Acta Oceanol. Sin., 2025, Vol. 44, No. 3, P. 3–34
https://doi.org/10.1007/s13131-025-2466-4

Overview of the studies on the interactions between atmosphere, sea ice, and ocean in the Arctic Ocean and its climatic effects: Contributions from Chinese scientists

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Received 5 October 2024; accepted 16 December 2024

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Abstract

The year, 2024, marks the 40th anniversary of Chinese research expeditions in the polar regions and the 25th anniversary of its Arctic research expeditions. China has conducted 14 national Arctic research expeditions. With the increase of understandings on the global impacts of the changes of Arctic climate system, especially on China's weather and climate, and demands for commercial utilization of the Arctic sea routes, Chinese scientists have made great progresses on in site and remote sensing observation technologies for Arctic Ocean, interaction mechanisms between atmosphere, sea ice, and ocean, the connection mechanism between the Arctic Ocean and other regions, and have achieved a series of research results. This study summarizes the research achievements by Chinese scientists in the above-mentioned aspects or beyond, identifies knowledge gaps, and based on this, discusses prospects and provides suggestions. From a perspective of observation, improving the observation capabilities of the Arctic Ocean in winter and the ocean under the ice, as well as floe-scale processes of sea ice and mesoscale and submesoscale processes of the ocean, is an urgent task to be addressed. Strengthening international cooperation is necessary for building a monitoring network for the Arctic marine environment. From a perspective of numerical simulation, the descriptive ability and parameterization scheme of sub-grid processes based on observational evidence need to be developed. From a perspective of cross-sphere interactions, in addition to the multi-media coupling within the Arctic Ocean that this review focuses on, the interaction between the Arctic Ocean and land or ice sheet (Greenland), especially the water cycle process, is also a scientific domain that needs to be considered, in the context of Arctic warming and humidification. From a perspective of climate effects, the physical mechanisms that affect the robustness of teleconnection need to be clarified.

Key words Chinese National Arctic Research Expedition (CHINARE), Arctic Ocean, atmosphere, sea ice, climate

Citation Lei Ruibo, Zhang Fanyi, Yang Qinghua, Zhang Ruonan, Zhong Wenli, Shu Qi, Ding Minghu, HuiFengming, Min Chao. 2025. Overview of the studies on the interactions between atmosphere, sea ice, and ocean in the Arctic Ocean and its climatic effects: Contributions from Chinese scientists. Acta Oceanologica Sinica, 44(1): 1–32, doi: 10.1007/s13131-025-2466-4

Foundation item: The National Natural Science Foundation of China under contract Nos 42325604 and 42276253; the Program of Shanghai Academic/Technology Research Leader under contract No. 22XD1403600; the Fund of the Ministry of Industry and Information Technology of China under contract No. CBG2N21-2-1.

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1 Introduction

In our planet, the Arctic system is relatively independent but not isolated. The heat inflows from lower latitudes through ocean and atmospheric circulations play an important role in maintaining the energy balance in the Arctic system. Combined with local feedback mechanisms such as feedbacks of ice-albedo, cloud/water vapor-radiation, Planck, temperature lapse rate (Wu et al., 2019), the climate warming of the Arctic is amplified, which is 2–4 times higher than the global average, depending on the seasons and regions. The annual warming rate over the Arctic is 0.71℃/decade during 1979–2020, which exceeds that for global average (0.19℃/decade) (You et al., 2021). Seasonally, the warming in the Arctic was more prominent in autumn and winter. The amplification of Arctic warming is closely coupled with local interactions between atmosphere, sea ice, and ocean, associated with rapidly loss of Arctic sea ice, with the average annual minimum during 2000–2021 is 36% less than that during 1980–2000 (Shokr and Ye, 2023), and profoundly affects the biogeochemical cycles across multi-sphere, especially the cycle of greenhouse gases and biogenic elements (e.g., Christensen, 2014; Yue et al., 2023). As the most sensitive region of global climate change, the Arctic is an ideal region for conducting the mechanism research and assessment of climate change, and the knowledge gained from this region can guide climate change monitoring, assessment, and adaptation in other regions. In addition, changes in Arctic climate and marine environment prominently affect the marine ecosystem through exerting impacts on the key biological communities and their spatial distribution, as well as the primary productivity, through changing oceanic temperature, photosynthetic energy, dissolved oxygen, nutrients, and acidity, etc. (Solan et al., 2020).

The changes in Arctic climate system have significant impacts on human sustainable development within the region and beyond. The warming of the Arctic and the decrease in sea ice have further improved the utilization value of Arctic sea routes. In the summer of 2013, the first container vessel crossed the Arctic Ocean, reducing the transportation time from China to Europe by about two weeks. In this year, the Chinese cargo vessel also began commercial using the Arctic Northeast Passage. However, Arctic sea ice and extreme marine environments remain the main challenges constraining the utilization of Arctic sea routes (Lei et al., 2015). The rapid reduction of Arctic sea ice is accompanied by changes in its thermodynamic and dynamic properties, and its coupling with the lower atmosphere and upper ocean has undergone noticeable changes, increasing the uncertainty of numerical simulations of sea ice. The improvement of Arctic sea ice forecasting and prediction is an important foundation for supporting the medium- and long-term planning of the commercial utilization of Arctic sea routes, assessing the navigability of the sea routes, and ensuring shipping security in ice-covered waters.

Relative to the Antarctic system, the Arctic system has a closer connection with lower latitudes, and a closer relationship with multidimensional human activities. Particularly, the Arctic climate change has created a serious impacts on the natural environment and infrastructure that indigenous peoples rely on (Hjort et al., 2018). With the rapid warming of the Arctic, the Eurasian continent has shown a cooling trend in winter, which is known as the "Warm Arctic Cold Continent" pattern (Mori et al., 2014; Kug et al., 2015). Thus, the improvement of understanding of the Arctic climate system and involved atmosphere-ice-ocean interactions can provide a new perspective for enhancing the predictability of extreme weather and climate in Eurasia, thereby mitigating the harm and economical loss.

It is precisely because of the rapid changes and widespread impacts of the Arctic climate system, multiple components of the Arctic climate system, including sea ice, permafrost, vegetation, and the Greenland ice sheet, are considered to be in a critical state. These changes are often irreversible, far-reaching, and have global impacts. Therefore, improving the predictability of the Arctic climate system and its crucial components has become an scientific challenge that urgently needs to address. Among them, predicting changes in Arctic sea ice is considered one of the "major challenges" in global climate science. The Year of Polar Prediction (YOPP), the flagship activity of the World Meteorological Organization's (WMO) Polar Prediction Project (PPP) has the major aim to enable significant improvement in environmental prediction capabilities for the polar regions, especially for the sea ice (Bauer et al., 2020). The Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition organized by Germany and guided by the International Arctic Science Committee (IASC), has main motivations to obtaining observed data on the interactions between the atmosphere, sea ice, ocean, and biota in the central Arctic Ocean through the year, identifying the impact mechanism of energy and mass exchanges between atmosphere and ocean on Arctic climate change and sea ice reduction, and improving the overall predictive ability of the Arctic climate system (Shupe and Rex, 2022).

The Chinese National Arctic Research Expedition (CHINARE-Arctic) began in 1999. From the beginning, revealing and understanding the changes in Arctic sea ice and marine environment, as well as their climate effects, and based on this, improving the assessment and prediction capacity of the Arctic climate system have been one of main motivations of CHINARE-Arctic. Since the fourth International Polar Year (2007–2008), China has actively increased its efforts in Arctic expeditions and researches. So far, China has conducted 14 CHINARE-Arctic cruises. In the summer of 2020, during the eleventh

CHINARE-Arctic cruise, the icebreaker R/V *Xuelong 2*, built in China, began to be used for oceanographic surveys in the Arctic Ocean, enhancing investigation capabilities. During recent years, Chinese scientists also have actively participated in the Arctic international cooperation programs such as YOPP and MOSAiC, making contributions to the practice of addressing climate change in the Arctic.

The year, 2024, marks the 40th anniversary of Chinese research expeditions in the polar regions and the 25th anniversary of its Arctic research expeditions. It is necessary to summarize the achievements derived from previous expeditions and related researches in order to identify the gaps and provide supports for planning of expeditions and researches in the future. To promptly share the research results of a certain CHINARE-Arctic cruise, the Journal *Acta Oceanologica Sinica* has organized multiple special issues (e.g., Lei and Wei, 2020). In addition, Li et al. (2023) have systematically reviewed the recent progresses of China concerning climate change researches for both Arctic and Antarctic regions over the last decade. But it is not a review specifically focusing on Chinese scientific expeditions in the polar regions. Lei et al. (2017) have reviewed the researches of Arctic sea ice observation and the relative physical studies based on CHINARE-Arctic cruise from 1999 to 2016. However, a systematic review of China's researches, since the beginning of CHINARE-Arctic, on the mechanism and climate effects of the coupling processes between atmosphere, sea ice, and ocean in the Arctic Ocean has been lacking. Thus, it is not conducive to expanding interdisciplinary researches based on the observation and sampling during the CHINARE-Arctic cruises, and to optimizing the discipline configuration, observation strategy, and survey regions for future CHINARE-Arctic cruise.

In this review, we provide a detailed introduction to the progresses of CHINARE-Arctic cruises, as well as the in site and satellite remote sensing observation techniques applied for Arctic Ocean monitoring in Section 2; review the research progresses of Chinese scientists on the physical processes of atmosphere, sea ice, and ocean and their coupling mechanisms in the Arctic Ocean, in Section 3; summarize the research progresses of Chinese scientists on Arctic sea ice forecasting and prediction, as well as their applications, in Section 4; introduce the main achievements of Chinese scientists in the field of the impacts of Arctic sea ice loss and climate change on mid-latitude weather and climate in Section 5; identify knowledge gaps and discuss the key sub-branches that need to be strengthened in the researches on the observation, mechanism, prediction, and climate effect of the Arctic atmosphere-ice-ocean system in Section 6; and give a summary finally (Section 7). Note that, our review work mainly focuses on the physical coupling mechanisms and interactions across multi-sphere in the Arctic Ocean. The researches on the biogeochemical cycles across multi-sphere, and the changes in ecosystems and biodiversity in the Arctic Ocean are beyond our scope, although these studies are very important for the Arctic system and Chinese scientists have also made massive efforts and contributions on these topics. This is mainly to summarize achievements and identify core gaps in a more concentrated manner in the field of physical coupling. In terms of spatial scope, this study mainly focuses on the investigations and the physical processes in the Arctic Ocean, rather than the territorial processes, although China has also conducted extensive researches on multi-sphere coupling based on the Chinese Arctic Yellow River Station, established in Ny-Ålesund, Svalbard in 2004.

2 Development of observation technology and survey implementation

2.1 *In site observation technology and survey implementation*

In the 1990s, China purchased one icebreaker from Ukraine and, after renovation, initially built a marine scientific survey platform for the polar regions on the basic of this icebreaker, R/V *Xuelong*. In 1999, China dispatched its first research expedition to the Arctic Ocean, which became a milestone in the field of oceanographic surveys or field observation experiments of earth science in China (Chen, 2002) (Fig. 1). The observation of the coupling system of atmosphere, sea ice, and underneath ocean based on ice camps during this Arctic expedition has pioneered China's oceanography survey in the polar regions and provided an operation paradigm for subsequent CHINARE-Arctic cruises. However, this Arctic expedition also demonstrated quite a few limitations, such as the severe lack of ice navigation services supporting by satellite remote sensing or sea ice forecasting. In addition, on the ice camp, only the eXpendable sensor of Conductivity Temperature and Depth (XCTD) was used to observe the profiles of ocean temperature and salinity beneath the ice layer. These limitations have also become aspects of optimization efforts for the subsequent CHINARE-Arctic cruises.

Due to budget constraints, the CHINARE-Arctic cruise was intermittently implemented in the first few years since 1999. The discontinuous observations have limited understanding of the rapid changes in the Arctic Ocean. In the process, the strengthening of international cooperation, as well as the advancement of the oceanographic measurement technologies in the ice-covered waters, have gradually enriched the instruments applied in the CHINARE-Arctic cruises. For instance, the application of underwater Autonomous Remotely-operated Vehicle (ARV), e.g., Polar ARV, and Autonomous Underwater Vehicle (AUV), e.g., TS-4500 and Xinghai 1000 (Fig. 2), have supported the acquisition of marine physical and ecological data under the ice, as well as the observation of ice bottom morphology (Li et al., 2011; Lei

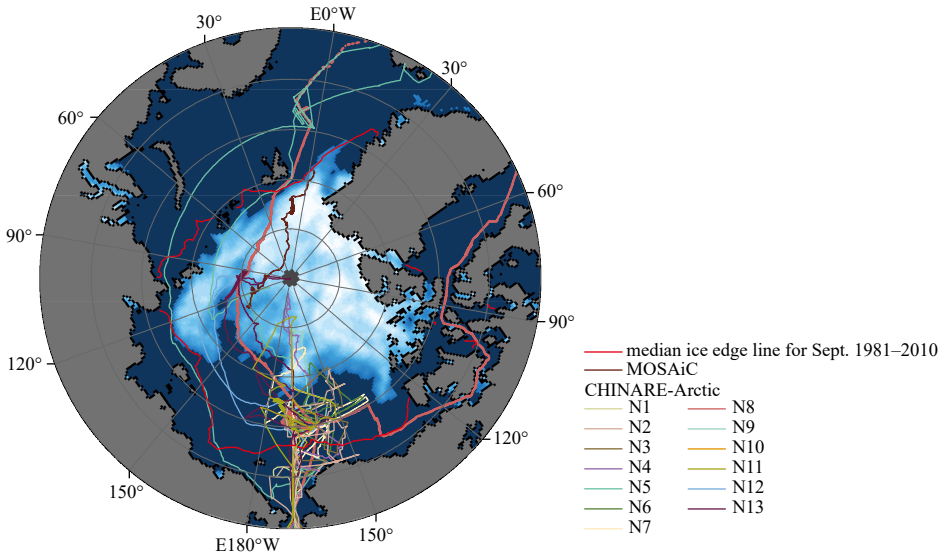


Fig. 1. Trajectories of the ship north of 70°N during the first to thirteenth Chinese National Arctic Research Expedition (CHINARE-Arctic) cruises (N1–N13) and the drifting trajectory of Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC) ice camp. Also shown is the ice concentration obtained on 17 September, 2023, with the annual minimum ice extent being observed, and the monthly averaged ice edge in September 1981–2010.

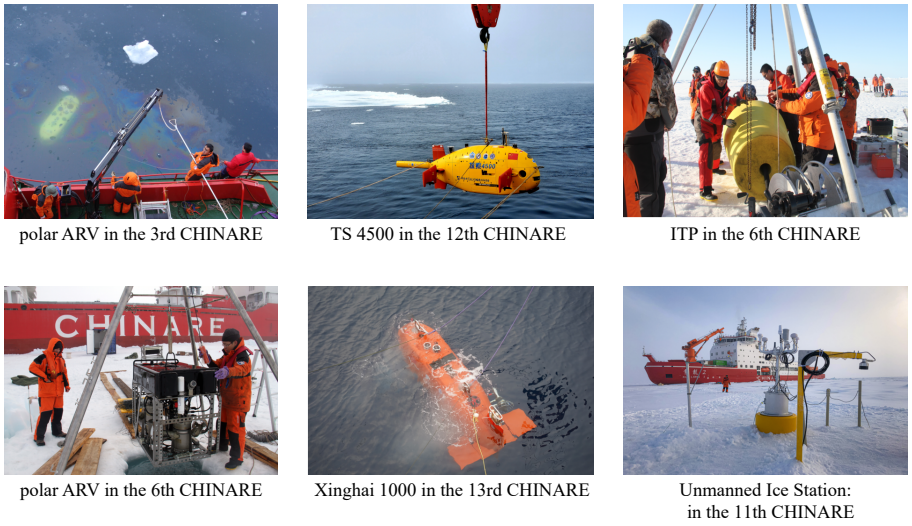


Fig. 2. ARVs (left), AUVs (middle), and buoys (right) deployed during the Chinese National Arctic Research Expedition (CHINARE-Arctic) cruises. ITP represents Ice-Tethered Profiler.

et al., 2017; Fan et al., 2024). The early prototype of the Ice Atmosphere Arctic Ocean Observing System (IAOOS) developed by French scientists was deployed in the Arctic Ocean during the third CHINARE-Arctic cruise. On the other side, the application of these observation devices in the Arctic is conducive to the updating and iteration of the associated technologies. The fourth International Polar Year (IPY) has not only promoted the process of CHINARE-Arctic cruise, which has been conducted annually or every other year since 2008, but also further facilitated international cooperation. The European Union flagship project, Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES), for the IPY has supported several European scientists to participate in the CHINARE-Arctic cruise (Gascard et al., 2015).

With the deepening understanding of the Arctic marine environment and sea ice conditions, as well as the continuous growth of China's maritime trade, China has recognized the importance of the Arctic sea routes in the international commercial shipping framework. In order to evaluate the navigability of the Arctic sea routes, the CHINARE utilize the R/V *Xuelong* to conduct observations through the Northeast and Northwest passages, and the high-latitude sea routes through the central Arctic Ocean in 2012 and 2017, respectively (Lei et al., 2015; Mu et al., 2018b).

The launch of R/V *Xuelong 2* in 2019 have greatly improved the operation ability of CHINARE in the Arctic ice-covered waters. This ship has an ice breaking level of

Polar Class 3 (PC3) and is capable of continuously breaking ice through the waters covered by level ice of 1.5 m and snow cover of 0.2 m. The R/V *Xuelong 2* is equipped with a moon pool that can be used to deploy CTD and other ocean observation devices, and a Dynamic Positioning (DP)-2 system, which is beneficial for enhancing the maneuverability of the ship in conducting the ice-camp observations in the Arctic Ocean, as well as in recovering ocean observation devices such as buoys, mooring systems, or AUVs in the water covered partially or completely by the sea ice. Therefore, using the R/V *Xuelong 2*, the CHINARE has expanded its oceanographic investigations from the western Arctic Ocean to the regions of North Pole and over the Gakkel Ridge in the recent years (Fig. 1). During the summer 2024, China dispatched three icebreakers for CHINARE-Arctic cruise, including R/Vs *Xuelong 2*, *Jidi*, and *Zhongshan Daxue Jidi*, significantly enhancing survey coverage over the pan Arctic Ocean during one season.

Although the R/V *Xuelong 2* has the Arctic observation region, especially the Pack Ice Zone (PIZ) in the central Arctic Ocean, it still cannot support the winter surveys in the central Arctic Ocean because of the limitations of the cold-proof technologies and ice breaking capability. Fortunately, the ice floes in the Arctic Ocean provides a unique platform for the deployment and operation of ice-tethered buoys, that can collect the data through the year. However, on the downside, extreme low-temperature and remote operating environments pose challenges to the energy supply and data transmission of Arctic ice-tethered buoys. The ice dynamic deformation, extreme storms, polar bears, as well as the ice melting, or other factors that occur after approaching the summer or Marginal Ice Zone (MIZ), can lead to the destruction of buoys and unexpected interruptions in observation. For ice-tethered ocean profiler, shallow bathymetry is also one of the main reasons for buoy damage.

At present, there are mainly three types of ice-tethered sea ice or ocean buoys deployed in the Arctic Ocean by the international communities: (1) the sea ice drifting buoy having the location and other simple meteorological records, with the data mainly archived at https://iabp.apl.uw.edu/, and has been used for construction of sea ice motion vector field (Tschudi et al., 2020) and tracking of sea ice advection and age (Rigor and Wallace, 2004); (2) various snow or sea ice mass balance buoys, including the sea Ice Mass Balance (IMB) buoy (Richter-Menge et al., 2006; Planck et al., 2019), with the data archived at http://imb-crrel-dartmouth.org/, snow and ice mass balance array (SIMBA) (Jackson et al., 2013), snow buoy (Nicolaus et al., 2021), and sea ice Spectral Radiation Buoy (SRB) (Wang et al., 2014), which can be used to measure the seasonal evolution of snow and ice mass balance and the associated heat flux through the ice cover (e.g., Lei et al., 2022); (3) ice-tethered ocean profiler, including the Ice-Tethered Profiler (ITP; Krishfield et al., 2008) with the data archived at https://www2.whoi.edu/site/itp/ and the IAOOS (Provost et al., 2015), which can be used to monitor the seasonal change in stratification, and heat content and salt budget of the upper ocean. Most types of buoys have been deployed during the CHINARE-Arctic cruises (e.g., Lei et al., 2014, 2018, 2020a) (Fig. 2).

Snow cover and sea ice thickness have high spatial heterogeneity, and sea ice with different thicknesses can significantly affect the heat exchange with the lower atmosphere or the upper ocean. Therefore, it is necessary to further integrate the observation techniques or buoys to measure the crucial physical parameters across spheres of atmosphere, sea ice, and ocean at the same site. Thus, the Chinese scientists have developed a new ice-tethered multi-parameter integrated buoy aimed at expanding the gradient measurements of meteorological parameters such as wind, temperature, and humidity in the near-surface atmospheric boundary layer, which has not yet been measured by previous ice-tethered buoys, although the data is an important basis for the estimations of the turbulence fluxes over the ice using the bulk method. This new type of buoy also has the ability to observe shortwave radiation flux through the ice, which is crucial for estimating the extinction coefficient of ice layers with different textures. Unlike previous ice-tethered profilers, the new profiling instrument, named as Drift-Towing Ocean Profiler (D-TOP), adjusts the buoyancy for up or down movement and measurement through shrinking or enlarging the oil pocket, working similar as the Argo. In order to complement the previous profiling instruments, such as the ITP, the D-TOP is designed to measure the ocean from surface to the depth of 120 m under the ice. In a sense, the synchronous observation of multi-sphere and parameters of atmosphere, snow, sea ice and ocean, can partially replace the observations of ice camps, so the entire observation system is called as the Unmanned Ice Station (UIS, Fig. 3). The UISs have been deployed in the central Arctic Ocean by the CHINARE-Arctic cruises since 2018, and by the MOSAiC expedition in 2019–2020 to investigate the seasonality of sea ice thermodynamic mass balance and its coupling with lower atmosphere and upper ocean (Lei et al., 2022). Totally, about 250 ice-tethered buoys for ice or ocean measurements, including the UIS have been deployed during the CHINARE and MOSAiC cruises in the Arctic Ocean by Chinese scientists (Fig. 4).

In order to match the pixel scale of satellite remote sensing and the grid scale of numerical models, it is necessary to construct a buoy array based on ice floes (e.g., Rabe et al., 2024). The buoy array with sufficiently dense deployments also is essential for characterizing the oceanic mesoscale and submesoscale processes beneath the ice (Hoppmann et al., 2022). In the Pacific sector of the Arctic Ocean, mainly including the Canadian Basin and the Beaufort Sea, which are also the core areas for marine survey of CHINARE-Arctic cruises, buoy arrays were de-

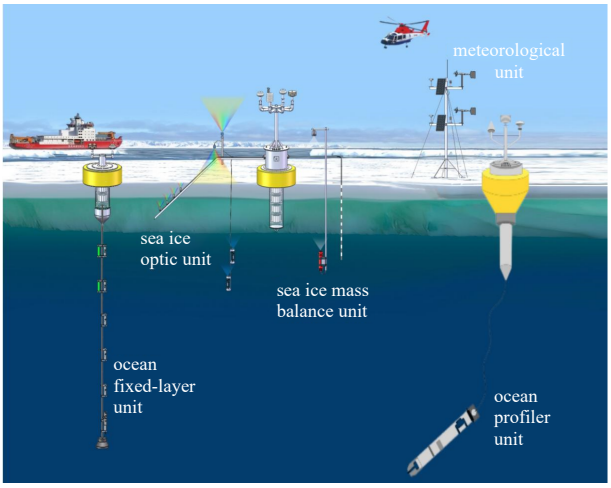


Fig. 3. Deployment schematic diagram of the unmanned ice station, which includes the units of meteorology, sea ice mass balance, sea ice optic, ocean fixed-layer measurement, and ocean profiler.

ployed over the ice floes during the 6th, 7th, and 9th CHINARE-Arctic cruises, mainly composed of sea ice drift buoys and sea ice mass balance buoys. The ocean under the ice was observed by the UIS during the 9th and subsequent CHINARE-Arctic cruises, or the ITP during the 6th CHINARE-Arctic cruise. The data of buoy array have been used to characterize the seasonality of sea ice deformation rate (Lei et al., 2020a, b, 2021), the formation and evolution of leads (Qu et al., 2024), and the mass balance process of sea ice (Lei et al., 2018).

2.2 *Satellite remote sensing for Arctic sea ice and ocean monitoring*

Satellite remote sensing has advantages for monitoring Arctic sea ice and ocean, because of a larger spatial coverage relative to the shipborne observations, that depends on the satellite orbit and its imaging swath, and of a high observation frequency, that depends on its revisiting cycle. However, compared to remote sensing for the open waters in lower latitudes, remote sensing monitoring of the Arctic Ocean is faced with the following challenges: (1) most areas are covered by sea ice through the year, making it difficult to obtain remote sensing products of the ocean, e.g., sea surface temperature, and mesoscale and submesoscale processes; (2) the discontinuity and anisotropy of sea ice distribution lead to great uncertainties in spatial interpolation of sea ice geophysical variables; (3) the polar nights in winter and the weather with heavy fog and low cloud in summer limit the monitoring effectiveness of optical remote sensing; (4) surface meltwater, combined with brine within sea ice, increases the absorption of electromagnetic waves, affecting the effec-

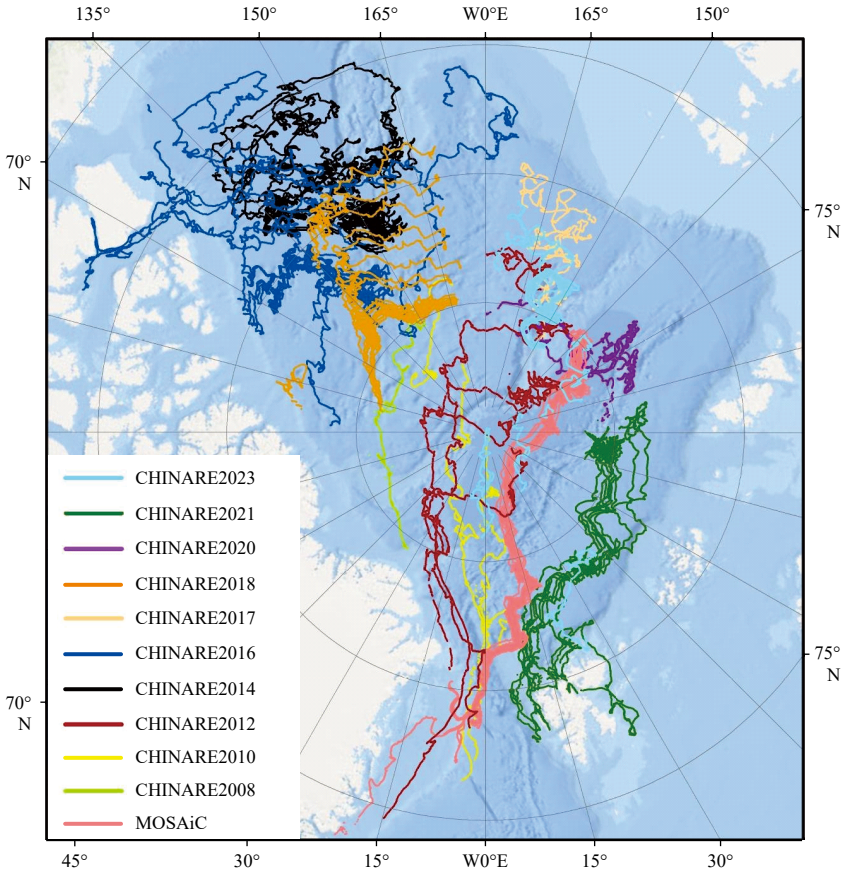


Fig. 4. Drifting trajectories of the ice-tethered buoys deployed during the 3rd to 13th Chinese National Arctic Research Expedition (CHINARE-Arctic) cruises (except for the 10th cruise, CHINARE2019) and the MOSAiC expedition by the Chinese scientists.

tiveness of satellite remote sensing in summer; (5) polar orbiting satellites often have observation blind area near the North Pole, resulting in data gaps; (6) the lack of ground receiving stations in the central Arctic Ocean seriously affects the efficiency of utilization of satellite remote sensing images for ship operation; (7) the insufficient ground observations of ice and snow in the central Arctic Ocean, especially the severe lack of winter observations, have brought difficulties to the development of retrieval algorithms and the ground verification of remote sensing products; and (8) apart from surface features, satellite remote sensing is still unable to determine the internal structure and bottom morphology of sea ice, which are crucial for the parameterizations of thermodynamic variables (internal) or dynamic roughness (bottom) of sea ice.

Although Chinese scientists, like their international counterparts, also have to face the aforementioned challenges in applications of Arctic remote sensing, and the China's polar monitoring satellites are still limited, they have made a series of progresses in the field of satellite remote sensing monitoring of Arctic sea ice, snow, and ocean, especially during the last decade. This was because the rapid reduction of Arctic sea ice and its resulting climate effects have attracted widespread attentions, and the security assurance of navigation and operation for both Arctic shipping and scientific expedition have a strong practical needs.

The main progresses of the Chinese scientific community in remote sensing monitoring of the Arctic Ocean includes the following aspects.

(1) Developing products for physical variables of sea ice and snow using remote sensing data derived from Chinese satellites. The Fengyun (FY) and Haiyang (HY) series satellites provide the main data sources. Lu et al. (2024) retrieved sea ice velocity in the Fram Strait by adopting a multi-template matching technique to calculate the cross-correlation and subpixel estimation using the images obtained from the Chinese HY-1D satellite equipped with the Coastal Zone Imager. Dong et al. (2023) derived the Arctic sea ice freeboard and thickness using the HY-2B radar altimeter, with the results revealing the sea ice thickness deviation between HY-2B and CryoSat-2 of within 0.2 m. Zhang et al. (2024a) introduced a more integrated two-step image quality enhancement strategy on the images obtained from the Spectral Imager-Ⅱ (MERSI-Ⅱ) onboard the Chinese FY-3D to produce the products of Arctic ice leads with a medium resolution of 250 m. Chen et al. (2023a) generated a new Arctic sea ice concentration product from November 2010 to December 2019, derived from the Microwave Radiation Imager (MWRI) sensors on board the FY-3B, FY-3C, and FY-3D satellites after a re-calibration of brightness temperature. The overall mean absolute deviation between this product and ship-based observations is 16% in the Arctic Ocean, which is close to the existing products and indicates its potential for application in the study of long-term changes in Arctic sea ice. Wang et al. (2022a) presented an algorithm for lead detection based on brightness temperature observations from a single thermal infrared channel of MERSI-Ⅱ onboard the Chinese FY-3D satellite. The results reveal the accuracy to be 85.6% for lead detection. Qiu et al. (2023) presented a method for detecting sea ice leads in the Arctic using infrared images from the Sustainable Development Science Satellite 1 (SDGSAT-1), with a resolution of 30 m in a swath of 300 km.

(2) By utilizing the international satellite remote sensing resources, new products of Arctic sea ice or snow physical variables have been developed through optimizing or developing retrieval algorithms, data fusion, or artificial intelligence methods. Wang and Li (2021) developed an approach for deriving a high-resolution (400 m) Arctic sea ice coverage product using Sentinel-1 Synthetic Aperture Radar (SAR) dual-polarization data in extra wide swath mode using the approach based on the modified U-Net architecture of a deep learning network. The results superior to the data derived from passive microwave in presenting detailed sea ice distribution, particularly in the MIZ. Huang et al. (2024) proposed a dual-branch encoder U-Net deep learning model to the SAR images for segmenting multi-year ice, first-year ice, open water, and leads over the Beaufort Sea. Finally, 454 Sentinel-1 SAR images were fed into the optimal dual-branch encoder U-Net to generate 80-m ice type products for winters 2018–2022, revealing the regulatory effect of the Beaufort High on the budget of multi-year ice in this region. Wang et al. (2020c) used Sentinel-2 imagery to demonstrate those previous algorithms assuming fixed melt pond-reflectance greatly underestimate melt pond fraction and proposed a new algorithm based on the polar coordinate transformation that treats melt ponds as variable-reflectance features. Qu and Su (2023) improved the passive microwave algorithm to derive the timing of ice surface melt and refreezing from AMSR-E/2 datasets. Cheng et al. (2023) proposed an algorithm to estimate broadband albedo of Arctic sea ice from Moderate-Resolution Imaging Spectroradiometer (MODIS) images. An iteration procedure with multiband spectral reflectance data was used to retrieve sea ice bidirectional reflectance distribution function. Finally, a daily 500 m albedo product over Arctic sea ice regions from 2000 to 2017 was generated. Chen et al. (2024a) proposed a generalized deep learning-based approach for automatic sea-ice lead detection in the Arctic wintertime using Sentinel-1 SAR images, deriving the Arctic-wide lead distribution at a spatial resolution of 40 m. To address the limitations of low spatial resolution or poor spatial continuity of ice motion product caused by the using of single-sensor remote sensing data, Wang et al. (2024a) proposed a sea ice drift retrieval framework based on multisensor data, utilizing the complementary sea ice drift information derived from passive microwave radiometers and medium-resolution

optical sensors. The result demonstrate this framework has ability to retrieve the ice motion field with a fine-resolution of 1 km. Li et al. (2022a) used the regression analysis to determine the best gradient-ratio combination of brightness temperatures, combined with one additional deep learning model for estimating snow depths over the Arctic Ocean from January to April during 2012–2020. The results reveal the average monthly snow depth in the Beaufort Sea and the Chukchi Sea mainly showed a downward trend, while an upward trend was observed in the Central Arctic in most months. He et al. (2024) presented an improved snow depth retrieval algorithm considering the impacts of snow density. The algorithm enable daily snow depth estimation on sea ice over the entire Arctic Ocean during the full winter season.

(3) Validate sea ice remote sensing products using in site or aerial observations obtained from Arctic expeditions. We recognize that, the observation data obtained from the international projects of Operation IceBridge, ice-tethered buoys, and up-looking sonars assembled in mooring systems are the most commonly used validation data. Here we mainly review the works on the satellite remote sensing verification using the data collected from CHINARE-Arctic cruises. Ship-based sea ice observation data collected from the Pacific Arctic section up to 88.5°N in the summer of 2010 during the fourth CHINARE-Arctic cruise was used to validate ice concentrations obtained from the Advanced Microwave Scanning Radiometer for the Earth (AMSR-E) observing system (Xie et al., 2013). It was found that, in the PIZ with high sea ice concentration, AMSR-E remote sensing products tend to overestimate ice concentration, while in the MIZ with sparse sea ice distribution, AMSR-E tends to underestimate ice concentration. Sea ice skin temperatures and near-surface air temperatures, measured by IMBs, SIMBAs, and automatic weather stations deployed during the Arctic expeditions of China and other countries, were used to compare with the ice surface temperature derived from 58 scenes of the Landsat 8 thermal infrared images at 100 m resolution (Fan et al., 2020). It proved that near-surface air temperature is still an optional substitute for validating the ice surface temperature derived from satellite if skin temperature data are not available because the close thermodynamic coupling between near-surface atmosphere and snow surface. The sea-ice motion products provided by the National Snow and Ice Data Center (NSIDC) and the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) were validated with data collected by ice drifters that deployed in the western Arctic Ocean in 2014 and 2016 during the CHINARE-Arctic cruises (Gui et al., 2020). The validation results indicate that the OSI-SAF product tended to overestimate ice speed, while underestimation was demonstrated for the NSIDC product, especially for the melt season and the MIZ. The evolution process of ice deformation rate over time calculated using a buoy array deployed in the summer 2018 by CHINARE-Arctic cruise was used to validate the formation and evolution of leads in the western Arctic Ocean retrieved from Sentinel-1 SAR images using an optimal random forest model (Qu et al., 2024).

(4) With the rapid reduction and thinning of Arctic sea ice, using satellite remote sensing products to clarify the long-term trends of crucial physical parameters of sea ice and their response to climate change is a very active research field, including that on the changes in extent or volume of sea ice (e.g., Cai et al., 2021; Li et al., 2021; Luo et al., 2020), the freezing-thaw cycle and albedo of sea ice surface (e.g., Lei et al., 2016; Peng et al., 2020; Liang and Su, 2021; Lin et al., 2022), sea ice thickness (e.g., Li et al., 2020a), sea ice advection and outflow (e.g., Bi et al., 2019; Zhang et al., 2022a, 2023b), sea ice lead (e.g., Zhang et al., 2018a; Qu et al., 2019, 2021, 2024) (Fig. 5), melt pond (Feng et al., 2022), landfast ice (Zhai et al., 2022), polynya (e.g., Lei et al., 2020c; Ren et al., 2022; Liu et al., 2024a), snow cover (e.g., Li et al., 2024), etc. With the expansion of the Arctic marginal ice zone, the dynamic processes in this region, including the waves, mesoscale processes, and internal waves (e.g., Wu et al., 2021; Zhu et al., 2024), have also attracted widespread attentions. The reduction of sea ice has made commercial use of the Arctic sea routes possible (Li et al., 2022b). China began using the Arctic sea routes for commercial transportation in 2013. Since then, significant progress has been made in evaluating the navigability of the Arctic sea routes using multi-source remote sensing products (e.g., Lei et al., 2015; Yu et al., 2021; Cao et al., 2022; Cheng et al., 2022).

3 Arctic atmosphere-sea ice-ocean coupling system and its evolution

The Arctic atmosphere-sea ice-ocean coupling system is relatively independent in the global climate system (Fig. 6), mainly because the Arctic Ocean is a semi-enclosed ocean, connected to the Pacific and Atlantic Oceans through Bering Strait, Barents Sea, Fram Strait, and narrow channels of the Canadian Arctic Archipelago. In addition, ideally, the Arctic counterclockwise vortex system is relatively stable, where the extremely cold air can be effectively locked in the high Arctic (Zhang et al., 2016). However, extremely complex interactions occur all the time between multi-sphere within the Arctic system. Meanwhile, material and energy exchanges also occur between Arctic and beyond through atmospheric (e.g., Liang et al., 2022; You et al., 2022) and oceanic (e.g., Polyakov et al., 2023; Wang et al., 2024b) circulations. Both results in the complexity for the Arctic system evolution. This section will provide a detailed introduction to the scientific progresses, contributed by Chinese scientists, in the field of Arctic atmosphere-sea ice-ocean coupling system and its evolution.

3.1 *Atmospheric circulation and processes*

The uneven distribution of solar radiation on the

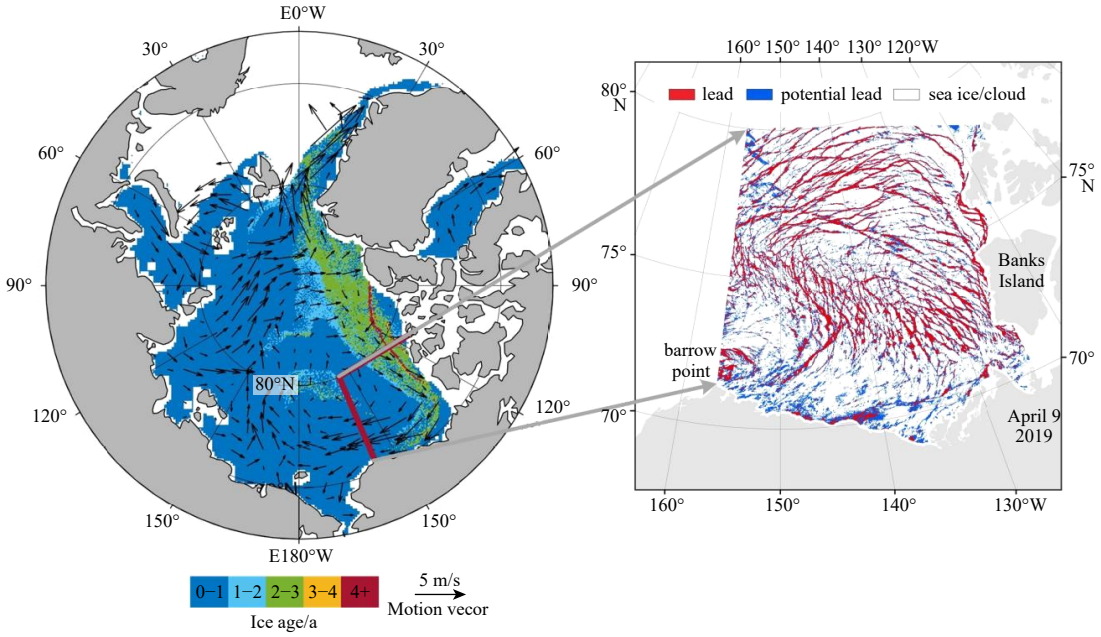


Fig. 5. Sea ice motion vector in the Arctic Ocean on April 9, 2019, and the ice age obtained in the week of April 16–22, 2019 (left); the lead distribution over the western Arctic Ocean on April 9, 2019 (right).

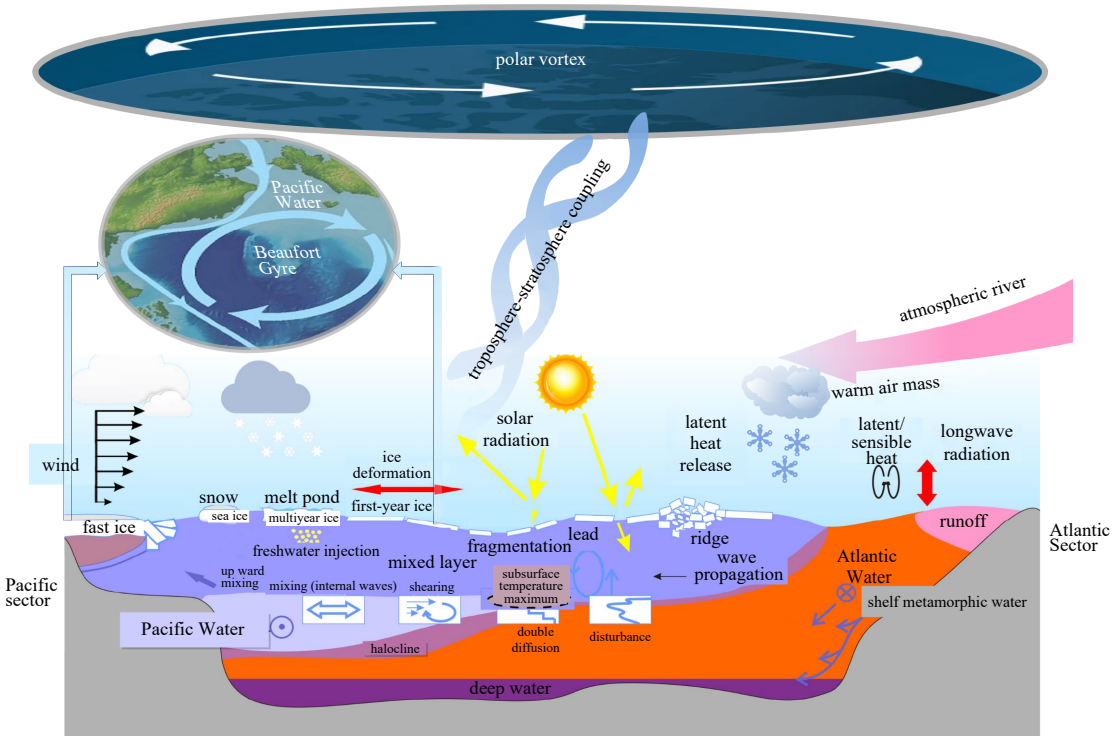


Fig. 6. Arctic atmosphere-sea ice-ocean coupling system and crucial internal interactions.

Earth's surface results in excess energy in low latitudes and energy depletion in high latitudes. Therefore, the energy transfer from low to high latitudes plays an important role in the energy balance in the Arctic. In the context of global climate change, there have been significant changes in the energy inflow from the low latitudes to the Arctic through the atmospheric circulations, creating obvious impacts on the Arctic climate system.

As the Arctic warms, the increased evaporation over ice-free regions enhances the poleward transport of moisture from peripheral seas, resulting in a rise in atmospheric boundary layer moisture and humidity in the high latitudes (Zhang et al., 2013). On a broader hemisphere scale, Liang et al. (2023) revealed that, on the climatological average, the passages through which atmospheric energy enters the Arctic during winter are mainly located in the waters near the Bering Strait, the Labrador Sea, and also extends to the Greenland Sea and the East Siberian Sea,

while the passages through which atmospheric energy enters the Arctic during summer are mainly located in the Beaufort Sea, Baffin Bay, and the Nordic seas. There is spatial heterogeneity in the long-term trends of atmospheric heat and moisture entering the Arctic. In winter, the total heat and moisture fluxes of the atmosphere show a significant northward increasing trend in the North Pacific, while in summer, the heat and moisture entering the Arctic from Eurasia increase significantly. The warm and humid air masses entering the Arctic would increase cloud cover and downward longwave radiation, which can promote sea ice melting in spring and summer seasons, which was well reflected along the Siberian coast in the spring and summer of 2020, and leaded to a major ice retreat in the Eurasian shelf of Kara, Laptev, and East Siberian Seas and the recorded July minimum Arctic sea ice extent in the satellite observations since 1979 (Liang et al., 2022). Using remotely-sensed observations and climate models, Liu et al. (2021) revealed that the changes in atmospheric heat and moisture fluxes to the Arctic play an important role in the interannual variability and long-term trends of Arctic summer sea ice. There is significant interannual variability and spatial differences in Arctic sea ice melting in summer, with the most rapidly ice retreat occurring in the western Arctic Ocean. The atmospheric circulation pattern of Pacific North American (PNA) is an important driving factor explaining over 25% of the interannual variability of sea ice in the western Arctic Ocean. In the context of global warming, the positive PNA pattern continues to strengthen and increases heat and moisture fluxes from the North Pacific to the western Arctic Ocean, resulting the increased lower-tropospheric temperature, humidity, downwelling longwave radiation, melting of sea ice there. In the Barents−Kara Sea, where a dramatic decline in winter sea ice occurred, recent intensification of the anticyclonic anomaly has warmed and moistened the lower atmosphere through enhancing poleward transport of warm and humid air masses and local processes (Liu et al., 2022). Furthermore, the anticyclonic anomaly can explain more than 50% of the interannual variability in the sea ice concentration in this region.

In addition to affecting the poleward transport of warm and humid air masses from lower latitudes to the Arctic, atmospheric circulation patterns mainly regulate the advection of Arctic sea ice by regulating the wind field, subsequently affecting the spatial distribution of sea ice and even its outflow to the North Atlantic. Using the longest reconstruction of Arctic sea ice extent available since 1850, Cai et al. (2021) revealed that the reduction of Arctic summer sea ice during the recent four decades was enhanced with the positive ice-albedo feedback being accelerated by the Arctic amplification, contributed in part by the atmospheric thermodynamical forcing from the negative Arctic Oscillation, positive North Atlantic Oscillation, positive Dipole Anomaly, positive Atlantic Multidecadal Oscillation, and negative Pacific Decadal Oscillation and by the dynamical transpolar sea ice advection by positive Dipole Anomaly and positive Atlantic Multidecadal Oscillation. As a case study, an extreme Arctic sea ice thickness loss was observed during 2010–2011, which was associated with an extraordinarily large multiyear ice volume export through the Fram Strait caused by the Dipole Anomaly-associated meridional wind anomalies during the season of ice advance (Li et al., 2022c). In this ice season, there was a strong and sustained negative Arctic Oscillation phase that had not been observed since the late 1960s and the Dipole Anomaly index showed a strong positive phase, both of which were beneficial for the outflow of Arctic sea ice. Similar atmospheric circulation anomalies and their driving Arctic sea ice outflow anomalies through the Fram Strait were also observed in the ice season of 2020–2021, which led to cross-seasonal anomalies of sea ice and marine environmental conditions in its downstream areas, Greenland Sea (Zhang et al., 2023b). In terms of spatial distribution of sea ice within the Arctic Ocean, atmospheric circulation associated with the Arctic Dipole pattern plays a crucial role in modulating the variations of summer sea ice concentration within the Pacific Arctic sector, because the Arctic Dipole would accelerate the Transpolar Drifting (TPD) system, causing the sea ice in this region to be transported northward (Bi et al., 2021). This mechanism might also trigger positive albedo feedback, promoting further retreat of sea ice in this region (Lei et al., 2016).

As an important component of the Arctic climate system, the atmospheric physical processes near the surface are closely related to the Arctic amplification and rapid reduction of sea ice, and are key processes that requires a deep understanding for improving the predictability of Arctic weather and sea ice. Based on a large number of observation experiments, combined with satellite remote sensing, reanalysis data, and numerical simulation, Chinese scientists have conducted extensive researches on the Arctic atmospheric boundary layer, in especial the inversion layer and the mass and energy exchanges between atmosphere and ice or ocean.

Bian et al. (2016) analyzed the impact of changes in sea ice as the underlying surface on atmospheric structure and found that the rapid reduction of sea ice caused by Arctic warming can feedback to increase boundary layer temperatures and significantly promote an increase in atmospheric convective processes. An improved Richardson number-based algorithm that incorporates the effects of clouds was applied to analyze the characteristics and variations of the Arctic boundary layer height, revealing that the annual variations in the Arctic boundary layer height are governed by the evolution of the thermodynamic structure of atmospheric boundary layer (Peng et al., 2023). Based on high-resolution soundings, Zhang et al. (2023a) carried out an assessment of the applicability of satellite data for the characterization of Arctic atmospheric boundary layer. Chang et al. (2024) used radio occulta-

tion data to extract the height of the Arctic boundary layer on the basic of the minimum refractive index gradient method, revealing that the height of the boundary layer is typically higher in the summer than in other seasons, as well as a negative correlation with sea ice concentration. In addition, based on MOSAiC observations, Liu et al. (2023b, 2024c) revealed the impact of the Arctic atmospheric boundary layer structure on turbulent intermittency characteristics and sea ice-atmosphere sensible heat flux. They developed a new algorithm capable of identifying spectral gaps on the Arctic sea ice surface, revealing that the weakening of low-level jets and the strengthening of inversion structures lead to an enhancement of turbulent intermittency. The contribution of turbulent eddies to sensible heat over the ice is controlled by the atmospheric inversion structure.

The Arctic inversion structure is characterized by complex spatial and temporal variations and has far-reaching effects on the Arctic atmospheric system. Tian et al. (2020) analyzed sounding data during the CHINARE-Arctic expedition in 2018 and noted that the inversion was stronger and deeper in the ice region compared to open water. Wang et al. (2020a) combined data from atmospheric soundings, satellite remote sensing, and reanalysis to identify a close relationship between cloud cover and the structure of atmospheric temperature inversions. Regarding the factors affecting the structure of the atmospheric inversion (Fig. 7), the decrease in Arctic ice concentration would strengthen the following feedback mechanisms: (1) the influence of synoptic processes is more significant than the local feedback, (2) the subsidence process can also strengthen and extend the existing inversion, and (3) the warm air advection is conducive to the strengthening and deepening of the inversion structure (Zhang et al., 2021b).

Changes in the lower atmospheric structure, particularly the rise in the freezing layer height, can significantly influence Arctic weather phenomena. Moreover, the transition in precipitation type from snowfall to rain (Cai et al., 2024; Han et al., 2018) results in the enhanced Arctic wetting. Especially, spring precipitation in most regions of the Arctic has shown a trend of shifting from solid to liquid states, stimulating the albedo feedback and accelerating the melting of Arctic sea ice (Dou et al., 2021; Yang et al., 2021).

3.2 *Sea ice thermodynamic and dynamic processes*

The Arctic sea ice and overlying snow cover isolate partly the exchanges of material, energy, and momentum between atmosphere and ocean, which has a significant impact on changes in the Arctic climate and ocean systems. It also has important effects on the seasonality and spatial patterns of Arctic climate warming (Dai et al., 2019; Previdi et al., 2021), as well as on the seasonal and long-term variations in stratification, heat content, and available radiation for heating or photosynthesis in the upper ocean (e.g., Arndt and Nicolaus, 2014; Bianco et al., 2024). The reduction of sea ice would create more open waters and enhance dynamic processes, particularly the waves and ice fragmentation (e.g., Bacon, 2023). On the other hand, the Arctic amplification and sea ice reduction significantly affects the thermodynamic and dynamic parameters and processes of sea ice itself, as well as its interactions with the lower atmosphere and upper ocean (Fig. 8). Since the first CHINARE-Arctic cruise in 1999, the observations of sea ice characteristics and processes have been the core content of the expedition, and the observation and related results support the multi-disciplinary studies, because sea ice is an intermediate medium in the multi-sphere interactions.

As shown in Fig. 8, sea ice is a material composed of multiphase substances, including pure ice lattice, brine, and bubbles. The upper part may include ice from atmospheric sources, which is originating from the refrozen melting snow. Except for this part, the majority of the ice layer is composed of ice from seawater freezing. On the Arctic shelf or adjacent areas, a large amount of ice floes are rich in sedimen, usually derived from the entrainment of suspended matter from the water during the ice growth period, or the imprints left by the activities of mammals on the ice surface. The structure and material composition of sea ice columns determine its optical (Light et al., 2004), thermodynamic (Vancoppenolle et al., 2019), and mechanical (Timco and Weeks, 2010) properties. In summer, the snow type, grain size, thickness, and water con-

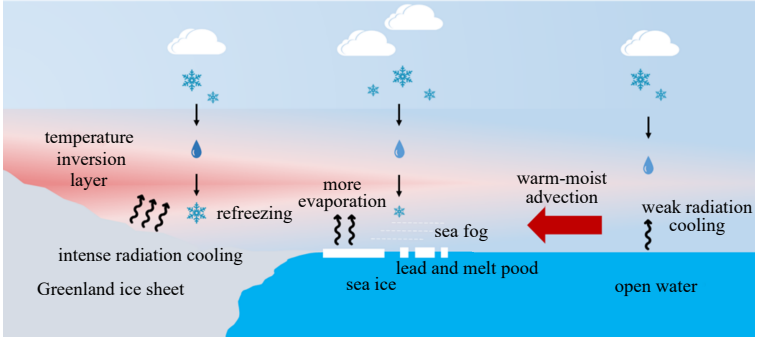


Fig. 7. Mechanism of the formation and maintenance of Arctic atmospheric inversion layer.

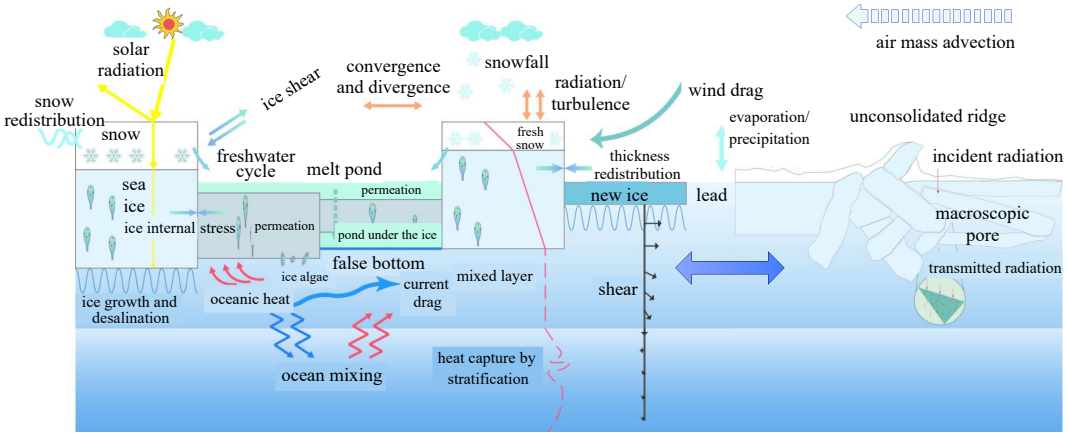


Fig. 8. Crucial thermodynamic and dynamic processes of Arctic sea ice and their coupling mechanisms.

tent are the main physical parameters for determining the albedo of snow-covered sea ice. Rainfall sleet events can significantly alter these physical parameters of snow, especially for the water content, resulting in obvious changes in spectral albedo and transmittance (Lei et al., 2012). Based on the ice-core observations of physical parameters of temperature, salinity, and density and texture structure, Huang et al. (2016a) estimated the volume fractions of brine and air inside the ice cores collected from the western Arctic Ocean, with the results indicating the decreased volumetric fraction of pure ice and the interior melt at the end of summer. The changes in the interior properties of sea ice would affect the reliability of retrieving sea ice thickness using satellite altimeter observations (Ji et al., 2021). In addition, the uniaxial compression strength of sea ice has a significant power-law relationship with its porosity, determined by volume fractions of air and brine within the ice, so the ice interior melting during the summer would significantly weaken its mechanical strength (Wang et al., 2018). The ice-core measurement data collected from 2010 to 2018 during the CHINARE-Arctic cruises reveals the porosity of late summer sea ice generally reached 20%–30% (Wang et al., 2020b). Thus, the melting inside sea ice absorbs a large amount of heat and partially buffers the melting at the ice bottom, but would weaken the strength of ice layer. The increased ice porosity has enhanced the scattering coefficient inside the ice layer, reducing the transmitted radiations under the ice (Yu et al., 2024).

The morphological parameters of sea ice, including concentration, thickness, floe size, surface and bottom roughness, and melt pond distribution, are not only the main parameters for characterizing local sea ice conditions, but also an important input for the parameterization of sea ice numerical simulations, especially the distribution of sea ice thickness (e.g., Ungermann et al., 2017). Chinese scientists have provided a quantitative description of the spatiotemporal variations of the above parameters in the Arctic Ocean by combining satellite remote sensing, aerial survey, ship-based observation, and ice surface investigation. Analysis of more than 9 000 aerial images collected from eight helicopter flights during summer 2008 by the third CHINARE-Arctic cruise indicates that, the areally averaged albedo increased from 0.09 in the MIZ at 77°N to 0.63 in the far north zone at 86°N, with the increase in ice concentration and reduced melt pond fraction (Lu et al., 2010). Huang et al. (2016b) further utilized aerial remote sensing imagery to obtain spatial variations of the geometric parameters of the melt pond, including its area, perimeter, mean caliper dimension, roundness, and convex degree, in the Pacific sector of Arctic Ocean, which can indicate the melting state of the melt ponds and significantly affect the albedo (Lu et al., 2016, 2018). The enhanced multi-year sea ice inflow from north of the Canadian Arctic Archipelago caused by an exceptionally strong anticyclonic circulation would increase the multi-year ice coverage and the compactness of sea ice in the western Arctic Ocean (Lei et al., 2017). The upward looking sonar mounted on the ARV has used to obtain the morphology of the ice bottom. Combined with surface observations, it reveals that the melting rate at the ice bottom below the surface melt pond would increase, forming local mirror melt ponds at the ice bottom, indicating the albedo feedback at a small scale (Lei et al., 2017). Using the full-scan laser altimeter data obtained in the Operation IceBridge mission, Zhang et al. (2024b) reveal that the surface features have a larger height and smaller spacing over multi-year ice than over first-year ice, and the central Arctic experienced a drop of around 50% for the surface form drag coefficient from 2001/2002 to 2008/2009 as the loss of multi-year ice.

The vertical mass balance of snow-covered ice layer includes the accumulation, melting, or refreezing of surface snow, as well as the formation of melt ponds caused by the local water amassing after the melting of snow and ice surface, phase transitions and porosity changes within the ice, and the growth or decay at the ice bottom. During the growth of sea ice, from a thermodynamic perspective, the thickening of Arctic sea ice is mainly achieved from the bottom, which is different from the sea ice in the Southern Ocean, where the snow depth is relatively large, facilitating for formations of snow ice (with brine) or su-

perimposed ice (without brine). The ice growth rate at bottom depends on the competition between conductive heat flux through the ice and upward oceanic heat flux. Utilized the observation data of sea ice growth and decay obtained from the IMB deployed during the third CHINARE-Arctic cruise, Lei et al. (2014) identified the impacts of shallow water on the ocean upwelling mixing and the ice growth rate over the Romonosov Ridge. Although hundreds of various types of IMBs were deployed in the Arctic Ocean to date, to our knowledge, only this buoy observed the impact of shallow water on sea ice growth over the Romonosov Ridge. This also indicates that this type of Lagrangian observation using the IMB deployed on the floe has randomness, and in order to obtain representative observations at the basin scale, sufficient buoys should be deployed to construct an observation network. This highlights the importance of international cooperation on the buoy deployment in Arctic Ocean. Using the IMBs deployed over the regions with various initial ice conditions from MIZ to PIZ, Lei et al. (2018) further identified the impacts of the initial sea ice condition in early autumn on the onset of ice basal growth. This work also reveals that in the Arctic TPD region, atmospheric circulation can affect the mass balance process of sea ice through adjusting the advection trajectory and length of ice growth season in the high Arctic. Combining the data of IMBs, mooring uplooking sonars, and passive microwave remote sensing, Lin et al. (2022) pointed out that due to the regulation effects of phase transition and heat content inside the ice layer, the freezing-thaw transtion at ice bottom lags behind those at the surface. However, as the sea ice becomes thinner, this regulating effect would weaken, thereby accelerating the heat release from upper ocean to lower atmosphere. Using the data collected by a buoy array deployed over the floes with various ice thickness at a scale of dozens of kilometers, Lei et al. (2022) revealed that almost all the timing of ice growth and decay are related to its initial ice thickness, and dynamic deformation can lead to ice surface compression and snow ice formation. Since the observation data of this buoy array covered both the first-year and second-year ice, and has a wide range of ice thickness coverage and a good representativeness, it is therefore widely used in the verification for both numerical simulation and satellite remote sensing (e.g., Li et al., 2024; Zampieri et al., 2024).

The material mechanics properties of sea ice are crucial for conducting numerical simulations of sea ice dynamics and the interactions between sea ice and ship or other structures. Chinese scientists have conducted measurements of sea ice mechanics parameters based on ice samples during the CHINARE-Arctic cruises. However, due to the constraints of sampling, the measurement parameters are mainly limited to uniaxial compression strength (Wang et al., 2018), and the measurement of other decisive parameters such as bending strength, friction coefficient, borehole strength, elastic and strain modulus, Poisson's ratio, and fracture toughness of sea ice is very scarce or missing. In addition, sampling and mechanical measurements during the freezing season are absent.

The dynamic deformation of sea ice can cause a redistribution of sea ice thickness, resulting in the formation of leads and ice ridges, affecting the heterogeneity of the ice field. As Arctic sea ice thins, its response to wind stress strengthens, especially for the extreme strong wind forcing (Zhang et al., 2022a), thus enhancing the dynamic deformation of the ice field. Two-year observations of buoy arrays deployed in the western Arctic Ocean in 2014 and 2016 reveal that the ice concentration at the end of summer would continue to affect the deformation rate of ice fields in autumn and early winter (Lei et al., 2020a). Compared with the observation results in the close region nearly 20 years ago, the annual cycle of ice deformation rate has been significantly amplified, which is consistent with the changes of annual cycle in ice thickness and consolidation (Lei et al., 2020b). In the Beaufort Gyre (BG) region, the collapse of the Beaufort High will cause the overturning of the ice anticyclonic circulation, accelerating the northward advection of sea ice to the region of TPD (Lei et al., 2021). This process would intermittently enhance the deformation of the ice field and promote the formation of leads (Qu et al., 2024).

3.3 *Ocean dynamic processes*

The upper ocean circulation system in the Arctic Ocean is primarily composed of two large-scale circulations of the BG and TPD, and incorporates the inflow systems from both the Pacific and Atlantic Oceans (Figs 6 and 9). The largest "freshwater reservoir" in the Arctic Ocean is located within the BG (Proshutinsky et al., 2019). This freshwater reservoir plays a critical role in regulating changes in the Arctic Ocean's hydrological and ecological environment (Timmermans and Pickart, 2023). The freshwater released into the North Atlantic influences the formation of deep waters, which in turn affects the Atlantic Meridional Overturning Circulation and the global climate system (Zhang et al., 2021d). Therefore, continuous monitoring of the BG and exploring the potential mechanisms that regulate its variability are crucial. These efforts are indispensable for addressing the current challenges in the assessment of heat and freshwater budgets of Arctic Ocean, and are fundamental to understanding how the rapidly changing Arctic affects the global climate. Thus, the BG region has always been the core area of CHINARE-Arctic cruises.

The freshwater reservoir within the BG is influenced by Pacific inflow, runoff, precipitation, and sea ice meltwater at various depths (Proshutinsky et al., 2019; Lin et al., 2023; Timmermans and Pickart, 2023). The resulting halocline strongly restricts the vertical mixing. In the upstream of the TPD, the observations obtained from the joint research cruise by the Chinese and Russian scien-

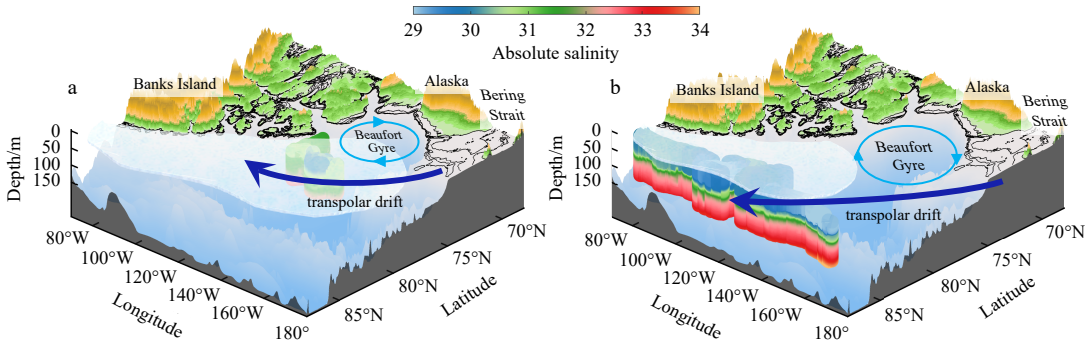


Fig. 9. Evolution of the large-scale circulation in the Arctic Ocean: early period with a limited BG and a large extent of sea ice (a) versus later period with an expansion of BG and dramatic retreat of sea ice (b). The salinity profile sections were obtained from the drifting profiling platform with the drifting along the BG during 1988 (a), available from the World Ocean Database at https://www.ncei.noaa.gov/products/world-ocean-database, and the D-TOP with the drifting along the TPD during 2020–2022 (b).

tists in the East Siberian Sea have revealed that local wind regulates freshwater transport from the Arctic shelf into the deep basin (Wang et al., 2021), which contributes to the freshwater balance and the halocline in the BG region. Furthermore, a significant increase of Pacific Winter Water (PWW) within the BG is reported when the gyre spins up (Zhong et al., 2019a). However, in recent years, due to notable freshening, the amount of PWW available to ventilate the halocline in the deep basin has sharply decreased (Lin et al., 2023). On the other hand, the spatial structure of the BG not only modulates the distribution of double diffusion staircases (Lu et al., 2022), which further affects the spatial distribution of heat release from the Atlantic Water (Li et al., 2020b), and also interacts closely with the recently identified Chukchi Slope Current (Li et al., 2019; Leng et al., 2022).

The initial explanation for the apparent stabilization of the total freshwater content in recent years suggests a balance between wind-driven Ekman pumping in the BG and lateral eddy fluxes (Manucharyan and Spall, 2016; Yang et al., 2016a). This highlights the crucial role of mesoscale eddies, generated by baroclinic instability, in maintaining the equilibrium of the freshwater reservoir. Zhong et al. (2018) found that the strengthening of the geostrophic current due to increasing freshwater could alter the ice-ocean stress, thereby modulating wind-driven Ekman pumping and limiting the gyre's ability to converge freshwater. In addition, Zhong et al. (2019b) revealed the relationship between the stepwise changes in total freshwater content within the gyre and the input of surface stress energy into the ocean, providing an important basis for short-term predictions of changes in the freshwater reservoir. The future changes in total freshwater content within BG remain a focal point of concern. The observational studies indicate that, after a period of stability at high freshwater levels, the gyre shows signs of potential freshwater release (Lin et al., 2023). However, due to the complexity of ice-ocean coupling processes, many uncertainties remain in the study of freshwater balance changes in the BG, posing higher demands on both observational and modeling efforts.

In the context of future sea ice retreat, the increased vertical mixing may promote the release of heat from subsurface warm waters, further accelerating sea ice melt and lower atmosphere warming. From this perspective, the BG system is also a key region for characterizations of ice-ocean interactions. Studies have found that thinning sea ice and changes in ice-bottom morphology affect the generation and development of internal solitary waves (e.g., Zhang et al., 2022c), which play an important role in vertical heat exchange. Observations reveal that the southern BG is a hot spot for high ice-ocean heat flux, and there has been an increasing trend in winter ice-ocean heat flux during 2006–2018. This is due to the enhanced entrainment at the base of the mixed layer, which brings subsurface heat upward (Zhang et al., 2022c).

The Arctic Ocean is connected to the Atlantic Ocean on both sides of Greenland. Warm and saline Atlantic Water enters the Arctic Ocean with two branches. One branch passes the Fram Strait and supplies the warm Atlantic Water layer to the Arctic Ocean (Rudels et al., 2015). The volume and heat transport of this branch is about 3.0×10^6 m^3/s and 29 TW (Schauer et al., 2004), respectively. The other branch, with the volume transport of about 2.0×10^6 m^3/s and heat transport of 70 TW, enters the Barents and Kara Seas and finally flows to the surface, intermediate and deeper layers of the Arctic Ocean (Smedsrud et al., 2010). The Atlantic Water circulates mainly cyclonically along the peripheries of the Arctic basins, following the contour of the continental slope, and finally exports from the Arctic Ocean through the Fram Strait. The changes in the exchanges between the Arctic Ocean and the Atlantic Ocean have significant impacts on both bodies of water.

The exchanges between the Arctic Ocean and the Atlantic Ocean have undergone pronounced changes during the past decades. The poleward ocean heat transport by both branches has significant positive trends over the past

decades (Wang et al., 2019; Shu et al., 2023; Wang et al., 2024b). The increase of ocean heat transport through the Fram Strait and Barents Sea Opening is about 16 TW from 1980–2000 to 2000–2020, and is projected to be 70 TW from 1980–2000 to 2090–2100 under high CO_2 emission scenario based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models (Wang et al., 2023). Using a high-resolution ocean-ice model, Wang et al. (2020d) revealed that Arctic sea ice decline can lead to the intensification of the Atlantic Water supply to the Arctic Ocean through Fram Strait. The decline of Arctic sea ice reduces its export through Fram Strait, thus increasing the salinity in Greenland Sea, reducing the sea surface height and speeding up the gyre circulation in Greenland and Nordic Seas, and the Atlantic Water volume and heat transport to the Nordic Seas and Arctic Ocean is consequently strengthened. Conversely, there is no significant changes in the volume transport of Atlantic Water through the Barents Sea Opening. The increase of poleward ocean heat transport through the Barents Sea Opening mainly stems from warming in the subpolar North Atlantic (Wang et al., 2019). In addition, an extreme event of high freshwater export west of Greenland from the Arctic Ocean caused by pronounced dynamic sea level drop in the North Atlantic subpolar gyre in the mid-to-late 2010s was also emphasized (Wang et al., 2022b).

The exchanges between the Arctic Ocean and the Atlantic Ocean have great impacts on heat content of the Arctic Ocean (Wang et al., 2023). Remarkable impacts of the advection of anomalous Atlantic Water on the Barents Sea and the upper Eurasian Basin, termed Atlantification, have been observed over the past 20 years (Polyakov et al., 2017, 2020; Asbjørnsen et al., 2020; Wang et al., 2023). Based on the reanalysis dataset and climate model simulations, Shu et al. (2021) further reveal that the atmosphere-ice-ocean interactions and the ocean stratification in the Barents Sea are also influenced significantly by the increased Atlantic Water heat transport to the Barents Sea, and furthermore, Arctic Atlantification will be enhanced and pushed poleward in the future. Pan et al. (2023a, b) showed that the magnitude of Arctic climate change is proportional to the strength of the increase in poleward ocean heat transport by the Atlantic Water. The increased ocean heat transport by the Atlantic Water will lead to the Arctic Ocean rapid warming in the twenty-first century (Fig. 10). The CMIP6 climate models project that over the twenty-first century, the upper 700 m and 2 000 m of the Arctic Ocean warms at 1.7 times and 2.3 times the global averages, respectively, which is called the "Arctic Ocean Amplification" (Shu et al., 2022). This indicates that the Arctic Ocean is one of the oceans most susceptible to climate change.

The exchanges between the Arctic Ocean and the Atlantic Ocean also have potential impacts on the Atlantic Ocean. Observations show that the Arctic Ocean freshwater storage has increased over the last 30 years. Climate models project that the freshwater content in the Arctic Ocean is likely to increase in the twenty-first century, mainly due to the increase in runoff, precipitation and the decline in sea ice growth in a warming climate (Shu et al., 2018; Wang et al., 2022b, 2023). Consequently, the accumulated freshwater in the Arctic Ocean may result in more freshwater release into the subpolar North Atlantic Ocean, which is majorly caused by the weakening of BG constraint effect. This could subsequently alter the buoyancy in the subpolar North Atlantic and impact the strength of the Atlantic Meridional Overturning Circulation (Shu et al., 2017).

4 Arctic sea ice prediction and its applications

4.1 *Arctic sea ice modeling and forecasting*

Accurate forecasting of Arctic sea ice is essential not

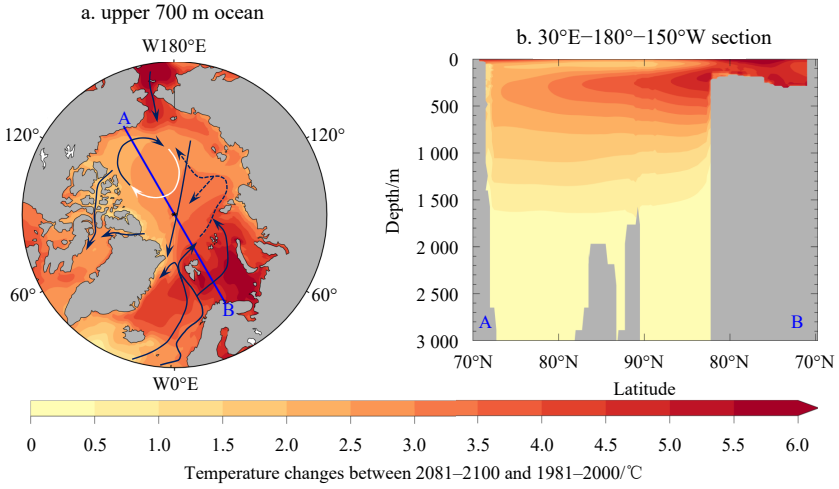


Fig. 10. Ocean temperature changes between 2081–2100 and 1981–2000 projected by CMIP6 climate models under high CO_2 emission scenario: a. upper 700-m ocean temperature changes and b. ocean temperature changes along the section of A–B (30°E–180°–150°W), with black or white arrows denoting the Arctic oceanic circulation system.

only for understanding broader climate system feedbacks but also for ensuring the safety and efficiency of Arctic navigation. Recognizing the importance of improving polar prediction capabilities, the World Meteorological Organization (WMO) launched the Polar Prediction Project (PPP) in 2013, a decade-long initiative aimed at promoting international collaboration to enhance prediction services for the polar regions (Wilson et al., 2023). Notably, Chinese scientists have made significant contributions to advance high-resolution sea ice numerical models and develop sophisticated data assimilation systems. These innovations provide a valuable foundation for improving the accuracy of forecasts in key parameters such as sea ice concentration and thickness.

Numerical models are extensively used to investigate key physical processes governing polar atmosphere-ice-ocean interactions, ice mass and heat balance, and to forecast sea ice changes across short-term, seasonal, and long-term scales (e.g., Mu et al., 2019; Yang et al., 2019, 2020; Zhang et al., 2021c, 2023c; Yu et al., 2022). Despite notable advancements in simulating these complex interactions over recent decades, significant challenges remain in accurately representing critical thermodynamic and dynamic processes within these models. Recent changes in the Arctic climate system, particularly in sea ice thermodynamics, dynamics, and their coupling with the atmosphere and ocean, have increased the complexity of accurately representing these processes in numerical models, posing challenges in simulating multiscale sea ice variability. To address these challenges, various studies by Chinese scientists have developed parameterization schemes and high-resolution models that incorporate recent observational data, enhancing the representation of the interactions of sea ice with lower atmosphere and upper ocean (Shi et al., 2021; Zhang et al., 2021c, 2023c; Yu et al., 2022). These advancements include refined simulations of sea ice kinematics, such as multi-fractal spatial scaling of sea ice deformation, where improvements in elastic-viscous-plastic (EVP) rheology schemes play a vital role in reproducing realistic ice kinematic behaviors (Xu et al., 2021). More recently, developments in high-resolution sea ice models have introduced innovative parameterization schemes that improve various aspects of sea ice simulations. For example, a lateral melting parameterization that accounts for the spatial distribution of ice floe sizes has enabled more accurate numerical simulations of ice-wave interactions (Yang et al., 2024). Additionally, a novel three-equation boundary condition parameterization has been integrated into First Institute of Oceanography-Earth System Model (FIO-ESM) v2.1 to better represent ice-ocean heat fluxes, effectively reducing biases in sea ice simulations (Shu et al., 2024). Furthermore, an online Lagrangian tracking module within the Community Ice CodE (CICE) component of the Community Earth System Model (CESM) enhances the model's diagnostic capabilities, particularly for thermodynamic and dynamic processes, improving the representation of multi-fractal sea ice deformation (Ning et al., 2024).

As Arctic Ocean expeditions and commercial shipping activities continue to increase (Liu et al., 2024b), there is a pressing need for accurate sea ice predictions to support safe and efficient navigation (Zhou et al., 2021; Min et al., 2023a). Despite advances in numerical models, substantial uncertainties in initial conditions persist, resulting in significant errors, even in state-of-the-art dynamic forecasts such as those from the European Centre for Medium-Range Weather Forecasts (ECMWF), particularly in sea ice thickness predictions (Xiu et al., 2022; Yang et al., 2022).

To improve accuracy in Arctic sea ice predictions, the assimilation of multi-source satellite data through advanced methods like the Ensemble Kalman Filter (EnKF) is crucial, as it effectively reduces initial errors. Yang et al. (2014) employed the Localized Singular Evolutive Interpolated Kalman (LSEIK) filter to assimilate Soil Moisture and Ocean Salinity (SMOS) sea ice thickness data—critical for monitoring thin sea ice—into the MITgcm sea ice-ocean model, resulting in notable improvements in Arctic winter ice thickness estimates. To address the scarcity of summer sea ice thickness observations, Yang et al. (2015) introduced an innovative assimilation method incorporating sea ice concentration observations, which dynamically accounted for atmospheric uncertainties, thereby enhancing summer ice thickness forecasts. Building on this progress, Mu et al. (2018a, b) successfully performed the joint assimilation of Special Sensor Microwave Imager Sounder (SSMIS) sea ice concentration data alongside CryoSat-2 and SMOS ice thickness product, producing a high-precision reanalysis dataset that spans both freezing and melting periods. Lyu et al. (2021, 2023) further employed 4-Dimensional-Variation (4DVar) assimilation techniques to reconstruct Arctic ocean-sea ice reanalysis that adequately captures the spatial and temporal variations in the Arctic sea ice and ocean. Moreover, the Arctic Ice Ocean Prediction System (ArcIOPS), has been developed and provided crucial ice forecasting services during the CHINARE-Arctic cruise in 2017 (Mu et al., 2019). Subsequent enhancements to ArcIOPS, including improved sea surface temperature data assimilation (Liang et al., 2019), have further strengthened its predictive capabilities, as demonstrated during the 2018 Arctic cruise of the CHINARE. In response to the growing demand for sea ice predictions, Yang et al. (2019) developed the Sea Ice Seasonal Prediction System (SISPS), which has demonstrated better performance in retrospective predictions compared to the results derived from the version 2 Coupled Forecast System (CFSv2) model.

In addition to advancements in Arctic sea ice prediction using coupled ice-ocean models, Chinese scientists have made notable progress in enhancing sea ice data assimilation and prediction through fully coupled atmosphere-ice-ocean models (e.g., Yang et al., 2020, 2022;

Ren et al., 2021; Shu et al., 2021; Liu et al., 2023a). However, previous studies have yet to incorporate summer sea ice thickness because of the challenge of remote sensing retrieval during the melt season. The release of the CryoSat-2 year-round ice thickness record recently (Landy et al., 2022) presents new opportunities for improving summer sea ice thickness assimilation and forecasting (Min et al., 2023b; Song et al., 2024). Min et al. (2023b) successfully assimilated this data using an Incremental Analysis Update (IAU) scheme, overcoming the challenge of discontinuous data availability and significantly improving the accuracy of sea ice thickness estimates in regions with pronounced sea ice deformation (Fig. 11).

4.2 *Projecting Arctic sea ice and marine accessibility*

In recent years, the development of fully coupled numerical models, particularly CMIP6 models, has enabled long-term simulations of Arctic sea ice. Evaluations of these models, using satellite observations and reanalysis datasets, show improvements in capturing changes in sea ice volume and extent (e.g., Shu et al., 2020; Shen et al., 2021; Chen et al., 2023b). Most CMIP6 models accurately reproduce the climatological mean, seasonal cycle, and long-term trends of Arctic sea ice thickness from 1979 to 2014, as compared to the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) reanalysis (Chen et al., 2023b). These improvements enhance our ability to project future changes, with recent efforts focusing on projecting an Arctic "ice-free" (with sea ice extent below 1×10^6 km^2) summer. However, previous studies often overlooked the inherent instability of the climate system. Zhao et al. (2022) improved the projection of Arctic sea ice by applying a weighting scheme that considered both model skill and independence, allowing for more constrained CMIP6 projections. This approach reduced the spread in the projected first year of an "ice-free" Arctic under the SSP3-7.0 scenario. Based on the constrained projections, the Arctic is expected to become "ice-free" between 2040 and 2072 under the SSP3-7.0 scenario, highlighting the accelerated rates of sea ice loss. Shen et al. (2023) introduced a time-variant emergent constraint approach, which links simulated sea ice extent with future projections, accounting for potential climate system changes. This innovative approach also provided a relatively precise estimate of future Arctic sea ice extent. Their analysis revealed that, under the SSP3-7.0 and SSP5-8.5 scenarios, the likely timing range for the Arctic to experience a summer "ice-free" state would fall between 2041–2071 and 2037–2066, respectively. Importantly, under the high-emission SSP5-8.5 scenario, after applying the constraint, the Arctic is projected to become ice-free 27 years earlier than previous projections. In a medium-emission scenario (SSP2-4.5), the likelihood of an Arctic ice-free summer is projected around 2080.

As Arctic sea ice is projected to decline continuously across all future scenarios, the navigability of Arctic sea routes is expected to improve, highlighting the significance of navigation projections for strategic planning. Chen et al. (2020, 2021a) utilized sea ice data from CMIP6 models to project changes in Arctic sea ice and navigability under various climate warming scenarios. Wei et al. (2020) employed PIOMAS sea ice reanalysis to refine sea ice projections from 16 CMIP6 models and assess the navigability of Arctic sea routes. They found that navigability for the icebreakers of PC6 along the central Arctic sea route, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, would increase from approximately 6.7%, 4.2%, and 2.1% during 2021–2035 to 14.7%, 29.2%, and 67.5% in 2086–2100, respectively. Furthermore, Min et al. (2022) optimally selected CMIP6 models and utilized high temporal resolution sea ice data to produce ensemble projections of Arctic navigability under different climate warming scenarios. This study identified key areas that influence the accessibility of Arctic sea routes and navigational safety. Notably, it demonstrated that even under the low-emission SSP1-2.6 scenario, the navigability of Arctic sea routes for both Open Water (OW) vessels and moderately ice-strengthened PC6 vessels would increase significantly (Fig. 12). More importantly, under the high-emission SSP5-8.5 scenario, when the global decadal mean surface air temperature anomaly reaches +3.6℃ compared to the pre-industrial era (1850–1900), the PC6 vessels could achieve year-round navigation by the 2070s.

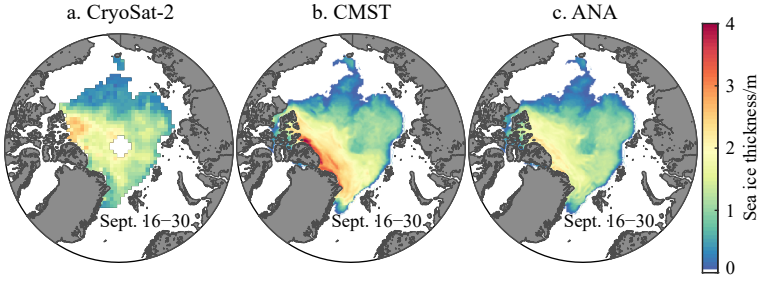


Fig. 11. Comparison of average sea ice thickness during late summer (September 16–30, 2016), based on CryoSat-2 (a), Combined Model and Satellite Thickness (CMST) (b), and Analysis (ANA) (c). The ANA estimates incorporate both sea ice thickness and concentration observations for assimilation, whereas CMST assimilates only sea ice concentration during the summer.

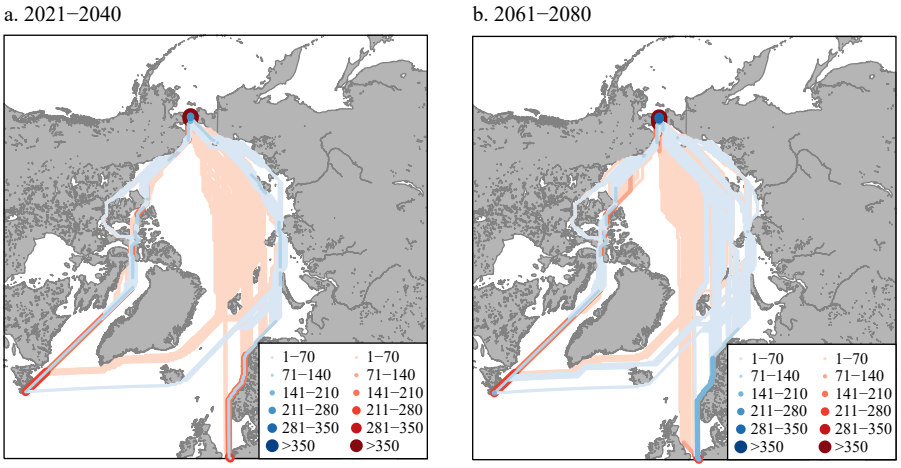


Fig. 12. Projected fastest available trans-Arctic sea routes for 2021–2040 (a) and 2061–2080 (b) under the low-emission SSP1-2.6 scenario, based on 20-a daily averaged sea ice thickness and concentration data. Blue lines represent sea routes accessible for the Open-Water (OW) vessels, while red lines indicate routes for the vessels of Polar Class 6 (PC6). The color gradient and varying line width reflect the density (days per year) of overlapping routes at specific locations.

The findings from studies on Arctic marine accessibility indicate that the potential for trans-Arctic sea routes will expand considerably.

5 Synoptic and climate effects of Arctic system changes

5.1 *Climate effects*

The remote impacts of Arctic amplification and sea ice loss include large-scale atmospheric circulation anomalies in both troposphere and stratosphere, as well as a range of weather and climate extremes that have caused substantial societal impacts in the affected regions (Cohen et al., 2020; Li et al., 2023; Wu, 2024). The schematic view of the Arctic influence on the Northern Hemisphere mid-latitude winter weather and climate is succinctly summarized in Fig. 13. Extensive ice-free waters and thinner sea ice in the Arctic Ocean allow for the enhancement of upward heat fluxes from warm surfaces, which results in greater heating of the overlying atmosphere that can be thermodynamically advected to adjacent continents via climatological sub-monthly transient eddies (Deser et al., 2010). In contrast, in mid-latitude continents, there has been a notable cooling trend, characterized by a series of unusually harsh cold winters and record snowfall, known as the "Warm Arctic Cold Continents" pattern (Kug et al., 2015). Among these, the impacts of dynamically induced changes are more critical than the thermodynamical impacts (Osborne et al., 2017). Although numerous observational and modelling studies have examined the hemispheric response to Arctic sea ice loss, a consensus is lacking. The intermittent Arctic-mid-latitude linkage is partly driven by the uncertainty regarding the strength, pattern and physical mechanisms involved in the remote impacts. However, there is a greater agreement on the downstream effects of regional sea ice loss and warming.

Regional anomalies in Arctic sea ice or air temperature can force regional responses in mid-latitude weather and climate (He et al., 2021). The effects of the Barents-Kara Seas (BKS) ice loss on the variability of the Eurasian winter climate have been the subject of the most extensive researches. Preferential BKS warming during the autumn and winter promotes a more meandering atmospheric circulation, increasing the likelihood of slower and amplified Rossby waves, and blocking situations and southward transport of air masses associated with cold extremes (Wu et al., 2011). There are two general pathways

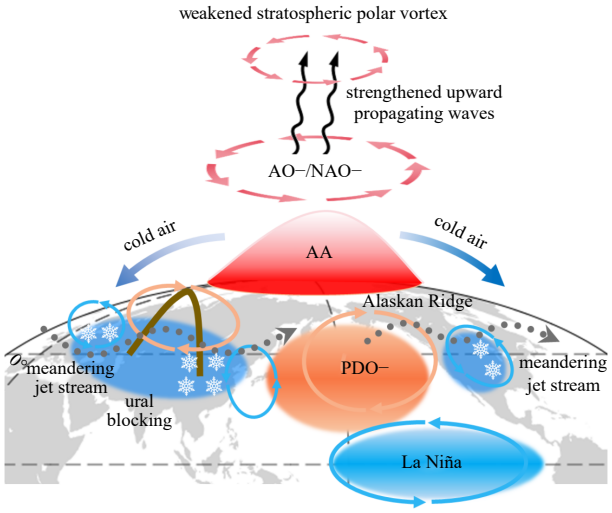


Fig. 13. Sketch of the influence of Arctic amplification and associated sea ice loss on the Northern Hemisphere mid-latitude winter weather and climate. AA, AO, NAO, and PDO denote the Arctic amplification, Arctic Oscillation, Northern Atlantic Oscillation, and Pacific Decadal Oscillation, respectively. The symbol − indicates that the atmospheric circulation pattern is in the negative phase.

for how Arctic amplification contributes to the enhanced meridional circulation that delivers a severe mid-latitude winter climate. The tropospheric pathway is usually linked to the emergence of high-latitude blocking, whereby Arctic amplification and concomitant melting of sea ice reduce the meridional background potential vorticity by weakening the mid-latitude winter zonal winds, intensifying Ural blockings and exacerbating the severity of severe winters in midlatitude Eurasia (Luo et al., 2016, 2017, 2019; Yao et al., 2017; Gu et al., 2018). The anomalous warming of the lower Arctic atmosphere can also increase barocline wave activity and the amplitude of Rossby waves, thereby making blocking activities more frequent and synoptic systems move more slowly (Yang et al., 2016b). In addition, the Arctic sea ice loss has been observed to generate extensive snow cover across the Eurasian continent through the transportation of abundant water vapour, which further promotes the Siberian high and instigates consecutive cold winters and springs in midlatitude Eurasia (Liu et al., 2012; Xu et al., 2019; Zhang et al., 2019). A second crucial mechanism responsible for the Arctic-midlatitude linkage has been identified as the stratospheric pathways in response to surface boundary condition anomalies. Specifically, changes in BKS ice and Eurasian snow cover are dynamically linked to the occurrence of enhanced upward-propagating waves into the stratosphere, which, in turn, potentially drive weakened stratospheric polar vortex and the concomitant surface cooling across the Eurasian and North American continents (Zhang et al., 2018b). Moreover, the BKS ice loss can further modulate the surface impacts of a weakened stratospheric polar vortex, including both the stratospheric sudden warming and polar vortex stretching events (Zhang et al., 2020a; Tian et al., 2023; Zou and Zhang, 2024). However, most of these mechanisms, regarding the intermittent Arctic-Eurasia relationship, are not yet sufficient clear and even controversial. For instance, the large-scale atmospheric responses to BKS ice loss are strongly dependent on the magnitude and seasonality of ice loss (Chen et al., 2021b; Zhang and Screen, 2021), the decadal change in mean climate and background flow (He et al., 2023; Wang and Wu, 2024), the intrinsic atmospheric variability (Blackport et al., 2019), and many others.

In addition to the Atlantic sector of the Arctic, sea ice loss in the Pacific sector is becoming increasingly important. The predominant atmospheric responses to sea ice reduction in the East Siberian−Chukchi−Beaufort Seas are anticyclonic anomalies in northern Europe, coolings in west-central Eurasia, and higher probability of extremely low temperatures in west-central China through the cold seasons, which are attributed to the increased upward propagation of quasi-stationary planetary waves in the troposphere (Chen and Wu, 2018; Ding et al., 2021, 2023). Regional warming of the Chukchi−Beaufort Sea and Baffin Bay−Greenland Seas is related to below-normal air temperatures across North America, with the elevated high-pressure over the Arctic−North America regions and the Greenland blocking, respectively, acting as critical factors influencing the southward penetration of cold air masses (Zhao et al., 2023). While the robust atmosphere-ice-ocean interactions in the Chukchi−Bering Seas may invoke a significant increase in the mean duration of the Alaskan Ridge pattern, and the troposphere-stratosphere coupling of the polar vortex has actively involved in the mechanisms behind, thus contributing to the recent cooling trend of Central North America (Yao et al., 2023; Gao et al., 2024).

5.2 *Synoptic effects*

The recent mid-latitude winter cooling period has coincided with an increase in severe winter weather and related disasters, typically observed following the record Arctic sea ice minimums. These include the historically unprecedented snowstorm and sleet that impacted China in winters 2008, 2016, and 2020. Recent case studies have emphasized the occurrence of cold surges during winter 2020/2021, which have identified the successive Ural blockings as a crucial physical mechanism facilitating the efficient transport of cold air to East Asia (Yao et al., 2023). Furthermore, a synergistic effect of BKS ice loss and La Niña can modulate the surface impacts of sudden stratospheric warming events, thereby causing cold spells in western North America in February 2021 (Zhang et al., 2022b, d). The sea ice anomalies in the Bering Sea can persist from December until the subsequent February, which stimulates an eastward-propagating Rossby wave train to North America, providing conditions that are conducive to the increased episodes of cold spells (Ma et al., 2022; Zhao et al., 2023).

The summer synoptic effects of Arctic sea ice loss have also been investigated with a particular focus on the potential for heat waves, wildfires and flooding (Tang et al., 2014; Wu and Francis, 2019). Arctic sea ice loss can potentially intensify the East Asian summer monsoon, deepening the low-pressure system over the Eurasian continent and increasing the incidence of heat waves over mid-latitude East Asia (Wu and Li, 2022). Additionally, the decadal reduction of Arctic sea ice may increase European heat waves, as a consequence of the weakened mid-latitude westerlies and strengthened high-latitude westerlies that dynamically facilitate sustained positive geopotential height anomalies (Zhang et al., 2020b, 2024c). In turn, the persistent, widespread and intense high-latitude warming and vapour pressure deficit contribute to the recent increase in Eastern Siberian wildfires (Luo et al., 2024b). Nevertheless, the impact of Arctic sea ice on summer flooding in East Asia, particularly in the Changjiang River (Yangtze River) basin and southern China, remains relatively limited (Chen et al., 2024b) and uncertain (Wu, 2024).

6 Knowledge gaps and prospects

For scientific expeditions, the lack of observation dur-

ing the freezing season is the biggest shortcoming. The use of R/V *Xuelong 2* can be appropriately expanded the expedition to autumn, but its icebreaking ability is still unable to meet the requirements for winter and spring survey in the central Arctic Ocean. It is necessary to improve the ice breaking capability and the cold resistance of the assembled deck equipment such as winches, profile observation equipment such as CTD, and online observation devices for the turbulence and radiation fluxes of atmospheric boundary layer, when developing and constructing the next generation of icebreaker research vessels. At the appropriate opportunity, international cooperation can be considered to launch a winter drift observation program to enrich winter observations in the central Arctic Ocean because there are still abundant limitations to the representativeness of data collected from a single MOSAiC year on a small scale of tens of kilometers, although this is already the most successful Arctic expedition in history. The insufficient unmanned autonomous observation capability of the ocean beneath the ice layer is another key deficiency that needs to be addressed. Developing the medium-depth ice-tethered profiler and long-endurance underwater vehicles through solving technical problems of underwater navigation and positioning is the technical issue that need to be addressed. In addition, from the perspective of observation strategy, constructing a sub-kilometer scale observation system using underwater profilers and vehicles, establishing buoy and mooring observation arrays in key areas, and using buoys as communication nodes to solve the technical bottleneck of transmitting underwater observation data to satellites, are all urgent issues that need to be addressed. This could enhance the ability to acquire observational data for large scales, e.g., basin scale, or fine processes, e.g., mesoscale processes, in the Arctic frozen waters. For sea ice mass balance, it is particularly necessary to develop buoys that are suitable for deployment in ice leads, unconsolidated ice ridges, and unfrozen melt ponds to meet the observation needs for Arctic ice field with the extremely complex spatial heterogeneity. For the lower atmosphere over the ice in Arctic Ocean, overcoming the challenge of mechanical anemometers and radiometer domes being frozen is a key technology that needs to be innovated for continuous observation through the winter.

At present, Chinese satellites used to monitor physical variables of Arctic sea ice are still insufficient. Especially, satellite observation using the payloads of optics, SAR, altimeter, and ultra-wideband radar are particularly lacking. With the increased deployment of polar orbiting satellites, the design of satellite constellations, and the geolocation and calibration of satellite imagery (e.g., Zhang et al., 2021a) will be an important research field in the future. In terms of navigation services for research or merchant vessels, data communication from the land-based data processing center and the ship, and the interpretation of remote sensing image are currently the biggest challenges. To solve the issues involved the high-latitude communication, on the one hand, we need to develop communication satellite networks covering the polar region, and on the other hand, we can consider improving the ship-based capability to receive satellite images and developing shortcut-interpretation algorithms for satellite remote sensing images that can be applied on the way. In terms of interpreting remote sensing images, although the CHINARE-Arctic cruise already has the ability to provide ground observations as the basis for developing retrieval algorithms and verifying retrieval results for some satellite remote sensing products, the data acquisition capability is still very limited. Developing standardized data acquisition techniques covering the regions with various ice types throughout the full ice season is the important foundation to breaking through the bottleneck involving satellite remote sensing retrieval algorithms, among which the observation data at the sub-kilometer scale is particularly important for creating high-resolution remote sensing products and for explaining the small-scale process of sea ice. With the further improvement of satellite remote sensing resolution, combining satellite remote sensing with aerial remote sensing or on-site observations to conduct cross-scale physical process studies is also an important research field. Efforts in this field are conducive to matching with numerical models and applying the results for the parameterization or verification of numerical simulations.

The thinning of Arctic sea ice may fundamentally alter the thermodynamic and dynamic mechanisms of sea ice. In particular, a decrease in the retention time of sea ice in the high Arctic may lead to reductions of snow accumulation over the ice (Webster et al., 2018) and the cumulative deformation of ice field (Sumata et al., 2023). However, an increase in cyclones entering the Arctic Ocean may increase precipitation, even rainfall in spring and summer. In addition, the deformation intensity of dominant first-year or second-year ice is expected to increase. These changes can make the thermodynamic and dynamic processes of sea ice more complex. The contribution of snow will no longer be a trivial matter, and the contributions of snow ice or superimposed ice to the mass balance of sea ice will be enhanced. The dynamic deformation of thin ice will form unconsolidated ice ridges. The refreezing of macroscopic pores inside the unconsolidated ice ridges will play an important role in the heat budget of sea ice. In the severe ice regions north of Greenland and Canadian archipelago, the loss of multi-year ice over the years, as well as the collapse of ice arches at the narrow ice outflow gateways, especially in the Nares Strait, will strengthen the atmosphere-ice-ocean interactions there. The northward expansion of the Arctic MIZ will increase the interaction between waves and sea ice. These changes in the thermodynamic and dynamic mechanisms of sea ice will constraint timely updates of our comprehension for the thermodynamic and dynamic mechanisms of sea ice and their changes.

The lack of *in-situ* data for validation has led to significant uncertainties in numerical models that attempt to solve and characterize the finer-scale processes (mesoscale of 10–100 km and submesoscale less than 10 km). Manucharyan and Thompson (2022) emphasized that Arctic Ocean models often lack the spatial resolution to properly simulate submesoscale eddies, resulting in an underrepresentation of their effects on larger-scale circulation and heat transfer. The indirect way to estimate the eddy activity in Armitage et al. (2020) highlighted that satellite altimetry struggles to capture finer-scale features due to sea ice cover, and cloud cover complicates optical remote sensing. The unique stratification and ice-ocean interactions demand observational data to refine model outputs. Addressing the deficiency of observations related to mesoscale and submesoscale processes in the Arctic Ocean requires expanded deployment of autonomous platforms of ice-tethered buoys, Autonomous Underwater Vehicles (AUVs), and gliders, and improved satellite technology capable of penetrating the cloud and even ice. The ocean-sea ice-biogeochemical coupled model has been used to identify how ecosystems, in especial the phytoplankton assemblage, the biological carbon pump efficiency, and carbon cycle and ocean acidification, respond to rapid sea ice and marine environmental changes in the Arctic Ocean (e.g., Zheng et al., 2023; Luo et al., 2024a). However, in order to improve the simulation effect and optimize the parameterization configuration of the model, it is necessary to strengthen the collaborative observations of ocean and sea ice dynamic processes and key components and parameters of the ecosystem.

The vertical resolutions of the year-round observations on the water exchanges between the Arctic Ocean and the Atlantic Ocean, although which is extremely important for both water bodies, are relatively low and only parts of the ocean currents are covered by moorings. Meanwhile, low-resolution climate models tend to underestimate the positive trend of the poleward ocean heat transport (Docquier et al., 2019), and the state-of-the-art climate models exhibit larger inter-model spread and biases in the Arctic Ocean simulations and projections (Shu et al., 2020; Pan et al., 2023a). Therefore, both observations and climate models need to be improved and strengthened to better understand the changes and its climate effects of the water exchanges between the Arctic Ocean and the Atlantic Ocean.

The connection between the Arctic Ocean and beyond, as well as the associated exchanges of material and energy, is not only limited to the pathways of the ocean and atmospheric circulations, but also includes the exchanges between ocean and ice sheet (Greenland), through water cycle and heat exchange, and between ocean and land, through runoff and coastal erosion. The latter will also affect the internal interactions and feedbacks of the Arctic atmosphere-sea ice-ocean coupling system, especially the expectedly increased freshwater injection from the melts of ice sheet or mountain glacier, and runoff due to the Arctic warming and humidification, which is crucial for increasing buoyancy over ocean surface and stabilizing upper ocean stratification, as well as increasing the nutrients and trace elements to marine ecosystem.

This review provides an overview of the progress on the causes and mechanisms of Arctic climate variability and the Arctic-midlatitudes connection. We have attempted to elucidate the complexity of the topic by surveying various mechanisms and conclusions from both observational and modelling studies. However, we have to admit that there is still a lack of consensus on the hemispheric response to sea ice loss, particularly the Arctic-midlatitude linkage projections indicate that the classical "Warm Arctic Cold Continent" pattern will have occurred in an alternation pattern with the newly emerging "Warm Arctic Warm Continent" pattern in the near future. It remains a challenge to extricate the causation relationship and signals from the inherently chaotic climate system, ultimately leading to the disruption of effective climate predictions. Precise representation of the atmospheric dynamics in coordinated models may help thoroughly understand the mechanisms behind the intermittency of Arctic-midlatitude linkage. Although the present debate is extensive, the ongoing research will facilitate the formation of a consensus on these scientifically significant issues.

7 Summary

China has been conducting scientific expeditions to the Arctic Ocean for 25 years since 1999. As a process of 14 expeditions, the CHINARE-Arctic cruises gradually expanded the survey region from the western Arctic Ocean to the regions close the North Pole and over the Gakker Ridge. Navigability surveys have also been carried out for the Northeast and Northwest Passages, and sea route across the central Arctic Ocean. Multiple ice-tethered buoys, AUVs, and Remotely Operated Vehicles (ROVs) suitable for using in frozen waters have been developed and deployed during the CHINARE-Arctic cruises. The sea ice and ocean observation data obtained from CHINARE-Arctic cruises provide important foundation for the optimization and validation of satellite remote sensing retrieval algorithms. Based on the HY and FY series satellites, Chinese scientists have also developed a series of retrieval algorithms for multi parameters of Arctic sea ice and created sets of remote sensing products.

Focusing on the studies on the interactions between atmosphere, sea ice, and ocean in the Arctic Ocean, as well as their climate effects, a series of achievements have been made, with significant improvements in the capabilities of observation, numerical simulation, and the mechanism cognition. Studies on the evolution of the Arctic system have revealed new mechanisms for the thermodynamic and dynamic processes of Arctic sea ice and its interactions with the atmosphere and ocean. Especially based on

the buoy array observations, the dependence of sea ice freezing processes and ice-field deformation during winter on the initial sea ice conditions in autumn have been identified. The structural characteristics of the Arctic atmospheric boundary layer and its response and feedback to sea ice changes have been described. The regulatory mechanisms of freshwater storage budget in the BG system, as well as the heat and momentum exchange between ice and ocean have been clarified. The crucial role of increased poleward oceanic heat transport in the rapid warming of the Arctic Ocean has been revealed, and the concept of "Arctic Ocean amplification" has been proposed. The key role of atmospheric heat and moisture transport towards the Arctic from the lower latitudes in the melting of Arctic sea ice in the summer has been elucidated. Based on the parameterization scheme with the observational evidences, high-resolution sea ice models adapted to the rapid changes in the Arctic have been developed, which can be applied to sea ice forecasting models and Earth system models to improve the prediction ability of Arctic sea ice. By assimilating multi-source sea ice and ocean observation data, especially the annual remotely-sensed ice thickness products, the simulation of Arctic sea ice has been significantly improved. The predictions on the year with the Arctic ice-free summer and the navigability of Arctic sea routes has aroused widespread interests in the community of sea ice numerical simulation.

Although there is a lack of consensus on the hemispheric response to sea ice loss, there is an agreement on the downstream responses to regional Arctic sea ice loss. Specifically, the BKS ice loss appears to cause winter surface cooling and cold spells in mid-latitude Eurasia and summer heat waves in Europe and East Asia, combined with simultaneous snow cover changes. In comparison, regional warming in the Pacific sector of the Arctic is related to below-normal air temperatures across North America, usually in combination with La Niña and weakened stratospheric polar vortex. The diversity and intermittency in the Arctic-midlatitude links could be interpreted with the varying magnitude, region, seasonality, and duration of sea ice forcings and the complexity of mid-latitude atmospheric dynamics.

There are still lots of shortcomings and limitations in the studies on the evolution of the Arctic atmosphere-sea ice-ocean coupling system and its climate effect. The observation capabilities of the Arctic ice regions in winter and the marine environment under the ice are still very limited or missing during the CHINARE-Arctic cruises. Insufficient observation has led to unclear understanding for some crucial processes and feedback mechanisms, making it difficult to represent them reasonably in numerical models. Specifically, it includes (1) the microphysical processes of Arctic clouds and the radiation feedback mechanisms they generate, as well as their impacts on lower atmospheric structure, near-surface warming, and surface heat budget; (2) the mixing of the ocean under the ice and its response to mesoscale or submesoscale oceanic processes, extreme weather, and ice deformation, as well as its impacts on the ice basal growth and decay; (3) formation, evolution, and dissipation processes of mesoscale and submesoscale processes beneath the ice; (4) the formation process of melt pond, ice ridges and leads, and their unique thermodynamic processes relative to the level ice; (5) snow and ice surface melting in summer and its impact on freshwater cycle at the floe scale, and (6) sea ice and ocean dynamics at some crucial channels, and their impacts on sea ice or oceanic heat advection from or toward the Arctic Ocean, etc.

As sea ice continues to decrease, the sensitive regions of Arctic Ocean that may have an impact on weather and climate in Eurasia and North America may also undergo spatial shifts, and the seasonality of remote impacts may also vary accordingly. In particular, the key regions identified in the past that affect weather and climate processes in China, mainly the Barents and Kara Seas, is expected to undergo spatial migration as the ice edge and MIZ moving northward. There are also significant uncertainties regarding the trend of the impact extent of Atlantic and Pacific waters entering the Arctic Ocean on Arctic sea ice and ocean processes. These are research fields that need to be strengthened.

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