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

Sinead Louise Farrell¹,², Kyle Duncan¹,², John M. Kuhn², Ellen Buckley¹,²
¹University of Maryland, ²NOAA Laboratory for Satellite Altimetry
High Latitude Altimetry

---|---|---|---|---|---|---|---|---
orbit | Repeat | 91 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 >

**PARTIAL POLAR COVER**
- 81.5°
  - 27 days
  - Past
  - Operating
  - Proposed
- 81.5°
  - 35 days
  - ERS-1 (ESA)
  - ERS-2 (ESA)
  - ENVISAT (ESA)
- 86°
  - 91 days
  - ICESat (NASA)
- 88°
  - 369 days
  - ICESat-2 (NASA)
  - CryoSat-2 (ESA)

**POLAR ORBIT**
- 88°
  - 91 days
- 88°

**Sensors**
- Sentinel-3A (EU)
- Sentinel-3B (EU)
- Sentinel-3D (EU)
- SARAL/AltiKa (Fr/In)
- CRISTAL (EU)
- ICESat (NASA)

*Sinéad L. Farrell, University of Maryland*

*Virtual Meeting, October 2020*
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)

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

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

- 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)
**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

- 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

- 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
Bering Sea Phenomenal Sea State Events

- 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

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

- 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.