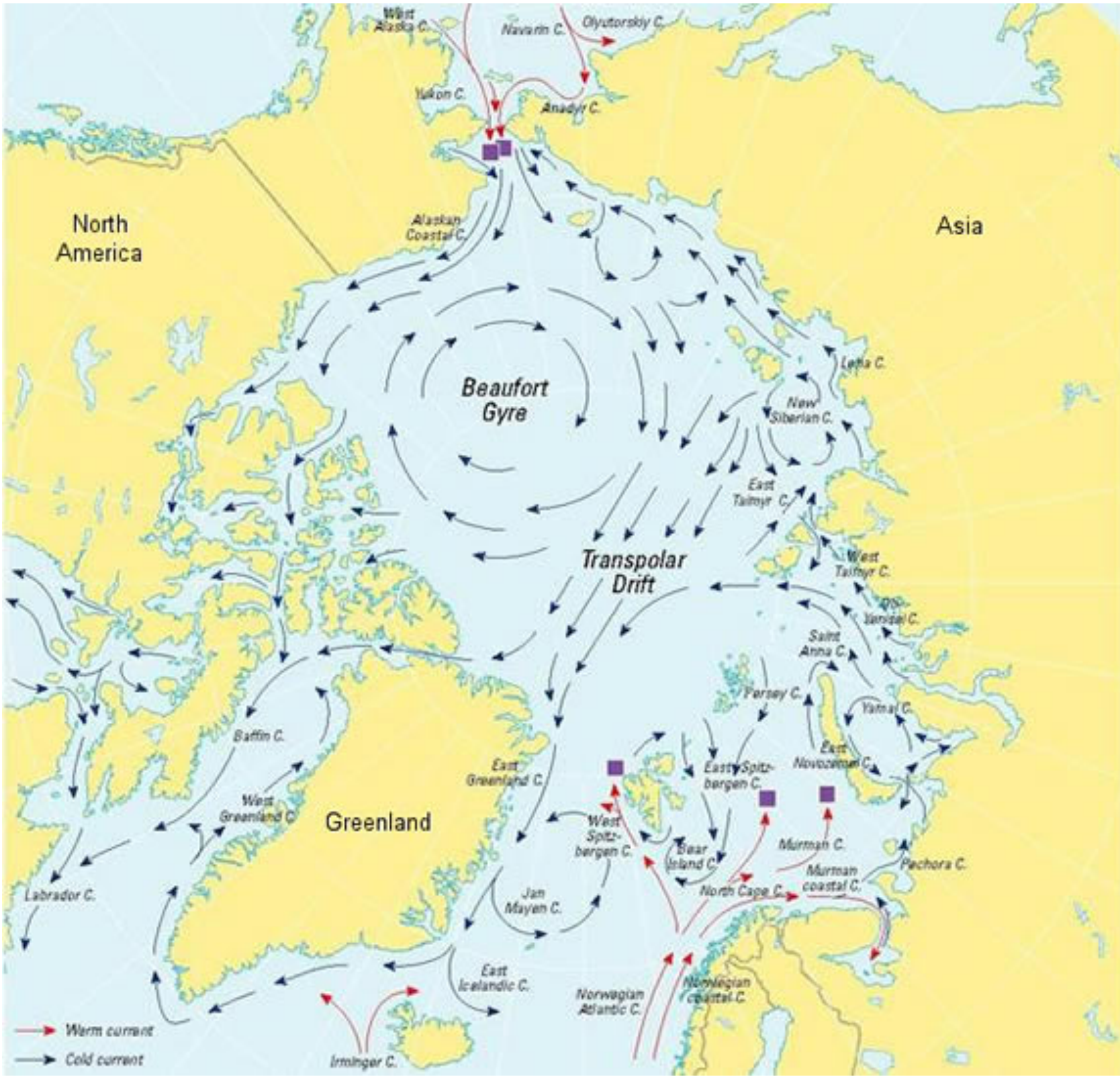
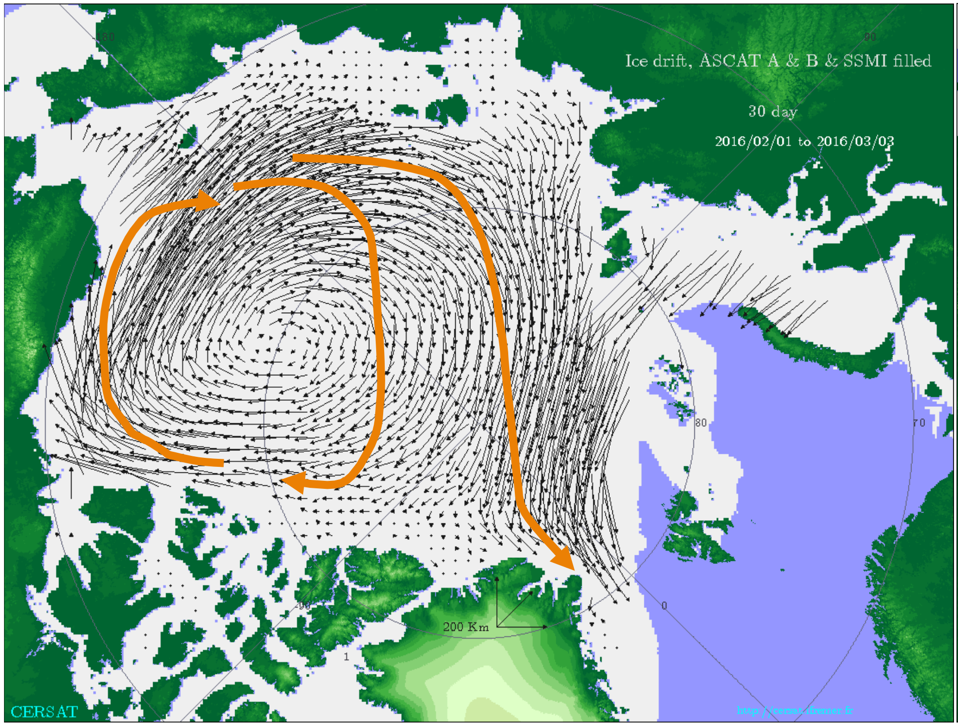
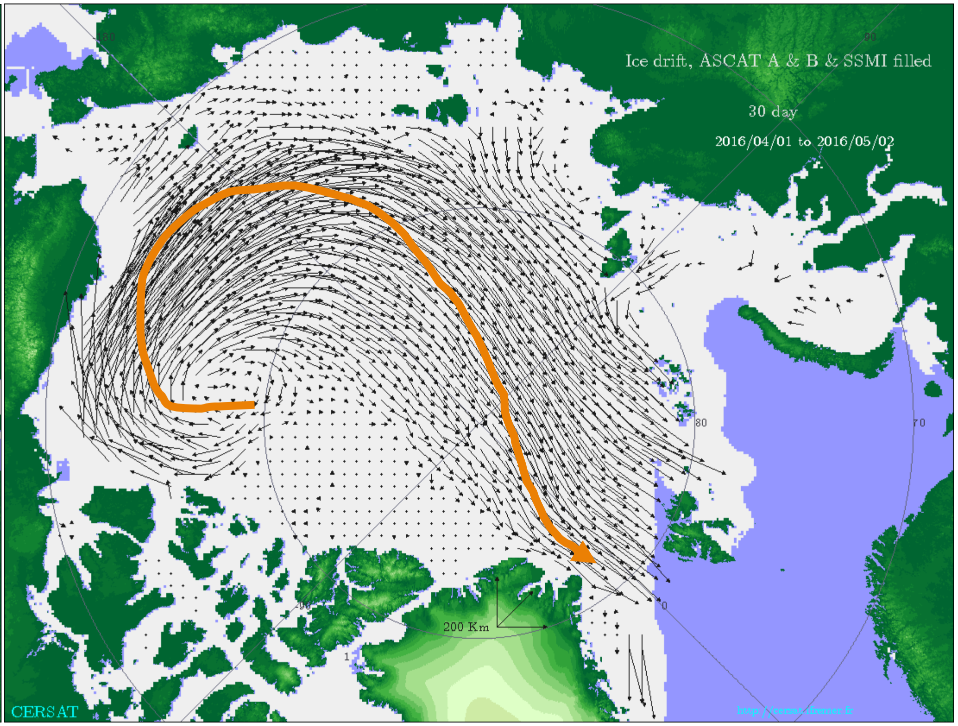


Image credit: Arctic Monitoring and Assessment Programme (AMAP), Figure 3.29, AMAP (1998).

Sea Ice Drift

- Variety of techniques to map drift velocity of sea ice:
  - SSM/I radiometers, scatterometers, SAR imagery
  - correlation of ice parcels between successive maps
- Validated using drifting buoys (International Arctic Buoy Program, IABP)



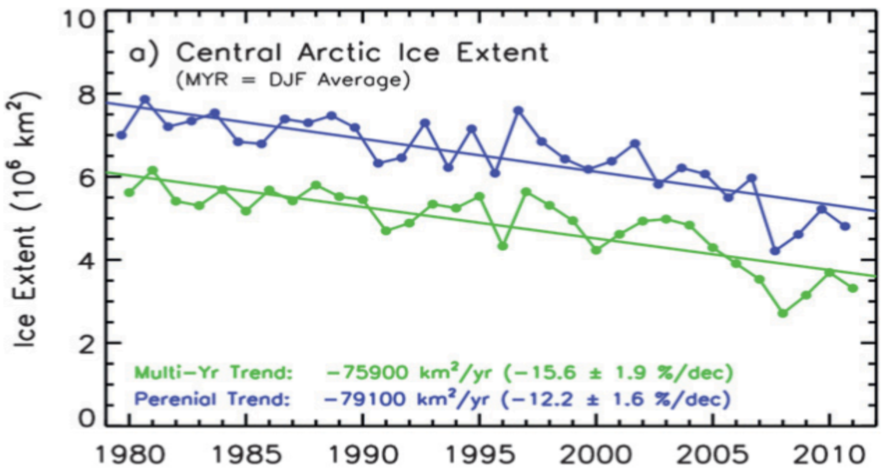


Source: IFREMER/CERSAT Sea Ice Drift Vectors
ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-drift/

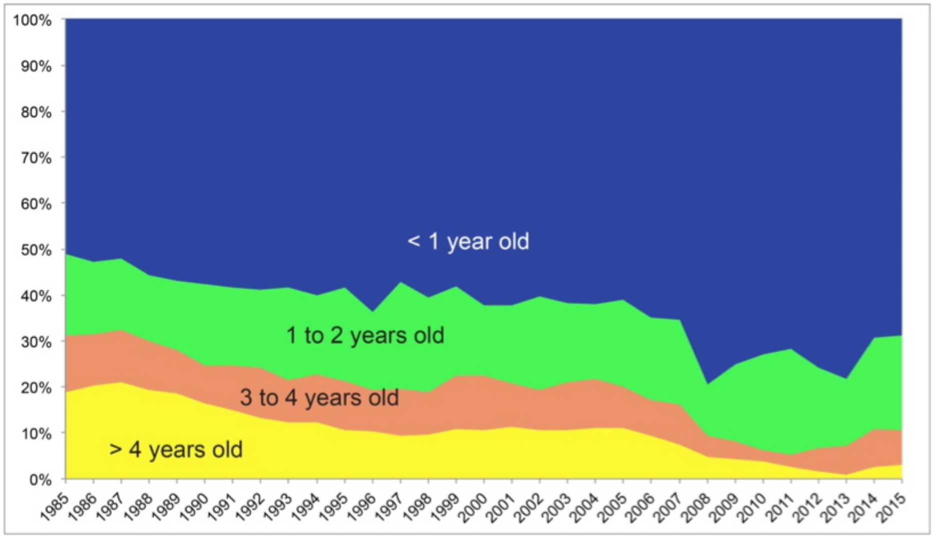
Arctic: 1.5 – 9 km/day
Antarctic: > 20 km/day

Sea Ice Age

- Observations over last 3 decades show largest losses in the Arctic Ocean are to MYI cover
- *Comiso* [2012] measured a decline of ~ 15% in the extent of MYI cover from 1979-2011



Comiso [2012]



Tschudi et al., CU-Boulder, Arctic Report Card [2014]

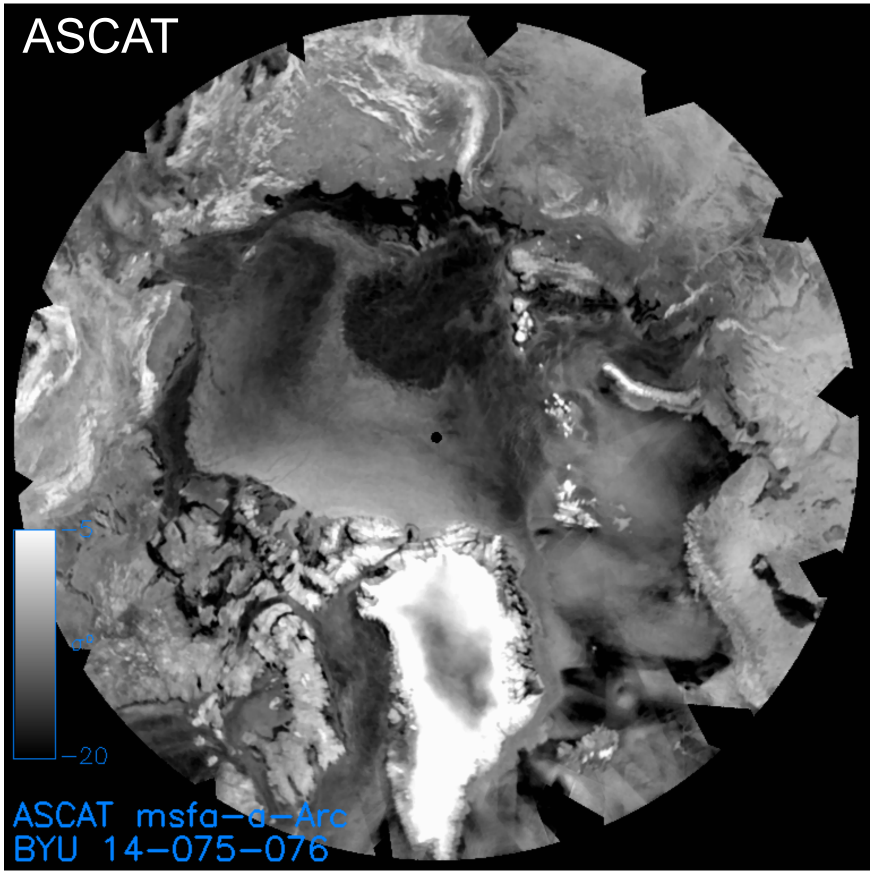
A declining MYI cover will precondition the pack for further loss: altering the mass and energy budgets of the Arctic Ocean

Sea Ice Age 1990 - 2016

Sea ice age estimated by tracking ice parcels using satellite imagery and drifting ocean buoys

Animation by NOAA Climate.gov, based on research data provided by Mark Tschudi, CCAR, University of Colorado.
https://www.climate.gov/sites/default/files/Tschudi-IceAge-v2.3_HD1080p-mstr.mp4

Scatterometer Data for Sea Ice Drift and Type



- High-resolution data set (4.45 km) → consistent with resolution of altimetry observations
- Small pole hole → MYI mask area extends to 89.5 °N

Ice-type masks are derived from radar backscatter(σ_0) acquired by SeaWinds on QuikScat (1999 – 2009) and the Advanced Scatterometer (ASCAT) on METOP-A (2009 – present)

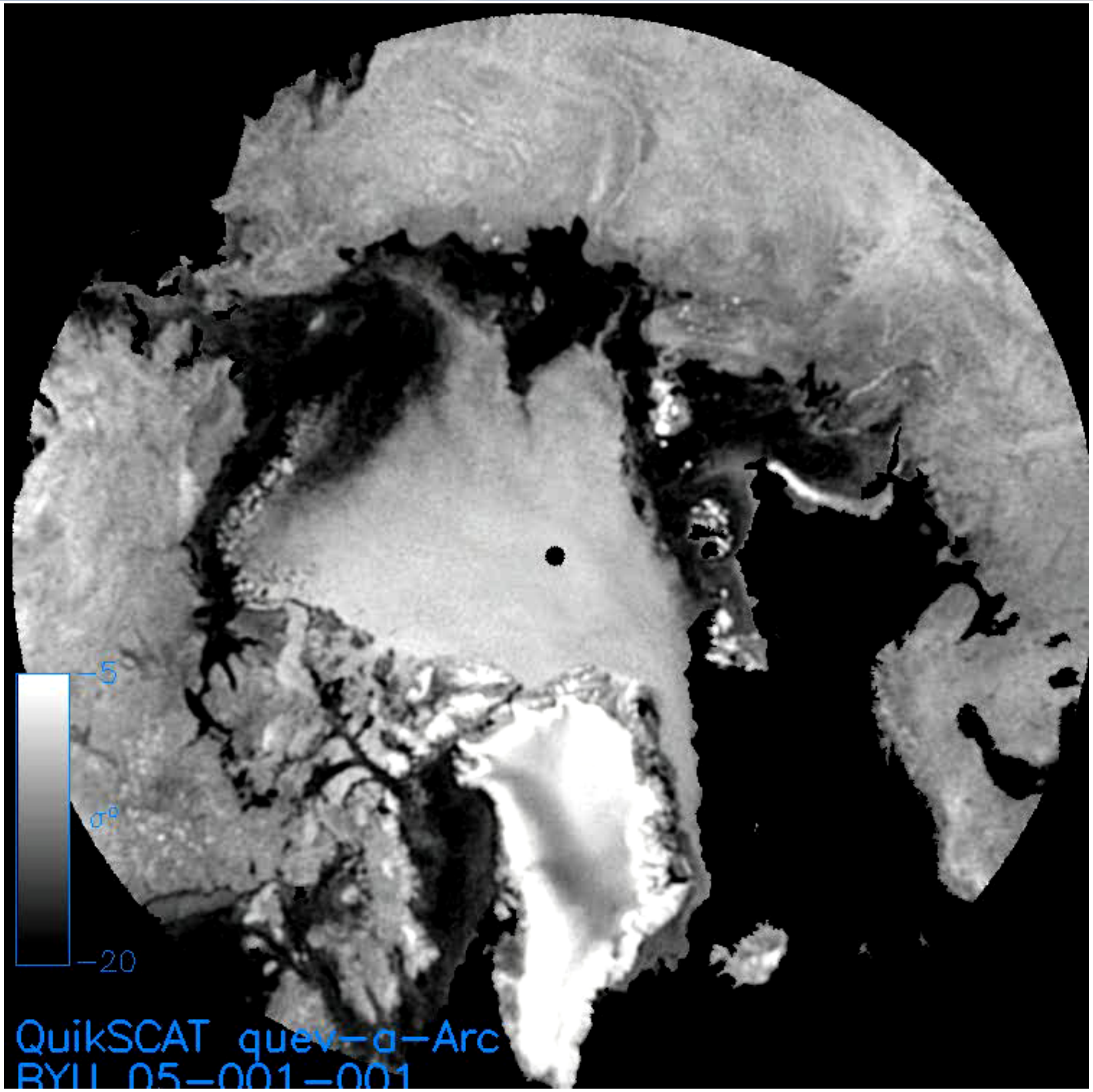
QuikScat :moderate resolution Ku-band
ASCAT: moderate resolution C-band

Data and sea ice type available at the Scatterometer Climate Record Pathfinder website at Brigham Young University (David Long, et al.)

Daily normalized radar cross-sections & thresholding can be used to define the perennial (multi-year) sea ice zone

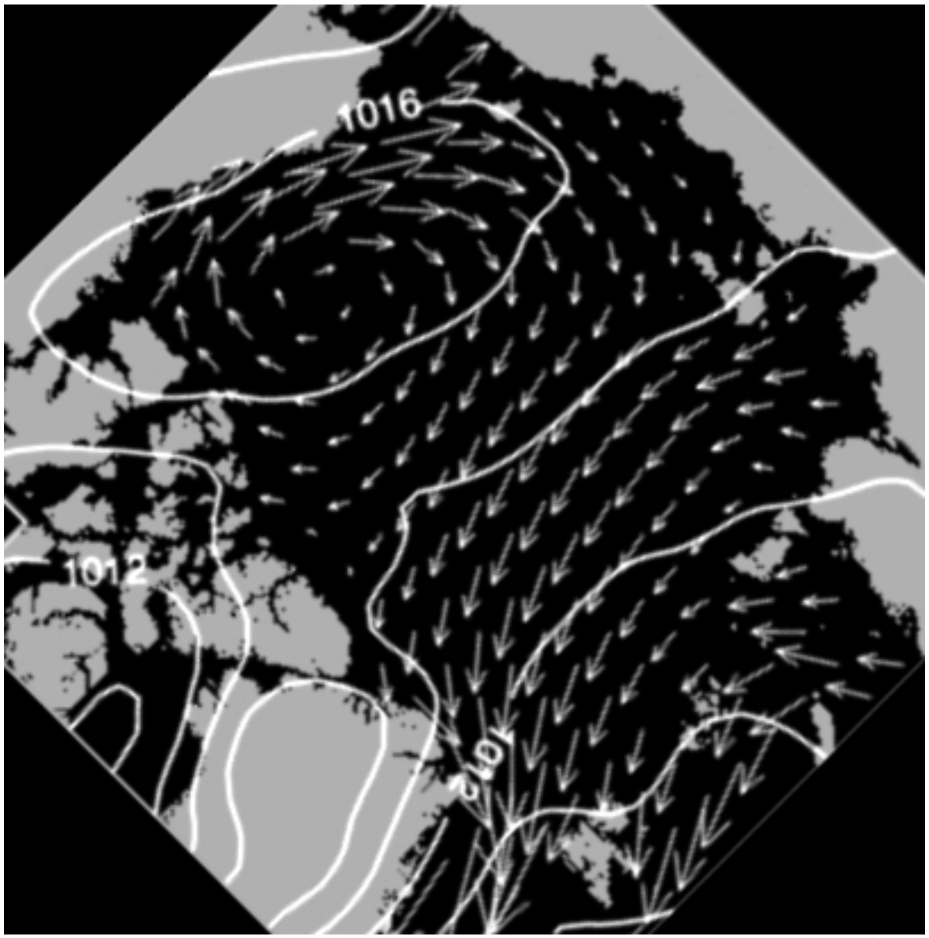
A correction is applied to account for high σ_0 due to motion of Marginal Ice Zone[MIZ]

QuikScat Scatterometry Time-series: Jan – Dec 2005



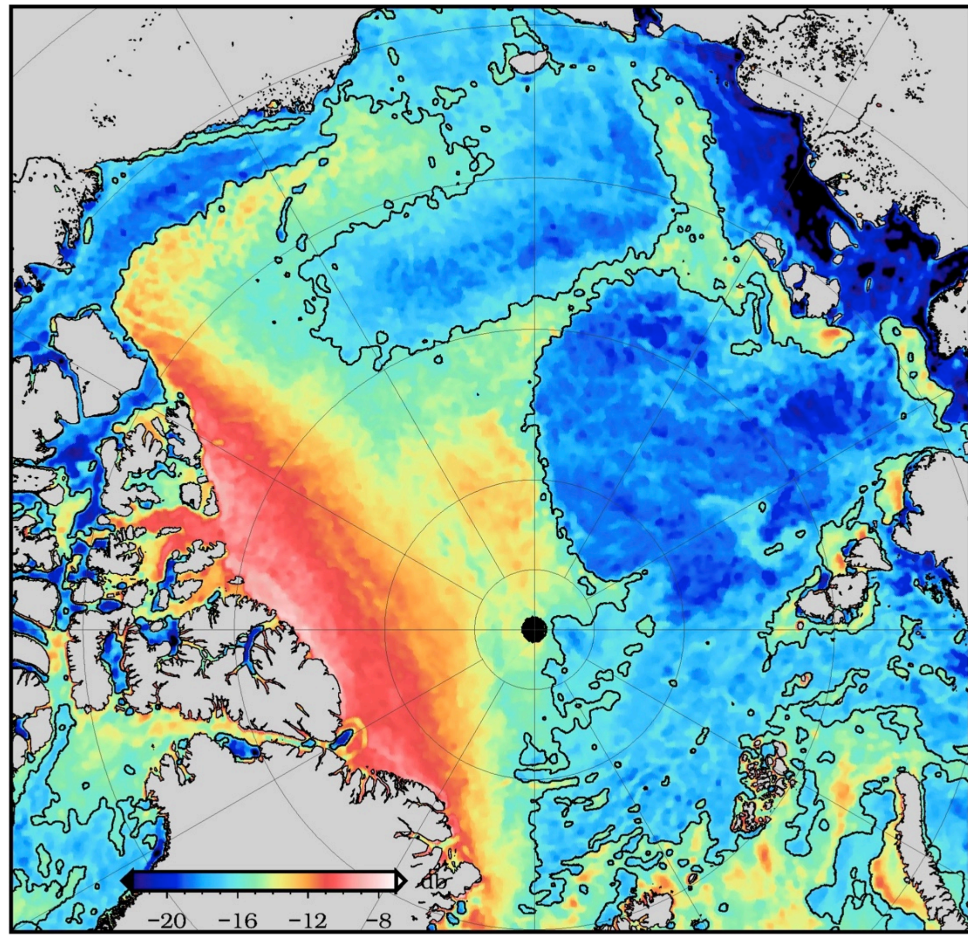
Mean Ice Drift vs. Location of Multiyear Sea Ice Cover

Mean Sea Ice Drift



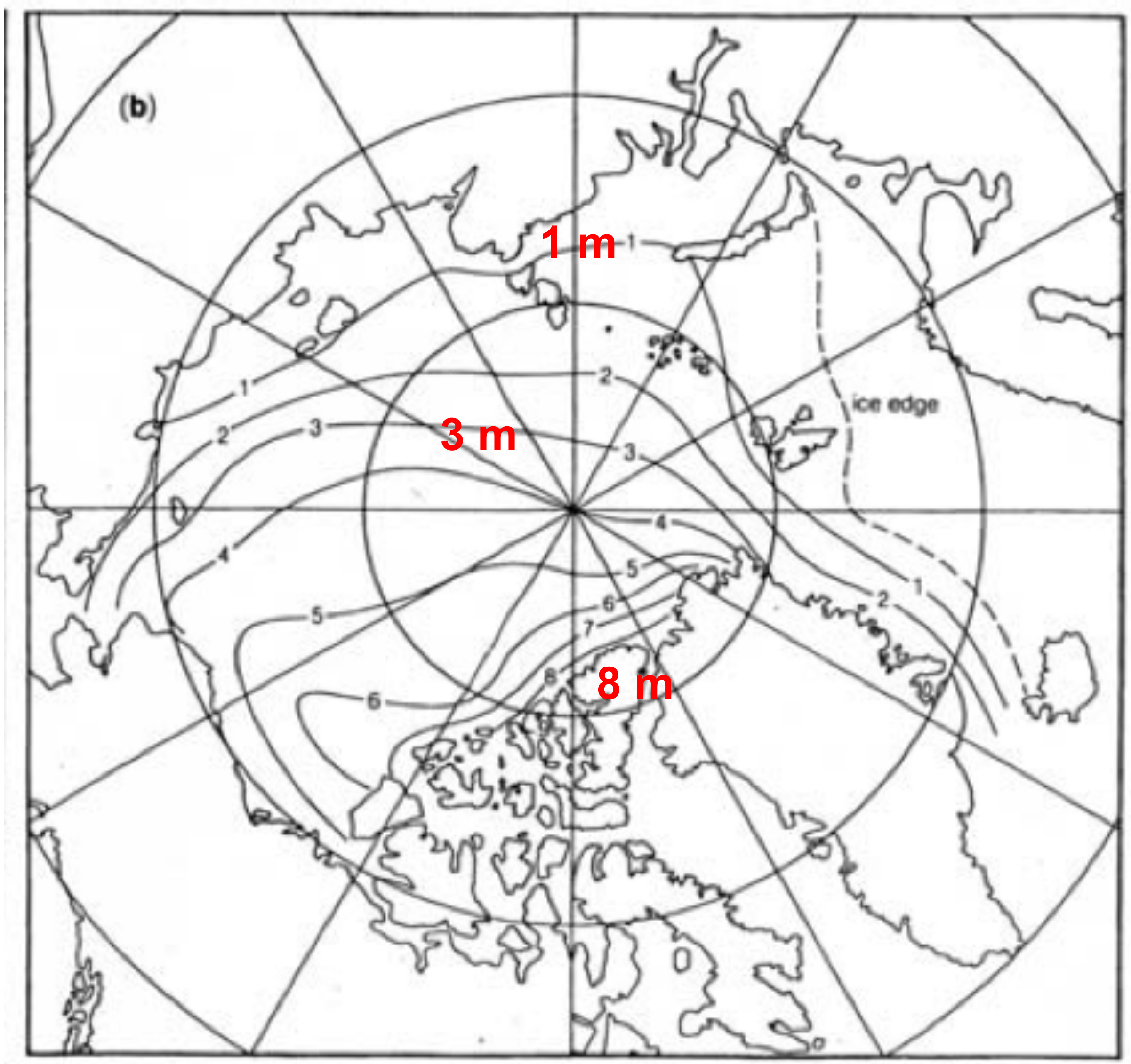
Kwok, 2015

Multi-year Sea Ice Cover (Winter 2014)



Farrell et al., 2015

The 3rd Dimension: Sea Ice Thickness

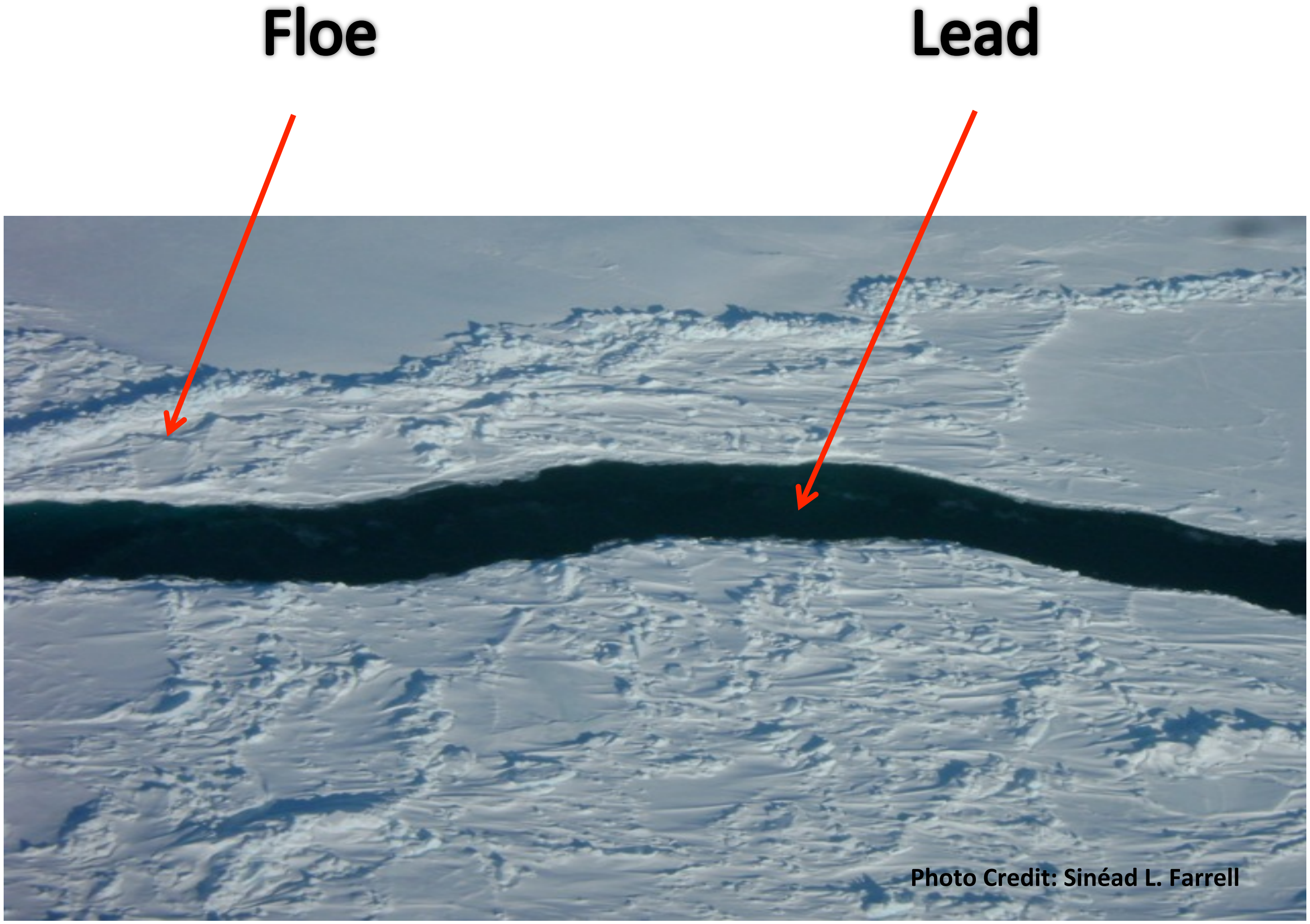


Sea ice thickness climatology
- Derived from submarine profiles.

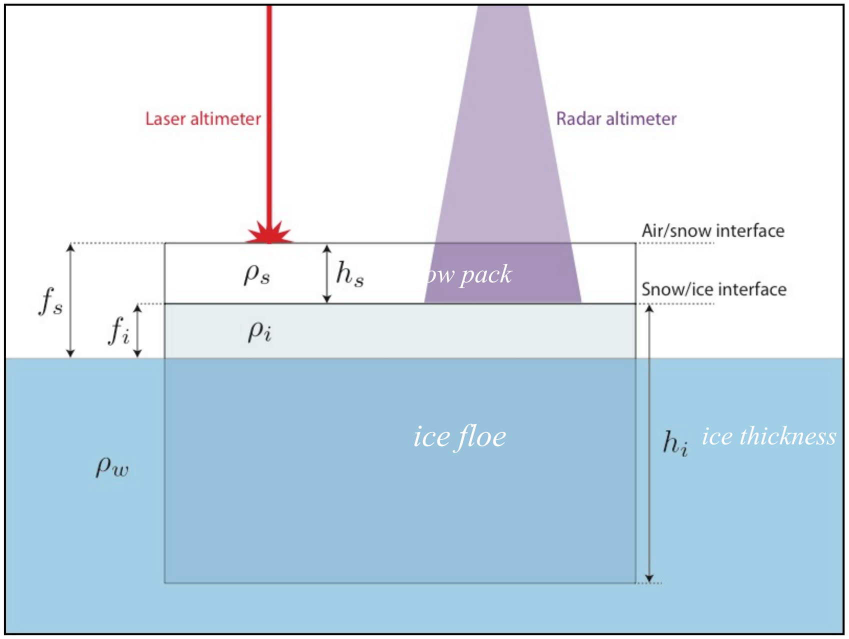
Contour maps -> mean ice thickness estimates for winter

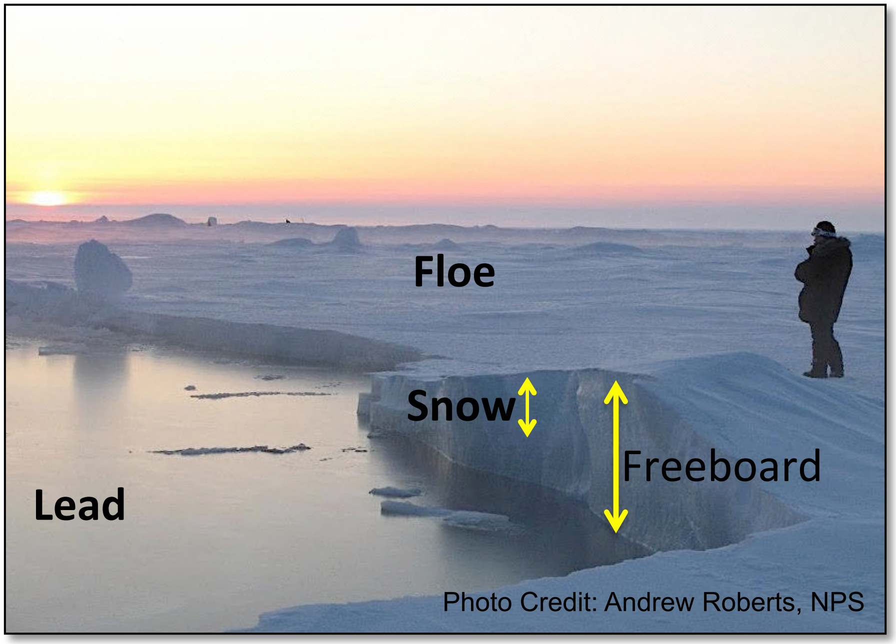
***Source**: Bourke and Garrett (1987), Sea ice thickness distribution in the Arctic Ocean, Cold Regions Sci. Technol., 13, 259-280.*

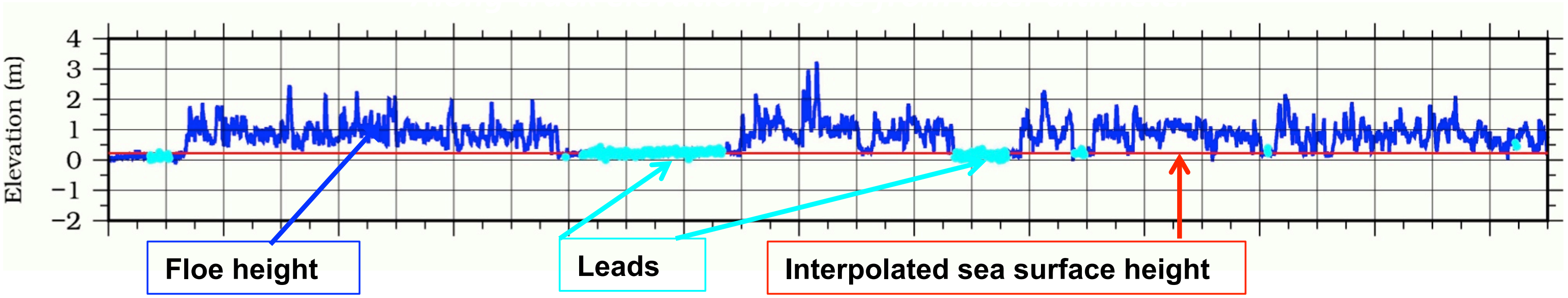
Distinguishing Leads from Floes



Altimetry Concept for Sea Ice Thickness







Adapted From: *Farrell et al.* (2014)

Inferring Sea Ice Thickness with Altimetry

Sea Ice Thickness, h_i, from a radar altimeter:

$$h_{\mathrm{i}} = \frac{f_{\mathrm{i}}\rho_{\mathrm{w}}}{(\rho_{\mathrm{w}} - \rho_{\mathrm{i}})} + \frac{h_{\mathrm{s}}\rho_{\mathrm{s}}}{(\rho_{\mathrm{w}} - \rho_{\mathrm{i}})}$$

Sea Ice Thickness, h_i, from a laser altimeter:

$$h_{\mathrm{i}} = \frac{f_{\mathrm{s}}\rho_{\mathrm{w}}}{(\rho_{\mathrm{w}} - \rho_{\mathrm{i}})} + \frac{h_{\mathrm{s}}(\rho_{\mathrm{s}} - \rho_{\mathrm{w}})}{(\rho_{\mathrm{w}} - \rho_{\mathrm{i}})}$$

From: Giles et al., *Rem. Sens. Environ.*, 2007

Where,

f_i = radar-measured ice freeboard (radar freeboard)

or

f_s = laser-measured snow freeboard (laser freeboard)

→ **Altimetric measurement**

h_s = snow thickness → **Measurement, climatology or model**

ρ_i = ice density
ρ_s = snow density
ρ_w = sea water density

→ **Climatological values; defined with respect to ice type**

First Satellite Estimates of Sea Ice Thickness

Mean winter sea ice thickness in the Arctic Ocean from ERS-1 and ERS-2 satellite radar altimetry data

Eight-year average: 1993-2001 valid for the winter (October to March).

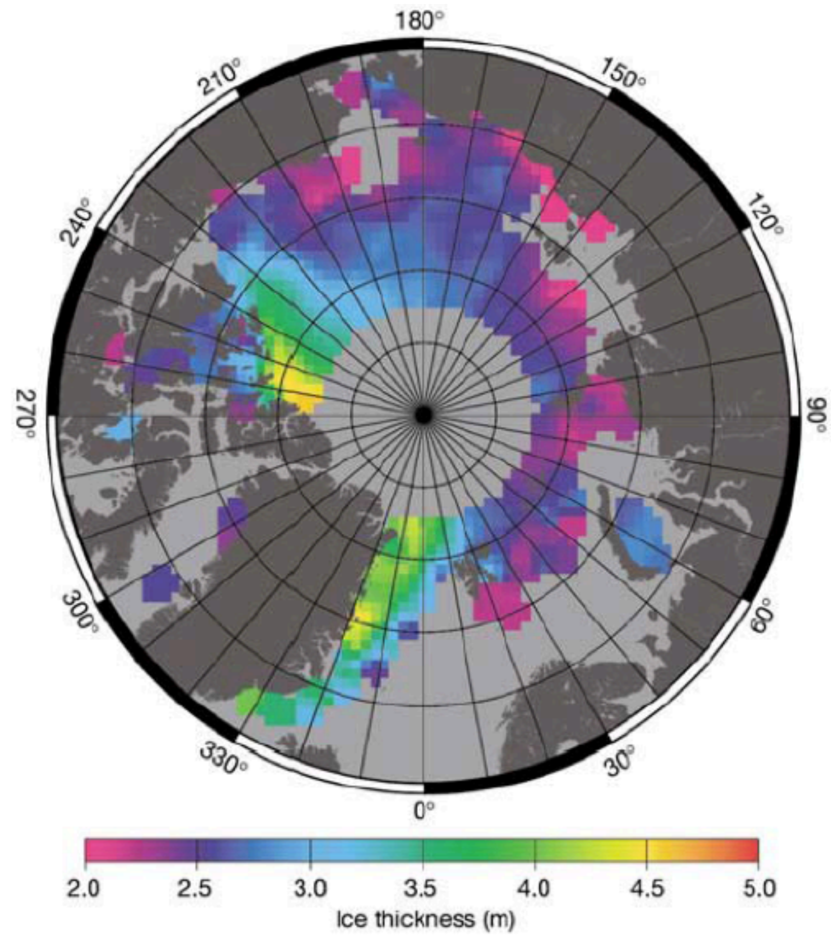
First determine sea **ice freeboard**

Next use auxiliary measurements of ice, water, and snow density and snow depth to **estimate thickness**

The standard deviation of mean ice thickness over 8-year period was 9% of the average ice thickness

Average winter ice thickness was strongly correlated to the length of the summer melt season

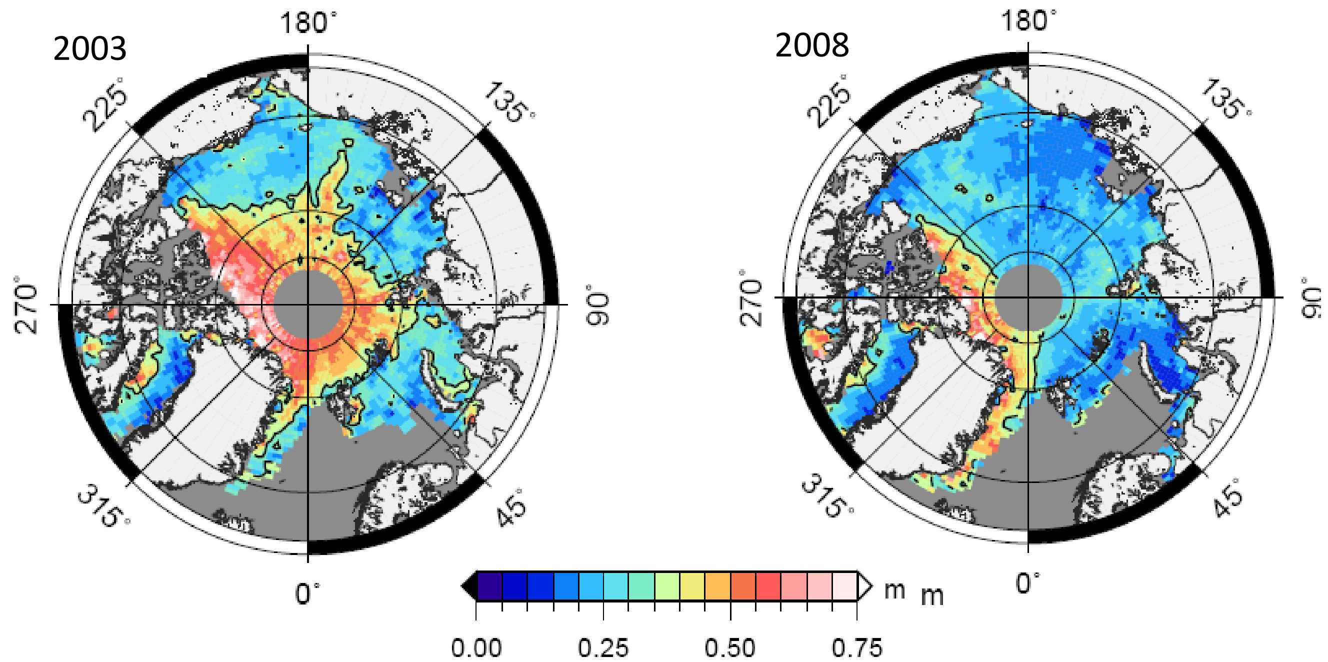
Significant variability between sea ice seasons



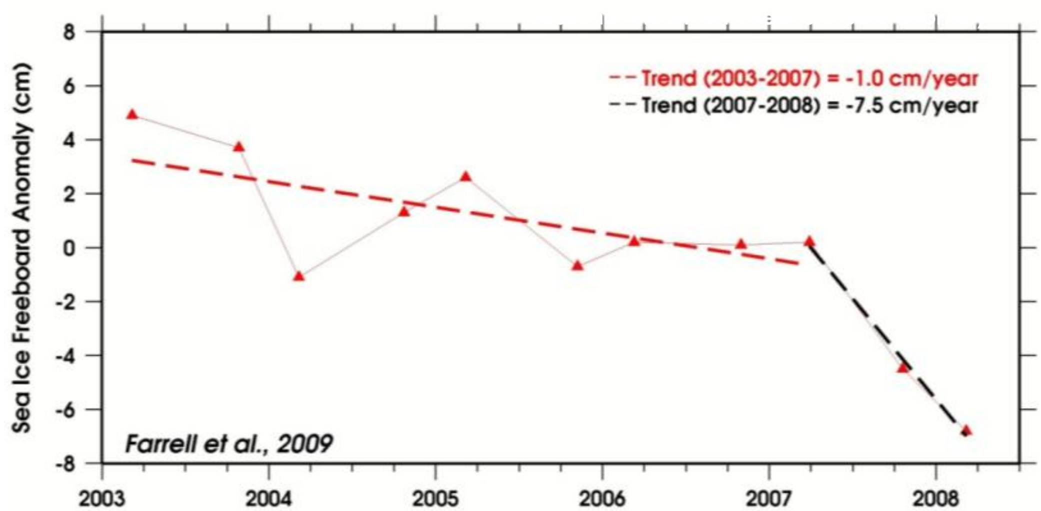
Source*: Laxon S. W., N. Peacock and D. Smith (2003), High interannual variability of sea ice thickness in the Arctic region, Nature, 425, 947-949.*

ICESat Sea Ice Freeboard: 2003 - 2008

Winter (Feb-Mar)

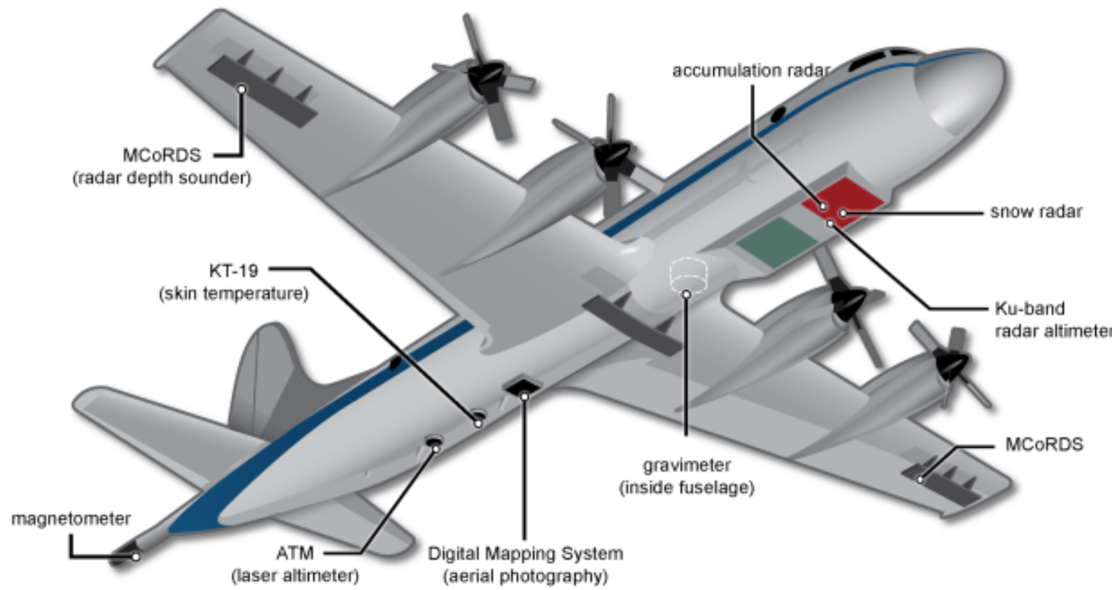


Loss of Winter-time Sea Ice Freeboard: -1.6 cm/yr



Source: *Farrell et. al. JGR, 2009*

NASA Operation IceBridge: 2009 – present (~2019)

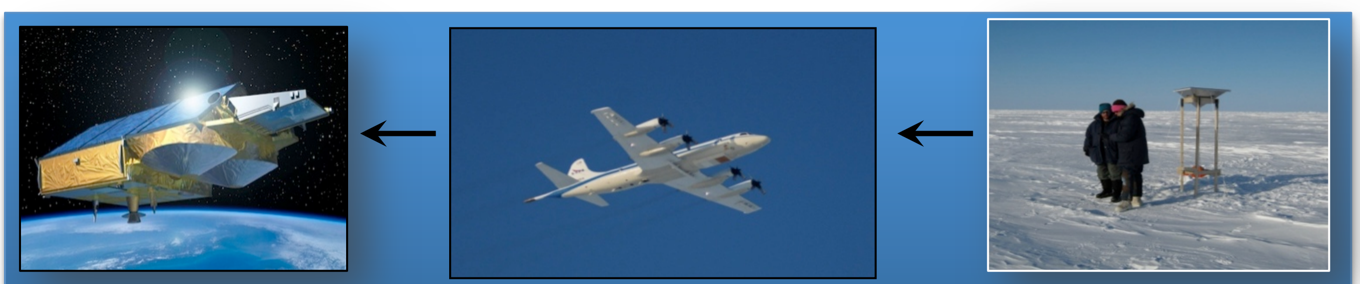


NASA's Operation IceBridge images Earth's polar ice in unprecedented detail to better understand processes that connect the polar regions with the global climate system. IceBridge utilizes a highly specialized fleet of research aircraft and a sophisticated instrument suite to characterize annual changes in thickness of sea ice, glaciers, and ice sheets.

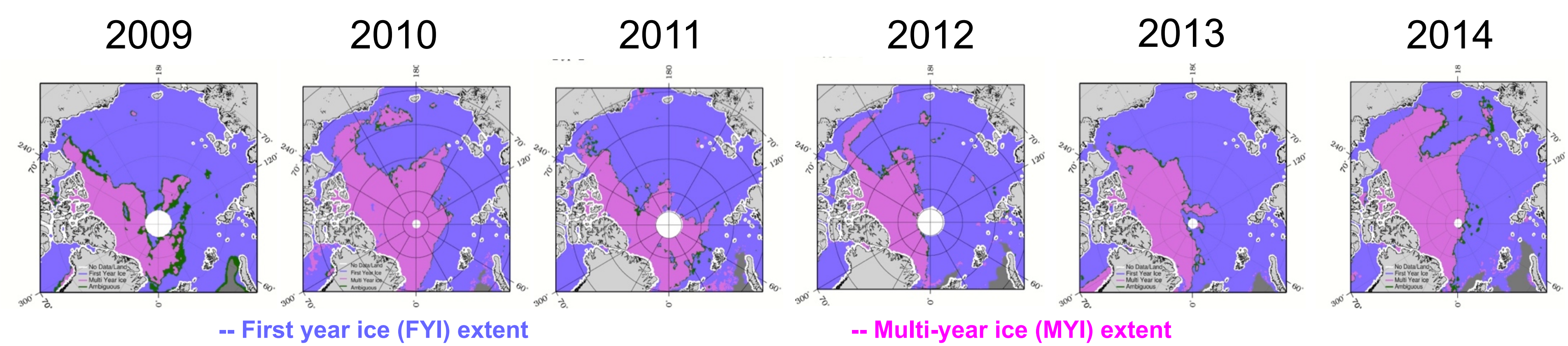
http://icebridge.gsfc.nasa.gov/
www.nasa.gov/icebridge

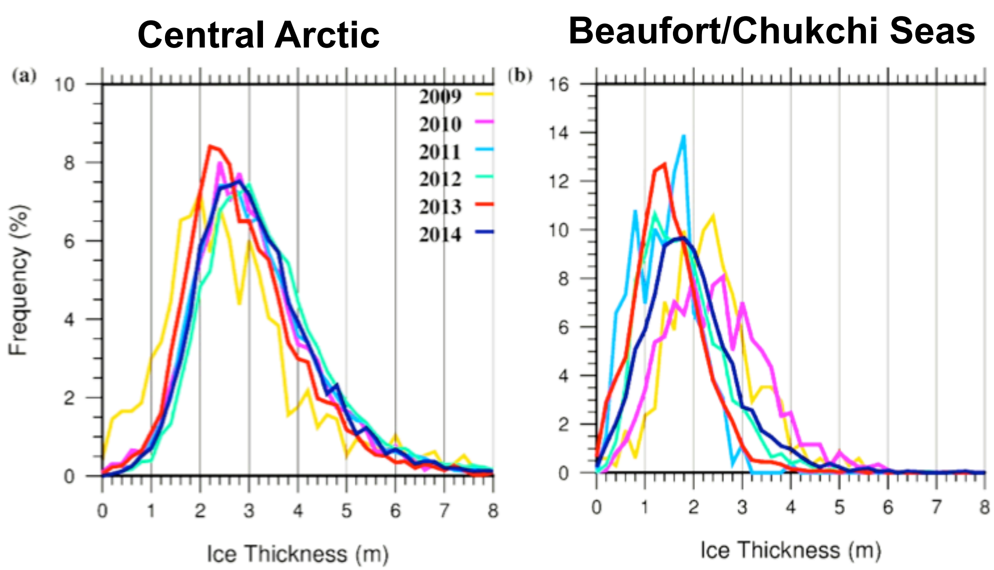
Key Sea Ice Goals for the IceBridge Mission

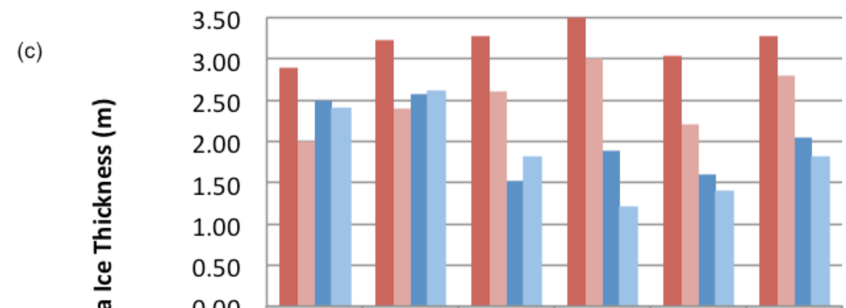
- To monitor changes in Arctic Ocean sea ice freeboard and thickness during the gap between ICESat-1 and ICESat-2.
- To provide cross-calibration and validation of freeboard and thickness from satellite lasers (ICESat and ICESat-2) and radars (Envisat and CryoSat-2).
- To improve understanding of the snow depth distributions on Arctic and Antarctic sea ice
- To support field programs in the Arctic and Southern Oceans.
- All instrument data freely available: nsidc.org/icebridge/portal/



Arctic Sea Ice Thickness: 2009 - 2014



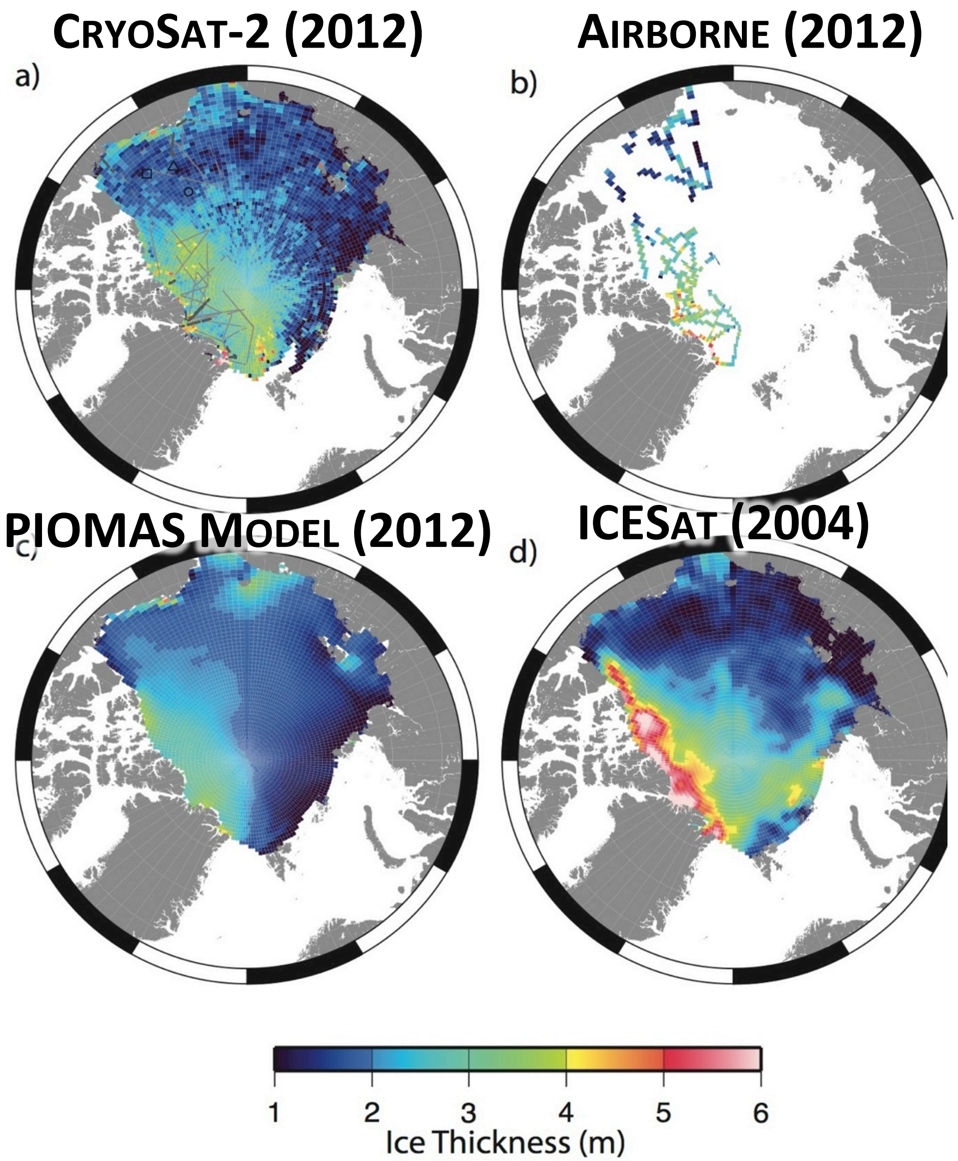




	2009	2010	2011	2012	2013	2014
Central Arctic Mean	2.90	3.23	3.27	3.50	3.04	3.28
Central Arctic Mode	2.00	2.40	2.60	3.00	2.20	2.80
Beaufort Sea Mean	2.49	2.57	1.52	1.88	1.60	2.04
Beaufort Sea Mode	2.40	2.60	1.80	1.20	1.40	1.80

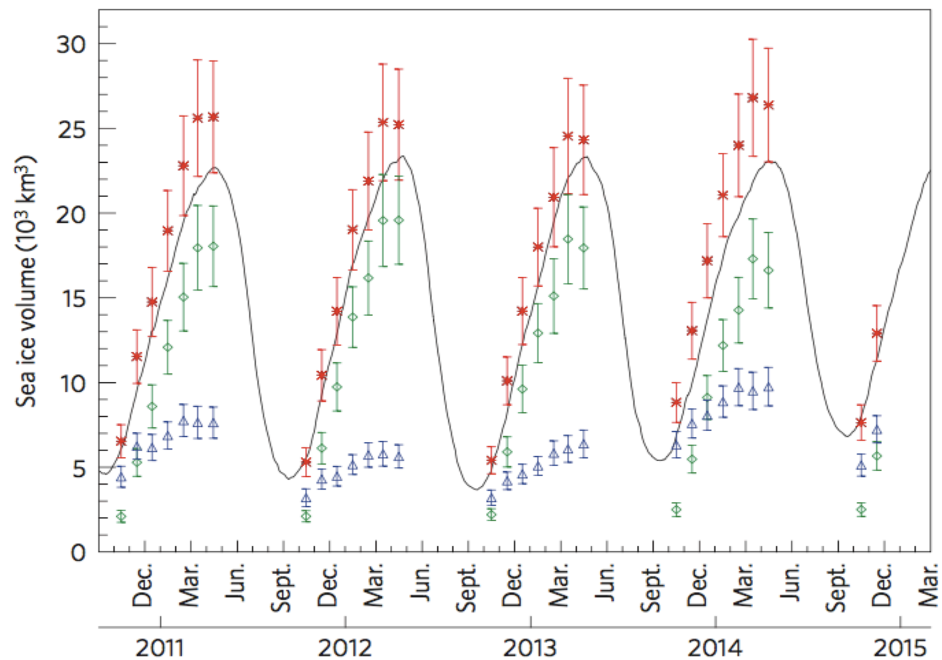
Source: *Richter-Menge and Farrell,* GRL, 2013 (updated)

Recent Changes in Thickness and Volume: CryoSat-2



Source: *Laxon et al.*, GRL, 2013

CryoSat-2 Arctic Sea Ice Volume (2010 – 2015)



High inter-annual variability in volume over last five years, particularly of the MYI pack

Source: Tilling et al., [2015]

What’s my favourite type of ice?

Useful Links and Further Reading

- WMO Sea Ice Nomenclature (illustrated): www.aari.nw.ru/gdsidb/XML/volume2.php?lang1=0&lang2=1&arrange=1
- NOAA Lab. For Satellite Altimetry: www.star.nesdis.noaa.gov/sod/lsa/
- Twitter: @sineadlfarrell
- Arctic Report Card: www.arctic.noaa.gov/reportcard/
- NASA Cryo: http://ice.nasa.gov/ and twitter: @NASA_ICE
- NASA IceBridge www.nasa.gov/icebridge and https://nsidc.org/data/icebridge
- NASA ICESat-2, ICESat and MABEL: http://icesat.gsfc.nasa.gov/icesat2/data.php
- NSIDC's "All about Sea Ice": nsidc.org/cryosphere/seaice/index.html
- NSIDC Sea Ice News: http://nsidc.org/arcticseaicenews/
- University of Bremen Sea Ice Pages: http://www.iup.uni-bremen.de/seaice/
- Sea Ice Concentration: http://www.iup.uni-bremen.de:8084/amsr2/#Arctic
- IFREMER/CERSAT sea ice drift: ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-drift/
- DTU Space sea ice pages: http://www.seaice.dk/
- Alfred Wegener Institut Sea Ice Portal: http://data.seaiceportal.de/
- CPOM Data Portal/CryoSat2 Sea Ice Thickness: www.cpom.ucl.ac.uk/csopr/seaice.html
- OSI-SAF Sea Ice Products: http://osisaf.met.no/p/ice/
- Brigham Young/NASA Scatterometer Climate Record Pathfinder: www.scp.byu.edu/
- BAMS State of the Climate Report: https://www.ncdc.noaa.gov/bams