KOPRI-FUNDED PROJECT:

Storm Induced Air-Ice-Sea Interactions in a Dramatically Changing Arctic Ocean

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Summary

I. Title
Storm Induced Air-Ice-Sea Interactions in a Dramatically Changing Arctic Ocean

II. Purpose and Necessity of Research
Improve understanding of the role that more frequently occurring synoptic storms in enhancing air-ice-sea interactions in the dramatically changing Arctic climate, and improve Arctic climate modeling ability.

III. Contents and Extent of Research

• Analyze in-situ and satellite observational data to reveal temporal evolution of selected Arctic storm development;
• Diagnose storm-induced changes in atmosphere, sea ice, and ocean from the in-situ and satellite observations;
• Delineate dynamic and thermodynamic processes in the interactions between atmosphere, sea ice, and ocean;
• Evaluate model simulations of Arctic weather and climate and reduce the most prominent model biases and errors.

IV. Research Results
Intense storms have more frequently occurred during recent years. In-situ observational analysis of a selected intense storm indicates that the storm can accelerate sea ice melt during the course of its summer seasonal melting process. The accelerated melting rate is predominately attributed to increased downward shortwave radiation through open water surface and enhance upward Pacific-origin water transport and ocean mixing by storm-driven Ekman pumping. High-resolution WRF model experimental forecast was also conducted in conjunction with the IBRV Aron field expedition in summer 2019 for participating in multi-model comparison and validation.

V. Application Plans of Research Results
We plan to carefully include sea ice and upper ocean modules in the WRF model so that air-ice-sea interactive process can be better represented, which would enhance model ability to accurately improve simulations and forecasts of the storm-forced extreme changes in surface meteorological conditions, sea ice melt/growth and distribution, and ocean mixed layer temperatures.
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Chapter 1 Introduction

Drastic changes in Arctic sea ice represent a prominent feature in the recently warming climate. Satellite observations indicate that Arctic sea ice has become one of the most rapidly changing components in the global climate system, clearly evident from repeated new historic lows in sea ice extent, as well as strikingly extreme summer sea ice cover loss events in 2007, 2012, and 2016, along with dramatic thinning of sea ice thickness (e.g., Comiso et al., 2008; Zhang et al., 2008; Kwok and Rothrock 2009; Meier et al. 2012; Overland et al. 2014). The Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 and CMIP5) climate models have also projected an acceleration in future Arctic sea ice decrease as well as an ice-free Arctic Ocean by the end of this century or even earlier, under various scenarios of greenhouse-gas-emissions forcing (e.g., Zhang and Walsh, 2006; Holland et al., 2006; Wang and Overland, 2009; Zhang, 2010; Wang and Overland, 2012; Stroeve et al., 2012).

In conjunction with the rapid decline of sea ice, extratropical synoptic storm tracks have shifted poleward and storm activities have intensified in the Arctic Ocean (e.g., Zhang et al., 2004). This shift is suggested to continue by climate models under the projected global warming forcing scenarios (e.g., Yin, 2005). Synoptic storms are the fundamental element in the Arctic for shaping weather patterns on a daily basis, and interactively contribute to variability of and change in the large-scale atmospheric general circulation. They can be either generated locally within or travel poleward from mid-latitudes into the Arctic Ocean. Storms are therefore the primary driving force for transient poleward transport of atmospheric heat and moisture from the lower latitudes into the Arctic Ocean, and the fundamental mechanism for generation and distribution of cloudiness over the Arctic Ocean. They also play an important dynamic role in modulating Arctic sea ice circulation. All of these naturally alter surface heat energy budgets, momentum fluxes across air-ice-sea interfaces, and sea ice export out of the Arctic Ocean and, finally, impacts sea ice states.

A number of previous studies have examined influences of the variability and changes of storm activities on some aspects of the underlying sea ice, as well as energy and water cycles, over the Arctic Ocean (Zhang et al., 2004; Serreze and Barrett, 2008; Simmonds and Keay, 2009; Zhang et al., 2013; Vihma et al., 2016). However, there have been few studies untangling the complex physical processes linking the dynamic and thermodynamic forcing induced by storm activities to the changes in sea ice states. In particular, it has been found that Arctic storms tend to have longer lifetimes, especially during summer and fall (Zhang et al., 2004; Sepp and Jaagus, 2011). Elongated lifetimes for storms may exert cumulative atmospheric forcing on the surface over an extended time period, which may result in pronounced impacts on deeper layers of the sea ice. The super storms, which occurred and followed by the record minima of sea ice extent in summer 2012 and 2016, would be an outstanding manifestation of the changes in storm activity and their possible impacts on sea ice (Simmonds and Keay, 2009). It is therefore a pressing need to understand, monitor, and predict Arctic storms and its induced air-ice-sea interactions.
Chapter 2 Current Status of Research in Korea and Other Nations

Intensification of Arctic storm activity and its possible driving role in Arctic sea ice and upper ocean circulation were identified by Zhang et al. (2014). Since then, continuing efforts have been made to improve understanding of various aspects of Arctic storm climatology and long-term changes (e.g., Serreze and Barrett, 2008). Especially, along with the observed increase in intense storms in the Arctic Ocean during recent years, Arctic storm dynamics and its impacts on sea ice and ocean has most recently becoming one of the most vigorous research areas. The U.S. Navy just began with a new initiative on the topic through field observations and model simulations, aiming to improve prediction of Arctic storm and sea ice. However, there are only a few studies existing so far, which have examined dynamic effects of storm, showing that occurrence or passage of storms can increase sea ice velocity, generate ocean waves, and modulate sea ice export out of the Arctic Ocean. These storm-induced changes can influence sea ice distribution and mass balance (e.g., Brümmer et al., 2003; Asplin et al., 2012; Zhang et al., 2013; Wei et al., 2018).

In Korean, research on the topic has begun in collaborating with international community. Dr. Joo-Hong Kim at KORPI had led GPS radiosonde observations onboard IBRV Araon each summer during last years. The in-situ observational data provide a basis from reality for Arctic storm-sea ice-ocean interaction studies and for validating and improving Arctic model simulations and predictions. In particular, the IBRV Araon captured an intense storm in August 2016 in the Chukchi Sea. The rare observational data during this period provide a unique opportunity to investigate structure and time evolution of the storm and its influence on sea ice and ocean, which comprises a major research task of this project (Peng, Kim, and Zhang et al., 2020). Dr. Baek-Min Kim at KOPRI also led a study to examine the driving role of an intense storm in causing an extreme Arctic warming event in January 2016 (Kim et al., 2017).

Arctic storms and their interaction with sea ice and ocean are complex and have not been well investigated. The rapidly changing Arctic climate and environment system has also raised grand challenges to the traditional theory and understanding. Extensive studies on the topic in an international collaboration setting would be continually a top priority for the coming years.
Chapter 3 Research Contents and Results

3.1 Analysis of in-situ and satellite observational data to reveal temporal evolution of a selected intense Arctic storm

As mentioned above, we employ the unique observations during the IBRV Araon expedition in summer 2016, when an intense storm occurred and following this storm the second record low of sea ice extent appeared in September. The intense storm originated from the eastern Barents Sea. Merging processes with other two storms also contributed to its dramatic intensification and persistence over a long period. At 00 UTC on 13 August, a weak surface low-pressure center at surface emerged near Novaya Zemlya and a storm with moderate intensity previously existed over the central Arctic Ocean (Figure 1a). At the same time, cold surface temperatures occurred over the northern Beaufort-Chukchi seas and the northern Barents-Kara seas, forming baroclinic zones with the warm temperatures to their north and south, respectively. These baroclinic zones, in particular the strong baroclinicity over the Barents Sea, provided driving mechanism for supporting the low-pressure system to develop and maintaining the prior storm to exist over the central Arctic Ocean.

Figure 1. The 850 hPa geopotential height (black solid contours) and surface air temperature (color scale shading) at the six selected times (a to f) based on the ERA-Interim reanalysis data. The intense storm track is shown by the solid magenta line. The storm center locations at each 6-hour time step are displayed by the black dots along the track. The thin magenta line shows the track of a small storm born at later time, which was merged with and reenergized the intense storm. The location of IBRV Araon is indicated by the black star. The blue dash line highlights the study domain. (g) shows time series of the surface pressures (black line), temperatures (red line), and the true wind speeds (green) observed onboard the IBRV Araon.
The surface low-pressure center over the Barents Sea then quickly intensified when moving eastward through the Eurasian shelf seas and finally northeastward into the central Arctic Ocean (Figure 1b). During this process, it merged with the previously existing storm in the central Arctic Ocean and considerably intensified. At 00 UTC on 16 August, the storm developed to its mature and the strongest phase and its central surface pressure reached 967 hPa (Figure 1c and g). Afterward, the storm entered the weakening phase. However, a surface low-pressure center born in the baroclinic zone along the Siberian coast of the Chukchi Sea traveled northeastward and merged with the intense storm, which sustained the intensity of the storm over an extended period (Figure 1d-f).

The surface observations onboard the IBRV Araon in the Chukchi Sea (shown by the star sign in Figure 1) captured the surface pressure decrease and its minimum of about 983 hPa on 15 August when the intense storm approached the ship and developed to its mature phase (Figure 1g). The ship observations also showed the weakening of the storm though the newly born low-pressure from the Chukchi Sea coast caused the second surface pressure low value when it merged with the intense storm during 18-19 August. The observed temperature demonstrated a large decrease from 14-15 August when the intense became closer to Araon and intensified, but a follow-up increase and fluctuations due to a time-varying intrusion of warm air to the north associated with the time evolution of the storm and the merging low-pressure from the Chukchi Sea.

3.2 Diagnosis of storm-induced changes in sea ice from the in-situ and satellite observations

To examine changes in sea ice associated with the storm and underlying physical mechanism using the in-situ observations, we defined a study domain from 65°N to 82°N and from 158°E and 148°W (the area bounded by the blue dashed lines in Figure 1). This domain was defined to be large enough to cover a relatively complete piece of pack ice and small enough to be approximately represented by the in-situ observations during the Araon expedition. The sea ice concentrations and extent within the study domain show an obvious decrease day-by-day throughout the lifetime of the storm (Figure 2). In particular, a considerably large decrease in sea ice concentration occurred along the western edge of the pack ice from 16 August, while the eastern edge only shows a slight westward retreat. Another large decrease also appeared around the two open leads within the pack ice.

To better understand the decrease in sea ice associated with the storm in the context of the long-term sea ice changes, we first constructed daily sea ice area anomalies in August for each year from 2010-2016, relative to the daily sea ice area climatology during the same time period, in the study domain. We then used the sea ice area on 1 August to standardize the time series of the anomalies for better revealing sea ice area changes with minimized influence of initial sea ice condition during this time period. The time evolutions of the sea ice area anomalies across different years are statistically represented by the boxplot (Figure 2g). We also in particular show the time series in 2012 and 2016 to compare sea ice changes. Intense storms occurred in the Augusts of these two years, followed by record minima of September sea ice extents.

The comparison indicates that changes in sea ice areas in August 2012 and 2016 drastically departed from the climatological track as shown by the median after the first 5 days, leading to the negative anomalies lower than the 25th percentile of climatological distribution. Especially, the anomalies in 2012 reached the minimum all the way throughout the end of August. It is worthwhile mentioning again that a super storm occurred from 2-14 August of 2012 (Simmonds and Rudeva, 2012), which was obviously responsible for the large sea ice area anomalies and might contribute to the record low sea ice extent in the following month (Parkinson and Comiso, 2013; Zhang et al., 2013).
Figure 2. Satellite observation of sea ice concentration on (a) 13 August. The differences of sea ice concentration on (b) 14 August, (c) 16 August, (d) 17 August, (e) 18 August, and (f) 19 August from that on 13 August. The ASI6k sea ice concentration dataset is used to display spatial distribution in a grey in (a) and in a blue-white-red color in (b)-(f). The SSM/I dataset is used to show the edge of sea ice extent in red. The southern boundary of the study domain is marked by the thick dashed line in red. (g) shows the boxplot of sea ice area anomalies superimposed by the time series of the anomalies in the Augusts of 2012 (blue) and 2016 (red). The anomalies were calculated using the SSM/I dataset. (h) The ratio between the sea ice area decline rate during the storm process and its 2010-2016 climatology from 13 to 21 August.

The trajectory of sea ice decrease in August 2016 was similar to that in August 2012 though the magnitude of the anomalies was smaller except for the last 5 days. To further quantify the changing rate of the sea ice area during the period of the 2016 storm process, we calculated the ratio of day-to-day sea ice area variation rate from 13-22 August between 2016 and climatology (Figure 2h). The decreasing rate of sea ice area was larger than its climatological value from 13-22 August and also considerably accelerated from 14-17 August along with the intensification of the storm. The maximum sea ice area decreasing rate is about 5.7 times larger than the climatological rate of 0.016 km²/day on 16 August when the storm reached its strongest phase. As a consequence, the sea ice area decreases in the study domain disproportionally contributed to about 43% of total sea ice area decrease.
in the entire Arctic Ocean, though the sea ice area in the study domain was only about 14% of the total sea ice area.

3.3 Delineation of dynamic and thermodynamic processes in the interactions between atmosphere, sea ice, and ocean

To understand the acceleration of sea ice area decrease associated with the intensification of the storm, we quantitatively analyzed the surface energy budgets and the oceanic heat flux from the ocean mixed layer to the bottom of sea ice within the study domain, using the in-situ observations during the Araon expedition. As described above, although west winds from the storm blew over the study domain, the pack ice within this domain did not exhibit obviously large movement (Figure 2). Instead, the western and eastern ice edges showed a shrinking toward the center of the pack ice due to ice melt. The enhanced day-to-day decrease in sea ice concentration, in particular after the drastic intensification of the storm, may also obviously suggest that thermodynamically forced sea ice decrease dominated in the study domain, even if there is an increase in sea ice concentration due to dynamically forced sea ice deformation for the pack ice. We therefore focused on sea ice energy budget analysis.

Figure 3. Daily averaged (a) net surface shortwave radiative flux ($F_{SW}$), net longwave radiative flux ($F_{LW}$), sensible heat flux ($F_S$), and latent heat flux ($F_L$), and (b) the total energy into the open water (red) and sea ice (blue) surfaces. (c) Cloud conditions are shown by selected all sky camera images with the number on the up-right corner indicating the days in August 2016.
The net surface shortwave radiative flux $F_{SW}$ (positive flux downward; weighted by sea ice and open water areas; the same for the net longwave radiation $F_{LW}$ and the turbulent heat fluxes, sensible heat flux $F_S$ and latent heat flux $F_L$, below) dominated throughout the study period (Figure 3a). It ranged from about 40 W/m$^2$ to 120 W/m$^2$, considerably larger than other energy flux terms. $F_{SW}$ was generally smaller during 13-19 August when the storm influenced the study domain. In particular, $F_{SW}$ decreased to reach a minimum on 15 August along with the drastic intensification of the storm. Further analysis indicated that the $F_{SW}$ decrease was mainly caused by the reduced downward shortwave radiation. This can be attributed to an increase in cloudiness as shown in the sky camera imageries (Figure 3c), especially considering that the decrease in sea ice concentration reduced upward shortwave radiation. $F_{SW}$ largely increased when the intense storm decayed and dissipated after August 19 and clear sky started to occur.

The net longwave radiative flux $F_{LW}$ and turbulent heat fluxes ($F_S$ and $F_L$) were generally negative, except the positive values of $F_S$ on 15 and 16 August when the northward intrusion of warm air occurred. Since 17 August, $F_{LW}$ and $F_L$ showed an obvious increase in magnitude with time, though $F_S$ is smaller than the other two terms. This suggests an increasing heat loss with time by these three heat budget terms, which can be attributed to a combination of a number of contributing factors. One is the warmer sea ice surface temperature than overlying air temperature. The air temperatures generally dropped down to about -2.0 °C at the observation site from 17-21 August (Figure 1h). But sea ice surface temperature was around the melting point from the in-situ observations at the ice-camp, which is consistent with previous observations and climatology during this summer season (e.g., Perovich et al., 2007). Also, the near surface ocean temperature measured by CTD was around -1.2 °C. The differences between sea ice/ocean and air increase vertical gradient of temperature and humidity as well as decrease near surface boundary layer stability, leading to increased upward turbulent heat fluxes. This temperature differences can also be manifested by the decrease in downward longwave radiation measured onboard Araon.

As a result, the net total surface heat flux demonstrated positive values, predominantly determined by the net shortwave radiation, with an obvious decrease from 13-15 August when the intense storm dominated in the area (Figure 3a). The two minimum values on 14 and 19 August were ascribed to relatively large heat loss by the negative net longwave radiation and turbulent heat fluxes due to the cold surface air temperatures and decreased cloudiness (Figure 1h and 3c).

The positive net total heat flux indicates a gain of heat energy by sea ice and ocean surfaces as a whole. To better understand its role in sea ice melt, we further quantified the amounts of the total heat energy into sea ice and open water surface, respectively (Figure 3b). In contrast to the total heat flux, the result shows a large heat loss from sea ice surface in spite of slight heat gain on 13 and 15 August. The largest heat loss occurred on 19 August when the negative net longwave radiation and latent heat flux became relatively large but the positive net shortwave radiation had not greatly increased. This temporal variation suggests that changes in sea ice surface heat budget did not contribute to the accelerated sea ice melt during the storm process (Figure 2). Nevertheless, the open water surface in the study domain gained heat energy due to the increased net total heat flux (Figure 3a) and decreased sea ice concentration (Figure 2), which may contribute to mixed layer ocean temperature increase and therefore sea ice bottom melt.

To have a complete understanding of thermodynamic and dynamic effects on sea ice energy budgets and accelerating sea ice melt under the forcing of the intense storm, we analyzed the vertical profiles of temperature and salinity measured by the two groups of CTDs and conducted diagnostic analysis of Ekman dynamics associated with the winds observed...
onboard the RBRV Araon. The temperature and salinity profiles show homogenized structures with almost the same values from near-surface down to about 20-30 meters, suggesting a well-mixed SML. This depth is well consistent with that of the diagnosed Ekman layer, suggesting a dynamic role of the storm in increasing upper ocean mixing process. As described above, the storm drastically intensified from 15-16 August (Figure 1). Correspondingly, the observed in-situ windspeed obviously increased and generally stayed stronger though there was a weakening on 16 August (Figure 1g). The stronger wind generated deeper Ekman layer and, in turn, SML than their climatologies in the region (e.g., Peralta-Ferriz and Woodgate, 2015). The small decrease in the depth of the Ekman layer from 06 UTC to 19 UTC on 16 August can be attributed to the slightly weakened winds at the same time. Similarly, a well-mixed mixed layer with almost same temperature extended from about 20 meters at 02 UTC to 30 meters at 11 UTC on 19 August along with the largely increased windspeed during the same time period when the storm reenergized due to a merging process with a newly develop small storm as discussed above (Figure 1).

A further comparison demonstrates a consistent warming change in the mixed layer within each group on both 16 and 19 August, respectively, with a considerably larger increase on the latter day. In contrast, the maximum warm temperatures from 30-70 meters in Group 1 and 50-80 meters in Group 2 largely decreased, indicating a cooling change of the Pacific-origin warm water layer. Meanwhile, an increase in temperature occurred in the layer just beneath the mixed layer and above the Pacific warm layer from 20-30 meters in Group 1 and 40-50 meters in Group 2. All of these changes could be ascribed to storm-induced changes in ocean dynamics. These vertical ocean temperature changes can be attributed to the Ekman pumping, which leads to vertical heat transport into the mixed layer and an elevation of the Pacific warm water layer and a weakening of the original Pacific warm water layer.

### 3.4 Evaluate model simulations of Arctic weather and climate and reduce the most prominent model biases and errors.

By using the in-situ observations onboard IBRV Araon, we have also conducted modeling activities. We have employed the latest version of WRF model to do experimental weather forecast during the Araon expedition during the summer of 2016. The new version of the WRF uses the physical parameterizations and treatments we have selected for the best performance in the Pacific Arctic Ocean using an earlier version of WRF, except sea ice thermodynamics we have coupled. The selected model output was archived and transferred to Dr. Joo-Hong Kim’s group for multi-model comparison and evaluation of Arctic weather simulation and forecast. Identification of biases would provide information for improving the model.

At the same time, we have also carried out sea ice-ocean coupled simulations using NCAR’s CESM to simulate impacts of Arctic storms. The sea ice-ocean component model CICE-POP was optimized through sensitivity experiments. After one-hundred-year spin-up simulation when sea ice and upper ocean hydrographic properties and circulation reached a quasi-equilibrium state, we have conducted a transient simulation from 1981-2018. Based on this simulation and reanalysis data, representative storms were selected. Composite analysis was used to examine impacts of storms on sea ice and ocean within their influencing areas. The preliminary results indicate that sea ice generally decreases when storms approach the study area, while sea ice either continuously decreases or increases when storms move away from the study area depending on the sub-region of the Arctic Ocean.
Chapter 4 Degree of Research Goal Achievement and Degree of Contribution to Outside Research Institute

The research goal is to improve understanding of the role that more frequently occurring synoptic storms in enhancing air-ice-sea interactions in the dramatically changing Arctic climate, and improve Arctic climate modeling ability. Through this research, we have made sound progress on achieving this goal. The research results provide new insights into the dynamic and thermodynamic processes responsible for the enhanced air-ice-sea interactions induced by storm. Due to the rare field observations of storms and sparse observational network, observational data analysis of sea ice melt and grow have been mostly focusing on ocean and sea ice surface. The research from this project for the first time reveals that the storm-driven upper ocean dynamics plays an important role in accelerating sea ice melt during the storm process. The new research finding would significantly contribute to the community and other institutions (in particular modeling centers) for understanding, simulating, and predicting storm forced extreme changes in sea ice and ocean.
Chapter 5 Application Plans of Research Results

Based on the results from this project, we plan to carefully include sea ice and upper ocean modules in the WRF model so that air-ice-sea interactive process can be better represented, which would enhance model ability to accurately improve simulations and forecasts of the storm-forced extreme changes in surface meteorological conditions, sea ice melt/growth and distribution, and ocean mixed layer temperatures.
Chapter 6 References


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