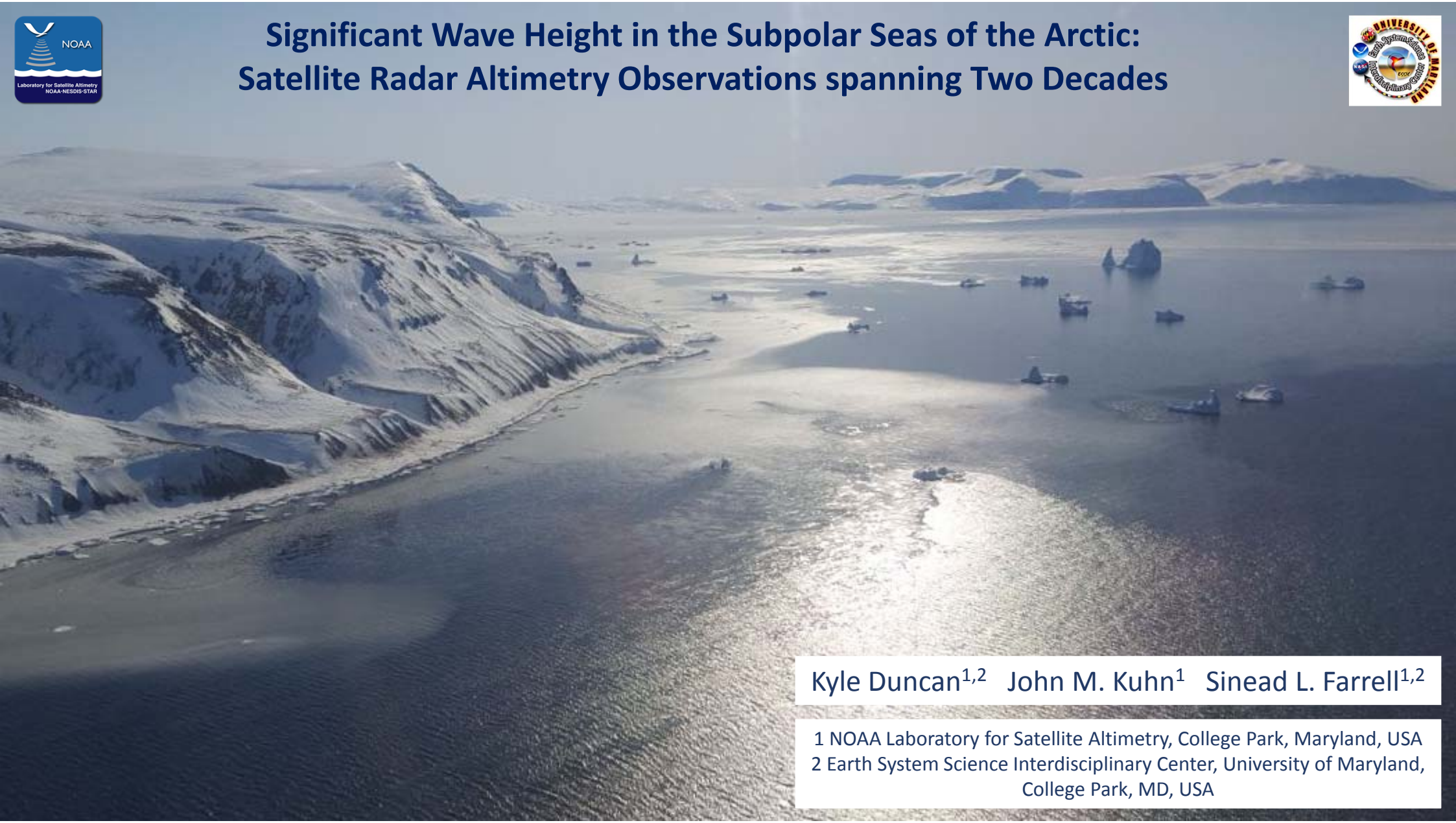
Significant Wave Height in the Subpolar Seas of the Arctic: Satellite Radar Altimetry Observations spanning Two Decades



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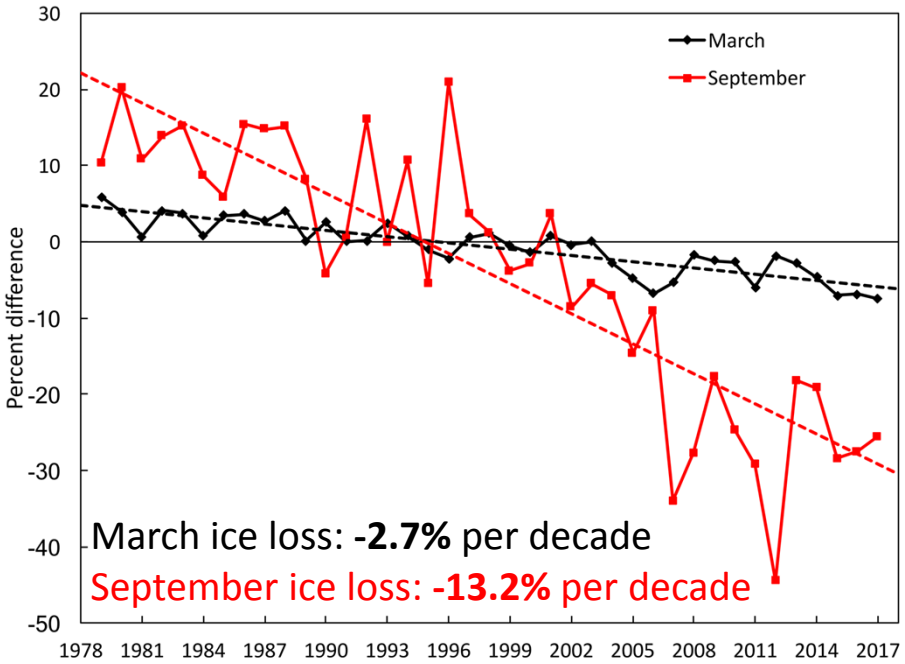
Changing Characteristics of Arctic Ocean & Subpolar Seas

- Sea ice in the Arctic Ocean is **declining** in extent, at sea ice margins, retreating from the subpolar seas
- Sea ice acts as a **barrier** between the ocean and atmosphere, and dampens the effects of ocean waves
- Exposure of new open ocean areas to impact of **winter storms**
- Potential consequences for marine activities in the subpolar seas such as fisheries and transportation, coastal inundation in low-lying regions

Extent anomalies (%), relative to 1981-2010



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

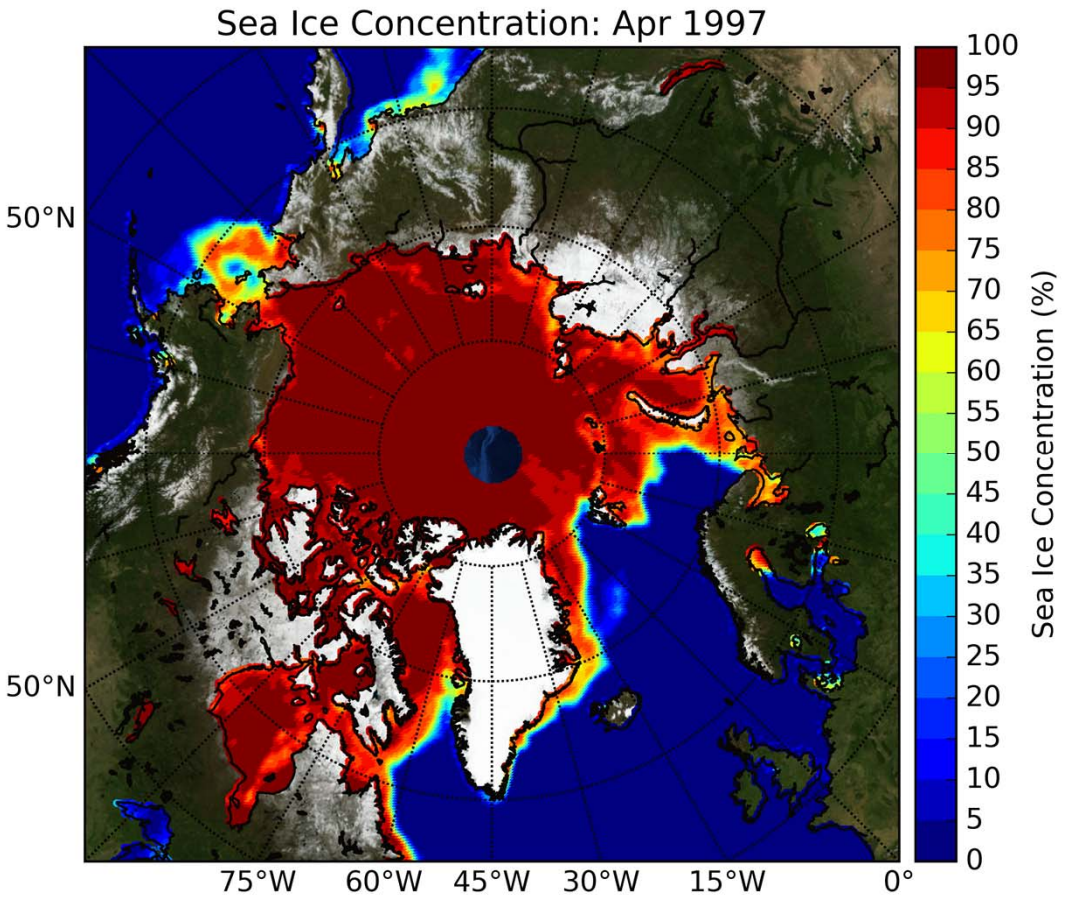
Changing Characteristics of Arctic Ocean & Subpolar Seas

Questions:

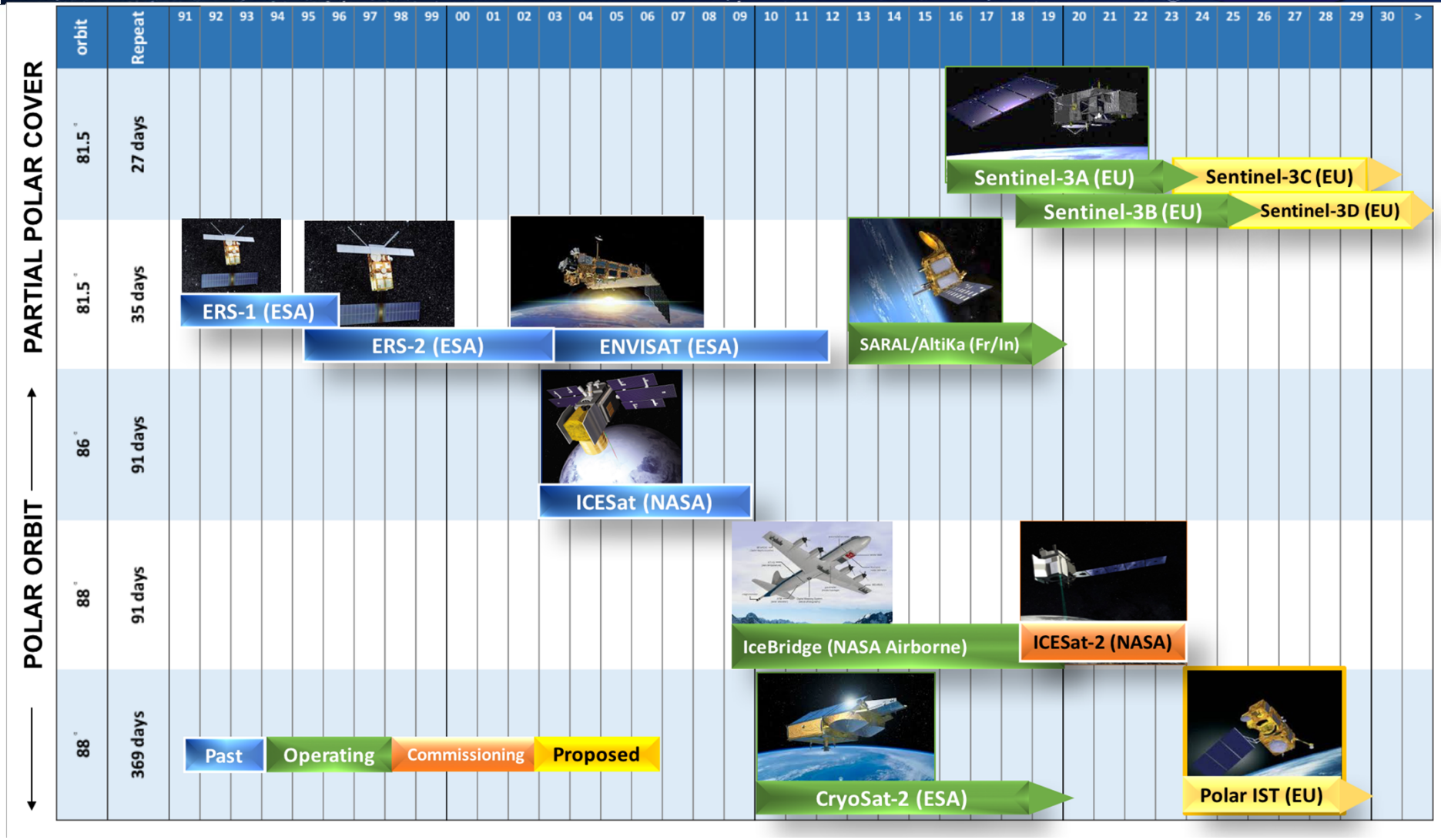
- As ice retreats, and fetch increases, has **wave height increased** in subpolar seas that were traditionally ice-covered during winter?
- Have **characteristics of sub-polar northern hemisphere seas** changed as the sea ice retreats?
- Have these regions become **stormier**?
- How **frequent** are instances of phenomenal wave heights?

Overall Goals:

- Create a climatology of regional characteristics that can be used for **future planning**.
- Provide NRT tracking to enable **timely & informed decisions**.



High Latitude Altimetry



Multi-decadal record of change

Study Period: Data analysis conducted over a **24-year** time period : **1995 – 2018**

- ERS-2 (1995-05-03 – 2011-07-04)
- Jason-1 (2002-01-15 – 2013-06-21)
- Envisat (2002-05-14 – 2012-04-08)
- Jason-2 (2008-07-04 – 2018-07-29)
- CryoSat-2 (2010-07-14 – 2018-07-29)
- SARAL (2013-03-14 – 2018-07-29)
- Jason-3 (2016-02-12 – 2018-07-29)
- Sentinel-3A (2016-03-01 – 2018-07-29)

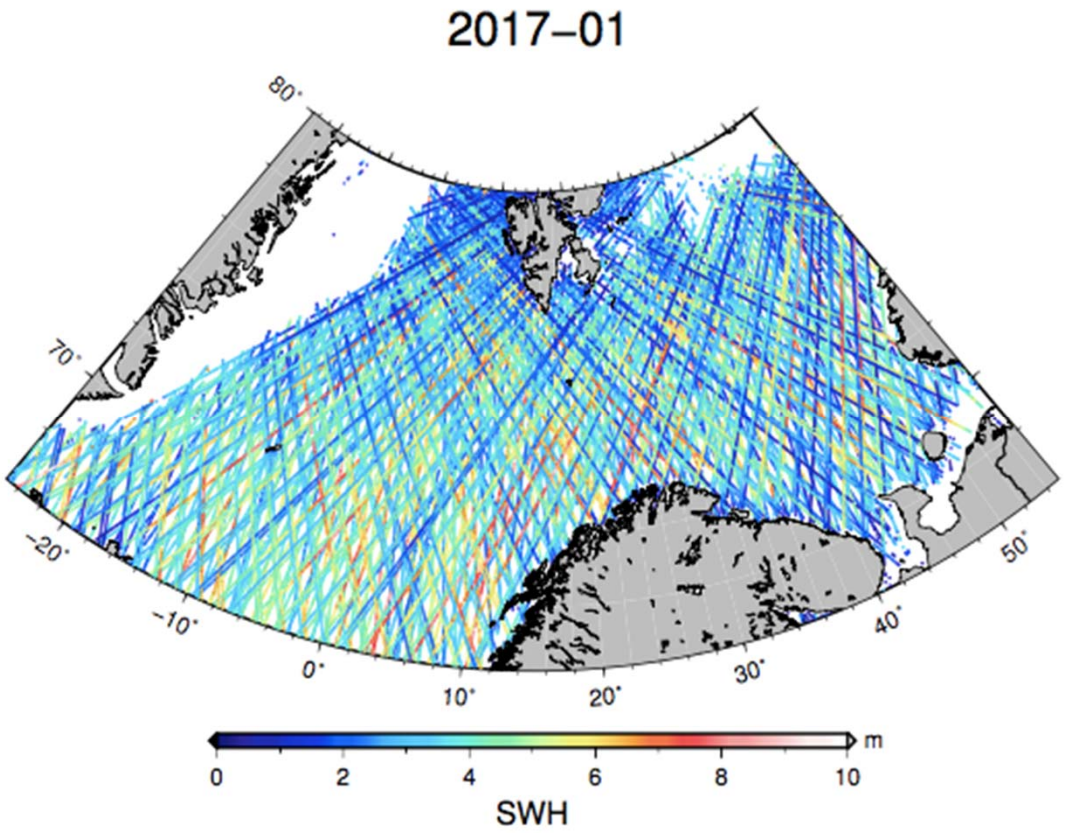
- We assess **significant wave height (SWH)**, as derived from leading edge slope of radar altimeter waveforms
- All valid SWH measurements are analyzed, but limited to 99th percentile, and anomalous coastal data excluded

Satellite Altimeter Data through RADS

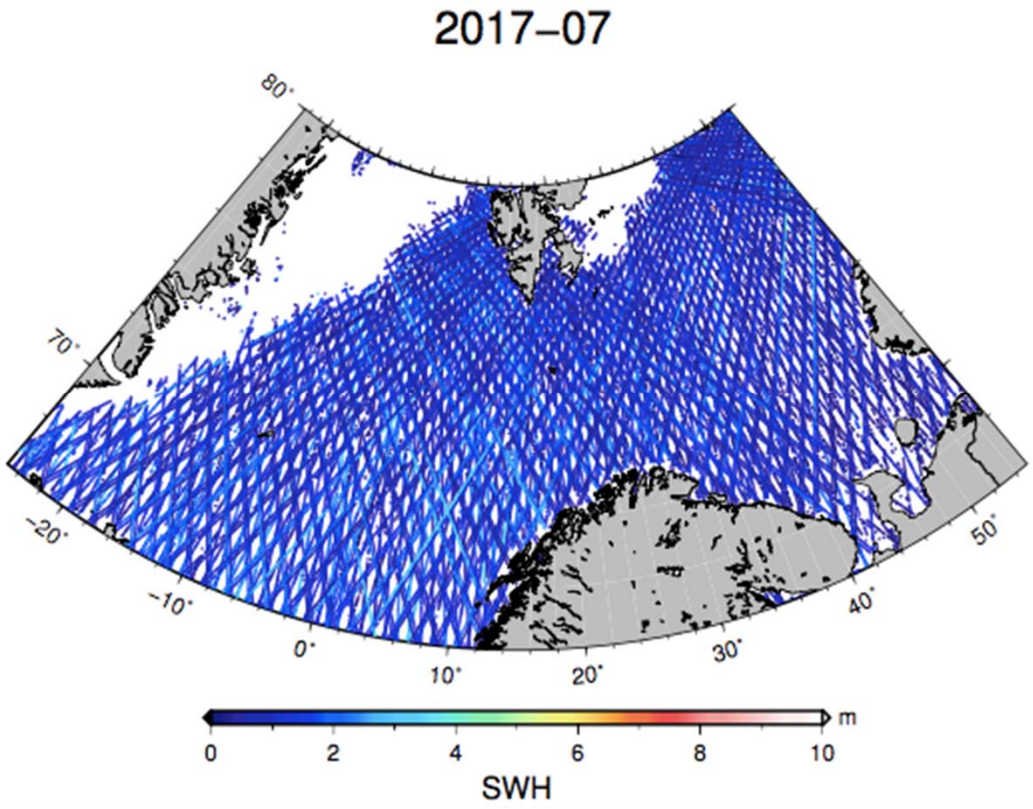
- Data are accessed through the Radar Altimeter Database System (RADS)
- RADS is a partnership between NOAA Laboratory for Satellite Altimetry, the Technical University of Delft and EUMETSAT, as originally created by Remko Scharroo.
- RADS provides a consistent, multi-mission satellite altimeter data record
- Database starts in 1985 with Geosat data
- Continuous data starting in 1991, with ERS-1
- Data available from 1991 - present (including near real time data)
- Further details:
  - https://www.star.nesdis.noaa.gov/sod/lsa/RADS.php
  - https://github.com/remkos/rads

Regional Analysis: Northern North Atlantic

Winter SWH

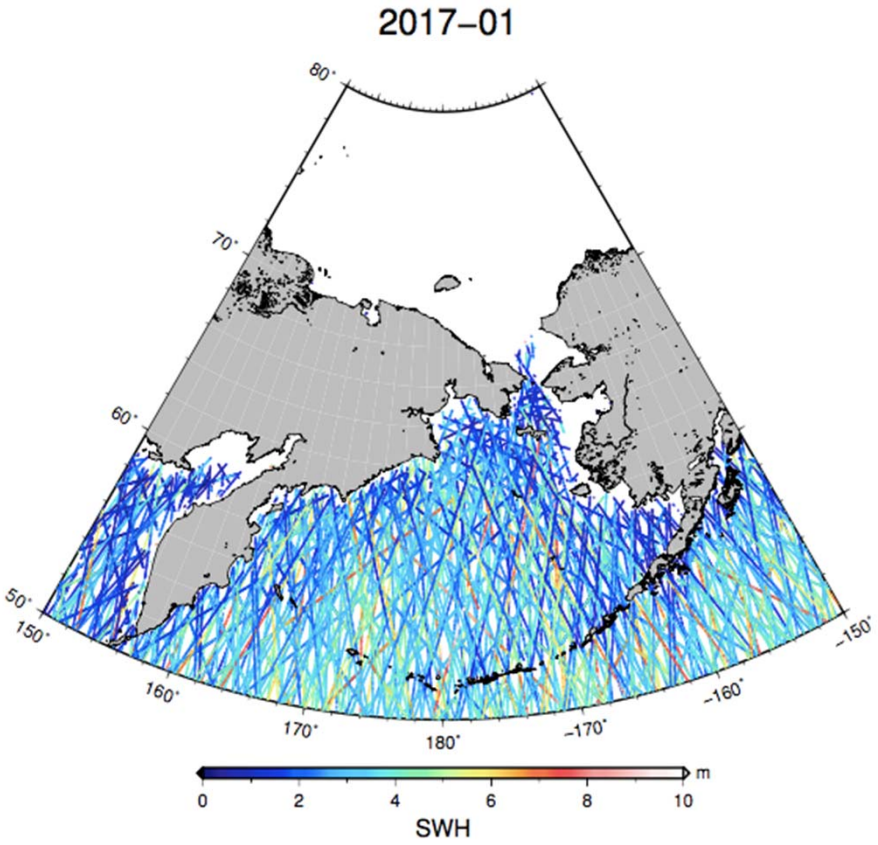


Summer SWH

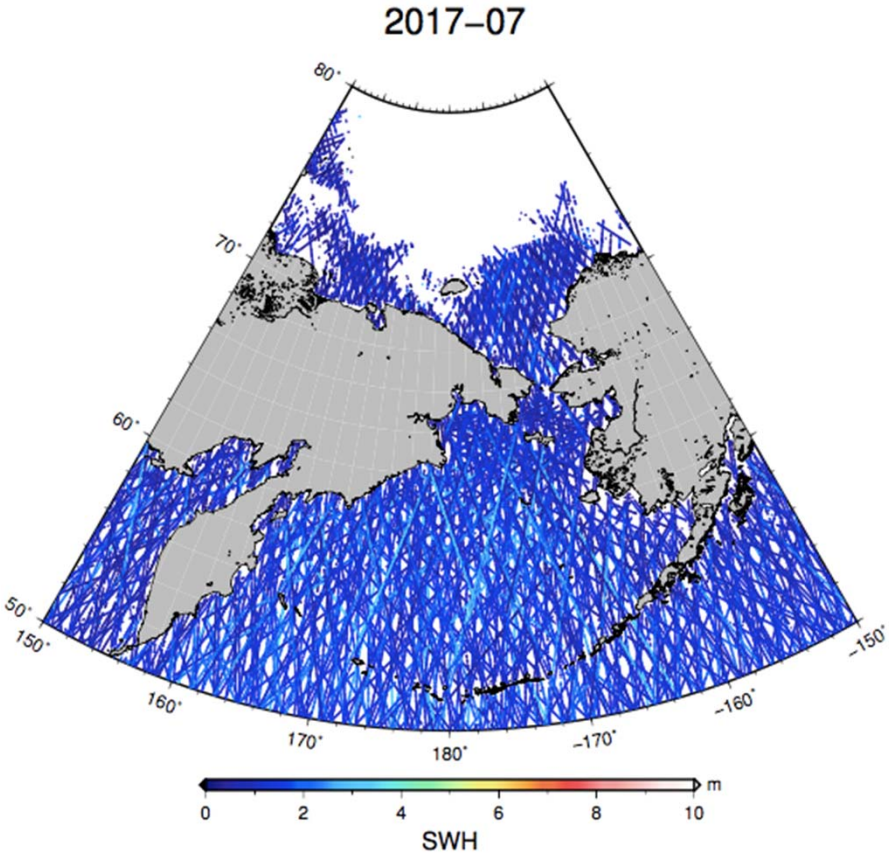


Regional Analysis: Bering Sea

Winter SWH

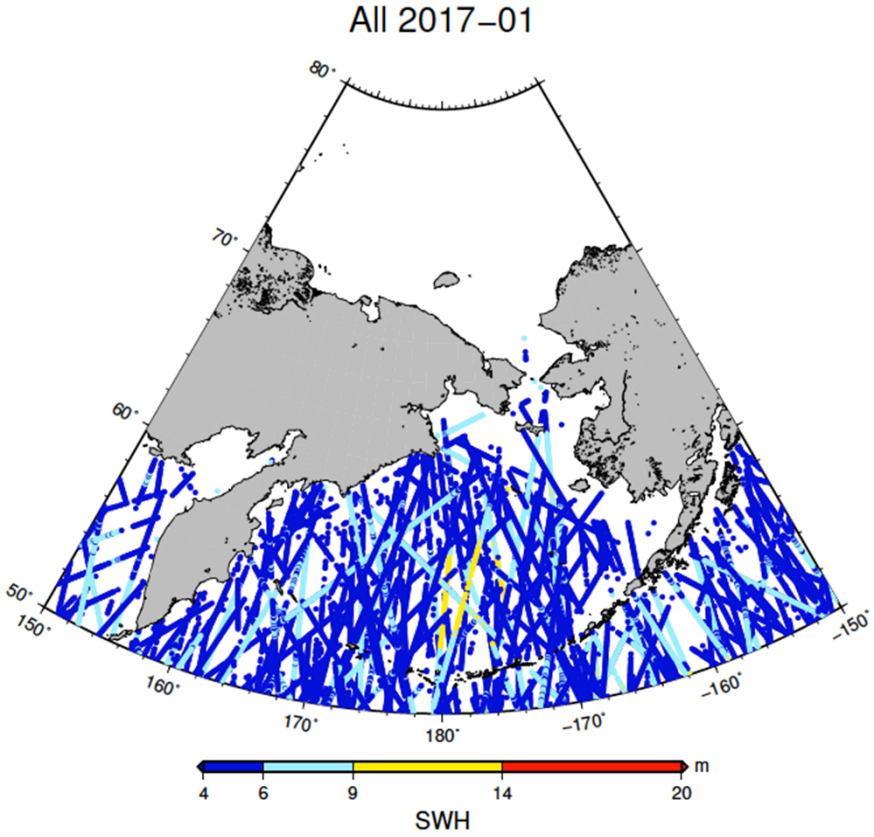


Summer SWH



Regional Analysis: Bering Sea

Winter SWH >= 4 m



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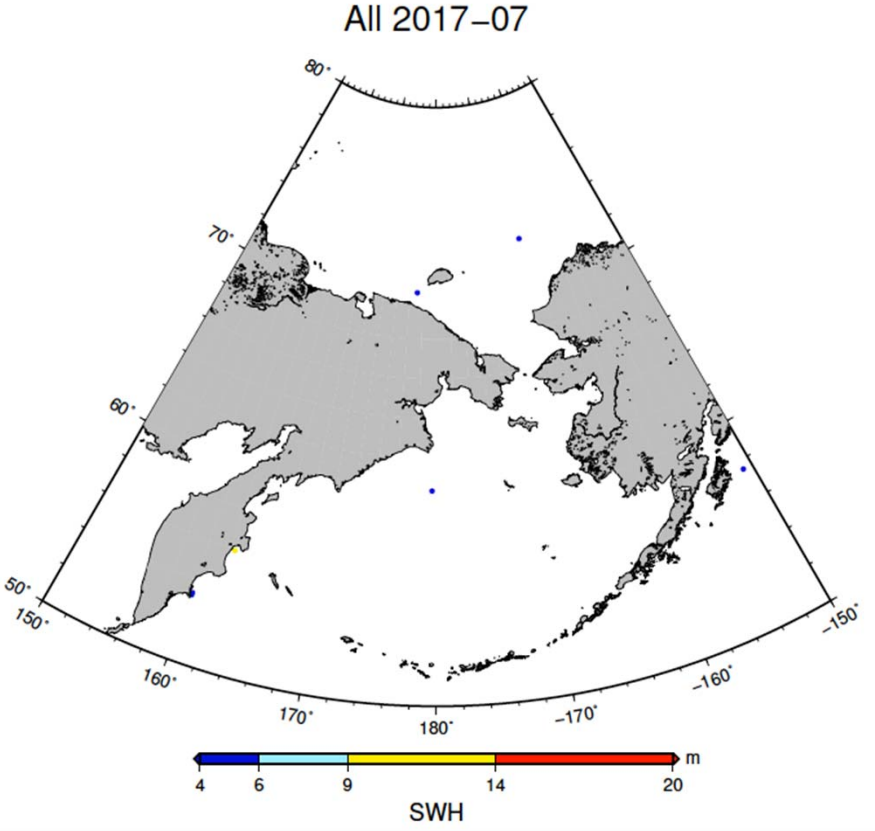
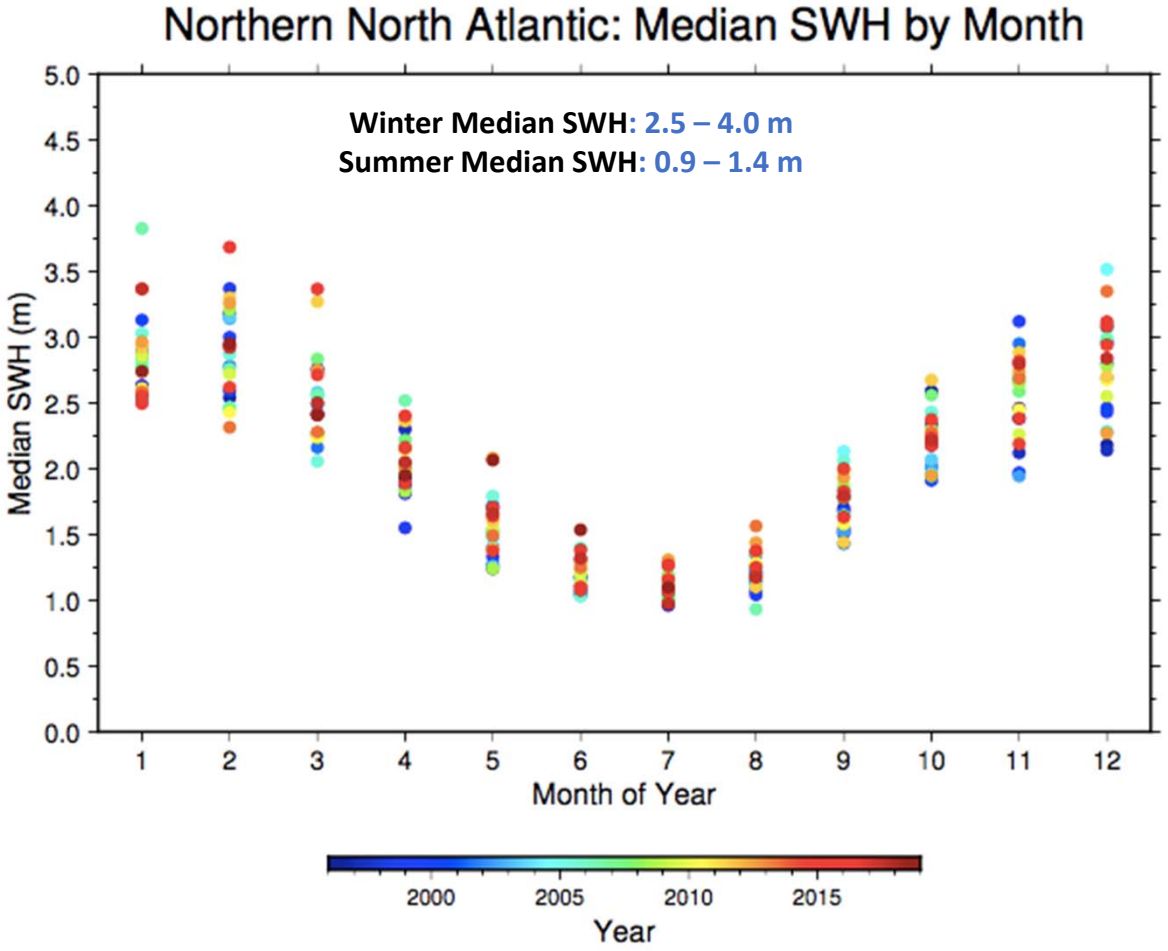


SWH Seasonal Cycle – Northern North Atlantic



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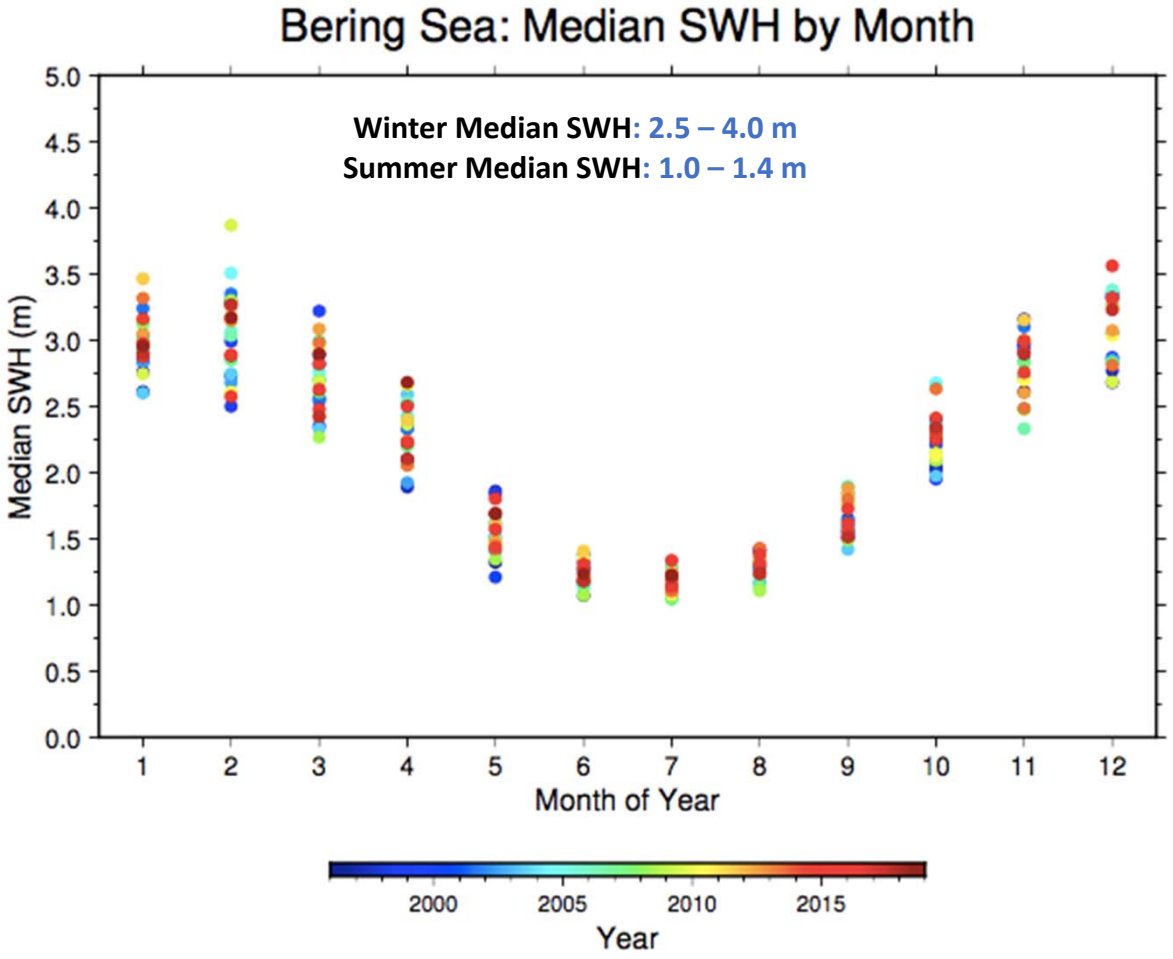
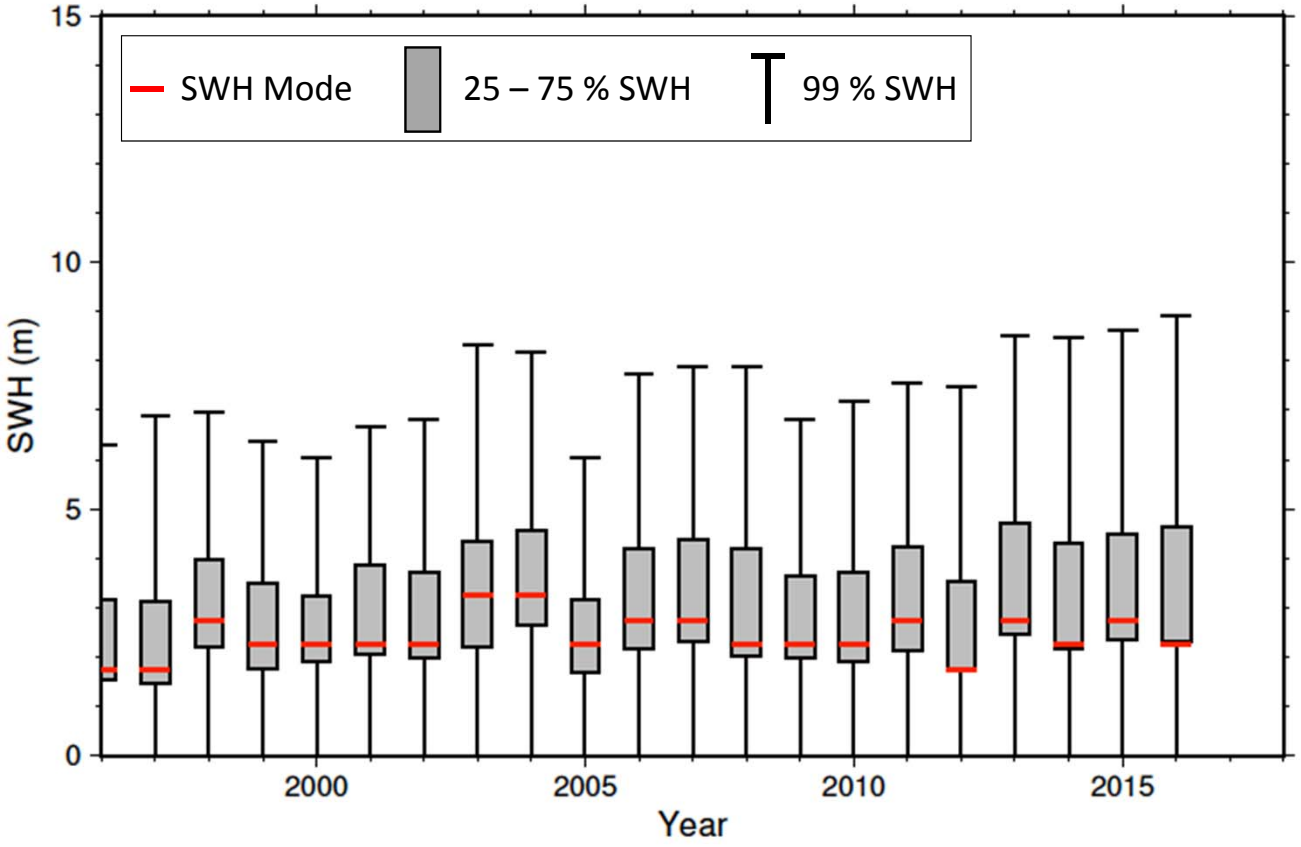


Inter-annual Variability in Winter SWH – Northern North Atlantic

SWH Statistics – Northern North Atlantic – December 1996 - 2016



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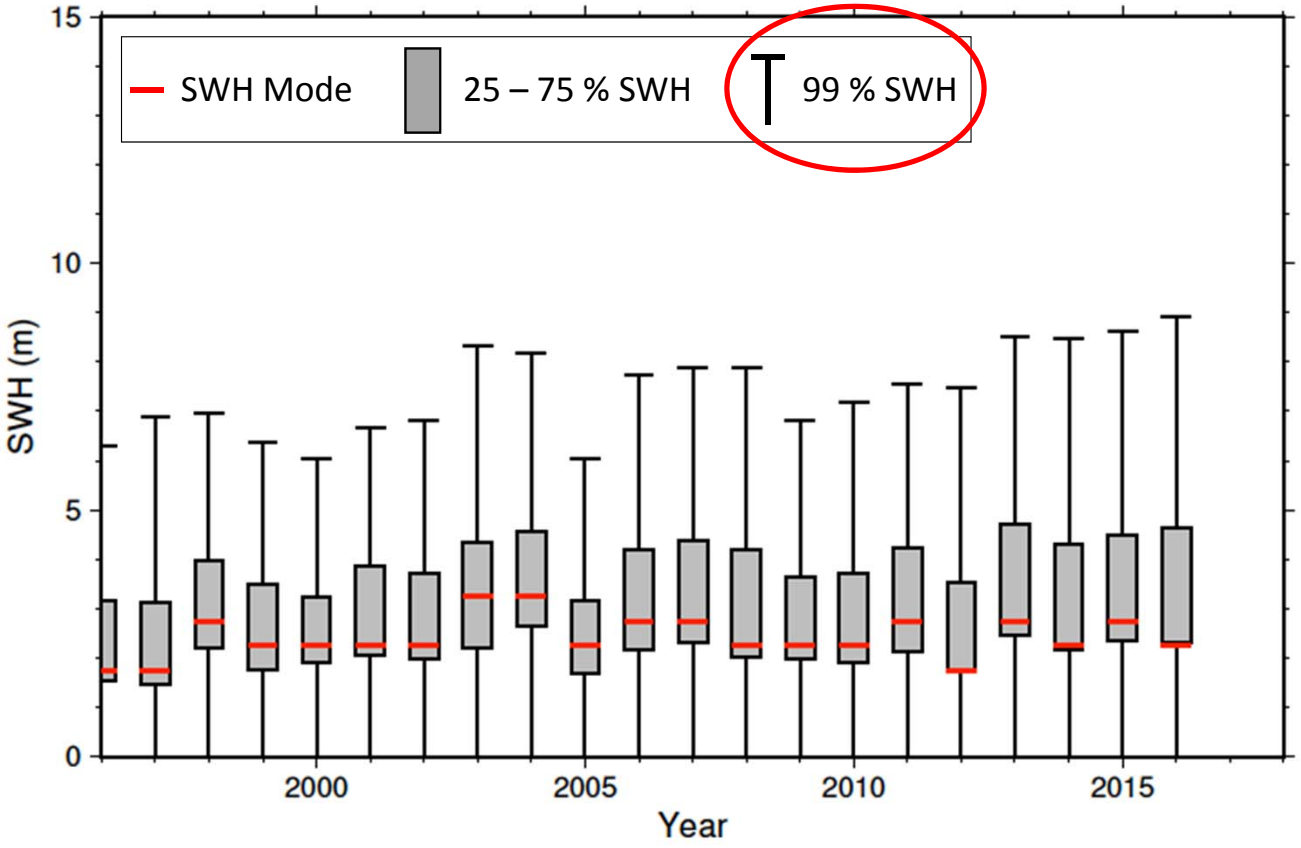

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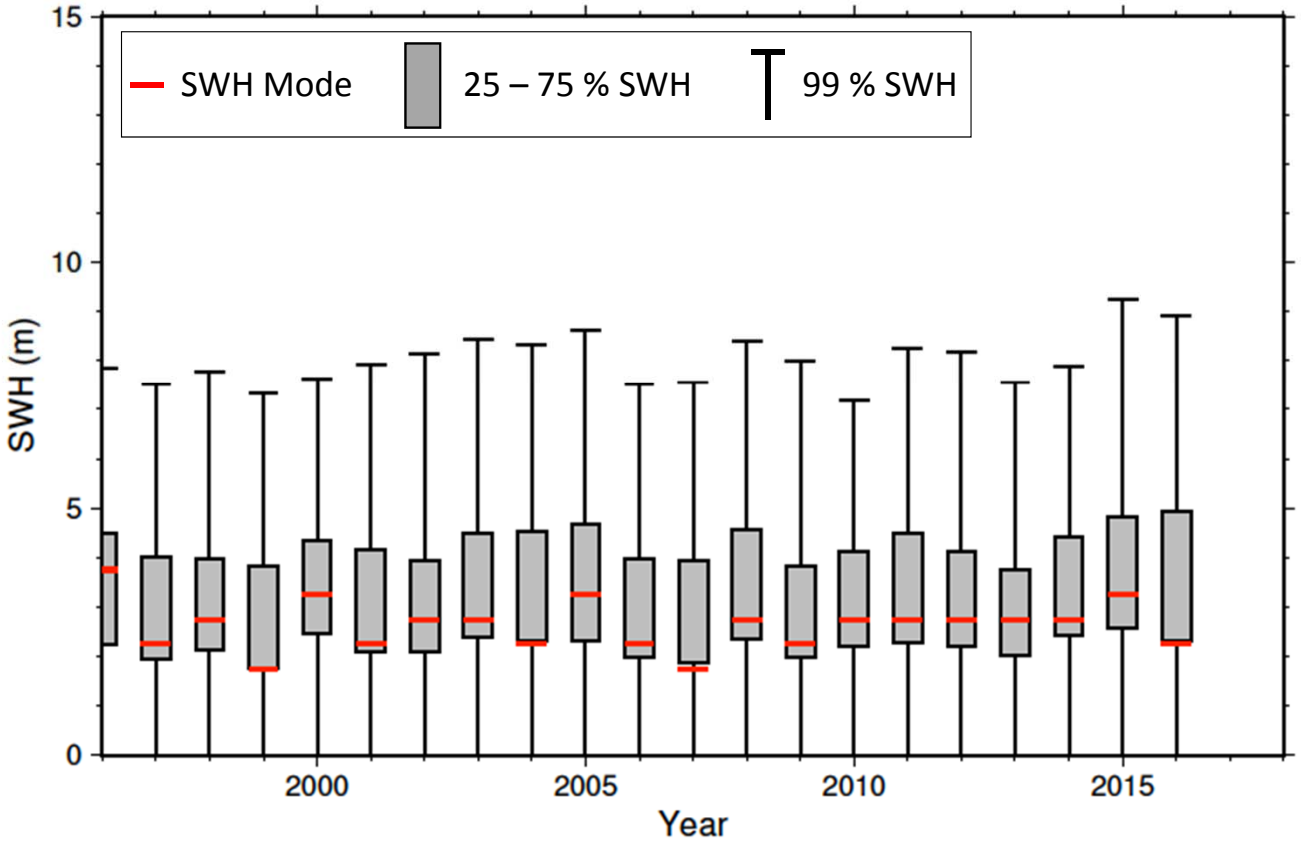

WMO Sea State

World Meteorological Organization (WMO) sea state code (WMO 3700)

WMO Sea State Code	Wave height	Characteristics
0	0 metres (0 ft)	Calm (glassy)
1	0 to 0.1 metres (0.00 to 0.33 ft)	Calm (rippled)
2	0.1 to 0.5 metres (3.9 in to 1 ft 7.7 in)	Smooth (wavelets)
3	0.5 to 1.25 metres (1 ft 8 in to 4 ft 1 in)	Slight
4	1.25 to 2.5 metres (4 ft 1 in to 8 ft 2 in)	Moderate
5	2.5 to 4 metres (8 ft 2 in to 13 ft 1 in)	Rough
6	4 to 6 metres (13 to 20 ft)	Very rough
7	6 to 9 metres (20 to 30 ft)	High
8	9 to 14 metres (30 to 46 ft)	Very high
9	Over 14 metres (46 ft)	Phenomenal

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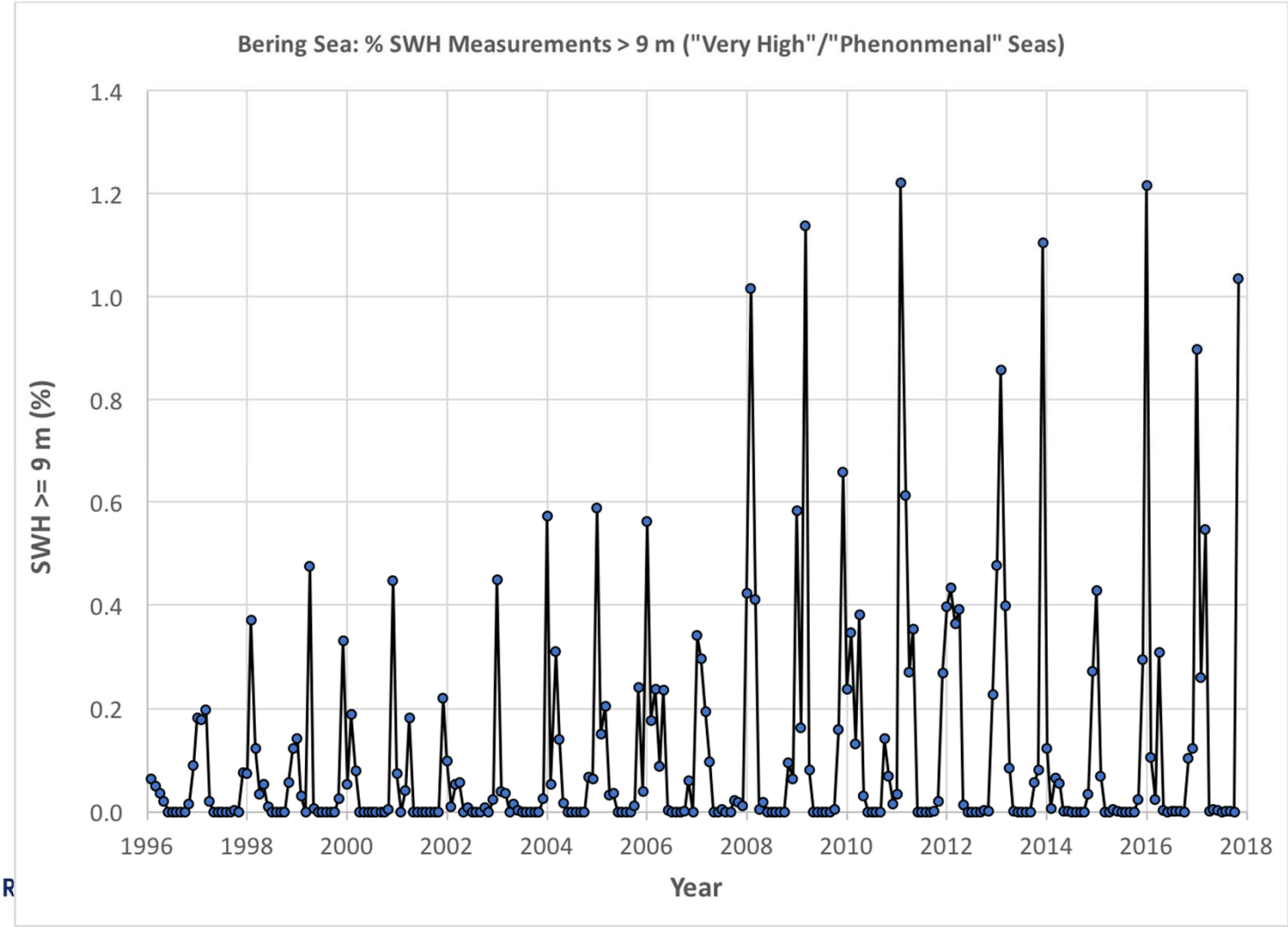
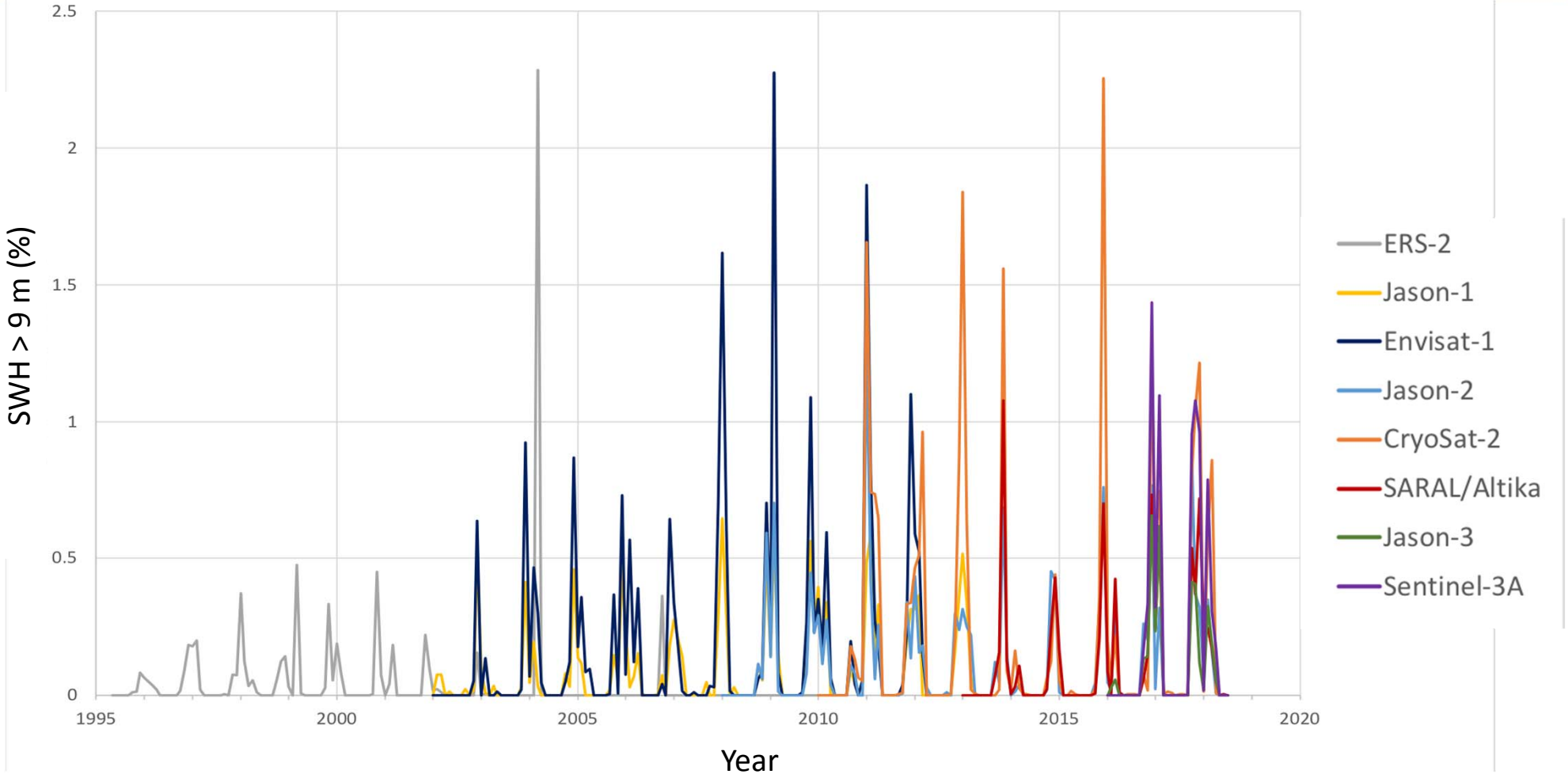
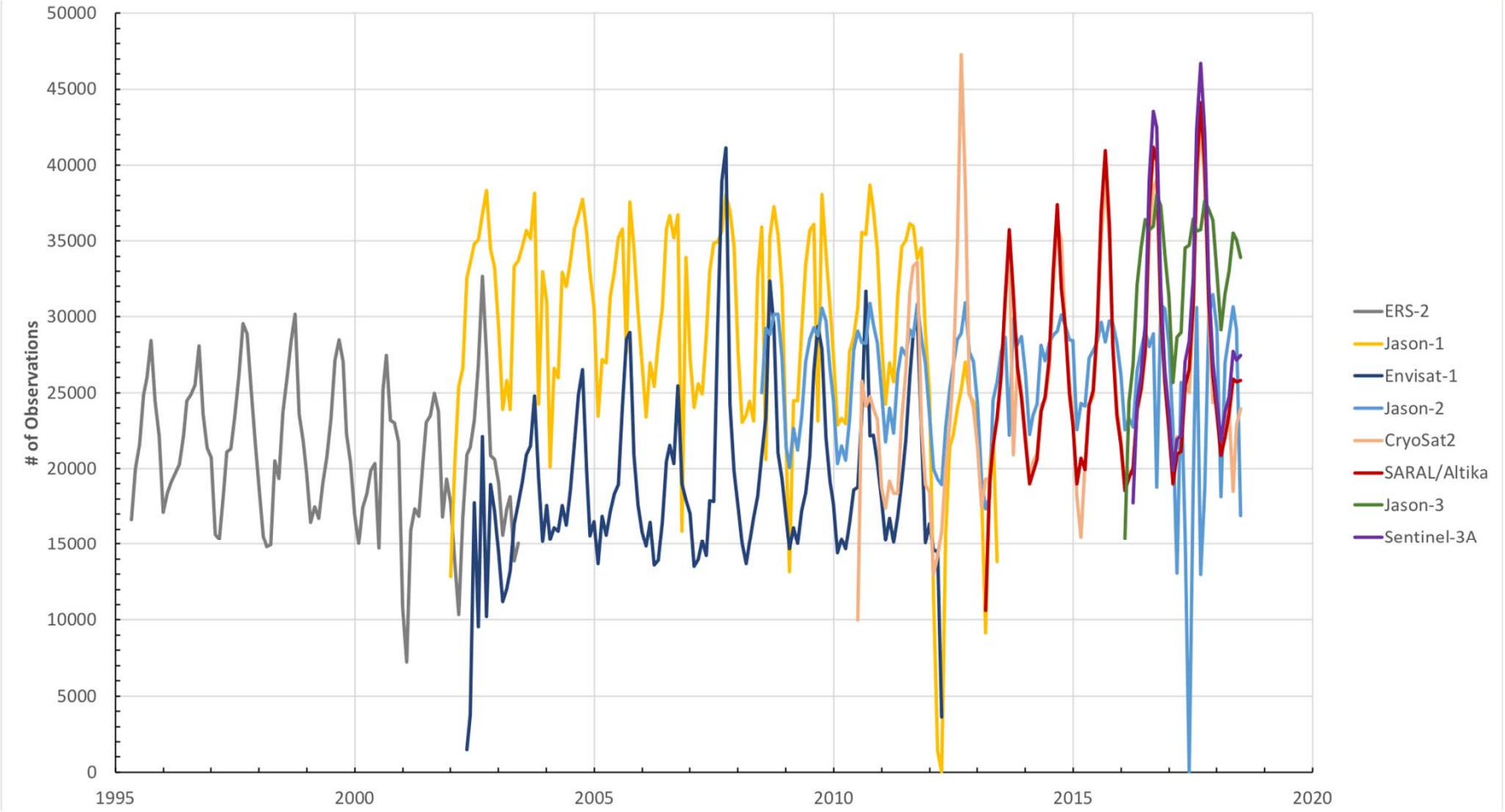
Stormy Seas (SWH > 9m) – Bering Sea



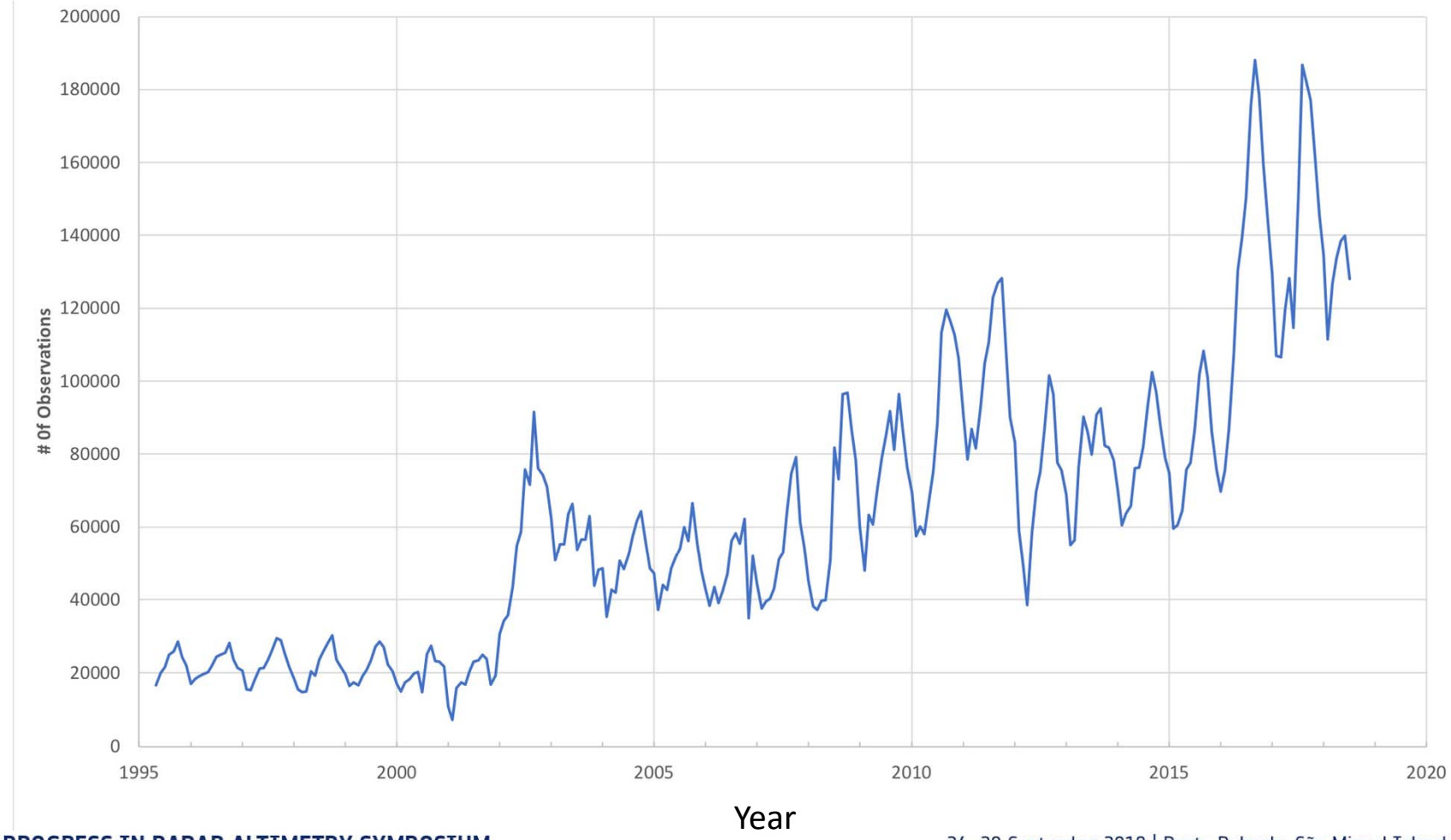
Stormy Seas (SWH > 9m) – Bering Sea



Number of Observations/satellite – Bering Sea



Total Number of Observations – Bering Sea



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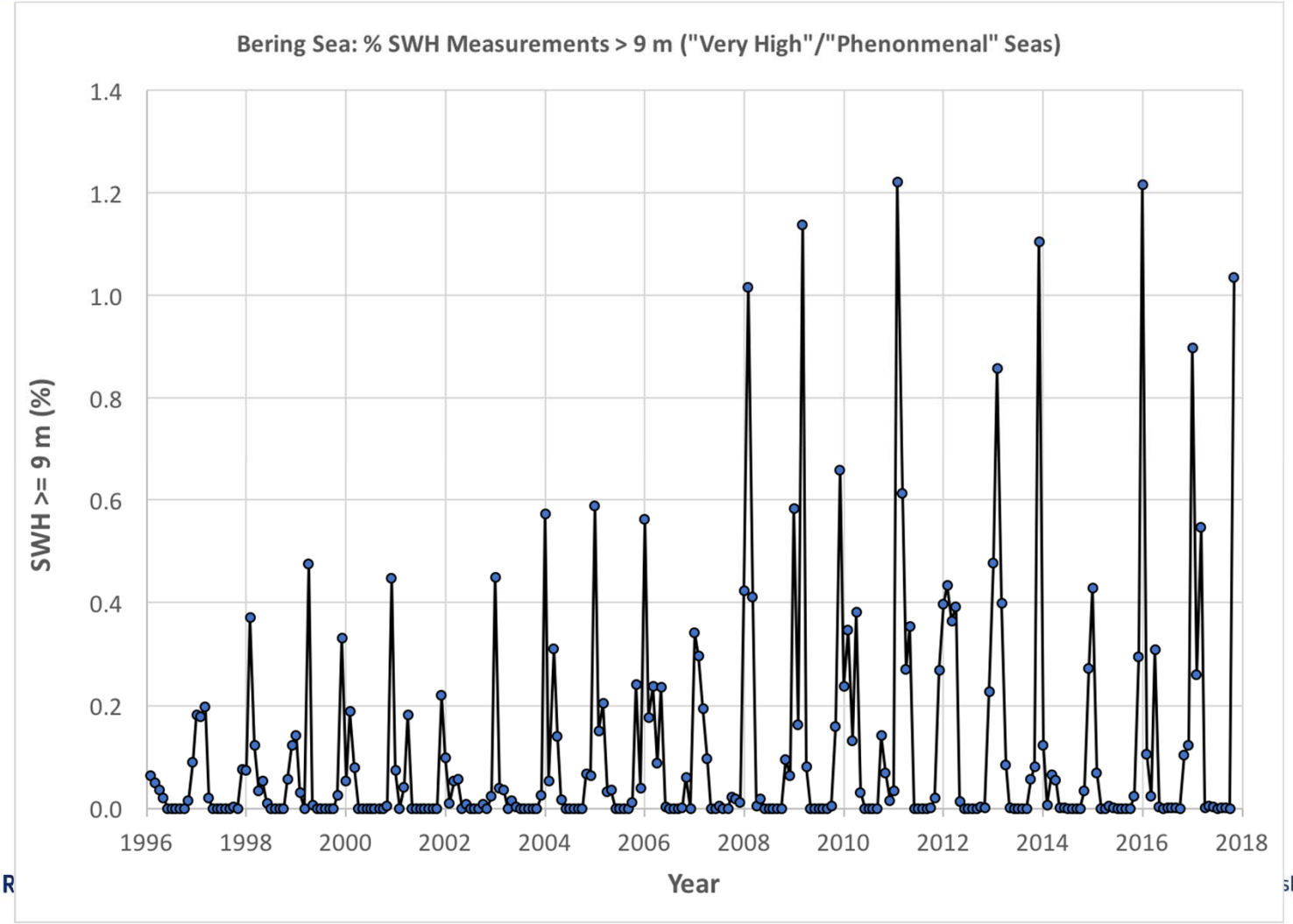
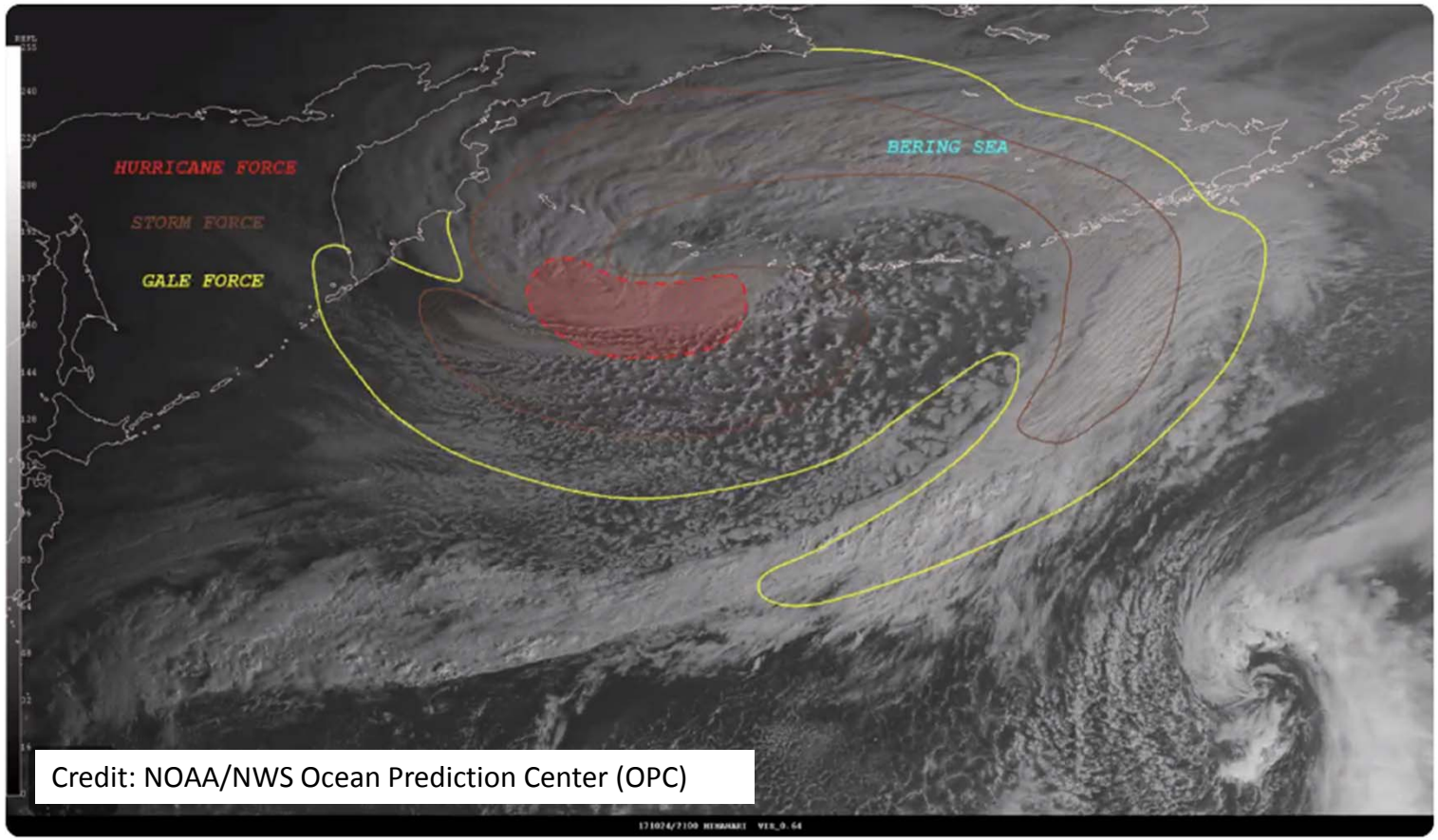


Ex-Typhoon Lan – October 2017

Himawari visible satellite imagery of hurricane force low (937 hPa) in Pacific and Bering Sea



Credit: NOAA/NWS Ocean Prediction Center (OPC)

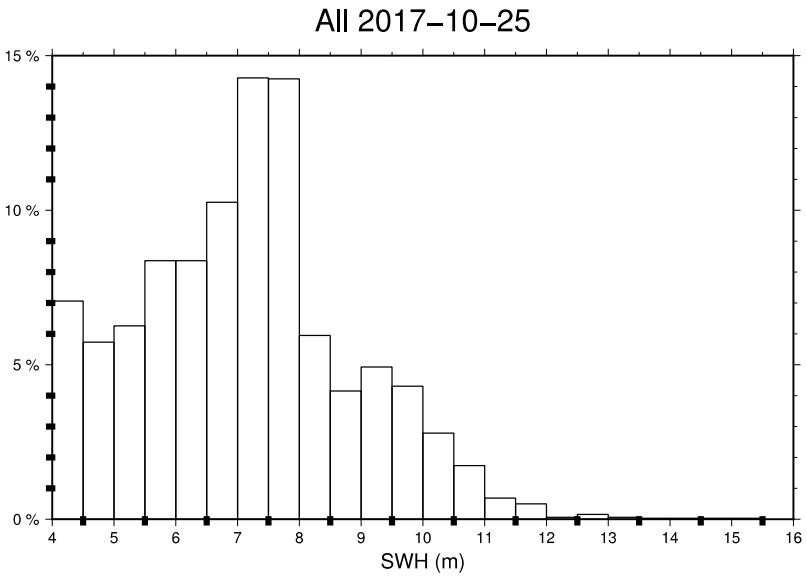
Ex-Typhoon Lan – October 2017

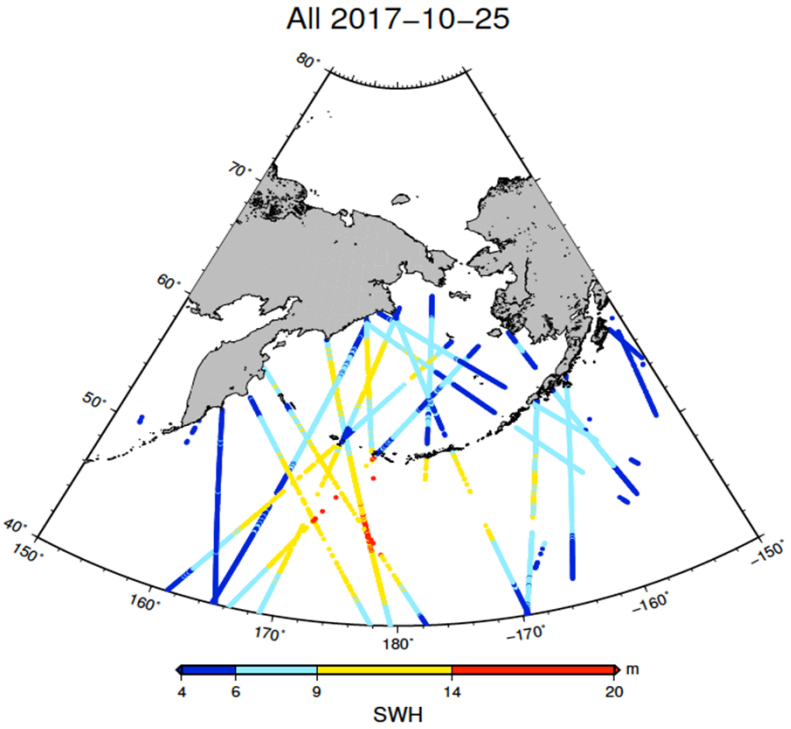
Major Winter Storm October 2017

Bering Sea and south of the Aleutian Islands

All radar altimeter tracks for 25th October 2017

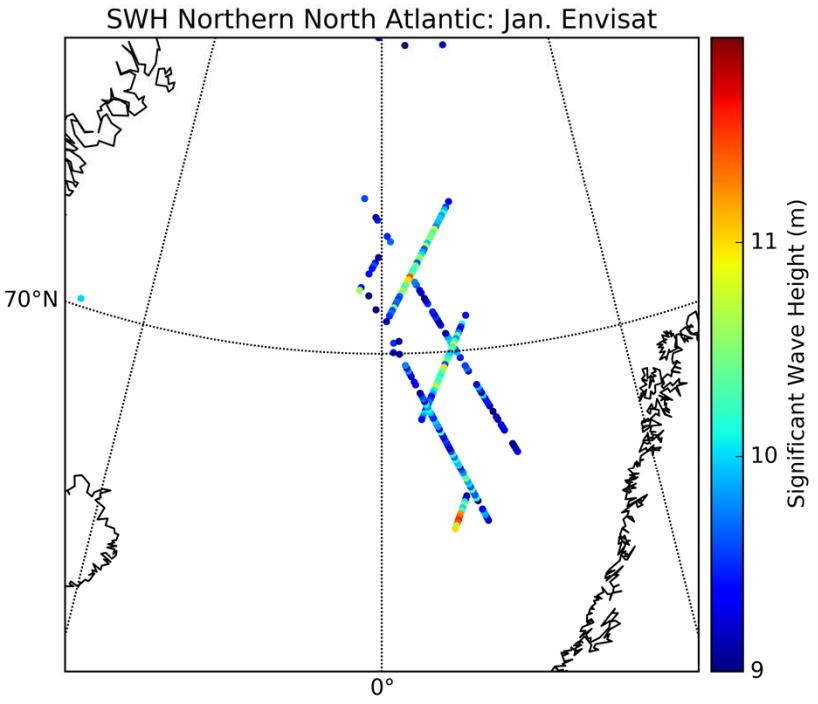
Seas in excess of 9 m, Largest SWH = 17.4 m

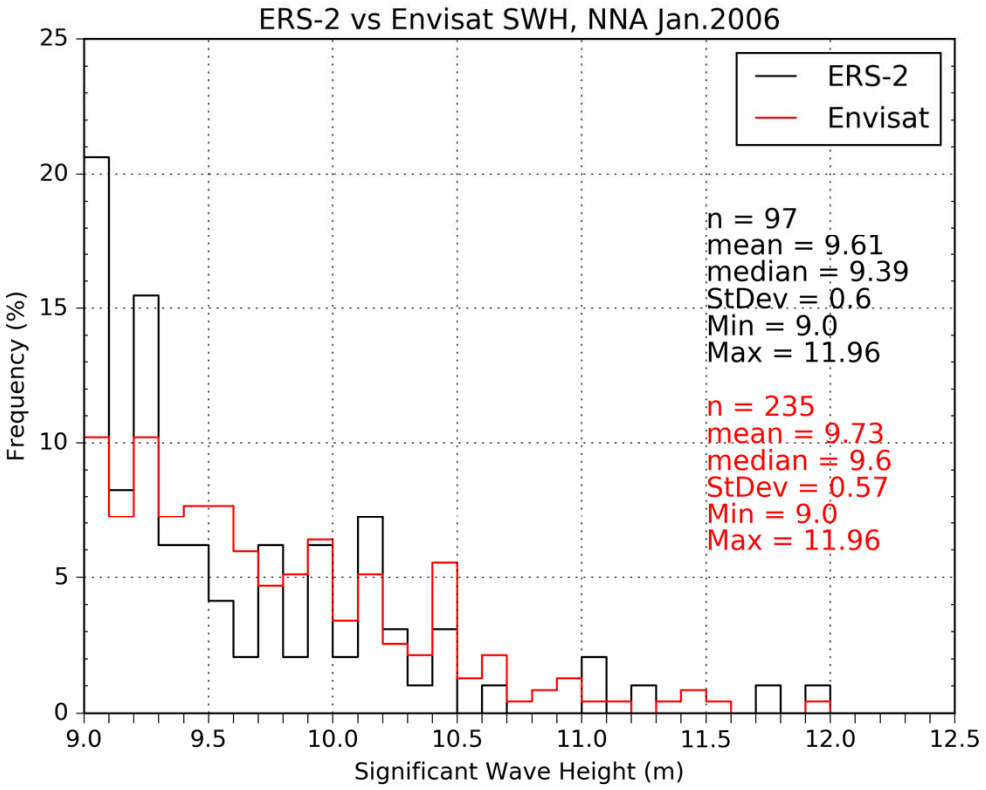




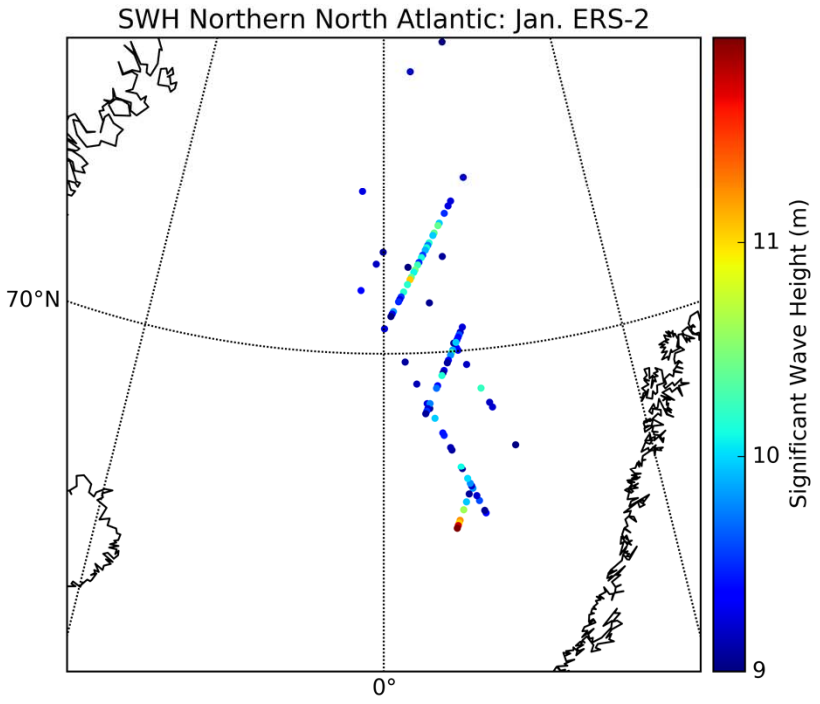
"Very Rough" to "Phenomenal" Seas

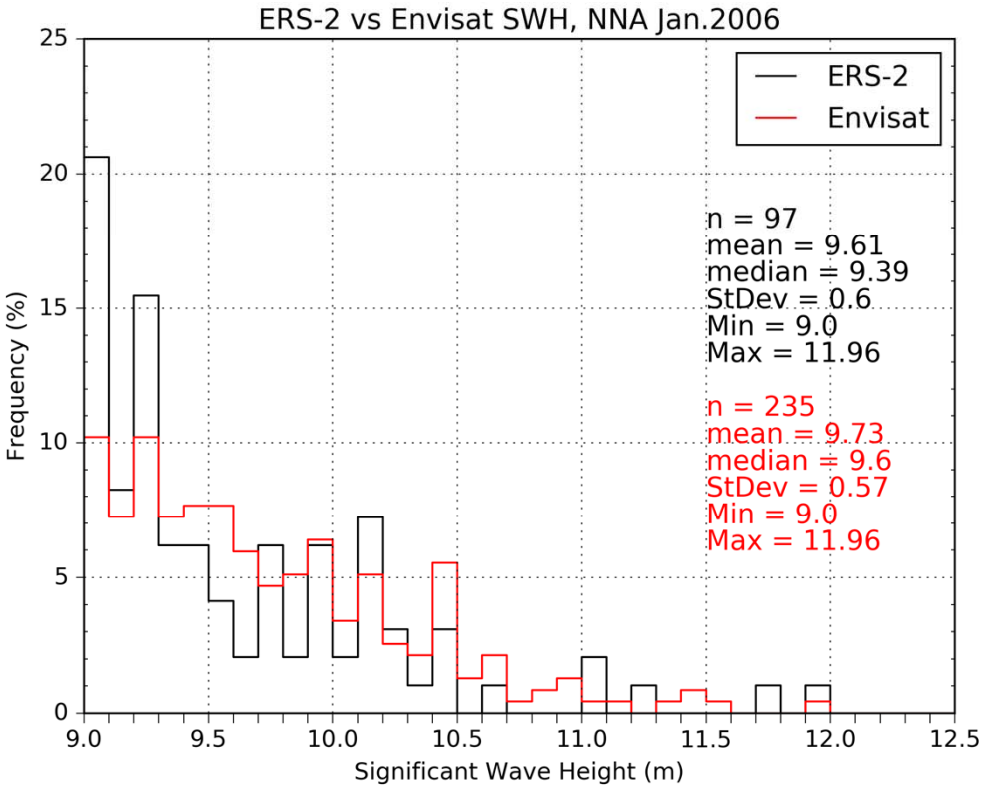
Satellite Sampling Bias - Envisat vs ERS-2: January 2006





Satellite Sampling Bias - Envisat vs ERS-2: January 2006



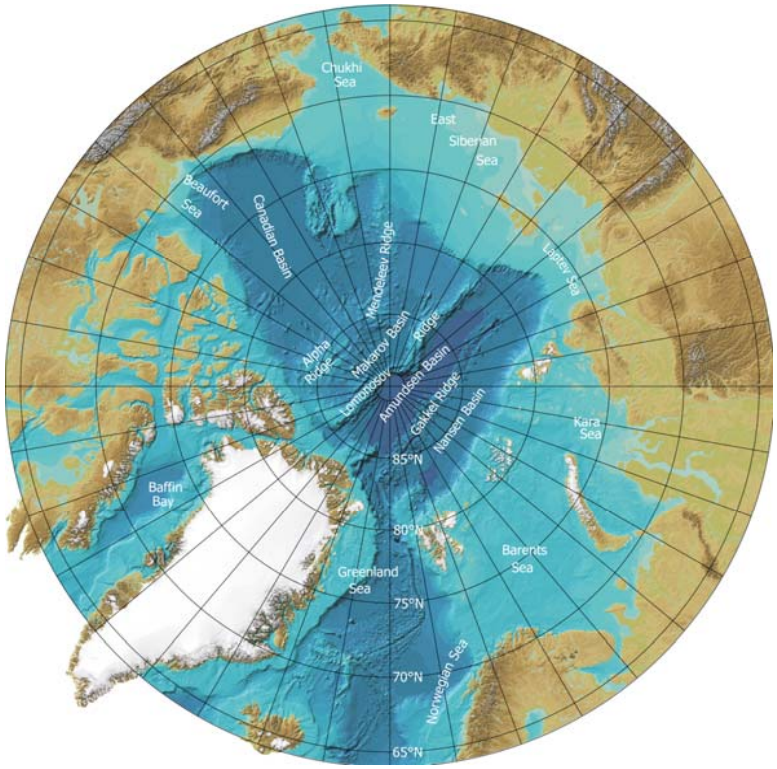


Conclusions

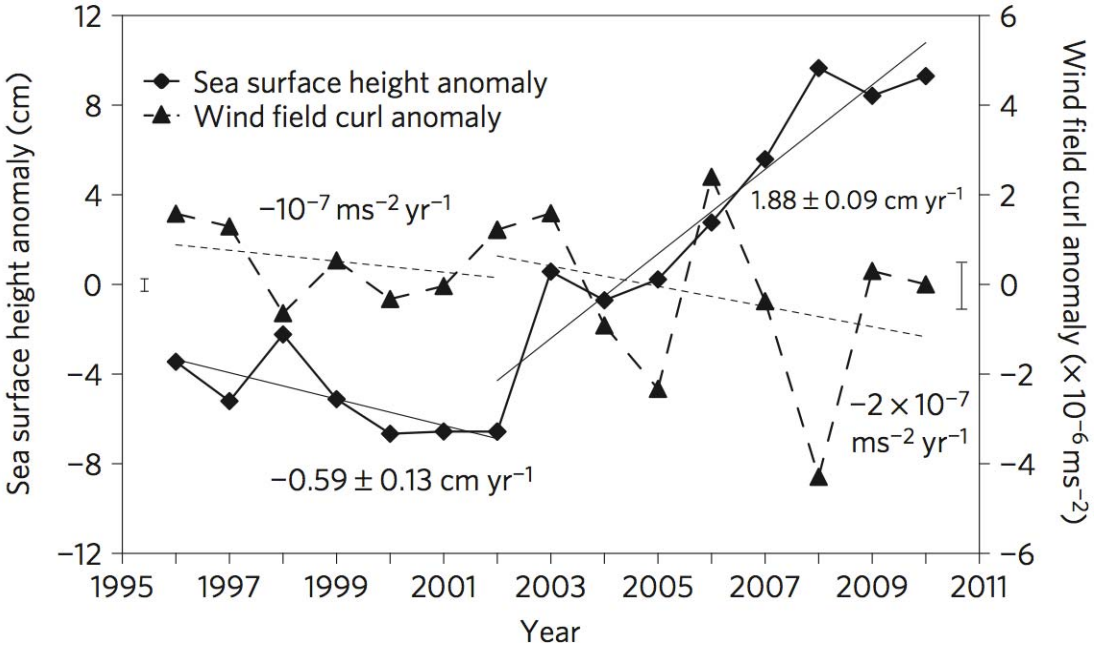
- Progress on characterizing SWH in subpolar seas of the Arctic Ocean over 20+ years
- Detected a **seasonal cycle in SWH** in both regions, with larger median waveheight variability in winter
- Indications of a **small increasing trend** in median SWH (in NNA)
- In Northern North Atlantic (NNA), occurrence of "very high" or "phenomenal" seas (SWH > 9 m) has tripled over 20-yr period (**~ 0.3 % in 1996-2003; ~ 0.6 % in 2004-2010; ~ 0.9 % in 2011-2017**)
- In Bering Sea, occurrence of "very high" and/or "phenomenal" seas has doubled (**~ 0.5 % in 1996-2007; >1 %2008 – 2017**)
- Occurrence of stormy sea observations is related to the number of observations available (multiple satellites with variability in spatial sampling and coverage)
- Difficult to **separate trends** that are a result of sea ice retreat and satellite sampling
- Next steps: normalize results both spatially and temporally to a/c for sampling; look at satellite sampling biases

The Arctic Ocean

International Bathymetric Chart of the Arctic Ocean



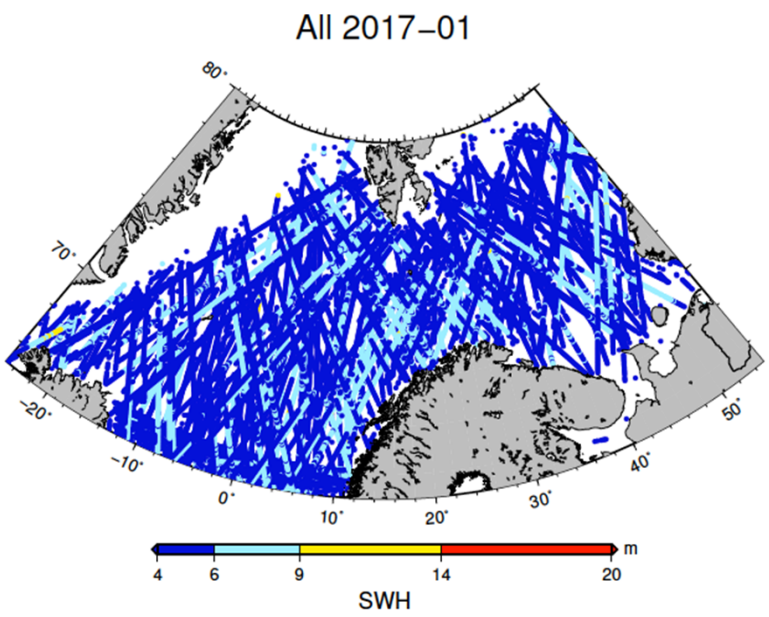
Trend in Arctic Ocean SSH: 1995 - 2010 from ERS-2 and Envisat



- Relationship between sea surface height (SSH) and wind stress curl across the Western Arctic Ocean
- Demonstrates freshening in the Beaufort Sea region
- Source: *Giles et al.*, 2012

Regional Analysis: Northern North Atlantic

Winter SWH >= 4 m



Summer SWH >= 4 m