Advances in Satellite and Airborne Altimetry over Arctic Sea Ice – Towards Improved Prediction

Sinéad Louise Farrell

Geographical Sciences, University of Maryland

and Visiting Scientist at NOAA/NESDIS/STAR/SOCD Lab. For Satellite Altimetry

With special thanks to the SOCD Sea Ice Team:

Larry Connor, Kyle Duncan, Chris Jackson,

Alejandro Egido, Ellen Buckley

STAR Science Seminar

NOAA NCWCP College Park, MD

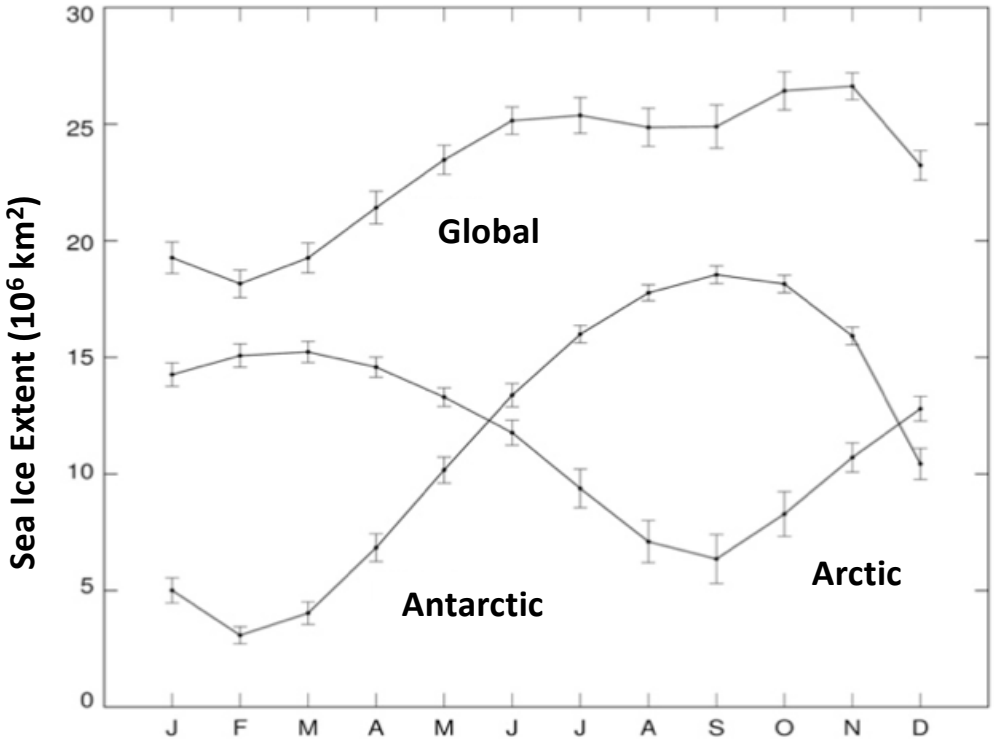
11 September 2019

Photo Credit: Sinéad L. Farrell, University of Maryland

Arctic Ocean

Southern Ocean

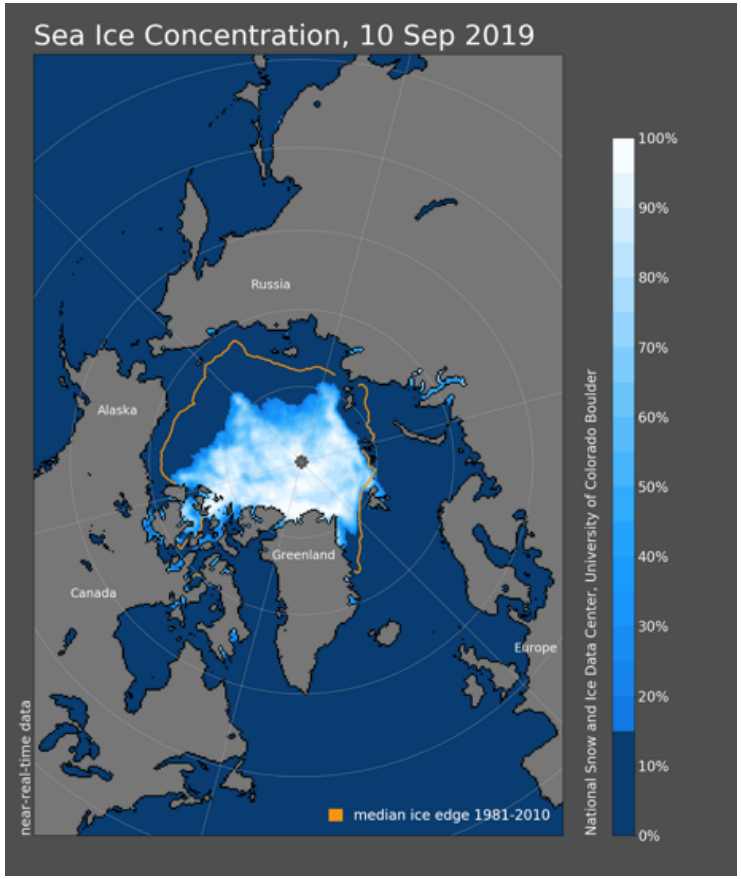
Annual average Arctic, Antarctic and Global sea ice extent (1979-2013)

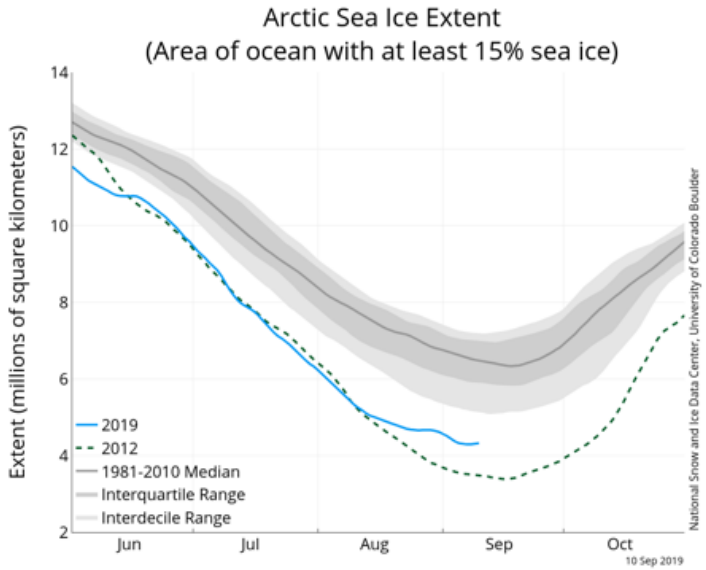


Min. extent: Feb. 18.2 x 10^6 km^2 • **Max. extent: Nov**. 26.6 x 10^6 km^2

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

Sea Ice at the Summer Minimum - 2019





- By August 31, 2019, sea ice extent was 4.62 million square kilometers (1.78 million square miles)
- The monthly average extent for August 2019, was the 2nd lowest extent for August in the satellite record.

Source: National Snow and Ice Data Center, 2019

Sea Ice Characteristics

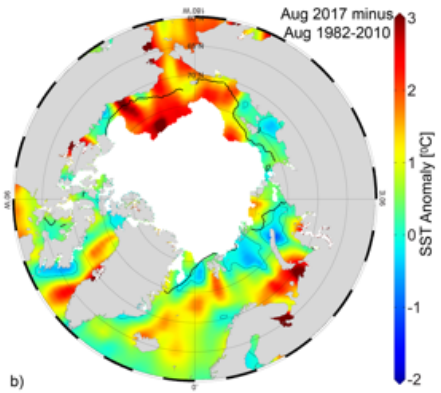
Photo Credit: Sinéad L. Farrell, University of Maryland

- Complex system of level, sea ice floes topped with snow, deformed ice, pressure ridges, interspersed with open water (leads and polynyas)
- Sea ice is a reflective barrier - insulates warmer ocean from cold atmosphere in winter
- High albedo surface – reflects incoming sunlight, regulates Earth's energy budget & cools the planet
- Melting and freezing of sea ice contribute to the global thermohaline circulation
- Provides a valuable habitat for marine ecology
- Melting provides source of nutrients to marine food web and stimulates phytoplankton blooms

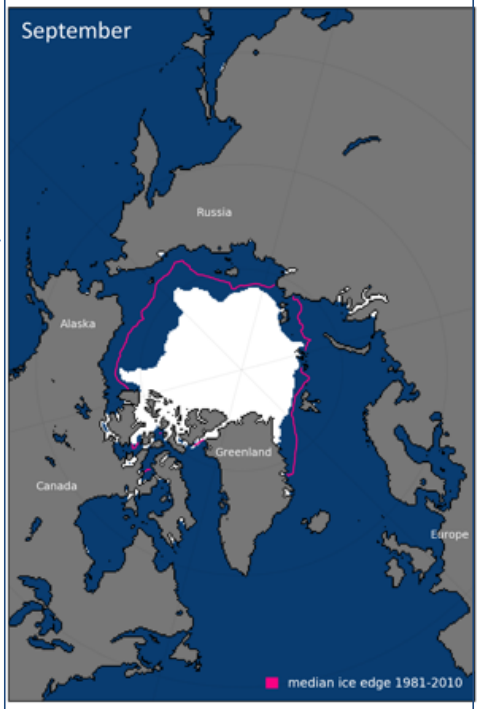
Source: S. L. Farrell, 2019

Arctic System Change – Impacts of Sea Ice Loss

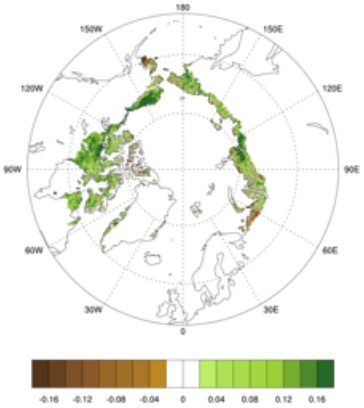
Ocean Surface Temp. Anomaly
August 2017 relative to mean (1982-2010)



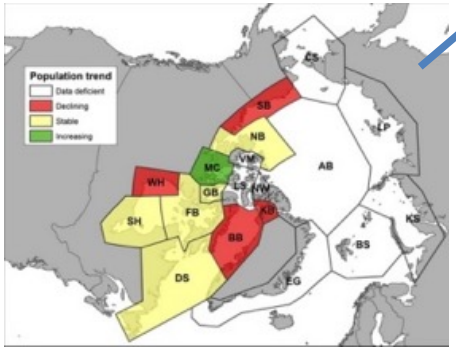
Sea Ice Extent
September 2017 Summer minimum



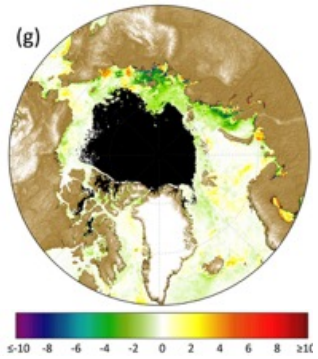
Vegetative Greenness
Max-NDVI Trend: 1982-2016



Polar Bear
Population trend: late 1980s - 2013



Primary Productivity
Chlorophyll-*a* Anomaly (mg m^{-3})
July 2017 relative to mean (2003-2016)

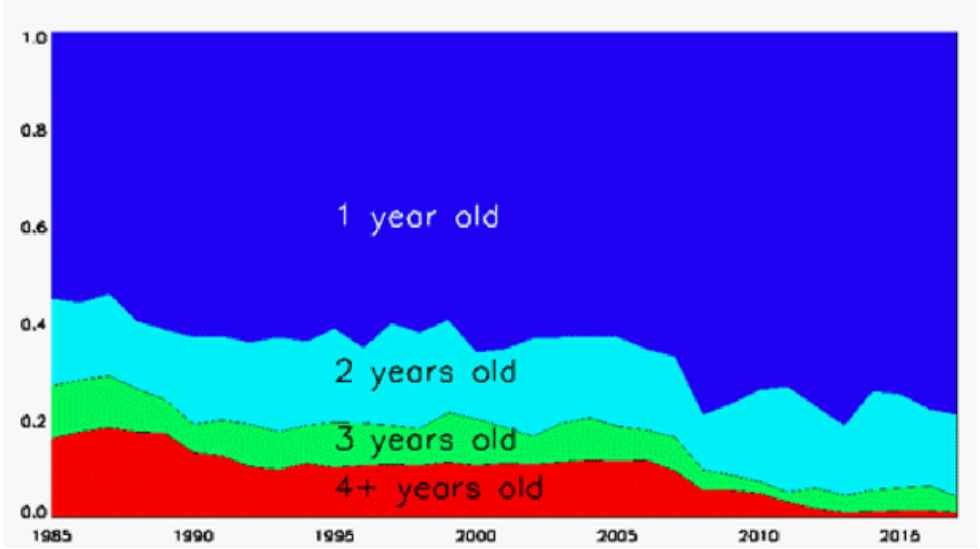


Impact of sea ice loss on peripheral seas

Source: Richter-Menge et al., Arctic Report Card, 2017

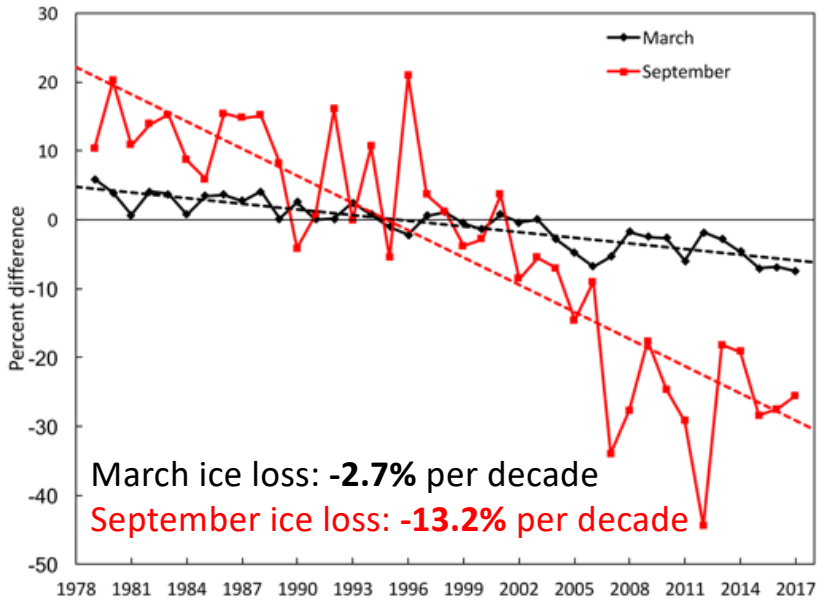
Declining Arctic Sea Ice Cover

Fraction of Ice Types, 1985 - 2017



Seasonal, first-year ice, now ~ 79 %, compared to ~ 50% in 1980s

Anomalies (%) in Ice Extent, relative to 1981-2010

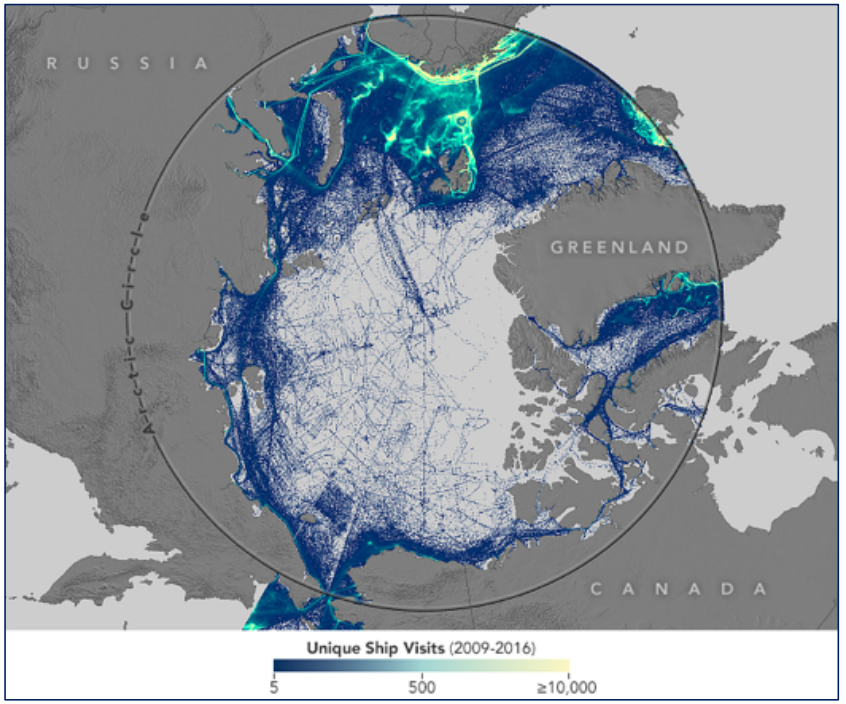


Source: Perovich et al., Arctic Report Card, 2017

Economic Activities in the Arctic

- Northern Sea Route (NSR) & North-West Passage are opening up in summer
- NSR can cut journey times from Asia to Europe by about 2 weeks

Shipping Activity in the Arctic: 2009-2016



Source: NASA/Greg Fiske, Woods Hole Research Center

Increases in Arctic Shipping

- 600+ voyages (oil tankers, cargo ships, research vessels, cruise ships) in summers 2017 & 2018 along NSR
- Oil tankers with ice-breaking capabilities and container ships with ice-hardened hulls making the headlines…

abc NEWS VIDEO LIVE SHOWS

Global warming's melting of polar ice allows 1st commercial container ship to cross Arctic Ocean

By CLARK BENTSON Rome — Sep 17, 2018, 2:51 PM ET

The Guardian

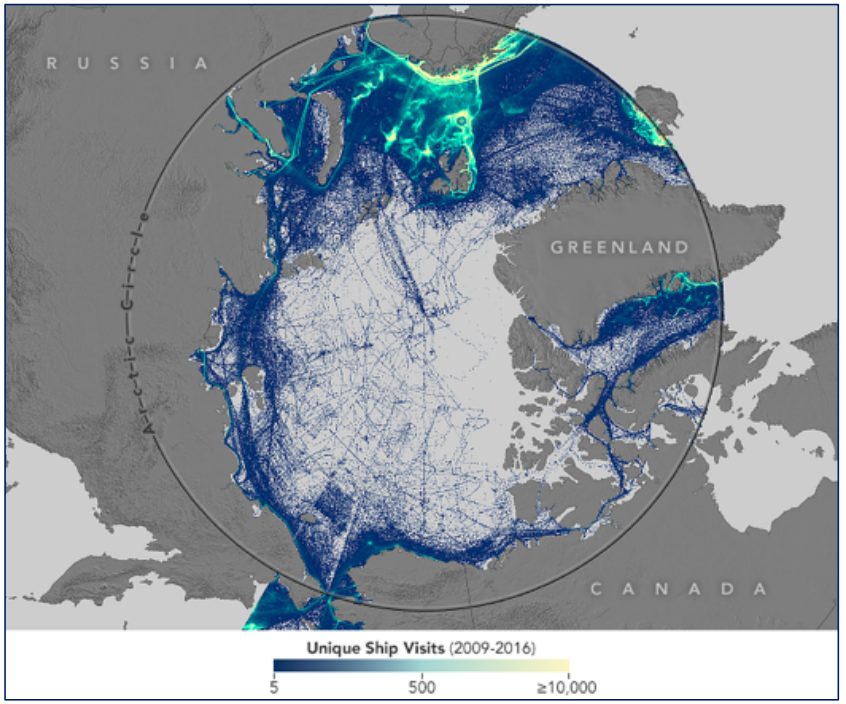
Shipping first as commercial tanker crosses Arctic sea route in winter

The crossing, unassisted by an icebreaker vessel, marks a milestone as thawing polar ice opens up Russia's northern coastline,

Megan Darby for Climate Home News

Tue 13 Feb 2018 12.19 GMT

Shipping Activity in the Arctic: 2009-2016



Source: NASA/Greg Fiske, Woods Hole Research Center

Ocean-Atmosphere Heat Exchange

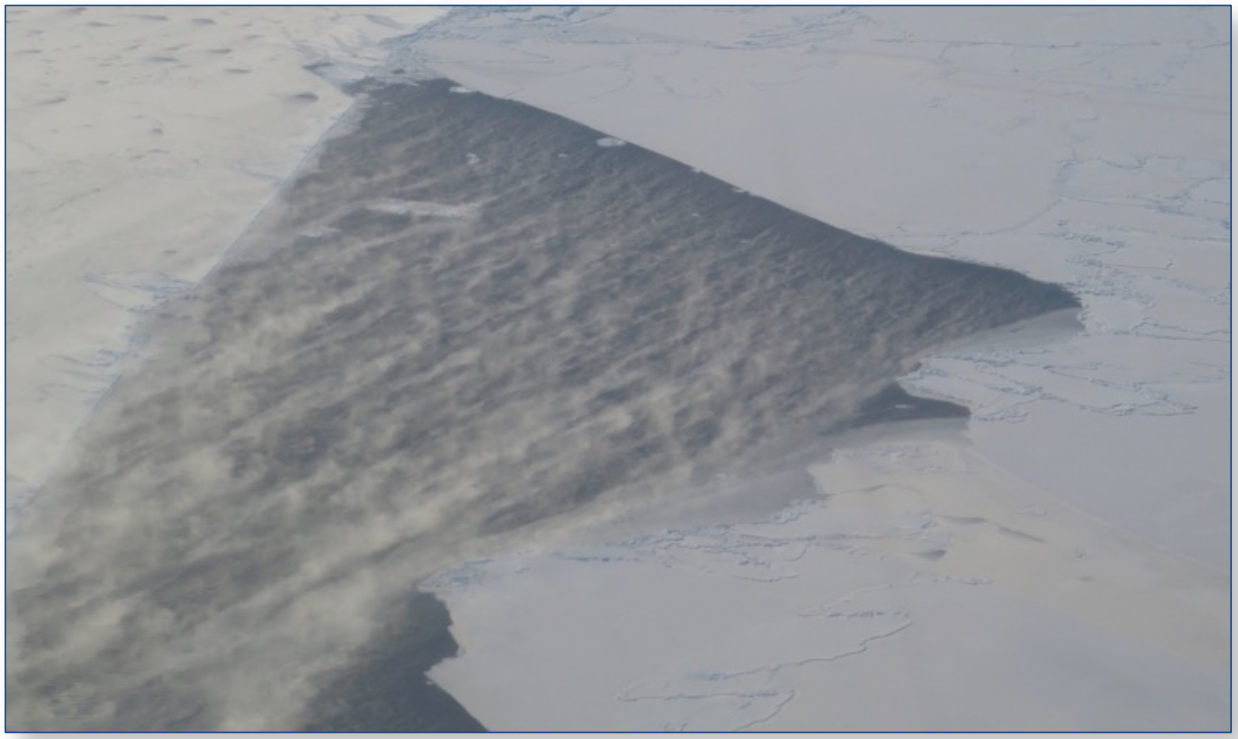


Photo Credit: Sinéad L. Farrell, University of Maryland

- As the ice thins, and drift speeds increase, areas of open water, leads and polynyas increase
- Sea ice may no longer efficiently insulate ocean from atmosphere

Source: S. L. Farrell, 2019

Socio-Economic Impacts → Motivation for our work!

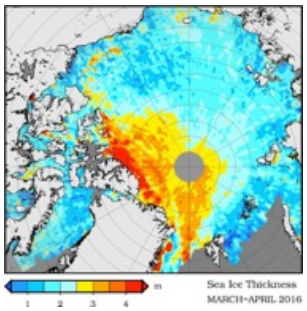
Photo Credit: Jennifer Hutchings, OSU

- Sea ice is **an indicator**, and potentially **an amplifier**, of global climate change
- Losses have **broad implications** for environment, ecosystems, biodiversity, national security, safety at sea (search and rescue activities), commerce and trade, …
- **Sustained, long-term observations** are needed to detect variability and trends
- We need to **improve our capability to forecast** sea ice, and **understand** forcing mechanisms
- **Enables timely decisions** by citizens, policy-makers, Arctic stake-holders, industry

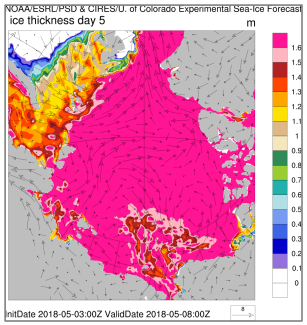
State of Sea Ice Cover

Photo Credit: Sinéad L. Farrell

Observations

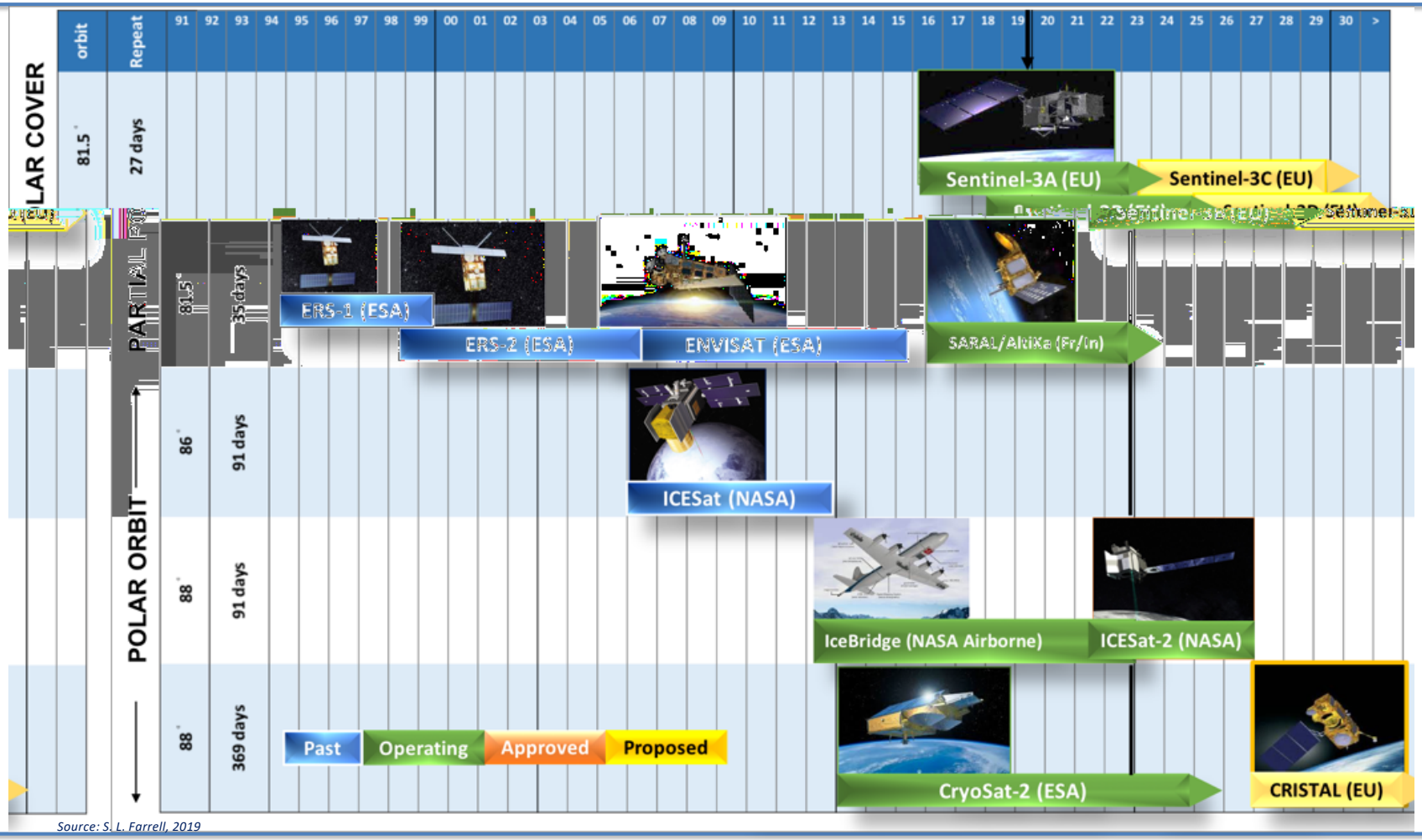


Forecasts



Source: S. L. Farrell, 2019

Evolution of High-Latitude Altimetry



Source: S. L. Farrell, 2019

ICESat-2 – First Year in Orbit!

NASA successfully launched ICESat-2 from Vandenberg Air Force Base, CA, on 15th Sept. 2018, at 13:02 UTC

ICESat-2 carries ATLAS: Advanced Topographic Laser Altimeter System

Single laser pulse (532 nm) split into 6 beams; photon counting

Redundant laser and detector

- **Surface Elevation**: over ice-covered ocean (**ATL07**), provides height measurements of level sea ice floes, ridged/deformed sea ice floes, lead/sea surface height (SSH)
- **Sea Ice Freeboard (ATL10)**: routine measurements of sea ice freeboard in both Arctic and Southern Oceans, available along-track

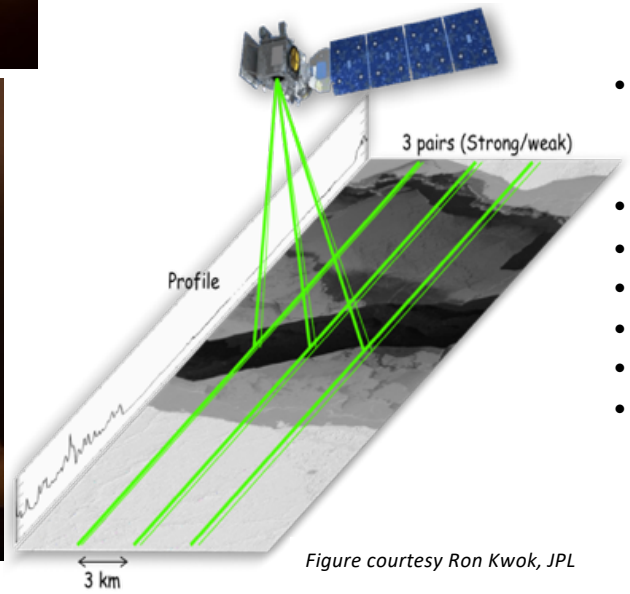


Figure courtesy Ron Kwok, JPL

- Beams arranged in pairs (strong/weak beam combination)

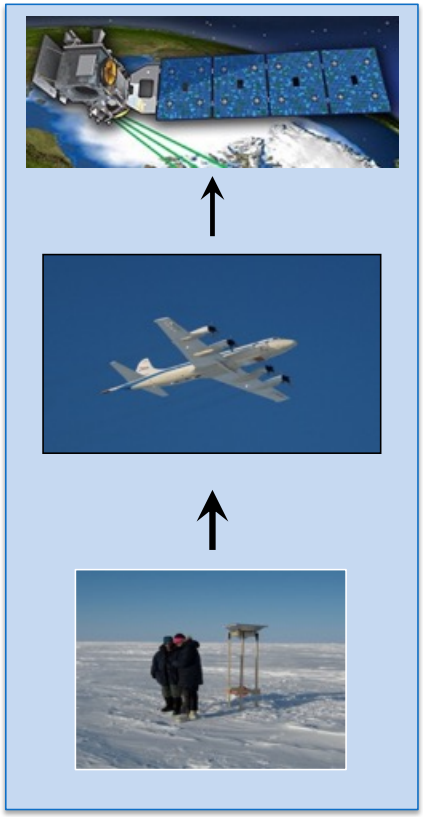
- Pair spacing: ~ 90 m, for slope determination
- Spacing between pairs: ~ 3 km, for spatial coverage
- Footprint spot size: ~ 14 m
- PRF: 10 kHz (0.7 m sampling along-track)
- Coverage: 88 °N to 88 °S
- Exact Repeat: 91 days; Sub-cycles: ~4 days; 29 days

More info. and orbits:
https://icesat-2.gsfc.nasa.gov/

Current Observational Tools for Sea Ice Monitoring

At the NOAA Lab. For Satellite Altimetry (LSA) we use the following tools for observing sea ice:

Δing Spatial Scale



- **Satellite Observations:**

  Altimetry: ICESat, CryoSat-2, IceBridge, ICESat-2, CRISTAL

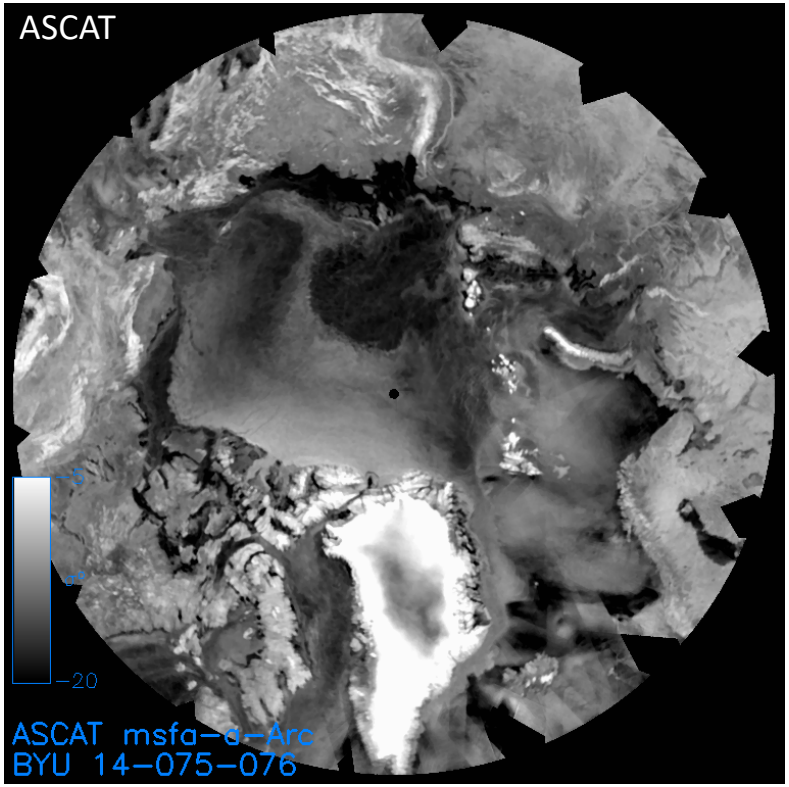
  Scatterometry: ASCAT on MetOp-A/B/C

  SAR: Sentinel-1 A/B; RadarSat-2; RCM; NISAR

- **Airborne observations:** IceBridge - provides measurements of sea ice freeboard, thickness, snow depth on sea ice, lead characteristics, pressure-ridge sail heights, surface roughness characteristics. Validation of satellite data products
- **Field-based surveys:** direct measurements of sea ice freeboard, thickness, snow depth
- **Direct, autonomous observations**: Ice mass-balance buoys (IMBs), upward looking sonar (ULS), snow buoys deployed on ice

Source: S. L. Farrell, 2019

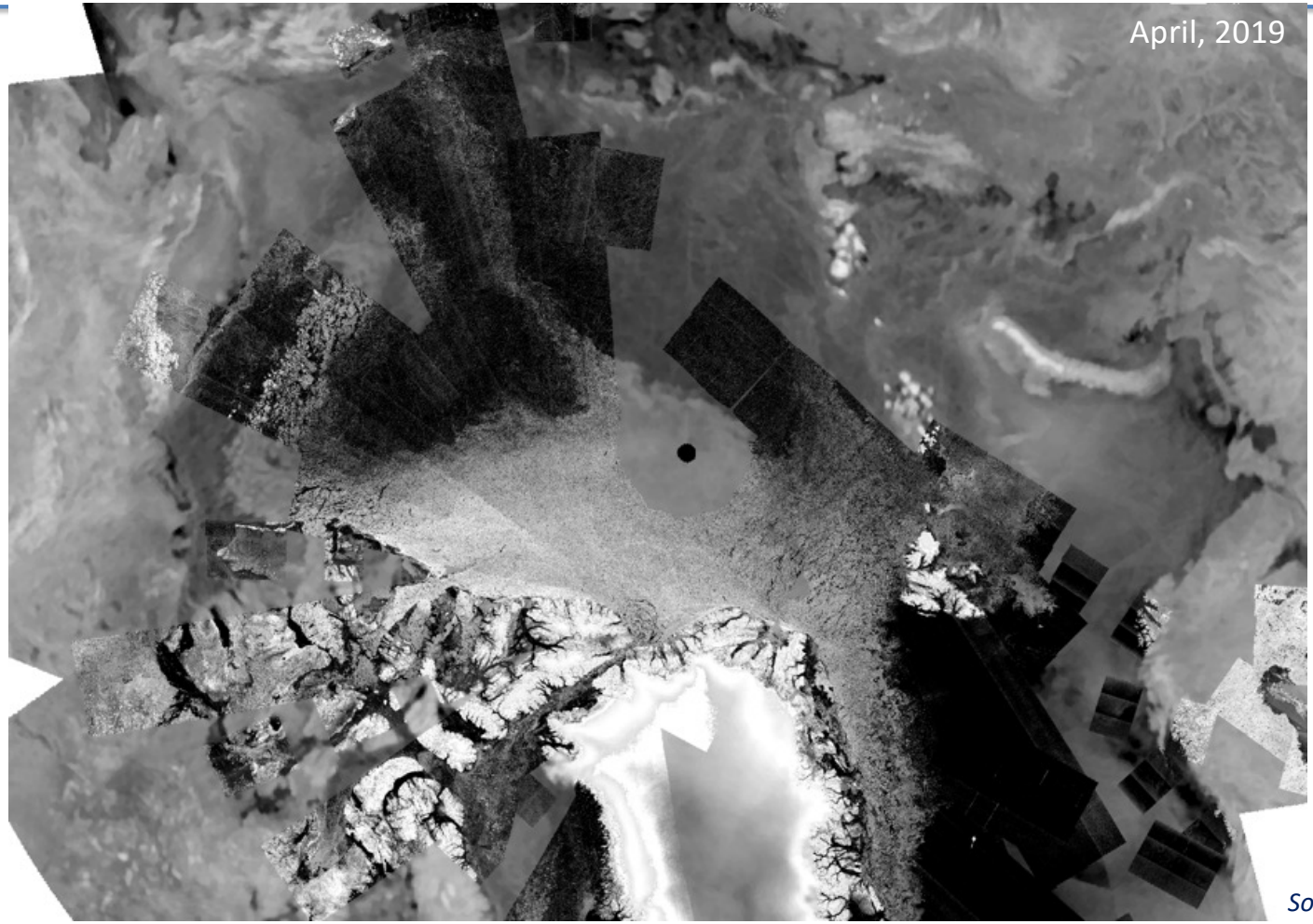
Sea Ice Type – Tracking Multiyear Ice Extent



- 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 and METOP-B (2009 – present)
- QuikScat :moderate resolution Ku-band
- ASCAT: moderate resolution C-band
- 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]
- High-resolution data set (4.45 km) → consistent with resolution of altimetry observations
- Small pole hole → MYI mask area extends to 89.5 ^{o}N

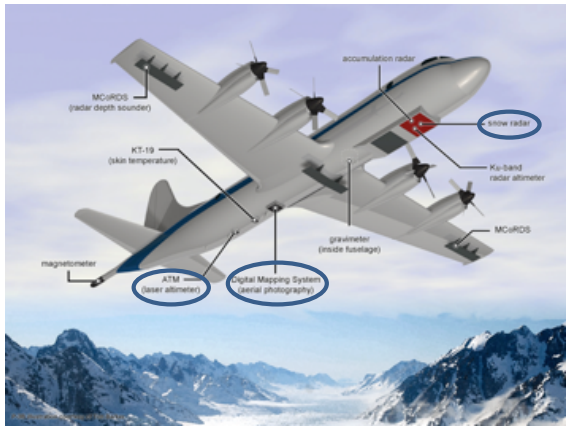
Source: C. Jackson, NOAA

Composite Sentinel-1 SAR Mosaic with ASCAT NRCS



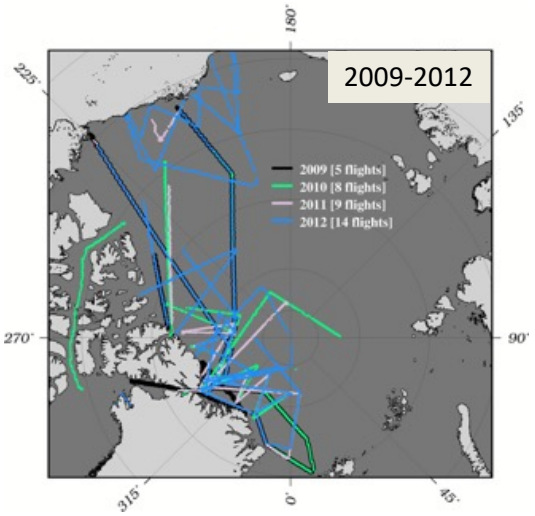
Source: Chris Jackson, 2019

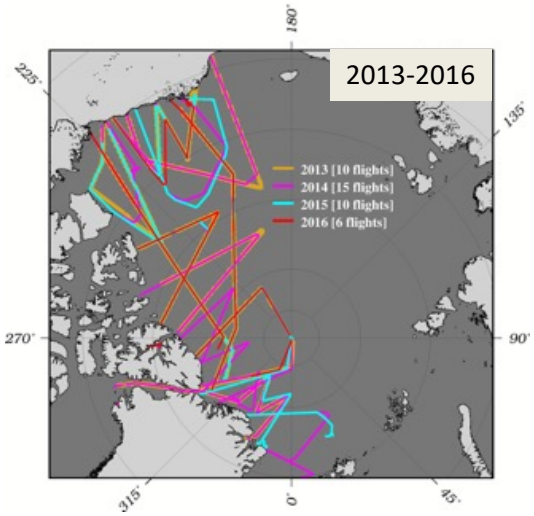
IceBridge Airborne Surveys over Arctic Sea Ice (2009 – 2019)

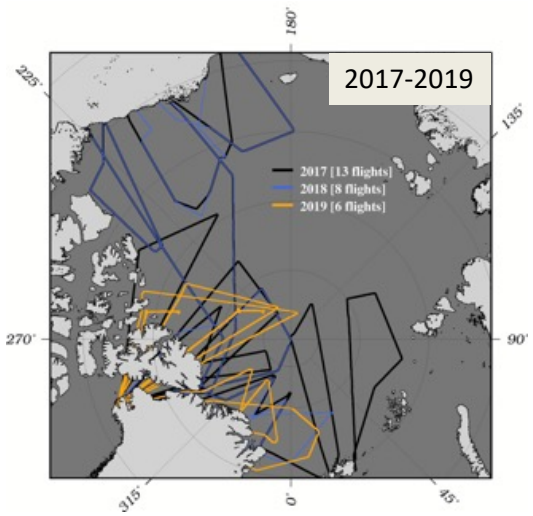


Operation IceBridge (OIB) airborne instrumentation for sea ice studies:

- **Airborne Topographic Mapper (ATM)** Laser Altimeter
  → **Surface Roughness; Sea Ice Freeboard; Sea Ice Thickness**
- **Ultra Wideband FMCW Snow Radar**
  → **Snow Depth; Lead delineation**
- **Digital Mapping System (DMS)** high resolution visible imagery
  → **Pressure ridge sail height; Lead delineation**







Year:	# of Sea Ice Surveys
2009:	5
2010:	8
2011:	9
2012:	14
2013:	10
2014:	15
2015:	10
2016:	6
2017:	13
2018:	8
2019:	6
Total:	**104**

Source: S. L. Farrell, 2019

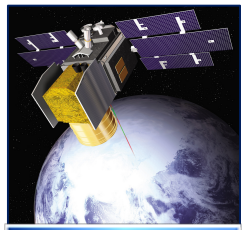
A decade of strong NOAA – NASA – ESA collaboration


IceBridge (NASA Airborne)

Operation IceBridge
Conducts spatially & temporally coincident under-flights of satellite altimeters over Arctic sea ice for data product cal/val


ENVISAT (ESA)

Envisat
- 5 under-flights
- Canada Basin
- 2006 - 2012


ICESat (NASA)

ICESat
- 2 under-flights
- Beaufort Sea / Canada Basin
- 2006


CryoSat-2 (ESA)

CryoSat-2
- 17 under-flights
- Western and Central Arctic Ocean
- 2010-2016; 2019


Sentinel-3A/B (EU)

Sentinel-3A
- 4 under-flights
- Beaufort Sea
- 2016; 2017; 2018

Sentinel-3B
- 1 under-flight
- Greenland Sea - 2019


ICESat-2 (NASA)

ICESat-2
Pre-launch survey flights
- 2 in Greenland Sea / Beaufort Sea
- 2012; 2016

Post-launch
- 4 in Central Arctic
- April 2019

More details of NOAA / LSA sea ice validation experiments and results at:
https://www.star.nesdis.noaa.gov/sod/lsa/SeaIce/ValidationExperiments.php

Source: S. L. Farrell, 2019

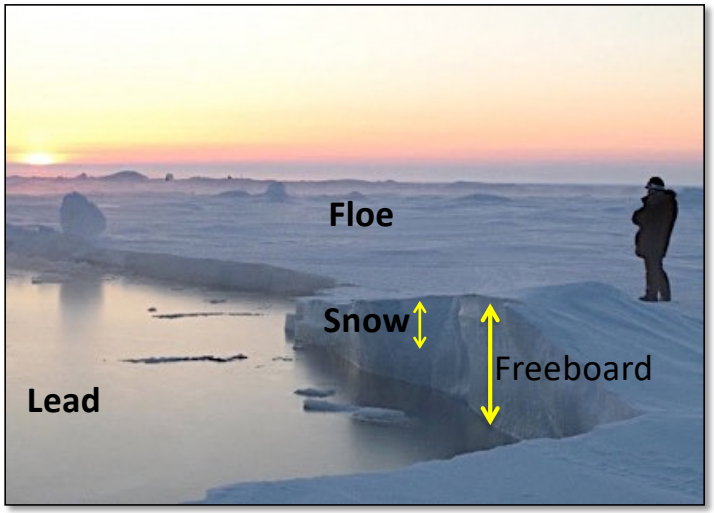


Photo Credit: Andrew Roberts, NPS

Sea Ice Thickness, h_i, from a laser altimeter:

$$h_i = \frac{f_s \rho_w}{(\rho_w - \rho_i)} + \frac{h_s(\rho_s - \rho_w)}{(\rho_w - \rho_i)}$$

Where,

f_s = measured freeboard (laser altimeter)

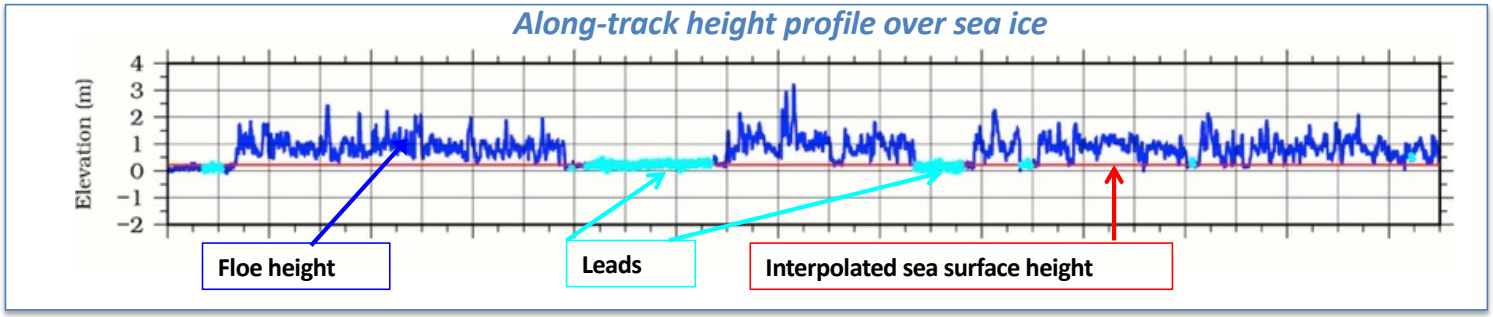
h_s = snow thickness

ρ_i = ice density

ρ_s = snow density

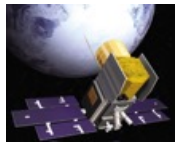
ρ_w = sea water density

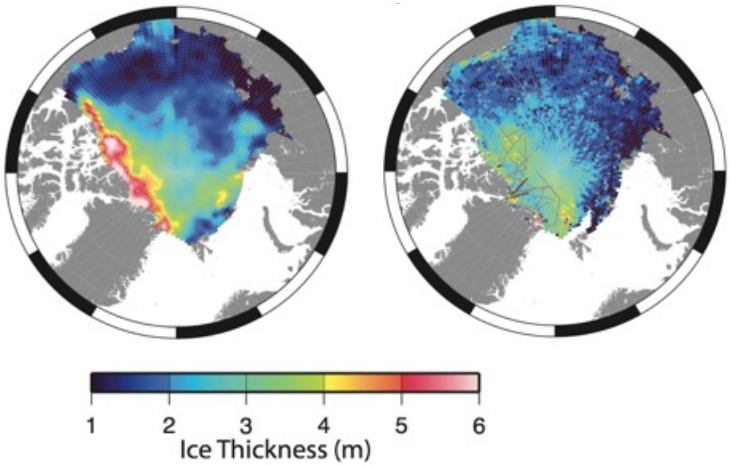
Auxiliary inputs

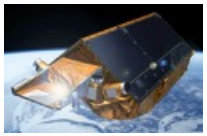


Source: *Farrell et al.* (2014)

Decline in Sea Ice Volume: ICESat → CryoSat-2

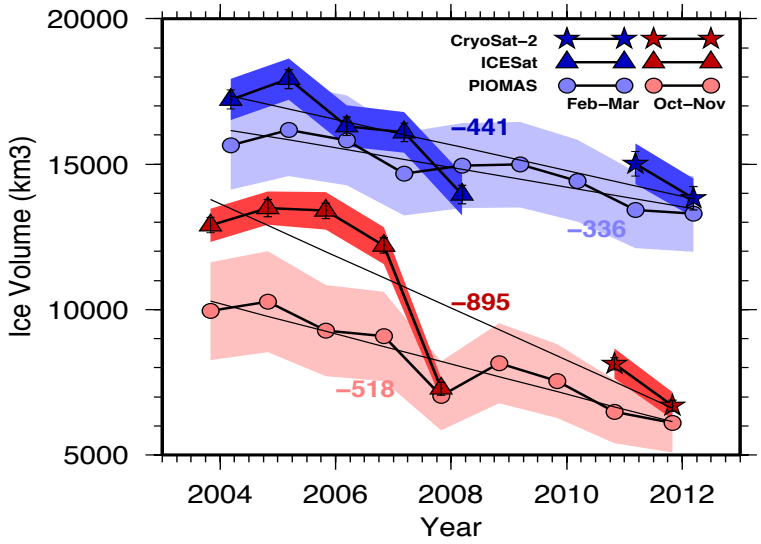






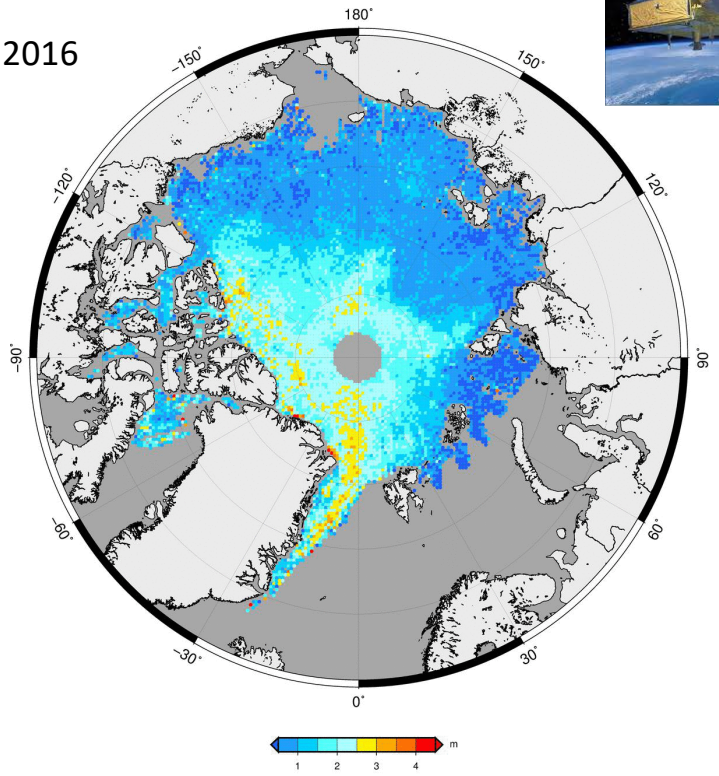
Between the ICESat and CryoSat-2 observation periods the winter volume declined by **~ 1500 km^3**

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

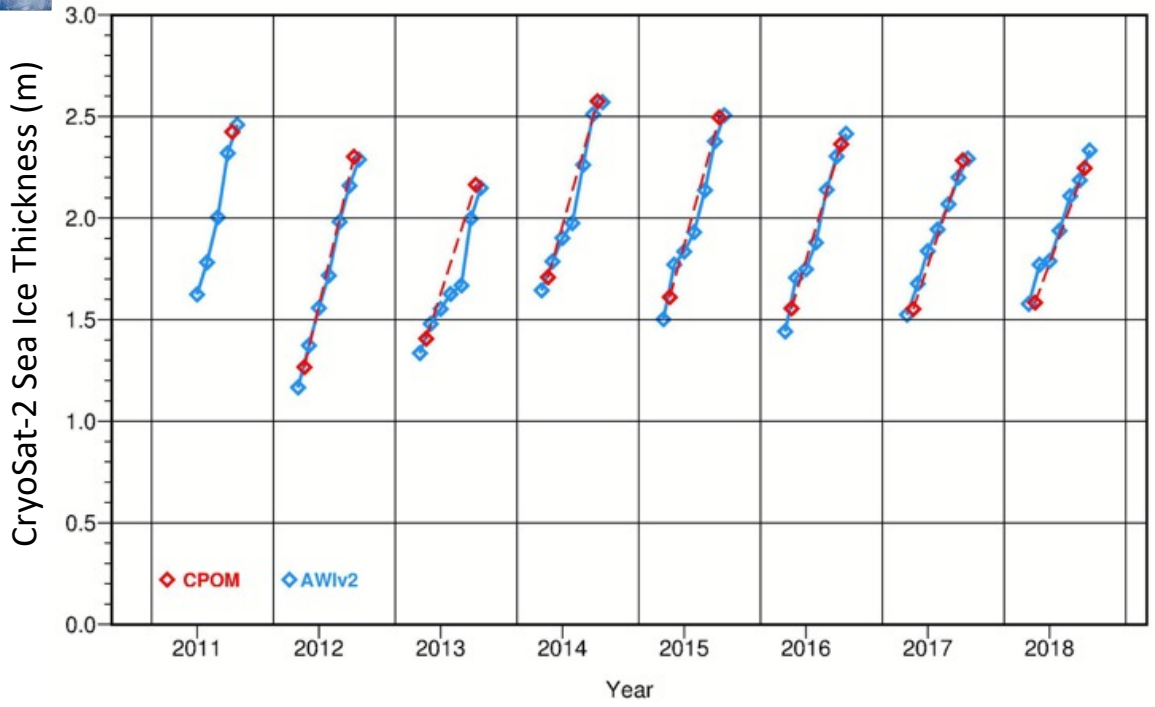


CryoSat-2 Tracks Seasonal and Inter-annual Change

2016



Seasonal Growth in Ice Thickness during Winter (October –> April)
2010 – 2018

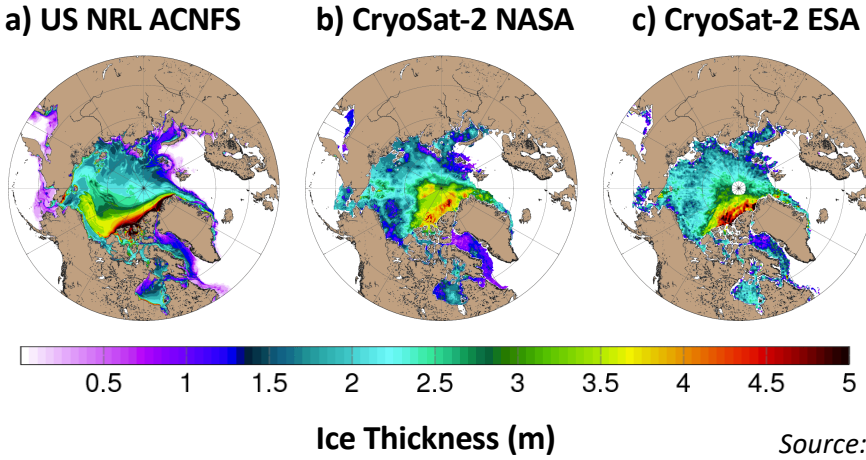


Adapted from Sallila et al., 2019

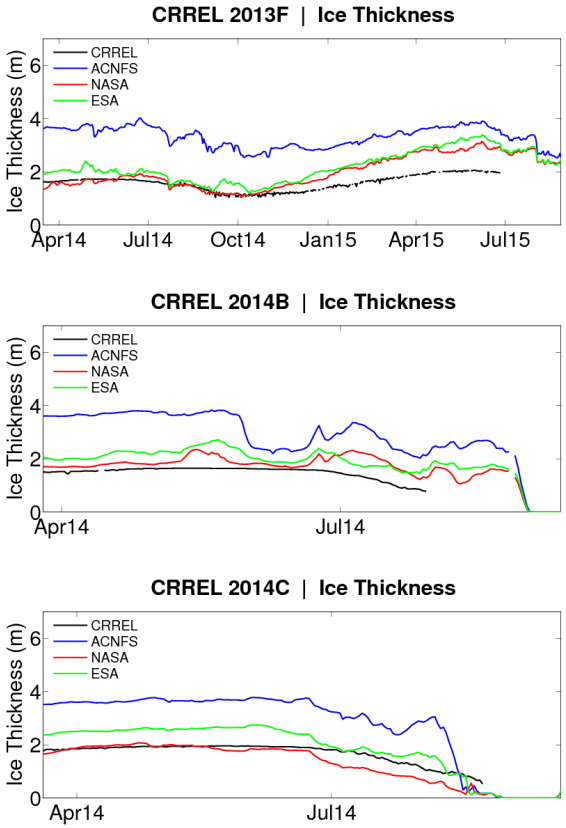
Utilizing CryoSat-2 Sea Ice Thickness to Initialize a Coupled Ice-Ocean Modeling System to improve sea ice forecast at US Naval Research Lab.

- US Naval Research Laboratory (NRL) Arctic Cap Nowcast/Forecast System (ACNFS) comprises the CICE sea ice model coupled with the HYCOM ocean model
- **ACNFS control run (blue)** was compared to two experimental model runs where ACNFS was ***initialized*** with the **ESA CryoSat-2 sea ice thickness product (green)**, and with the **NASA CryoSat-2 sea ice thickness product (red)**.
- Modeled sea ice thickness predictions were compared with

  direct measurements collected by **CRREL Ice Mass Balance Buoys (black)**



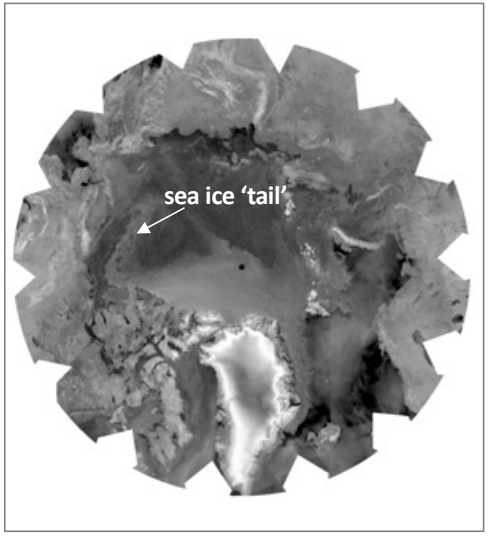
Source: Allard et al., 2018



Result: improved ice thickness prediction by ~ 2 m by using CryoSat-2 sea ice thickness in US Navy model

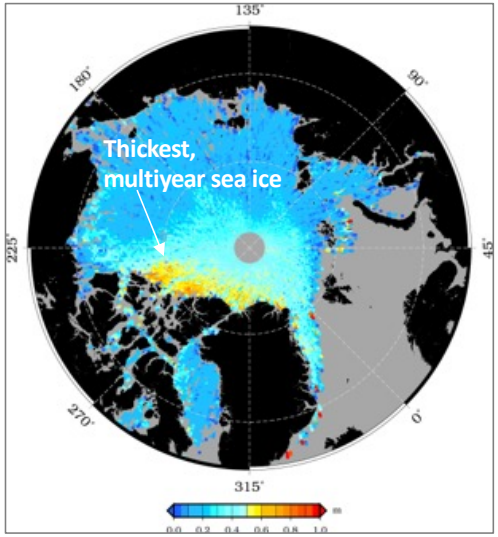
Arctic Sea Ice Conditions in Winter 2018

ASCAT MetOp-A
Normalized Radar Cross Section (NRCS)

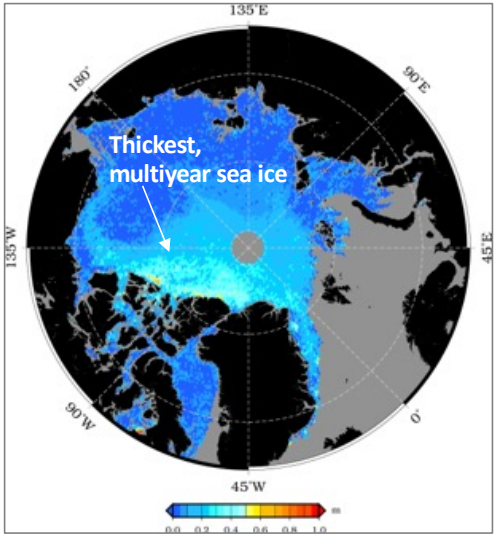


NOAA/SOCD
Sea Ice Mode Mask

NASA ICESat-2
(Laser) Sea Ice Freeboard



ESA CryoSat-2
(Radar) Sea Ice Freeboard



- **Multi sensor observations** of Arctic sea ice in December 2018, show extensive "tail" of thicker, multiyear sea ice in the Beaufort Sea.
- **Daily (NRT, 1 d latency) ASCAT NRCS, and derived Sea Ice Products**: ftp://ftp.star.nesdis.noaa.gov/pub/socd/lsa/SeaIceProducts/ASCAT/
- **Daily visualizations of ASCAT NRCS and Sea Ice Mode masks**: https://www.star.nesdis.noaa.gov/sod/lsa/SeaIce/DataProducts/products_SeaIce.php#
- **NASA ICESat-2:** Data are now publicly available at NSIDC! https://nsidc.org/data/icesat-2

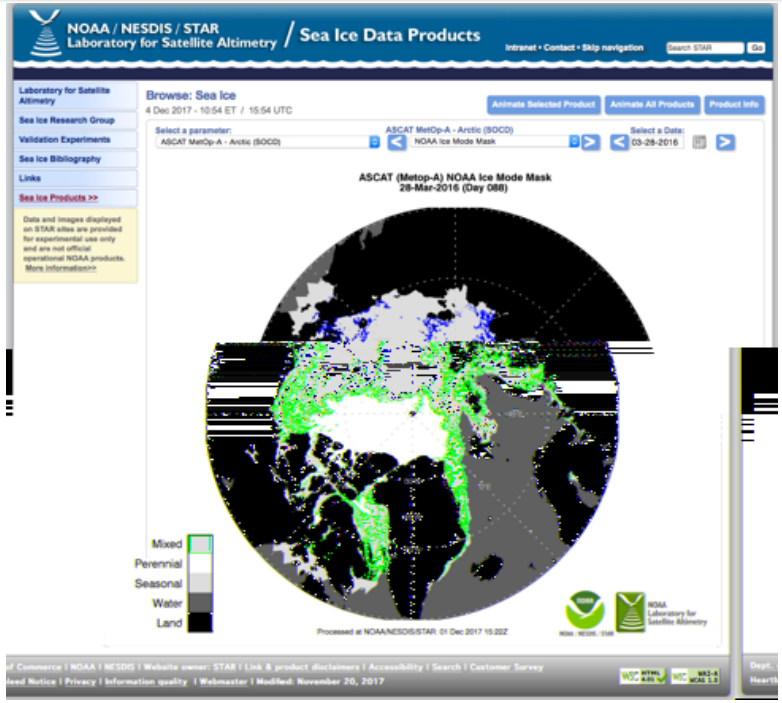
Source: S. L. Farrell, 2019

Airborne (2-D) Sea Ice Products

- Pressure Ridge Sail Height
- Surface Roughness
- Snow depth on sea ice
- Sea ice freeboard
- Sea ice thickness

Satellite (gridded) Sea Ice Products

- ASCAT sea ice type mask
- ASCAT 10-day backscatter variability
- ASCAT daily normalized radar cross-sections
- VIIRS & GCOM (AMSR-2) Ice Concentration
- VIIRS & GCOM (AMSR-2) Ice Surface Temperature



LSA sea ice team – products website

Web Link:
https://www.star.nesdis.noaa.gov/sod/lsa/SeaIce/DataProducts/products_SeaIce.php

FTP Data Access Link:
ftp://ftp.star.nesdis.noaa.gov/pub/socd/lsa/SeaIceProducts/

PolarWatch is a new joint venture between the Center for Satellite Applications and Research (STAR) within NESDIS and the West Coast Regional Node (WCRN) of CoastWatch which is based out of the SouthWest Fisheries Science Center of NMFS.

PolarWatch started in the Fall of 2016 and will provide a user-driven information portal for accessing multi-sensor physical and biological ocean remote sensing data in support of a broad suite of applications and research in the Arctic and Antarctic.

Sinead Farrell
Project Scientist
sinead.farrell@noaa.gov

Cara Wilson
Principal Investigator
cara.wilson@noaa.gov

Jennifer Patterson Sevadjian
Operations Manager
jennifer.patterson@noaa.gov

NOAA PolarWatch

polarwatch.noaa.gov

Increasing Access to NOAA's Ocean Remotes Sensing Satellite Data Products for the Arctic and Southern Oceans

NOAA NMFS SWFSC: Cara Wilson, Dale Robinson, Jennifer Sevadjian *in partnership with* **NOAA NESDIS STAR SOCD**: Paul DiGiacomo, Sinead Farrell, Veronica Lance

- **PolarWatch delivers multi-sensor physical and biological ocean remote sensing data to diverse end-users within NOAA, and across disciplines, in support of broad applications in the Arctic and Southern Oceans, to advance the priorities outlined in NOAA's Arctic Action Plan**
- **Goals: enable data discovery, easy access, and broader usage of high-latitude satellite data products, especially those developed by NOAA/NESDIS/STAR/SOCD**
- **Targeted Users across NOAA Line Offices**:
  Alaska Fisheries Science Center, NMFS/SWFSC Antarctic Ecosystem Research Division, NWS/NCEP Environmental Modeling Center (EMC), OAR Earth System Research Laboratory (ESRL), National Ice Center