Oceanic Supply of Ice-Nucleating Particles and Its Effect on Ice Cloud Formation: A Case Study in the Arctic Ocean During a Cold-Air Outbreak in Early Winter

Jun Inoue1,2, Yutaka Tobo1,2, Fumikazu Taketani3, and Kazutoshi Sato4

1National Institute of Polar Research, Tachikawa, Japan, 2The Graduate University for Advanced Studies, SOKENDAI, Tachikawa, Japan, 3Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan, 4Kitami Institute of Technology, Kitami, Japan

Abstract  The relationship between cloud phase, ice-nucleating particles (INPs), and ocean state is vital in climate system modeling. High wave conditions induced by the Arctic sea-ice decline and intensified atmospheric forcing over the ice-free ocean increase dynamical geochemical oceanic mixing and sea spray supply containing organic substances, which could act as INPs promoting formation of lower tropospheric ice-containing clouds. Here, we show that the surface ocean state regulates INP concentration and ice cloud presence in the boundary layer. Arctic research cruise data from the marginal ice zone in the Chukchi Sea in November 2018 revealed high number concentrations of INPs active greater than −10°C and ice-containing clouds under high wave conditions. Chemical analysis revealed high contents of organic carbon and sea salt that coincided with the increased oceanic turbidity. The findings suggest that elevated levels of marine organics will contribute to modification of cloud phase from liquid droplets to ice crystals.

Plain Language Summary It is recognized that global warming is causing sea ice loss and more frequent occurrence of active weather systems in the Arctic region. Stronger winds over larger areas of exposed Arctic Ocean can lead to bigger waves that could cause particles of organic matter in the seawater to become dispersed in the lower atmosphere via sea spray. These particles could enhance the processes that lead to cloud formation. Our study investigated whether the introduction of such particles into the air would specifically promote the development of ice-containing clouds, which might then lead to increased regional snowfall that could contribute to preservation of the sea ice. Analysis of oceanic and atmospheric data, collected during the cruise of a research ship in the Arctic, indicated that strong winds and high waves led to substantial increase in the number of organic matter particles transferred from the ocean into the lower atmosphere, which corresponded to greater quantities of ice crystals in lower-level clouds. However, the coverage and type of clouds in the Arctic not only regulate regional snowfall but also modify the surface heat budget, which could affect the long-term future of Arctic sea ice and have associated global climatic consequences.

1. Introduction

The cloud phase is fundamental information for determining the surface heat budget, particularly in the Polar regions. In comparison with ice clouds, liquid water clouds are more reflective against the shortwave radiation owing to particles’ sphericity and high number concentration of water droplets within the clouds. Mixed-phase clouds in the lower troposphere, which contain both liquid cloud droplets and ice crystals, have considerable influence on the surface heat budget (Morrison et al., 2012). Owing to recent Arctic temperature amplification and decline in the extent of Arctic sea ice, the moisture and temperature environments over the Arctic Ocean have been changed (Screen & Simmonds, 2010), presumably with modification of the surface heat budgets through associated changes in clouds (i.e., cloud cover and phase). However, the current representation in numerical models lacks consensus regarding Arctic cloud feedback associated with Arctic temperature amplification (Alkama et al., 2020; Pithan & Mauritsen, 2014). Increase in both intense cyclonic activity and strong upward turbulent heat flux (Inoue & Hori, 2011) would result in a trend of increased snowfall on sea ice (>2 cm decade−1) over the northern Chukchi Sea during November (Sato &
Inoue, 2018). Although modeling of clouds is an ongoing task (Inoue, Sato, et al., 2021), it remains difficult to distinguish the vertical structure of cloud phase, even in observations.

Satellite data could provide certain salient information from seasonal and regional perspectives. Once the differences in the cloud phase are established at different heights, seasons, and/or locations, the source of their origins (e.g., ice-nucleating particles [INPs] and cloud condensation nuclei) might be speculated. The fractions of ice clouds and liquid water clouds and their vertical structures in the Arctic region have been estimated using the Cloud-Aerosol Lidar with Orthogonal Polarization active sensor (Yamauchi et al., 2018). Through comparison of properties of clouds over the Barents Sea and East Siberian Sea, Yamauchi et al. (2020) revealed that the ice cloud fraction (randomly oriented ice crystals) during winter in the East Siberian Sea is 20% larger than that in the Barents Sea at the temperatures between −25°C and −10°C in the lower troposphere (height <2 km). They speculated that the source of INPs might be related to biological aerosols, mineral dust, ammonium sulfates, and black carbon. Over the terrestrial region of the Arctic, high-latitude dust is the more likely potential source of INPs rather than typical mineral dust transported from low-mid-latitude continental regions (Sanchez-Marroquin et al., 2020; Tobo et al., 2019). However, the magnitude of local supply of INPs from the Arctic Ocean remains poorly defined, particularly under the new state of the Arctic characterized by the recent temperature amplification and decline in sea ice extent. Developing comprehensive knowledge of the evolution and transport of natural aerosols in the Arctic, and the associated effects on cloud microphysics, is vital for understanding the present and future Arctic environment (Schmale et al., 2021).

The expanded open water area in autumn by a sea-ice decline is considered an indicator of a new state of the Arctic Ocean from the perspective of wave condition. Understanding the long-term trend of wave height is essential for identifying the current aerosol environment, particularly that of local aerosol sources. Waseda et al. (2018) reported an increase in the expected largest significant wave height ($\text{sH}$) from 2.3 to 3.1 m in the ice-free water from the Laptev to the Beaufort Seas during October, which they attributed to the decrease in the sea ice extent. The trend of increasing cyclonic activity over the ice-free Arctic Ocean is one potential reason for the observed trend in $\text{sH}$ (Waseda et al., 2021). In comparison with wind speed and $\text{sH}$, the wave Reynolds number is more indicative of sea spray emissions (Yang et al., 2019). Thus, an additional supply of sea spray aerosols would be expected during autumn and early winter.

Recent inflow into the Arctic of abnormally warm water from the Bering Sea, induced by the extreme atmospheric events (e.g., a long-lasting blocking high), has caused delay in the onset of freezing (Kodaira et al., 2020). Higher temperatures provide conditions favorable for the productivity of microorganisms that can effectively serve as INPs. Creamean et al. (2019) demonstrated how biologically derived INPs have likely been transported hundreds of kilometers from deep waters via the Bering Strait, upwelled into the Arctic Ocean surface waters, and become airborne. Potential key processes would be a summertime phytoplankton bloom, bacterial respiration, ocean dynamics, and wind-driven mixing. On the basis of bacterial profiling of shipboard aerosol samples obtained over the Southern Ocean, Uetake et al. (2020) suggested that the marine aerosols likely represent the primary source of cloud-active particles over the oceans, which implies that variation in cloud properties is strongly linked to oceanic biological processes. In the Arctic Ocean, marine organisms are frequently observed over the shelf region in the southern Chukchi Sea. Mooring data obtained at a biological hot spot indicated high concentrations of chlorophyll-a during spring and an autumn bloom (Nishino et al., 2016). The increase in turbidity and decreased dissolved oxygen in the bottom water prior to the autumn bloom are indicative of accumulation of particulate organic matter. On the basis of 2-week hydrographic data obtained at a fixed point in the northern Chukchi Sea, it was found that the wind-driven ocean mixing of the ice-free Chukchi Sea influenced the biological activities through the additional supply of nutrients brought from the bottom layer to the surface waters (A. Fujitwara et al., 2018; Nishino et al., 2015). Strong wind forcing also causes a positive indirect effect on the mesozooplankton through the temporal phytoplankton bloom during autumn within a short period (e.g., a week or less) (Matsuno et al., 2015). Therefore, the surface wind variability during the prefreezing season in the Arctic would be responsible for delivering the source of organic substances into the upper waters.

There is no comprehensive evidence linking ocean structure, sea surface condition, and aerosol/cloud characteristics, including their compositions and states. Using the observational data obtained during an Arctic research cruise during the prefreezing season during a cold-air outbreak, this study investigated how and
when sea spray aerosols are transported from the ocean surface into the atmosphere as INPs for ice cloud formation.

2. Observation

2.1. Cruise Information

The Research Vessel (RV) *Mirai* conducted an Arctic cruise in the Chukchi Sea during November 2018 (Figure 1). During November 10–21, we set a daily repeat section that consisted of several hydrographic stations at fixed points, which included the marginal ice zone (MIZ) (Figures 1 and S1). Although the position of the northernmost hydrographic station varied daily owing to the advance and retreat of the sea ice, the other stations were set up at the fixed points (i.e., 72.5°N, 164°W; 72.25°N, 165°W; and 72.0°N, 166°W). Kodaira et al. (2020) reported physical oceanographic results related to the delay of sea ice advance under the conditions of a cold-air outbreak.

2.2. Method and Data Analysis

A surface meteorological observation system was available on the ship (temperature/relative humidity sensor: HMP155, Vaisala; barometer: Model-370 Setra System; anemometer: KS-5900 Koshin Denki; and wave height meter: WM-2 Tsurumi-Seiki). During this cruise, cloud-base height was monitored continuously using a ceilometer (CL-51, Vaisala). Additionally, we conducted GPS radiosonde (Vaisala RS41-SGP) ascents at 6-h intervals and occasional cloud particle sensor (CPS) sonde observations (Meisei Electric Co., Ltd). The CPS was attached to the Meisei RS-11G radiosonde with the temperature and relative humidity sensors. On November 20, CPS sondes were launched at 01:36, 06:09, and 10:30 UTC (Figure 1). The first one was launched at the northernmost station near the MIZ, whereas the two subsequent CPS sonde observations were conducted over open ocean. It should be noted that RV *Mirai* moved in the downwind direction from the ice edge, on a course almost parallel with the surface wind direction (Figure S1d). Data from three additional CPS sondes launched on November 13, 14, and 16 were also used in this study (Figures S1a–S1c).

The CPS with a dipole sensor and two photodetectors measures the number and radius of cloud particles and obtains cloud-phase information (i.e., liquid, ice, or mixed) each second during its ascent (Fujiwara et al., 2016). This study used only the cloud-phase information obtained by the CPS. The technical details of a CPS are described in full by Fujiwara et al. (2016); therefore, only the essential features are introduced here. A CPS uses a near-infrared laser (typical wavelength: 790 nm) as a linearly polarized light source. Two
silicon photodiodes are placed at angles of 55° (detector no. 1) and 125° (detector no. 2) to the direction of the source light. A polarization plate is placed in front of detector no. 2 so that it receives only light polarized perpendicularly to the light source. The two detectors receive scattered light through slits (0.50 cm × 1.0 cm) placed in front of them. The particle signal voltage from the two detectors \( I_{55} \) and \( I_{125} \) in the range of 0–7.5 V (resolution: 0.03 V). To distinguish between cloud ice and cloud water, the degree of polarization (DOP), as defined by M. Fujiwara et al. (2016), is expressed as 
\[
DOP = (I_{55} - I_{125}) / (I_{55} + I_{125})
\]
When the DOP value is negative, the particle is ice (nonspherical particle). When the DOP value is positive but less than ~0.3, the particle is most likely ice. When the DOP value is more than ~0.3, the particle in many cases is water (spherical particle); however, a DOP value of 0.5 was considered most suitable for minimizing the possibility of counting ice particles as liquid particles based on the field campaigns in the Arctic regions (Inoue, Tobo, et al., 2021).

Ambient aerosol sampling was performed using aerosol samplers installed on the compass deck (18 m a.s.l.). To avoid collecting particles emitted from the ship’s funnel, the sampling period was controlled automatically by a custom-made wind-selector. This system supplied power to the sampling pumps only when the wind speed exceeded 2 m s\(^{-1}\) and came from the forward direction (within ±75° of the bow direction) of the vessel for a period >10 s.

Ambient aerosol samples for INP analysis were collected at a flow rate of 10 L min\(^{-1}\) on precleaned Whatman Nuclepore track-etched membrane filters (diameter: 47 mm, pore size: 0.2 \(\mu\)m), which were mounted in an MCI open-face filter holder system (Tokyo Dylec Corp.) and covered with a rain shield. To quantify the number concentrations of immersion-mode INPs at standard temperature and pressure (0°C and 1 atm) conditions, the ice-nucleating ability of the ambient aerosol particles collected on the filter was measured using the Cryogenic Refrigerator Applied to Freezing Test (CRAFT) in a temperature regime as low as −30°C (Tobo, 2016). The basic procedures for measuring the INP number concentrations using the CRAFT system were largely the same as those reported previously (Tobo et al., 2019, 2020). After extraction of the aerosol particles into Milli-Q purified water (≥18 MΩ cm), freezing experiments were performed using the particle-containing droplets (5 \(\mu\)L in volume) at a cooling rate of 1°C in the CRAFT system. To further examine the contributions of heat-sensitive organic substances (e.g., proteins) to the INP populations, additional freezing experiments were conducted using the droplets after heat treatment (the samples were boiled for ~60 min).

For chemical composition analysis, ambient aerosol particles with diameters <2.5 \(\mu\)m were collected on prebaked (900°C for 3 h) quartz filters (8” × 10”) using a high-volume air sampler (HVS, 120SL, Kimoto Electric Co., Ltd) with an impactor (HVI-2.5, Tokyo Dylec Co.) at a flow rate of 740 L min\(^{-1}\) over 2–3-day period. Prior to analysis, the samples were stored in a freezer at −20°C. Water-soluble mass concentrations of \(\text{Na}^+\) and \(\text{Cl}^-\) were analyzed by ion chromatography (ICS-1500, DIONEX). Mass concentration of organic carbon (OC) was determined using a thermal/optical carbon analyzer (DRI, Model 2001A) and following the Interagency Monitoring of Protected Visual Environments protocol.

As the cruising speed of the ship changed frequently when the observations were conducted (e.g., conductivity-temperature-depth [CTD] casts and radiosonde launches), the \(H_s\) data might contain the irregular variations (gray line in Figure 2d). To reduce such variability, a 3-h running mean was applied to the raw data (black line in Figure 2d). According to Nose et al. (2020), the values of \(H_s\) from ERA5 (Hersbach et al., 2020) and Arctic Monitoring and Forecasting Center (ARCMFC) (Carrasco et al., 2021) are well represented in this area; however, they tend to be overestimated at the MIZ because of negative bias associated with sea ice concentration (Nose et al., 2020) and the relatively large uncertainty regarding surface wind attributable to the lack of observational data for data assimilation (Nose et al., 2018). Therefore, we used the observed values of \(H_s\) to calculate the additional following parameters. The wave Reynolds number \(R_{HR}\), introduced to reflect the joint effect of wind and wave state, can be expressed as 
\[
R_{HR} = (u_* H_s) / \nu
\]
where \(u_*\) is friction velocity, \(H_s\) is the significant wave height, and \(\nu\) is a kinematic viscosity.

The value of \(u_*\) is estimated using the relationship

\[
\frac{u_*}{u_{ao}} = \frac{1}{K} \ln \frac{z_0}{z_0^*}
\]
where \(u_*\) is the wind speed at \(z_s\), \(\kappa\) is the Kármán constant (= 0.387) (Andreas et al., 2006), and \(z_0\) is the roughness length for the open ocean (= 0.0002) (Wieringa, 1992).
CTD casts were made at several stations using various sensors (SBE9plus, SBE03-04/F, and SBE04C, Seabird Electronics Inc.) with the turbidity meter (Seapoint Sensors, Inc.) to measure the depth dependence of sea information. Data of temperature and turbidity in the near-sea surface water ∼5 m below along with ship truck by the Continuous Sea Surface Water Monitoring System installed several sensors (SBE-45, Seabird Electronics Inc.; RINKO II; JFE Advantech Co., Ltd; C3, Turner Designs, Inc.; and HGTD-Pro, Pro Oceanus Systems Inc.) were also used for the analysis. The turbidity by the Continuous Sea Surface Water Monitoring System ($T_{b_{CTD}}$) values were corrected using the turbidity by CTD ($T_{b}$) values at 5-m depth due to the different instrument. On the basis of data at 75 stations along the MIZ transect, the regression line for correction of the surface turbidity data was derived as $T_{b_{CTD}} = 0.1073T_{b_{CTD}} - 0.6065$, with a correlation coefficient of 0.923.

The number of water samples obtained was minimal; however, stationary CTD casts during the MIZ transect were conducted continuously over a 10-day period. Although we had several CTD points along the MIZ transect (Kodaira et al., 2020), we used the CTD point at 72.5°N, 162.0°W, that is, a central CTD point along the MIZ transect (Figure 1). Kodaira et al. (2020) reported that the water stratification was weak along the

![Figure 2](image-url)
MIZ transect during this cruise. The obtained turbidity data were used in this study to understand how the marine organic matters mixed and upwelled into the surface layer (Nishino et al., 2016).

3. Results

Two phases characterized the synoptic situation during the cruise. The first phase had marked wind speed variability with reasonably high air temperatures (i.e., −9°C −3°C until November 17 (Figures 2b and S2a). A strong southwesterly wind accompanied by a warm air mass prevailed around November 15 (Figures 2a and S1b). The second phase had quasi-stationary conditions characterized by a cold northeasterly wind from the sea ice area (Figures 1 and S1d). The air temperature decreased gradually during November 17–20 (Figure 2b), while the wind speed reached a maximum during November 20–21 (Figure 2c). The air-sea temperature difference became as large as 5°C–10°C during this phase, causing substantial transport of heat and moisture through turbulent heat fluxes. Sea surface temperature during this month was a record maximum, which promoted the delay of sea ice advance in this area (Kodaira et al., 2020).

The vertical profiles of air temperature with DOP values obtained by the CPS sondes are shown in upper panels in Figure 3. During November 12–17, the top of the boundary layer exceeded 1,200 m, which corresponded to the level with high relative humidity (Figure 2a). Cloud-base height (black horizontal bars in Figures 3a–3c) was above the 600-m level. This was a common feature in the early period of the MIZ transect until November 17 (Figure 2a). The DOP values (indicated by colored marks when the relative humidity was >97%) were often >0.7, suggesting that spherical particles (i.e., supercooled droplets) dominated...
in the cloud layers. Air temperature in the cloud layer ranged between −15°C and −9°C that is, relatively high for ice nucleation without INPs. According to the vertical profiles of potential temperature (Supporting information Figures S3a–S3c), the cloud layer was limited to the upper part of the mixed layer for each case. On November 20, the occurrence of a cold-air outbreak from the ice-covered area (Figure 1) caused the air mass modification over the open ocean. The surface air temperature increased from −10°C at the MIZ to −6°C downstream, with an increase in the boundary layer height from 600 to 950 m (Figure 3d). The mixed layer was largely filled with low-level clouds during this period (Figure S3d). The cloud-base height also increased from 200 to 400 m (Figures 2a and 3d), suggesting that turbulent heat fluxes contributed to formation of the cloud-free layer. A notable feature is that the lower part of the cloud layer contained nonspherical particles (most likely, ice crystals) with lower DOP values (<0.5). Importantly, the temperature range within the clouds was almost the same as on November 13, 14, and 16, suggesting the possibility of enhanced INP conditions associated with the cold-air outbreak on November 20.

The number concentrations of INPs sampled onboard the RV Mirai support the differences in cloud characteristics. During November 20–21, the number concentration of INPs was 1 order of magnitude higher than that during the earlier period (black dots in lower panels in Figure 3), and even higher values were found in the temperature regime greater than −10°C. The presence of INPs active greater than −13°C corresponds to lower DOP values in the bottom part of the clouds on November 20 at the MIZ. The INP number concentrations measured using the samples heated to ~100°C (open circles in lower panels in Figure 3) were ~1 order of magnitude smaller than the untreated ones; specifically, INPs active greater than −14°C were rarely detected after heat treatment, suggesting substantial presence of organic substances in the untreated samples in the case of November 20. Therefore, the marked difference in the phase of the lower part of the cloud layer before/after November 20 could be attributed to the differences in the supply of INPs near the sea surface.

Variability of winds and waves is one of the potential indicators for understanding the supply process of INPs from the sea surface through bubble bursting and jet drops near the microlayer (Wilson et al., 2015). Early on November 21, the $R_H$ value, which is a function of surface wind speed and $H_H$, was nearly double than that of the previous peaks on November 15 and 17–20 (a black line in Figure 4c), indicating conditions favorable for introducing INPs into the atmosphere through sea sprays. However, this high value of $R_H$ does not always explain the increase in INPs active at higher temperatures. According to the chemical composition analysis of ambient aerosol particles, a high mass concentration of OC (1.4 μg m$^{-3}$) with a high content of sea salt was retrieved from the sample collected between 01:28 UTC November 20 and 23:22 UTC November 21 (blue and green lines in Figure 4b), whereas the OC value of most samples obtained before November 18 was <0.8 μg m$^{-3}$, except for the sample on November 15. These results imply that the surface ocean state is closely linked to abrupt changes in OC, INPs, and cloud phases in the atmosphere.

Though data on seawater organics were not available on this cruise, turbidity is useful for investigating how the water mass was mixed/changed near the surface, because the high-turbidity water is usually observed at the bottom as a result of benthos activity (Nishino et al., 2016). The high turbidity at the 5-m depth on November 21, with gradual increase from November 20 (Figure 4d), is consistent with the increase in atmospheric OC. This supports the assertion that organic matter in high-turbidity water can be supplied into the atmosphere via sea spray under high $R_H$ conditions. However, the secondary peak of the atmospheric OC on November 15 does not match the variability of the turbidity well, partly because of the different atmospheric conditions with an opposite wind direction (i.e., southwesterly, as shown in Figures 2a and S1b).

It is well known that the southern Chukchi Sea is a marine biological hot spot. For example, Nishino et al. (2016) found that turbidity increased and dissolved oxygen decreased in the bottom water at a mooring site prior to the autumn bloom, suggesting accumulation of particulate organic matter and its decomposition (nutrient regeneration) at the bottom. In our monitoring of the surface water of the MIZ, the dissolved oxygen was also found to have decreased on November 21 (not shown), indicating that the bottom water with high content of organic matter had reached the sea surface. The daily vertical profile of turbidity at 72.5°N 164.0°W during the MIZ transect (Figure 4e) shows that a vertically mixed water mass was evident during November 20–21. Although this is consistent with the surface turbidity at the 5-m level, the structure remained decoupled on November 15, despite relatively large values near the surface. The continuous strong surface winds and/or a change in the water mass could account for the well-mixed condition of the
Based on the 3-day mean salinity profiles (Figure S4), there was a strong stratification at 35-m depth in the early stage. Even in the middle of the period, the 40-m deep mixed layer was independent of the higher turbidity layer near the seafloor. At the last stage, finally, a well-mixed layer reached the seafloor. This development of an ocean mixed layer that eventually penetrates to the seafloor may tap into a reservoir of ice-nucleating entities in the seafloor by providing the turbulent kinetic energy required for suspension, in addition to vertically mixing active biology at or near the base of the water column.

Another mechanism for a change in the water mass might be the upwelling of the Atlantic water (warm and saline water) at the Barrow coastal region. Northeasterly winds, correlated with the north-south atmospheric pressure gradient between the Beaufort High and the Aleutian Low, are considered as a common trigger of such upwelling (Hirano et al., 2018). Although our CTD data do not indicate the high salinity, most of the water masses are thought to be transported westward or northwestward with the Chukchi slope current near the Beaufort Gyre.
Overall, the observed rapid change in the surface sea conditions, including winds, waves, and water mass, would contribute to the activation of the supply of INPs active at higher temperatures. Consequently, the formation of ice clouds was enhanced after the cold-air outbreak event in November.

4. Conclusions
On the basis of field observations acquired during an Arctic research cruise by the RV Mirai during a cold-air outbreak situation, the potential impact of the supply of INPs from the ocean mixed layer on ice cloud formation in the marine boundary layer was investigated. When the ice crystals were detected in the lower parts of boundary layer clouds under the high wave and strong wind conditions on November 20–21, 2018, INPs increased by 1 order of magnitude in comparison with the earlier period. Because most INPs are sensitive to heating to \( \sim 100^\circ \text{C} \), the INPs were considered to originate from certain marine organic substances. Chemical analysis of ambient aerosols indicated a high amount of OC associated with high content of sea salt, suggesting that the sea spray aerosols potentially represent a major source of INPs. The CTD casts along the repeat transect indicated that the observed sudden increase in oceanic turbidity from the seafloor to the surface coincided with the increase in INPs.

Cold-air intrusions from the ice-covered region during the freezing season are characteristic of the seasonal progression in polar regions. However, the surface boundary conditions in the Arctic regions have changed owing to decline in sea ice extent and delay in onset of freezing (Kodaira et al., 2020). The trend of increase in \( H_\text{s} \) over the ice-free ocean during late autumn and early winter (Waseda et al., 2018) will modify the exchange processes (e.g., heat, moisture, and momentum) and the supply of biochemical substances. The increased presence of ice clouds over the MIZ might lead to increased snowfall (Sato & Inoue, 2018) through the efficient snow conversion from ice crystals and intensification of surface cooling due to diminished downward longwave radiation (Inoue, Sato, et al., 2021), which presumably might contribute to advances of sea ice extent. Although our results are based on a single case study, a polar continental shelf would be one of the favorable regions for supplying marine-origin INPs. Moreover, it is recognized that events with high waves and strong winds would be instrumental in the supply of oceanic biochemical substances to the atmosphere and ice cloud formation. Such situations are frequently found in the MIZ in the Southern Ocean. Comprehensive and well-coordinated oceanic and atmospheric observations would be desirable for improving the overall understanding regarding the uncertainty of modeling clouds in polar regions.

Data Availability Statement
The CPS sonde data (https://ads.nipr.ac.jp/data/meta/A20210616-007), the surface meteorological and ocean data (https://ads.nipr.ac.jp/data/meta/A20210803-001), and \( N_{\text{INPN}} \) values and chemical analysis results (https://ads.nipr.ac.jp/dataset/A20210728-001) are publicly available through the Arctic Data archive System (ADS).

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