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
Sea Ice in the Climate System

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
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

- 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

Photo Credit: Sinéad L. Farrell, University of Maryland
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

- March ice loss: -2.7% per decade
- September ice loss: -13.2% per decade

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

*Source: NASA/Greg Fiske, Woods Hole Research Center*
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!

- 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.

*Source: S. L. Farrell, 2019*
Evolution of High-Latitude Altimetry

- **Polar Orbit**
  - **88°**
    - 369 days
    - Past
  - **88°**
    - 91 days
    - Operating
  - **86°**
    - 91 days
    - Approved
  - **81.5°**
    - 35 days
    - Proposed
  - **81.5°**
    - 27 days
    - Approved

- **Partial Polar Cover**
  - **81.5°**
    - 27 days
    - Repeat
  - **81.5°**
    - 35 days
    - Repeat
  - **86°**
    - 91 days
    - Repeat

- **Satellites**
  - **ERS-1 (ESA)**
  - **ERS-2 (ESA)**
  - **ENVISAT (ESA)**
  - **SARAL/AltKa (Fr/It)**
  - **ICESat (NASA)**
  - **IceBridge (NASA Airborne)**
  - **ICESat-2 (NASA)**
  - **CryoSat-2 (ESA)**
  - **Sentinel-3A (EU)**
  - **Sentinel-3B (EU)**
  - **Sentinel-3C (EU)**
  - **Sentinel-3D (EU)**

Source: S. L. Farrell, 2019

NOAA NESDIS STAR Science Seminar

Sinéad L. Farrell

September 2019
NASA successfully launched ICESat-2 from Vandenberg Air Force Base, CA, on 15<sup>th</sup> 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

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

**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($\sigma_0$) 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 $\sigma_0$ due to motion of Marginal Ice Zone (MIZ)

- High-resolution data set (4.45 km) \(\rightarrow\) consistent with resolution of altimetry observations

- Small pole hole \(\rightarrow\) MYI mask area extends to 89.5 °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

<table>
<thead>
<tr>
<th>Year</th>
<th># of Sea Ice Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>5</td>
</tr>
<tr>
<td>2010</td>
<td>8</td>
</tr>
<tr>
<td>2011</td>
<td>9</td>
</tr>
<tr>
<td>2012</td>
<td>14</td>
</tr>
<tr>
<td>2013</td>
<td>10</td>
</tr>
<tr>
<td>2014</td>
<td>15</td>
</tr>
<tr>
<td>2015</td>
<td>10</td>
</tr>
<tr>
<td>2016</td>
<td>6</td>
</tr>
<tr>
<td>2017</td>
<td>13</td>
</tr>
<tr>
<td>2018</td>
<td>8</td>
</tr>
<tr>
<td>2019</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>104</strong></td>
</tr>
</tbody>
</table>

Source: S. L. Farrell, 2019
A decade of strong NOAA – NASA – ESA collaboration

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

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

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

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

Source: S. L. Farrell, 2019
Sea Ice Thickness Retrieval

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
- $\rho_i$ = ice density
- $\rho_s$ = snow density
- $\rho_w$ = sea water density

Source: Farrell et al. (2014)
Between the ICESat and CryoSat-2 observation periods the winter volume declined by \( \approx 1500 \) km\(^3\)

Source: Laxon et al., GRL, 2013
CryoSat-2 Tracks Seasonal and Inter-annual Change

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).

![](image1.png)

**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**

- **Multi sensor observations** of Arctic sea ice in December 2018, show extensive “tail” of thicker, multiyear sea ice in the Beaufort Sea.
- **NASA ICESat-2**: Data are now publicly available at NSIDC! [https://nsidc.org/data/icesat-2](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

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
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, Sinéad 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 (NIC), NOAA/NESDIS/STAR, and the NOAA Climate Program Office (CPO).

- **Data Curation:**
  ✓ Arctic and Antarctic coverage
  ✓ Near-real-time data and science quality data products
  ✓ Full temporal range of the dataset
  ✓ Initial datasets include: sea ice concentration, sea surface height, salinity, sea surface temperature, ocean surface winds, ocean color

- **Data Discovery and Access:**
  An interface for ‘one stop shopping’ provides a suite of satellite data products from a variety of sensors and data providers (Fig. 1, right). Provides data preview/access pages with full dataset details and background information. Data previews available in Arctic, Antarctic, and global projections. Customized downloads by area, date, parameter, and file format.

Fig 1. PolarWatch catalogue interface (beta) to search and filter satellite datasets. Highlights data availability, in polarstereographic projection. Additional data products are available online.