Altimetry of the Arctic Ocean and Subpolar Seas
Ocean Surface Topography Science Team Report: 2016-2020

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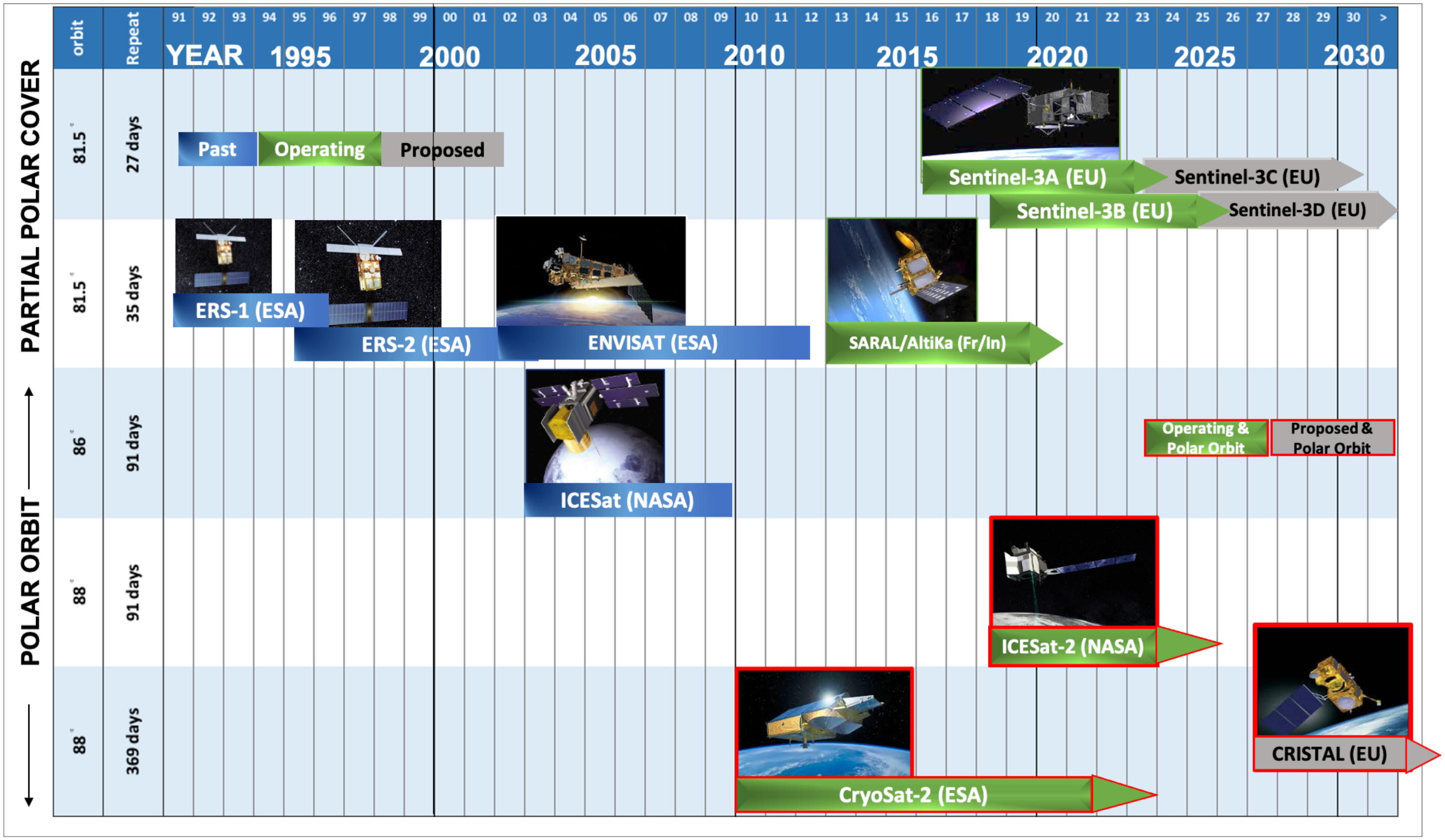
High Latitude Altimetry



Winter Storms in the Bering Sea

- Winter storms in the Bering Sea are frequent
- One of the most difficult seas to navigate in winter
- Severe winter storms produce waves > 12 m (40 ft)
- Often as a result of extratropical cyclones and/or bomb cyclones (storms with an explosive rate of intensification, min. pressure drops >24 mb in 24 hr)
- Environmental and Socio-economic Impacts
    - Very high → phenomenal sea states (WMO sea state code)
    - Storm-force → hurricane-force winds
    - Heavy precipitation
    - Coastal flooding, storm surge, coastal erosion
    - Structural damage
    - Widespread power outages
    - Vessel icing on superstructures of ships
    - Damage to fishing fleet
    - Diverts the jet stream, bringing polar air masses to the US

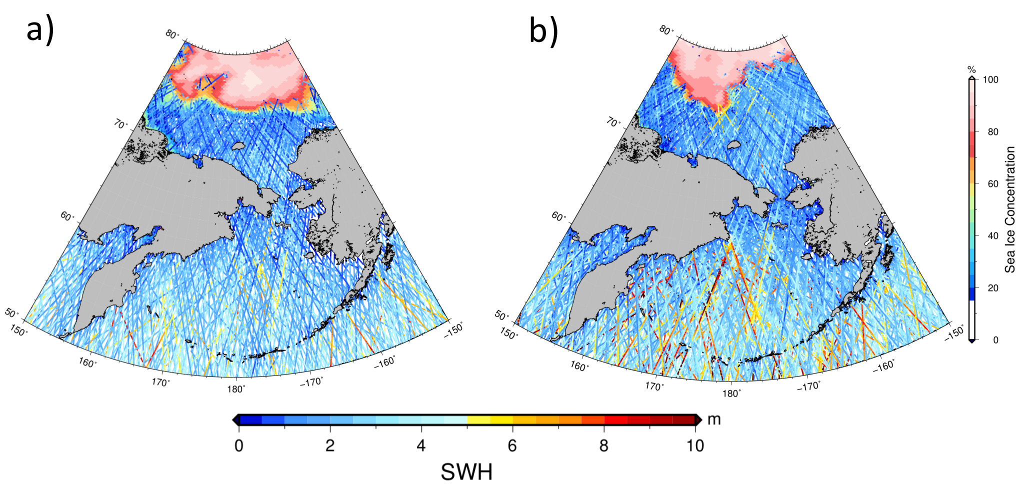
World Meteorological Organization (WMO)
Sea State Code (WMO 3700)

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

Analysis of Bering Sea Winter Storms with Satellite Altimetry

Significant wave height (SWH) in the Bering Sea

- Satellite radar altimeter measurements of SWH
- SWH derived from slope of leading edge of radar altimeter waveforms
- 21-year time period: 2000 – 2020
- We assess conditions in winter: November – April
- **Key Question**: Has the Bering Sea become stormier as Arctic sea ice has retreated?



Passive microwave radiometer Arctic sea ice concentration with altimeter-derived SWH in the northern Pacific in October (a) 2015 and (b) 2017

Satellite Mission	Altimeter	Operation Dates	Repeat Cycle (days)	Latitudinal Limit of Coverage (°N/S)
ERS-2	E2	1995-2011	35	81.5
Envisat	N1	2002-2012	35	81.50
Jason-1	J1	2002-2013	10	66.00
Jason-2	J2	2008-2019	10	66.00
CryoSat-2	C2	2010-date	369	88.00
SARAL/AltiKa	SA	2013-date	35	81.50
Sentinel-3A	3A	2016-date	27	81.35
Jason-3	J3	2016-date	10	66.00
Sentinel-3B	3B	2018-date	27	81.35

- SWH from the **Jason Series Altimeters (Jason-1, -2, -3)** compared with measurements from the **Envisat Series Altimeters (ERS-2, Envisat, CryoSat-2, SARAL/AltiKa, Sentinel-3A, -3B)**
- Data accessed through the Radar Altimeter Database System (RADS): http://rads.tudelft.nl/rads/rads.shtml

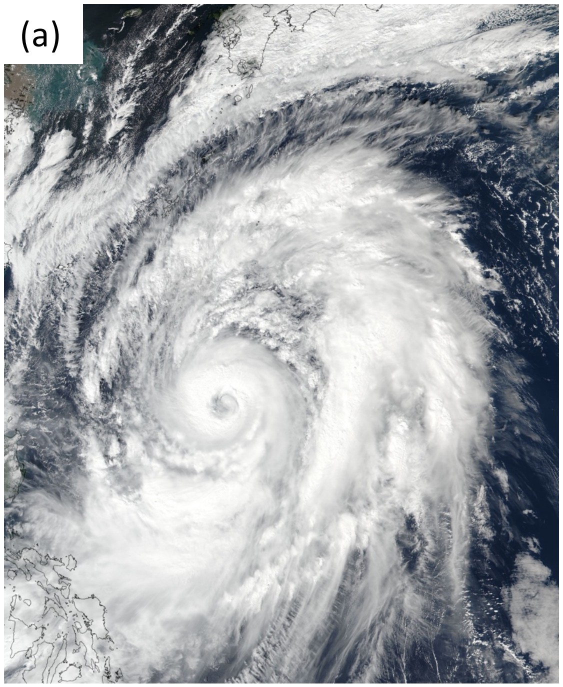
Major Winter Storm October 2017

a) Ex-typhoon Lan enters Bering Sea, 24th October 2017

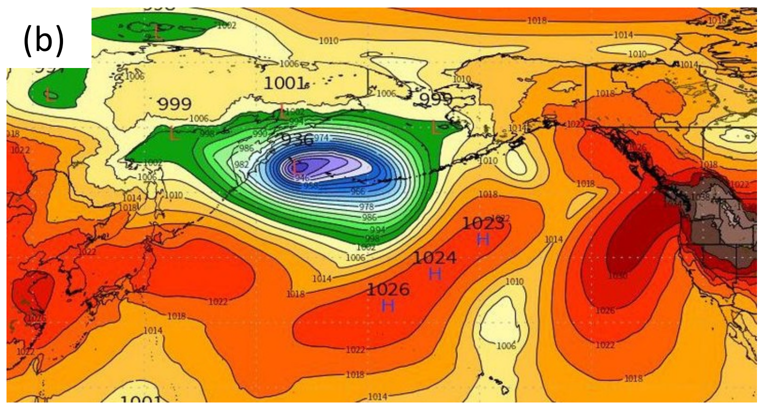
b) Hurricane force low (936 hPa) in SW Bering Sea

c) Radar altimeter SWH indicates sea states in excess of 9 m north of the Aleutian Islands, October 25, 2017

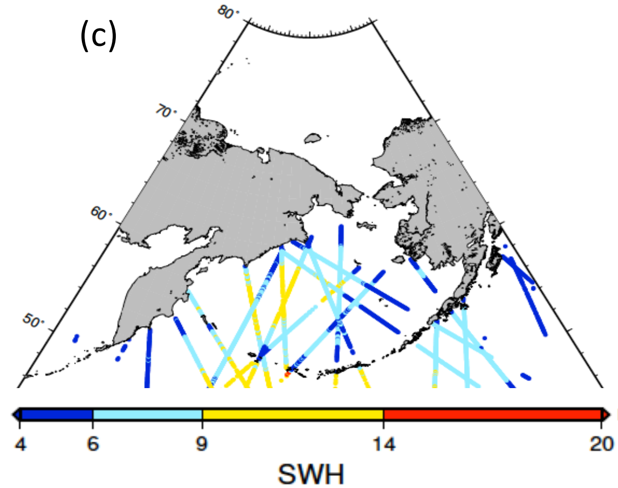
d) Phenomenal sea states were recorded south of Aleutian Island chain, where the largest SWH measured 17.4 m!

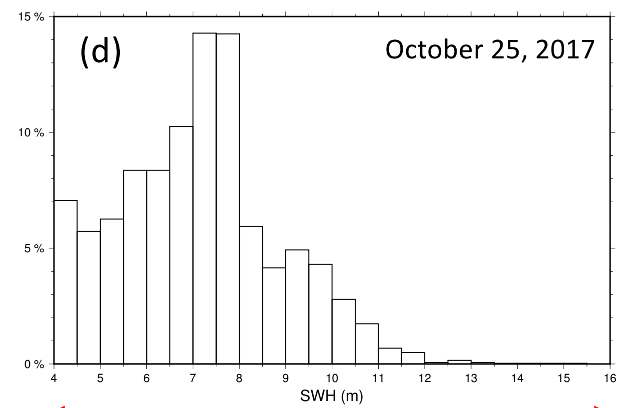


Visible image of Typhoon Lan from NASA-NOAA's Suomi NPP satellite, October 20, 2017, 04:30 UTC. Credits: NOAA/NASA Goddard Rapid Response Team



Low pressure system in Bering Sea, October 24, 2017

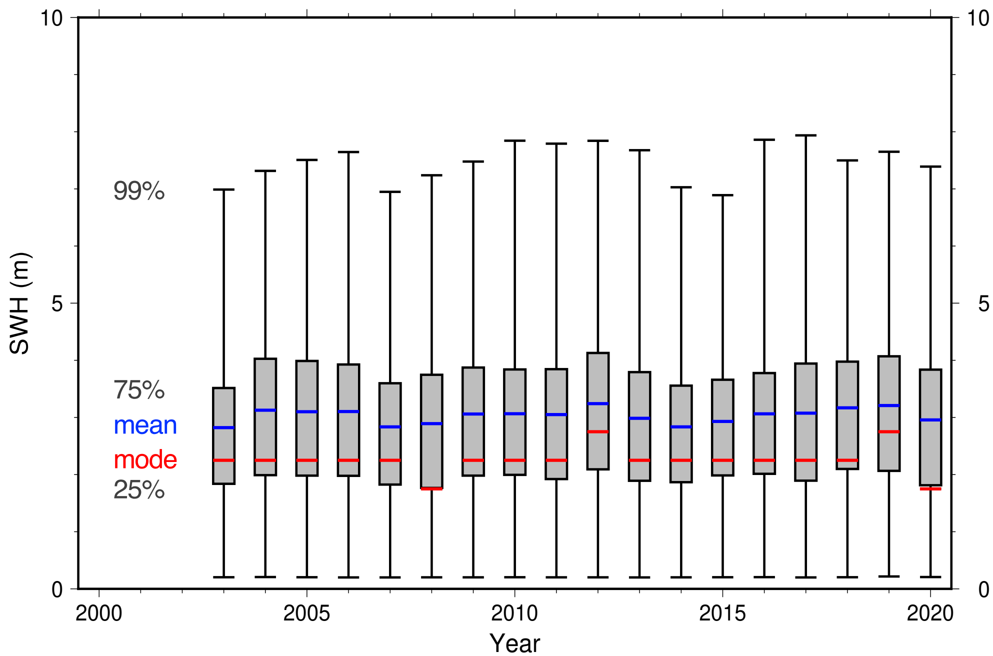




Very Rough to Phenomenal Seas (sea state code 6-9)

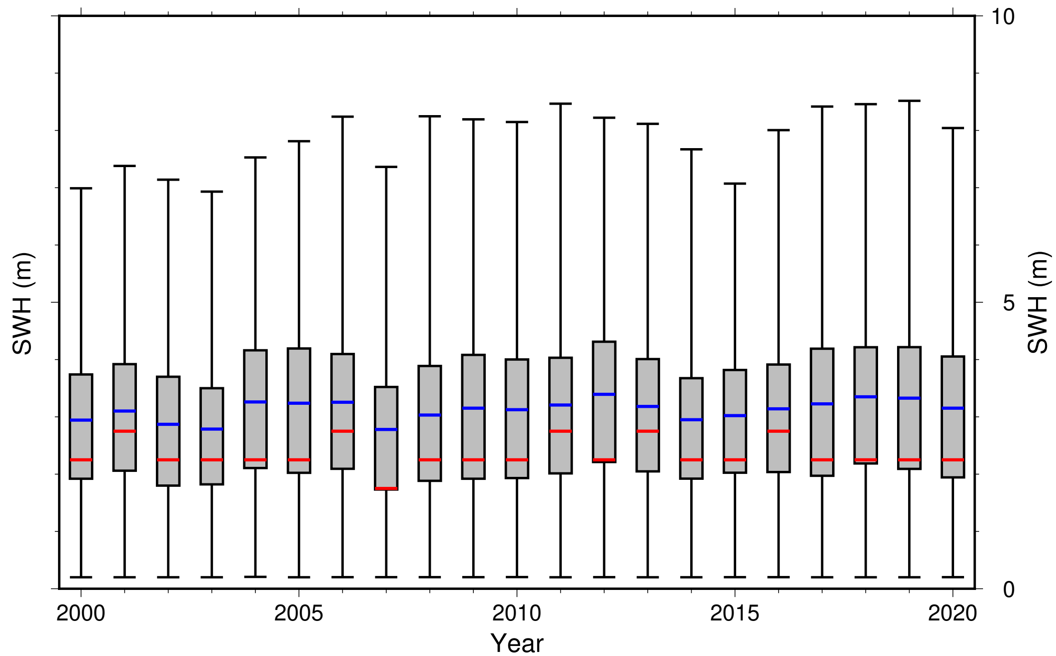
Inter-annual Variability in SWH

Bering Sea Winter: Jason Series Altimeters



- Winter SWH in Bering Sea dominated by interannual variability
- Mean (modal) SWH: **3.03 m (2.25 m)**
- 25% SWH > **3.84 m**
- 1% SWH > **7.47 m**
- **0.2%** observations show SWH > 14 m
- Roughest seas: 2006, 2010, 2017; Calmest seas: 2003, 2007, 2015

Bering Sea Winter: Envisat Series Altimeters



- Interannual variability from Envisat altimeters consistent with Jason altimeters
- Mean (modal) SWH: **3.12 m (2.25 m)**
- 25% SWH > **3.96 m**
- 1% SWH > **7.86 m**
- **0.4%** observations show SWH > 14 m
- Roughest seas: 2006, 2011, 2019; Calmest seas: 2000,2003, 2007, 2015

Bering Sea Phenomenal Sea State Events

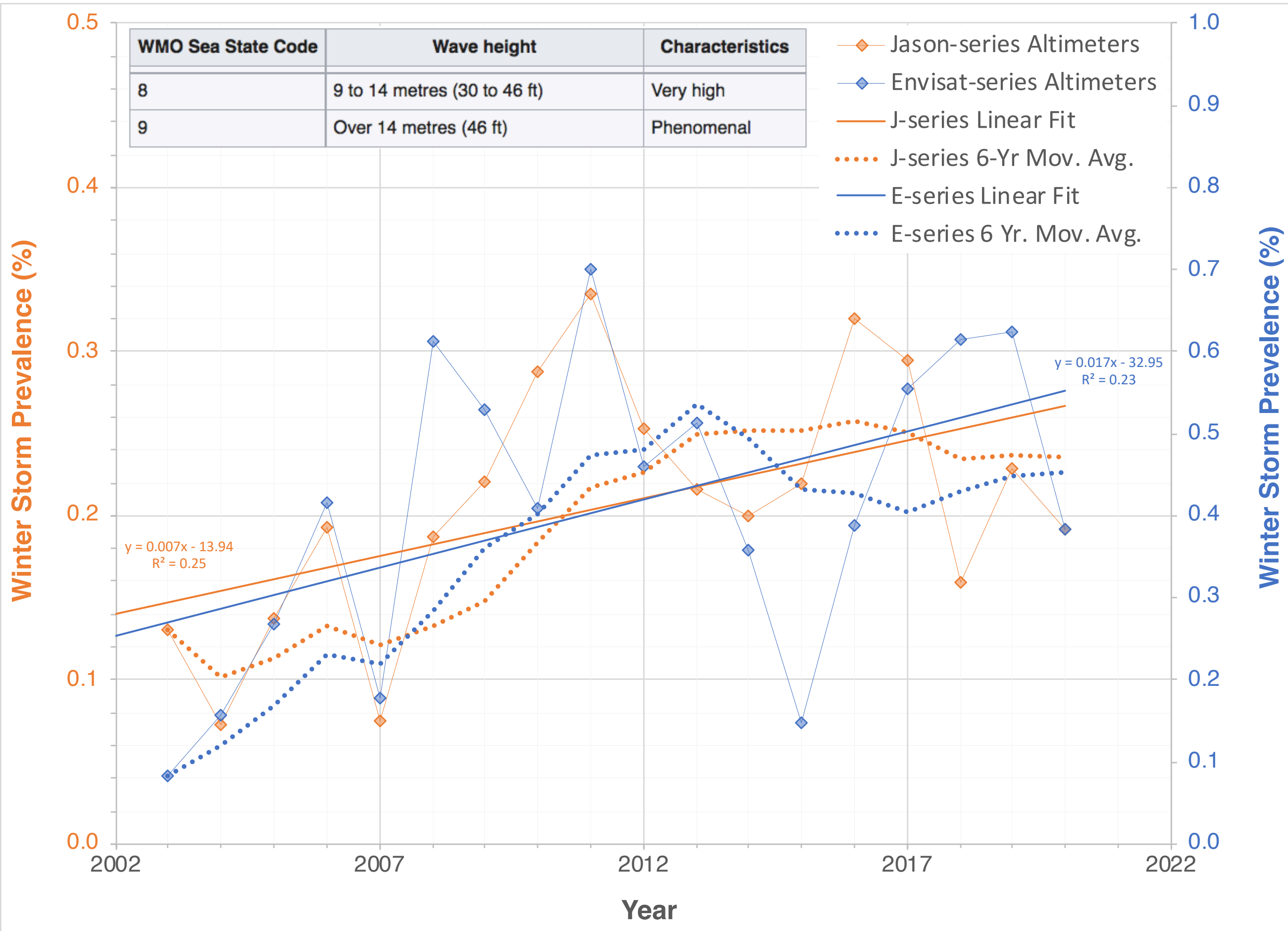
WMO Sea State Code	Wave height	Characteristics
9	Over 14 metres (46 ft)	Phenomenal

Event Number	Satellite	Date	UTC Time (hh:mm)	Latitude (°N)	Longitude (°E)	SWH (m)
1	Envisat	January 14, 2008	10:11	56.40	164.21	14.1
2a	CryoSat-2	February 24, 2011	14:00	59.61	184.00	14.2
2b	CryoSat-2	February 24, 2011	14:00	59.38	183.96	14.2
3	CryoSat-2	January 26, 2014	20:57	60.75	178.86	15.1
4	CryoSat-2	December 9, 2015	23:53	61.47	175.02	14.1
5a	CryoSat-2	December 13, 2015	10:16	52.32	190.34	14.5
5b	CryoSat-2	December 13, 2015	10:16	52.38	190.33	15.2
5c	CryoSat-2	December 13, 2015	22:11	53.77	196.62	14.4
5d	CryoSat-2	December 13, 2015	22:11	53.65	196.60	14.4
5e	Jason-2	December 14, 2015	3:08	54.13	198.93	14.3
6	Jason-3	October 31, 2016	2:31	53.65	197.19	14.1
7a	Jason-3	October 25, 2017	2:20	51.53	177.29	15.1
7b	Jason-3	October 25, 2017	2:20	51.69	177.50	14.9
8	Jason-2	November 27, 2017	1:08	53.02	200.45	14.1
9a	Sentinel-3b	December 22, 2019	22:15	54.03	188.07	14.3
9b	Sentinel-3b	December 22, 2019	22:15	53.05	187.57	14.8
9c	Sentinel-3b	December 22, 2019	22:15	52.94	187.52	14.2
10	Sentinel-3b	March 1, 2020	8:12	53.53	194.97	14.0

- Phenomenal sea states (SWH > 14 m) in the Bering Sea in winter are common
- 10 phenomenal sea state events during study period
- Largest SWH recorded in December, 2015: 15.2 m!
- 90 % of events have occurred in the last decade

Trends in Very High and Phenomenal Sea State in the Bering Sea in Winter

WMO Sea State Code	Wave height	Characteristics
8	9 to 14 metres (30 to 46 ft)	Very high
9	Over 14 metres (46 ft)	Phenomenal



- Extremely stormy winter seas are defined here as those with WMO sea state codes 8 and 9 (SWH > 9 m)
- We assess the prevalence of winter storms
- Winter storm prevalence is defined as the number of SWH measurements > 9m per winter per satellite as a percentage of the total number of SWH observations per winter per satellite.
- SWH from the **Jason Series Altimeters (Jason-1, -2, -3, orange diamonds)** are compared with measurements from the **Envisat Series Altimeters (ERS-2, Envisat, CryoSat-2, AltiKa, Sentinel-3A/B, blue diamonds)**
- We find an **increasing trend in storminess** in the Bering Sea during the 20-year study period (linear regressions, solid blue and orange lines)
- Two, independent altimeter time series show strong agreement, especially when a 6-year moving average is fit to the data (dotted blue and orange lines)
- The percentage of winter storms in the **Envisat** time series is twice that of the **Jason** time series. ***The reason for this doubling in the slope of the trend is currently unknown***.