Driving Mechanisms of Intense Cyclone for Extreme Summer Sea Ice Loss Event

Xiangdong Zhang
University of Alaska Fairbanks

In Collaboration With
Liran Peng, Joo-Hong Kim, Kyoung-Ho Cho, Baek-Min Kim, Zhaomin Wang, and Han Tang

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An intense cyclone occurred in August 2016, followed by the third minimum of sea ice extent.

The Korean icebreaker Araon captured this intense cyclone (the ship location is marked by star).

ERA5: geopotential height and temperature at 850 hPa.
Meteorological Observations onboard IBRV Araon

Wind Speed, m/s

Pressure, hPa

Temperature, °C

Day
Sea ice concentration changes during the process of the intense cyclone
The sea ice area reached its lowest value when an intense cyclone occurred in the Augusts of 2012 and 2016; The cyclone in August 2016 accelerated the sea ice area decrease.
Dynamic processes in sea ice change: Convergence/inflow and divergence/outflow
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Mean sea ice area outflow rate: -4274.2 km²/day

Domain-mean sea ice area decreasing rate: -29785.3 km²/day

Outflow/Change ratio: 14.4%
Thermodynamic processes in sea ice change: Heat energy budgets at the sea ice/ocean surface

- Net heat energy into sea ice/ocean surface;
- Minimum net heat energy when the cyclone intensified to its strong phases;
- Heat energy gain from SW, loss predominantly by LW;
- An increase in SW with a decrease in cloudiness.

Positive: downward into blended sea ice/ocean surface

In-situ observations consistent with the domain-average of ERA5 data
• The sea ice surface lost a net heat energy, while the open water surface gained a net heat energy.
• The net heat energy gained from the open water surface was not sufficient to increase ocean mixed layer temperature to the observed one by CTD.
Thermodynamic processes in sea ice change: Partitioning of energy into sea ice and ocean

\[ \Delta T = \frac{\dot{Q}}{(\rho C_p A \Delta D)} \Delta t \]

- \( \Delta T \): Surface mixed layer temperature change over \( \Delta t \)
- \( \dot{Q} \): Surface net energy flux
- \( \rho \): Surface mixed layer ocean water density
- \( C_p \): Specific heat of ocean water
- \( A \): Area of the study domain
- \( \Delta D \): Depth of surface mixed layer

<table>
<thead>
<tr>
<th>( \Delta T )</th>
<th>16 August 2016 (6-19h)</th>
<th>19 August 2016 (2-11h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{Q}_{ocn} ) Based</td>
<td>0.0076°C</td>
<td>0.0063°C</td>
</tr>
<tr>
<td>CTD Observed</td>
<td>0.05°C (0.08°C)</td>
<td>0.12°C (0.46°C)</td>
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(0.08°C) (0.46°C)
Dynamic processes in sea ice change: Cyclone-driven Ekman upwelling and mixing

Winds stress curl on (a) 15, (b) 16, (c) 18, and (d) 19 August 2016.
Dynamic processes in sea ice change: CTD observations

22 CTD Observations

09-Aug-2011
10-Aug-2011
10-Aug-2012
11-Aug-2012
15-Aug-2015
16-Aug-2016
24-Aug-2012
26-Aug-2012
28-Aug-2013
18-Aug-2015
16-Aug-2016

06-Aug-2011
08-Aug-2012
09-Aug-2012
27-Aug-2013
16-Aug-2015
19-Aug-2016
05-Aug-2011
30-Aug-2012
17-Aug-2014
17-Aug-2015
19-Aug-2016
Dynamic processes in sea ice change: Cyclone-driven Ekman upwelling and mixing

Warmed surface mixed layer:
- The surface mixed layer temperature increased about 0.05°C on 16 August and 0.12°C on 19 August 2016.

Weakened Pacific warm water layer:
- Decreased the core Pacific warm water layer temperatures;
- Elevated Pacific warm water layer to the level underneath the mixed layer.

Cyclone-driven Ekman upwelling:
- Transported heat upward to the mixed-layer from the Pacific-origin warm water layer.

Enhanced mixing in the surface mixed layer:
- Vertically-uniform distribution of T & S occurred in the surface mixed layer;
- Deeper mixed layer depth compared to multiyear observations.

CTD Observations of Temperature and Salinity Profiles and Diagnosed Ekman Transports on 16 and 19 August 2016
The oceanic heat flux (turbulent heat flux from ocean to the bottom of sea ice) increased:

\[
F_{io} = \rho_o c_p c_h u_*(T_{SML} - T_f)
\]

\[
T_f = -0.0575S + 1.710523 \times 10^{-3} S^{3/2} - 2.154996 \times 10^{-4} S^2 - 7.53 \times 10^{-4} \rho_{bar}
\]

The sea ice bottom melt increased, resulting in the acceleration of sea ice decrease:

\[
\frac{\delta h_{io}}{\delta t} = \frac{F_{io}}{\rho_i L_i}
\]

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<td>(F_{io})</td>
<td>3.6 W/m(^2)</td>
<td>57.9 W/m(^2)</td>
</tr>
<tr>
<td>(\delta h_{io})</td>
<td>0.1 cm/day</td>
<td>1.66 cm/day</td>
</tr>
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Take Aways:

- An intense cyclone occurred in August 2016, followed by the third minimum sea ice extent on record;
- Decrease in sea ice extent/area largely accelerated by about 6 times under the cyclone influence;
- Sea ice surface lost net heat energy due to its high albedo and reflected shortwave radiation, as well as outgoing longwave radiation;
- Open ocean surface received net heat energy from shortwave radiation, but not enough to increase the ocean mixed layer temperature to the observed one;
- Cyclone-driven Ekman upwelling of the Pacific-origin warm water and enhanced upper mixed layer mixing increased the oceanic heat flux, leading to an increased sea ice basal melt and then accelerated sea ice melt.
- This study provides an observational basis for validating and improving model simulations of storm-sea ice-ocean interactions, which is still a challenge.