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Predicted changes in the distribution of Antarctic krill in the Cosmonaut Sea under future climate change scenarios

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ABSTRACT

Antarctic krill (*Euphausia superba*) are the key species of the ecological system in the Cosmonaut Sea. Long-term habitat alterations in krill due to climate change have been considered in recent decades. However, there is still a lack understanding about krill distribution. The MaxEnt model was used to forecast the suitable distribution area of krill for this study, which is based on data from the Coupled Model Intercomparison Project in its sixth phase (CMIP6) in the near future and far future. A total of 145 occurrence points and 15 environmental factors were selected to build the MaxEnt model. The current suitable habitat regions for krill were mostly detected in the western and central regions of the Cosmonaut Sea, which accounted for 10.07% of the total area. The most important environmental variables that influenced krill distribution were minimum surface solar radiation downward (*ssrdmin*), the mean temperature (*tem*) and the mean northward velocity (*v*). In the near future and far future, the suitable area of krill was seen to decline under all shared socioeconomic pathways (SSPs), with the smallest reduction under SSP1-2.6 and the greatest reduction under SSP5-8.5. The suitable area for krill dropped quicker from the near future to the far future than the present to the near future. Krill habitats were expected to shift to the poles. The *tem* continued to rise in the future under all SSP scenarios, particularly under the high radiative forcing scenario. The increase in water temperature is the main reason for the decrease in suitable areas for Antarctic krill. Our results show the future distribution of krill in the future and provide a reasonable reference for the ecological protection policy of the Cosmonaut Sea.

1. Introduction

Euphausia superba (hereafter referred to as "krill") is a key species in the Southern Ocean ecosystem (Nicol & Endo, 1999). It is one of the single species with the biggest biomass on the globe (Everson, 2001; Krafft et al., 2021). Through selective grazing and perhaps nutrient regeneration, krill has a critical role in regulating energy flow in the food web of the Southern Ocean (Atkinson et al., 2001). Antarctic krill serves as a key connection between primary production and higher trophic levels, such as copepods and diatoms, and is responsible for the greatest regional fisheries of the Southern Ocean (Atkinson et al., 2002; Forcada et al., 2012; Schmidt et al., 2016). The temporal and spatial distribution of krill resources and changes may have major ecological implications of many aspects (Murphy et al., 2007). Antarctic krill, as a keystone species in the Southern Ocean, is extremely important for analyzing the impacts of climate change on ecological systems (McBride et al., 2021).

The temporal and spatial distributions of Antarctic krill are subject to ongoing climate change, such as sea ice retreat, ocean acidification and temperature rise (Flores et al., 2012; Jacquet et al., 2010; Sylvester et al., 2021). According to Atkinson et al. (2019), because of rapid regional warming, the range of krill has constricted southward during the last 90 years within their main population core in the southwest Atlantic sector. Yang et al. (2021) discovered that krill density decreased in the Atlantic-Bellingshausen sector while increasing in the Ross-Pacific sector because of variations in temperature and sea ice. These works, however, are centered on the Atlantic sector of the Southern Ocean, and further work is still needed since climate change has varied greatly in strength and direction among different sectors (Convey & Peck, 2019; Lenaerts et al., 2017).

The Cosmonaut Sea, located in western Enderby, East Antarctica, is

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one of the least explored regions in the Southern Ocean (Hunt et al., 2007). Both the Coastal Current, which flows westward in the south, and the Antarctic Circumpolar Current, which flows eastward in the north, impact the Cosmonaut Sea (Bibik et al., 1988). The Cosmonaut Sea is located within the northern zones of krill abundance in the Southern Ocean, where high-latitude water is mixed with water from the Antarctic Circumpolar Current (Makarov & Spiridonov, 1993; Pakhomov, 1993). Krill in the Cosmonaut Sea are closer to land and more quickly respond to environmental changes (Atkinson et al., 2008). Presently, studies of krill have focused on the growth, lifespan and mortality rates of krill using data from scientific surveys. These data, however, only cover a minute part of the Cosmonaut Sea, which is insufficient for investigating the distribution and future changes of krill. To support conservation efforts and account for the influence of climate change on the ecosystem in the Cosmonaut Sea, we must increase our understanding of the geographical distribution of krill and how this distribution will be altered by future climatic circumstances.

Species distribution models (SDMs), also called as "habitat" models, can assess the distribution of a given species simply based on presence data and various environmental parameters (Byeon et al., 2018). SDMs have been widely utilized to assess species habitat, identify areas of interest for biodiversity, and manage threatened species (Franklin, 2010). In recent years, SDMs have been increasingly employed to forecast the potential changes in the distributions of species with climate change by using various environmental parameters under various climate change scenarios (Hu et al., 2022). The maximum entropy (MaxEnt) model, which combines machine learning and maximum entropy principles, is currently the most commonly employed model for predicting the temporal and geographical changes in marine species habitats globally. For example, Hu et al. (2022) estimated the spatial and temporal distribution changes in 21 fish species under two climate change scenarios forward to the 2050s using MaxEnt in the China Seas. Their results showed that the habitats of most species would relocate northward by the 2050s. Lezama-Ochoa et al. (2016) discovered that the changes in the habitat of a shark (*Carcharhinus falciformis*) and a teleost (*Canthidermis maculata*) are larger in the Atlantic Ocean than in the Pacific and Indian Oceans under the A2 scenario. And sea surface temperature is the most significant variable explaining the habitat distributions of both species. Schickele et al. (2021) investigated the changes in the spatial distribution of seven fish species under three different climate change scenarios in Europe and discovered that while the Black and Baltic Seas may see an increase, the Mediterranean and western North Sea may experience a sharp decline in the environmental appropriateness for the majority of the seven species. Although MaxEnt models have been used to predict studies on global fish habitat change, these studies were mostly conducted in regions like Asia, America, and Europe, with a minor amount of research in the Antarctic. To promote adaptive conservation and management strategy, this study aims to investigate how the krill distribution in the Cosmonaut Sea will change over time under climate change and identify which factors control these changes. The lack of krill distribution records in the Cosmonaut Sea can be addressed by using SDM.

In this study, the MaxEnt model and the latest shared socioeconomic pathways (SSPs) from the Coupled Model Intercomparison Project in its sixth phase (CMIP6) were selected to investigate the temporal and spatial distribution of krill in the Cosmonaut Sea. The major goals of this study were to identify the key environmental factors of krill distribution; to estimate krill habitat suitability; and to assess the possible effects of climate change on krill habitats under different scenarios in the near future and far future.

2. Materials and methods

2.1. Current species data

The current distribution data of krill were collected from KRILLBASE and from the 36th Chinese National Antarctic Research Expedition (CHINARE). KRILLBASE is a circular pole collection of all accessible krill net sample data for krill from 1926 to 2016 (Atkinson et al., 2017). Only during the austral summer do ships approach the Cosmonaut Sea due to the harsh environment and thick sea ice. Almost all selected krill samples from the two datasets were concentrated in January, February, March, November and December. In this study, the latitude range of study region was approximately 60°S-70°S and the longitude range was 30°E-65°E (Fig. 1). To avoid the effect of spatial autocorrelation on the accuracy of the model, we randomly removed the points whose distance between two points was less than 0.1°. A total of 145 distribution points of krill were collected.

2.2. Environmental variables

Environmental variables such as ice concentration, temperature, mixed layer thickness, surface velocity, and chlorophyll are always employed in prediction models for krill (Davis et al., 2017; Leonori et al., 2017). Krill feed primarily on diatoms, and silicon is important for habitat selection (Cleary et al., 2018). Iron is an essential nutrient for krill (Schmidt et al., 2016). Solar radiation, sensible heat radiation, and latent heat radiation are known to influence krill in various ways (Bukatov & Babiy, 2021; Singh & Polvani, 2020). Therefore, we selected these environmental variables to detect the habitat of krill. Current environmental variables were obtained from Global Ocean Reanalysis Simulation (GLORYS2V4) (https://www.mercator-ocean.fr) and ECMWF Reanalysis v5 (ERA5) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form). Parameters comprised the average state of the variables and their variability (maximum mean and lowest mean).

For future scenarios, three SSP scenarios from CMIP6 were selected for this work. These scenarios are described as follows: (1) The SSP1-2.6 scenario is the low-end of the future scenario range, with radiative forcing stabilizing at 2.6 W/m^2 in 2100. (2) The SSP2-4.5 scenario is a moderately stable scenario in which radiative forcing stabilizes at 4.5 W/m^2 by 2100. (3) The SSP5-8.5 scenario, which is considered a high radiative forcing scenario, stabilizes radiative forcing at 8.5 W/m^2 in 2100 (Riahi et al., 2017). The environmental variables in CMIP6 were extracted from MPI-ESM1-2-HR (German Climate Computing Centre). Variables were downloaded from the historical experiment for the period 1993–2014 and from the SSPs SSP1-2.6, SSP2-4.5, and SSP5-8.5 for the periods 2029–2050 (near future) and 2079–2100 (far future). By averaging the CMIP6 projections, long-term environmental shifts were calculated. These variables used to forecast the suitable distribution regions were obtained as follows: First, the climatic anomalies of each SSP between the present and near (far) future were calculated from MPI-ESM1-2-HR; Second, these anomalies were resampled to the same resolution as current variables using bilinear spatial interpolation; Third, the forecasting dataset was created by combining the interpolated anomalies with the present data. (Hu et al., 2022; Tabor & Williams, 2010).

To avoid the influence of multicollinearity and the MaxEnt model overfitting of these variables (Fotheringham & Oshan, 2016), Pearson correlation analysis was performed on these variables in Statistical Product and Service Solutions (SPSS). When the correlation coefficient of two variables exceeded 0.80, the variable with higher significance was reserved (Dormann et al., 2013). In total, 15 environmental variables (*chl*, *chlmin*, *fe*, *ice*, *mlpmax*, *mlpmin*, *mslmax*, *si*, *slhfmax*, *sshf*, *sshfmin*, *ssrdmax*, *ssrdmin*, *tem*, and *v*) were maintained in the MaxEnt model (Table 1) for habitat suitability modeling of krill.

2.3. Model settings

In this study, MaxEnt 3.4.1 was used to predict krill distribution (Phillips et al., 2017). After importing the krill distribution data and the screened environmental variable data into MaxEnt, 75 % of the

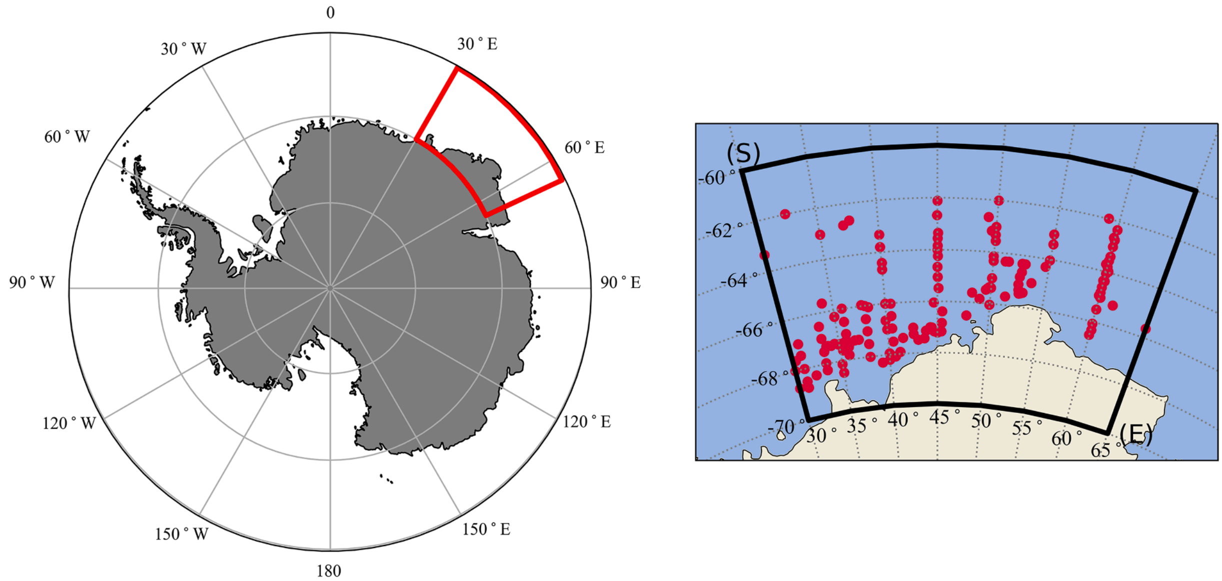

Fig. 1. Location of the Cosmonaut Sea (left) and distribution records of krill in the Cosmonaut Sea (right).

Table 1
Environmental variables.

Code	Name	Unit
chl	Mean total Chlorophyll	mg/m^3
chlmin	Min total Chlorophyll	mg/m^3
fe	Mean dissolved Iron	mmol/m^3
ice	Mean ice concentration	
mlpmax	Max density ocean mixed layer thickness	m
mlpmin	Min density ocean mixed layer thickness	m
mslmax	Max sea level pressure	Pa
si	Mean dissolved Silicate	mmol/m^3
slhfmax	Max surface latent heat flux	J/m^2
sshf	Mean surface sensible heat flux	J/m^2
sshfmin	Min surface sensible heat flux	J/m^2
ssrdmax	Max surface solar radiation downwards	J/m^2
ssrdmin	Min surface solar radiation downwards	J/m^2
tem	Mean temperature	K
v	Mean northward velocity	m/s

occurrence data are selected for training, and the remaining 25 % are selected for testing. The repeated iterative operation was set to 500 times in the settings window, and a bootstrap replicate run type for 10 replicates was selected. The threshold was set at the maximal test sensitivity plus specificity. Subsequently, The MaxEnt model generates a continuous map with a probability of occurrence ranging from 0 to 1. The contribution rate and importance of parameters were obtained using the jackknife test.

The receiver operating characteristic curve (ROC) and the area under the ROC curve were used to evaluate model performance, with the AUC value ranging from 0 to 1. An AUC value closer to 1 indicates more accurate prediction results. The performance of the model was classified as follows: failing (0.5–0.6), poor (0.6–0.7), fair (0.7–0.8), good (0.8–0.9), and excellent (0.9–1.0) (Nachtsheim et al., 2017; Phillips et al., 2006).

The value of the map of the MaxEnt model's output was used to define habitat appropriateness. Krill habitat appropriateness was categorized as follows: "Unsuitable": a value of less than 0.2 indicates that the environment is not suitable for krill in theory; "Marginally suitable": a value of 0.2 to 0.4, indicating that habitat elements are insufficient to allow persistent krill presence; "Moderately suitable": a value of 0.4 to 0.6, indicating that habitat characteristics support krill occurrence on a broad scale; "Highly suitable" means that the habitat characteristics enable krill presence at an ideal level, with a value larger than 0.6 (Boitani et al., 2002; Elith et al., 2011).

2.4. Distribution changes

To analyze and compare distribution maps between periods and different SSPs, we utilized gained and lost suitable areas for krill. Unsuited to marginally suitable, unsuitable to moderately suitable, and unsuitable to highly suitable were the areas gained. Marginally suitable to unsuitable, moderately suitable to unsuitable, and highly suitable to unsuitable were the areas that were lost. The areas remained unchanged except for the gained and lost areas.

We examined an environmental subspace suitable for krill to investigate the link between krill and the environment, as well as the degree of environmental shifts that occurred over times and SSPs. The whole environmental space was made up of the total set of environmental parameters that contribute the most to the model. The convex hull defined the environment inside the highly suitable area for krill.

3. Result

3.1. Current distributions and variable contributions

Maxent performed well in generating the potential distribution of krill, with a mean AUC of 0.856. The current potential distribution map for krill in the Cosmonaut Sea is shown in Fig. 2. The unsuitable, marginally suitable, moderately suitable, and highly suitable areas comprised 708.67 × 10^3 km^2, 375.24 × 10^3 km^2, 234.41 × 10^3 km^2, and 164.12 × 10^3 km^2, respectively. Almost half of the study area was unsuitable for krill, and the area that was highly suitable was the least among other suitable types. The highly suitable areas for krill in the Cosmonaut Sea were found to be primarily located in the western and central regions near the mainland, which accounted for 11.7 % of the total area. The moderately suitable area, which accounted for 15.81 % of the total area, was mainly located north of the boundary area of the highly suitable habitat. There were also moderately suitable areas in the eastern Cosmonaut Sea. The marginally suitable area was the largest area, which accounted for 25.31 % of the total area, spanning the entire Cosmonaut Sea, with the northernmost point at 62°S.

The top three environmental data included in the prediction of the MaxEnt model that impacted krill distribution were *ssrdmin* (37.4 %), *tem* (19.4 %), and *v* (7.1 %), with a combined contribution of 63.9 % (Fig. 3). The parameter with the highest gain when applied in isolation

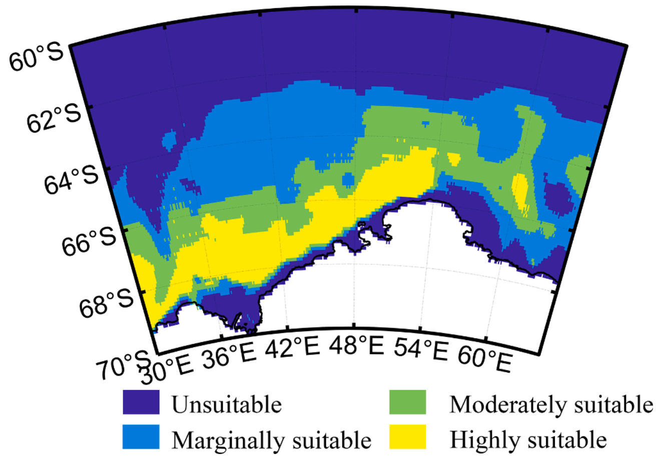

Fig. 2. Potential suitable areas for krill in the Cosmonaut Sea.

was *ssrdmin*. Therefore, *ssrdmin* appeared to have the most useful information by itself. In summary, the key parameters that limited the selection of suitable areas for krill were *ssrdmin*, *tem*, and *v*.

The probability of krill presence could be estimated using the response curves for environmental variables in MaxEnt (Fig. 4). The results showed that the probability of occurrence decreased with an increase in *ssrdmin*. The maximum probability occurred at 7.05×10^6 J/m^2, and the optimum range was below 7.78×10^6 J/m^2 (with a probability occurrence greater than 0.60). The results showed that krill were suitable for living in the lower *ssadmin* area. With an increase in *tem*, the probability of occurrence rose and then declined. The greatest probability was at 271.57 K, and the optimal range was between 271.45 K and 272.47 K. This result suggests that lower temperatures were not better for krill. For *v*, the largest probability was at −0.063 m/s, and the optimum range was between −0.09 m/s and −0.015 m/s. This result showed that southward currents were more suitable for krill.

3.2. Potential distribution under future climate conditions.

The distribution of krill habitat has undergone significant changes under climate change scenarios. Analysis in the near future under different SSPs showed that the suitable area was the largest under SSP1-2.6 and the smallest under SSP5-8.5 (Fig. 5). The marginally suitable area was the maximum under SSP2-4.5, which was 226.00×10^3 km^2. The krill habitat in the Cosmonaut Sea were found to be primarily located in the western and central regions near the mainland, while there were nearly no krill scattered at 60°E under SSP2-4.5 and SSP5-8.5. To sufficiently learn the distribution of krill suitable areas in the future, we intend to define three fractions of main suitable areas by the geographical characteristics as A (64°S-70°S, 30°E-40°E), a ridge, C (64°S-70°S, 48°E-56°E), Enderby Land, and B (64°S-70°S, 40°E-48°E). And the highly suitable areas of krill in regions A, B, and C accounted for 96 % current highly suitable areas. Compared with the present, krill habitat in the near future would decrease under all SSPs. Krill habitat was much smaller under SSP2-4.5 and SSP5-8.5 than under SSP1-2.6. The highly suitable areas decreased in B and C under all SSPs. Moreover, there will be no highly suitable areas in B under SSP2-4.5 and

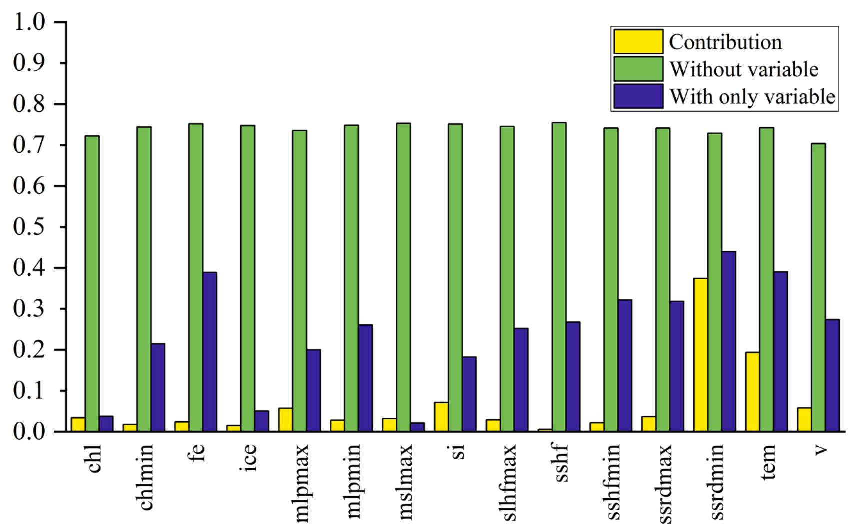

Fig. 3. The contribution and jackknife test of variable importance in Maxent.

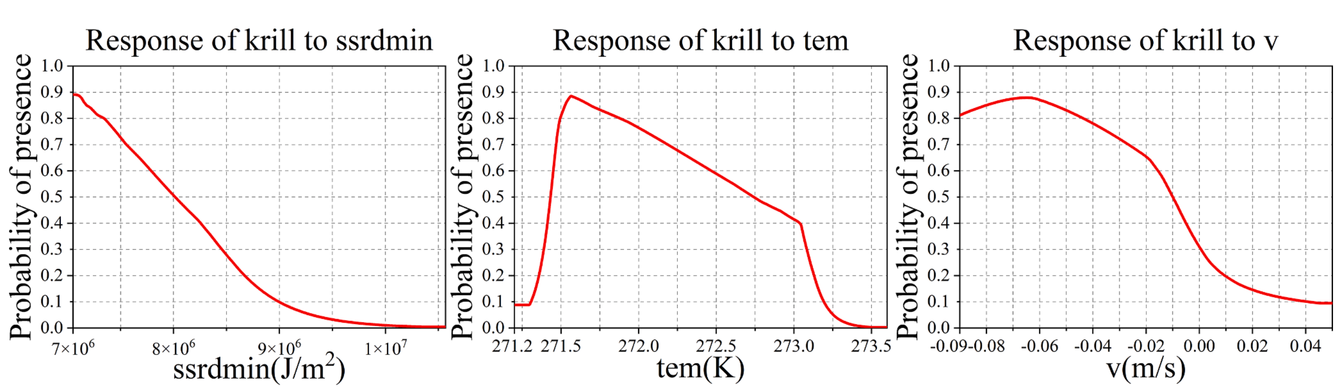

Fig. 4. The response curves between the probability occurrence and *ssrdmin*, *tem*, *v*.

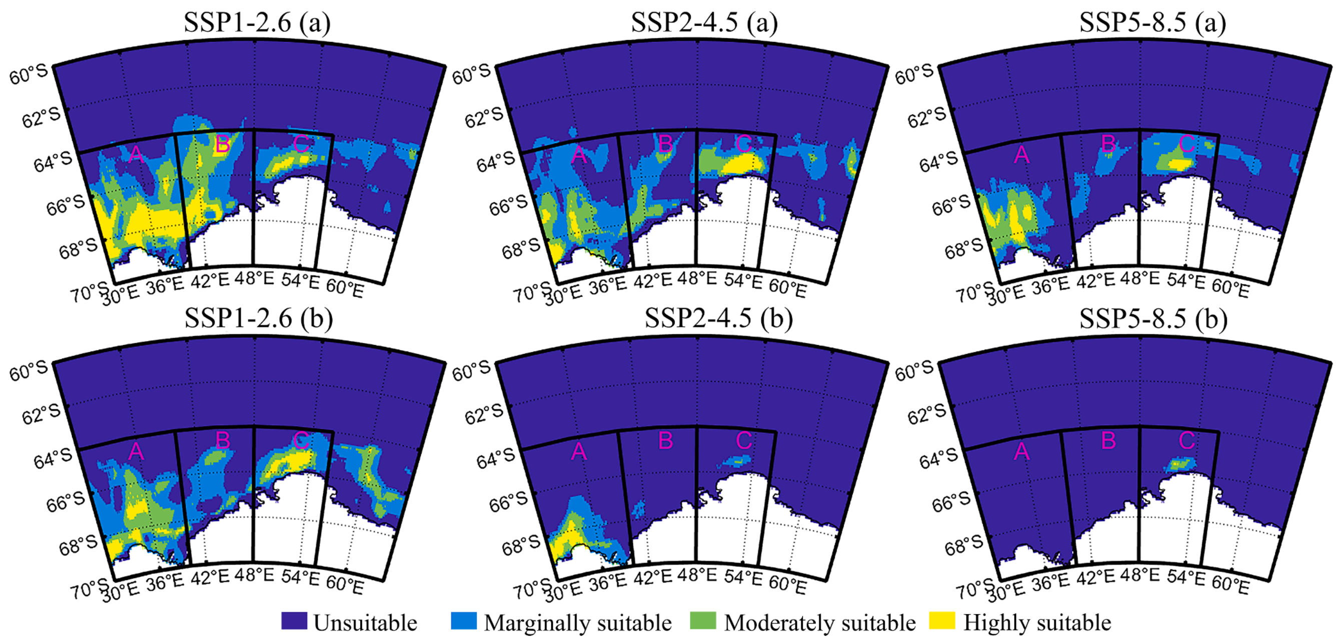

Fig. 5. Potential suitable area for krill under three SSP scenarios in the near future(a) and far future(b).

SSP5-8.5. Under SSP1-2.6, the highly suitable areas in A were similar to the current situation, but they declined drastically under SSP2-4.5 and SSP5-8.5.

In comparison to the near future, krill habitat significantly decreased under all SSPs of the far future. In particular, the highly suitable area for krill under SSP2-4.5 and SSP5-8.5 vanished in section B. Additionally, the krill habitat in region A significantly decreased under SSP2-4.5 and vanished entirely under SSP5-8.5. To sum up, the higher radiative forcing environment had a negative impact on krill.

3.3. Future changes in suitable habitats

The results showed that the habitat of krill may reduce under climate change scenarios, making it a potential loser species under climate change (Figs. 6–8). From the present to the near future, under the SSP1-2.6 scenario, the lost suitable habitat area (379.95 $\times$ 10^3 km^2) was 10.9 times the gained area (34.81 $\times$ 10^3 km^2). The majority of the lost area was in the north and east, where there was a change from a marginally or moderately suitable area to an unsuitable area. The gained area was focused in the southern and northern parts of the western Cosmonaut Sea, which created a marginally suitable krill habitat. The lost habitat was broad and widely dispersed, whereas the gained habitat was small and concentrated in the western part of the Cosmonaut Sea. Under the SSP2-4.5 scenario, the lost suitable habitat area (480.58 $\times$ 10^3 km^2) was 10.49 times the gained area (45.83 $\times$ 10^3 km^2). Under SSP2-4.5, both habitats lost and gained were greater than under SSP1-2.6, and the ratio

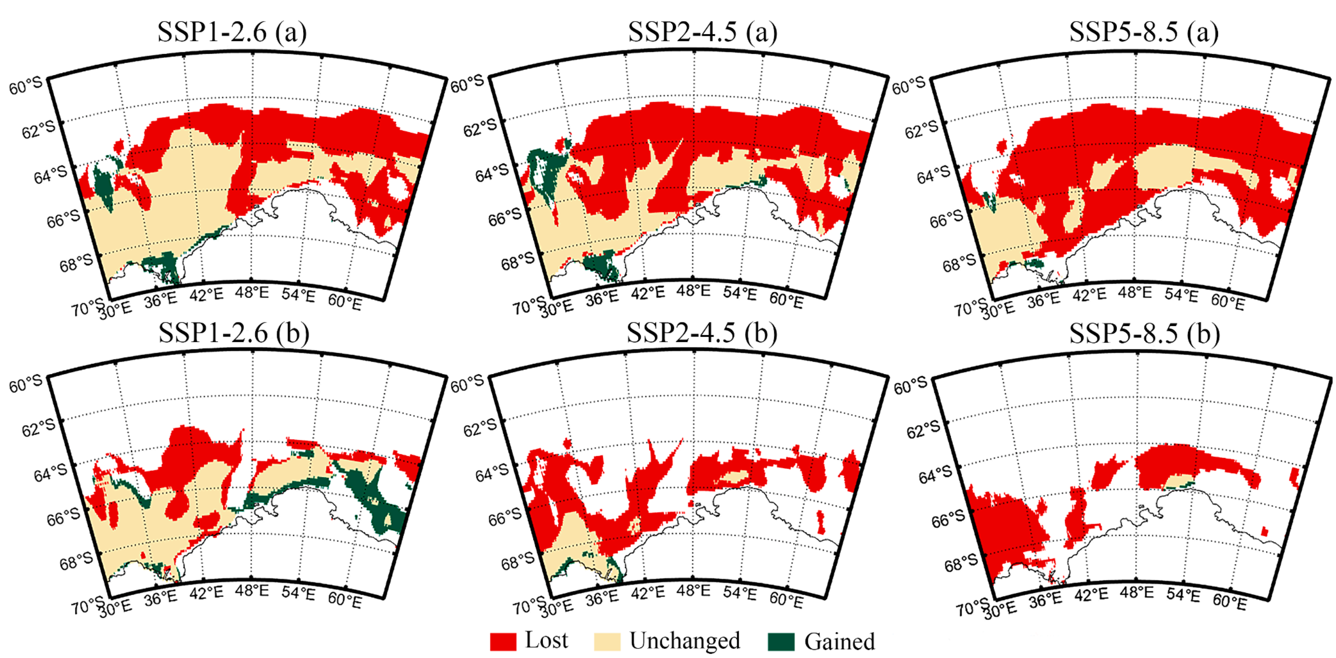

Fig. 6. Changes in the potential geographical distribution of krill under three SSP scenarios in the near future and far future (a is from the present to the near future and b is from the near future to the far future).

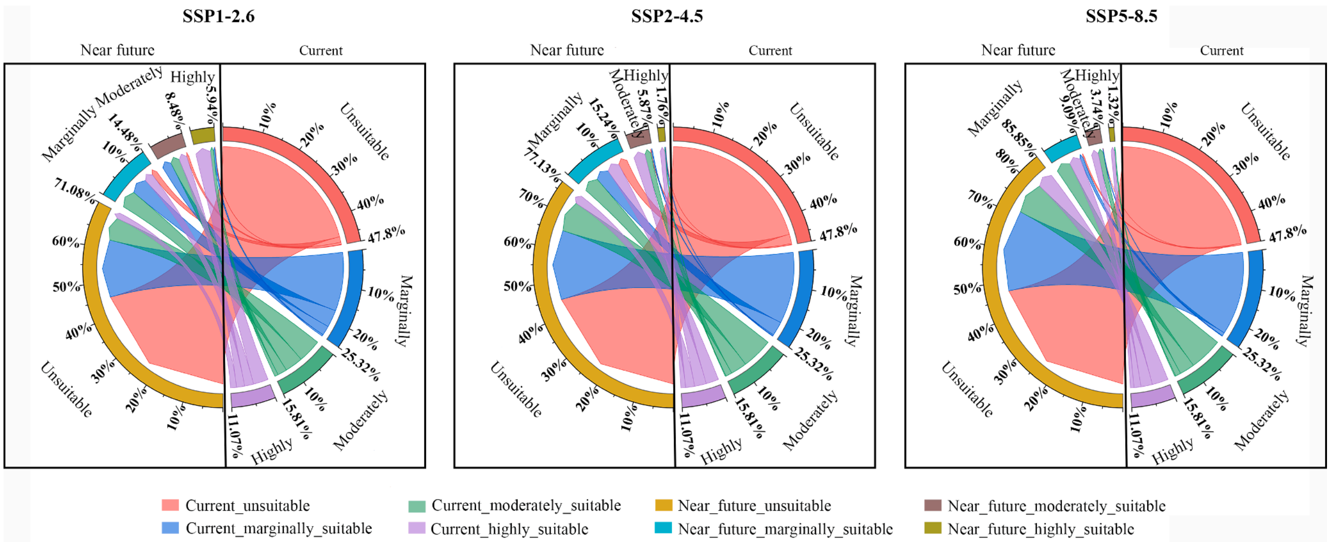

Fig. 7. Changes in different types of suitable areas under three SSP scenarios from the present to the near future.

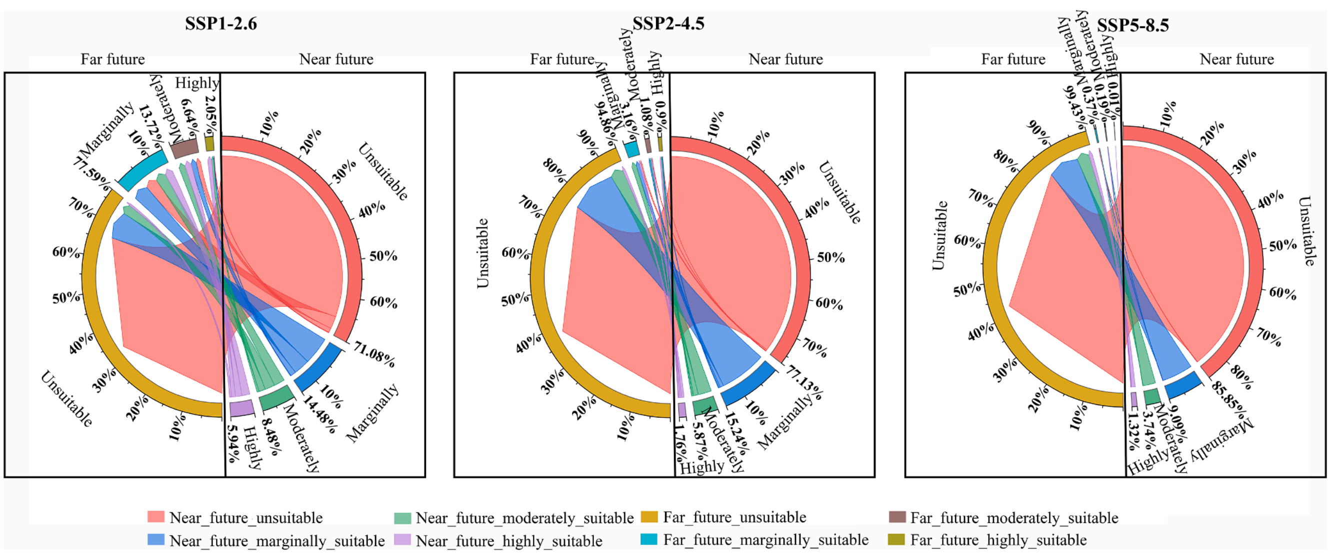

Fig. 8. Changes in different types of suitable areas under three SSP scenarios from the near future to the far future.

of lost to gained habitat was about ten under both scenarios. The distribution of krill habitat changed similarly to that of SSP1-2.6, the lost area was mostly in the center, northern, and eastern regions of the Cosmonaut Sea, where a marginally and moderately suitable area existed. The newly gained area was mostly in the western part of the Cosmonaut Sea, which became marginally suitable areas. Under the SSP5-8.5 scenario, the lost suitable habitat area (570.71 $\times$ 10^3 km^2) was 84.59 times the gained area (6.75 $\times$ 10^3 km^2). In comparison with the prediction of SSP1-2.6 and SSP2-4.5, the lost area was substantially larger under SSP5-8.5, whereas the gained area was extremely little.

In summary, the suitable distribution areas increased in the prediction under three future SSP scenarios, which were mainly located in south and north of the western part of the Cosmonaut Sea. The location of the gained areas under the three SSP scenarios were similar. The size of the gained area was varied, where the area under SSP2-4.5 was larger than that under SSP1-2.6, and the area under SSP5-8.5 was the smallest. Notably, a large number of suitable areas were lost under the three SSP scenarios. The area lost under SSP5-8.5 was the largest (73.8 %), and the area lost under SSP1-2.6 was the smallest (49.1 %). The types of lost area were mainly moderately and marginally suitable areas, and the types of gained area were mainly marginally suitable areas.

From the near future to the far future, under the SSP1-2.6 scenario, the lost suitable habitat area (170.84 $\times$ 10^3 km^2) was 2.3 times the gained area (74.41 $\times$ 10^3 km^2). In comparison to the present to the near future, under SSP1-2.6, the area lost was smaller and the area gained was larger. The gained area was mostly located east of the Cosmonaut Sea, which became a main marginally suitable krill habitat. Under SSP2-4.5, the loss area (270.12 $\times$ 10^3 km^2) was vast and the gained area (7.37 $\times$ 10^3 km^2) was extremely minor, was about 36.67 times. The lost area was extensive, with the exception of the southwest region and a small part of the central region of the Cosmonaut Sea, where there was a moderately and marginally suitable area. Under the SSP5-8.5 scenario, the lost suitable habitat area (203.02 $\times$ 10^3 km^2) was 118.12 times the gained area (1.72 $\times$ 10^3 km^2). The lost area was extensive, with the exception of a small part of the central region of the Cosmonaut Sea. Under SSP2-4.5 and SSP5-8.5, the Cosmonaut Sea has become unsuitable for krill since so much habitat has been lost and so little new habitat has been gained.

Certain similar conclusions can be obtained. The distribution of the gained area under the three SSP scenarios was relatively scattered. The gained area under SSP1-2.6 was the largest, and the gained area under SSP5-8.5 was the smallest. The types of gained areas under the three SSP scenarios were mainly marginally suitable areas. For the lost areas, the area lost was 39.9 %, 79.7 %, and 96.8 % percent of the suitable area in the near future under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. The suitable area was greatly reduced in the northern part, with the least reduction under SSP1-2.6.

3.4. Environmental shifts

To gain a deeper understanding the relationship between krill and the environment, the environmental subspace occupied by krill was delineated by drawing the values of the environmental descriptors *ssrdmin* and *tem* (Fig. 9). Under SSP1-2.6, a low radiative forcing scenario caused a small and slow increase in temperature, and the minimum *tem* in the near future was 272.00 K and that in the far future was 272.04 K. Therefore, there was a wide, suitable environment for krill in regions A and C. Although there was no highly suitable environment for krill in the B region, there was a large range of moderately and marginally suitable environments. Under SSP2-4.5, a middle radiative forcing scenario caused a faster increase in temperature than SSP1-2.6. The *tem* of regions B and C was higher than 272.6 K, causing krill to lose their highly suitable environment in the far future. Under SSP5-8.5, a high radiative forcing scenario caused a severe and rapid rise in temperature. The *tem* of regions A and B was higher than 273.3 K, also leading to the loss of krill in a highly suitable environment in the far future. The minimum *tem* of region C was 273.27 K, which was slightly lower than that in regions A and B. There was an extremely narrow highly suitable environment for krill in region C. Consequently, the temperature will continue to rise, which will have a negative effect on krill in the future.

The extent of the suitable area was represented by the average value of environmental parameters. The mean values of *ssrdmin* in areas A, B, and C were all within the optimal range for all periods of different SSP scenarios. When the average value of *tem* exceeded the optimal range, the krill suitable area was drastically reduced (Fig. 10). It was clear that under all SSPs, *ssrdmin* would be lower in the near and far future than it was then. Under SSP5-8.5, the biggest shift in *ssrdmin* happened in the far future, and *ssrdmin* declined the most in area A, with a decrease of 1.06×10^6 J/m^2 from the present to the far future. In other circumstances, *ssrdmin* is lowered by less than 0.55×10^6 J/m^2. Moreover, *tem* would continue to rise in the future under all SSPs, particularly under

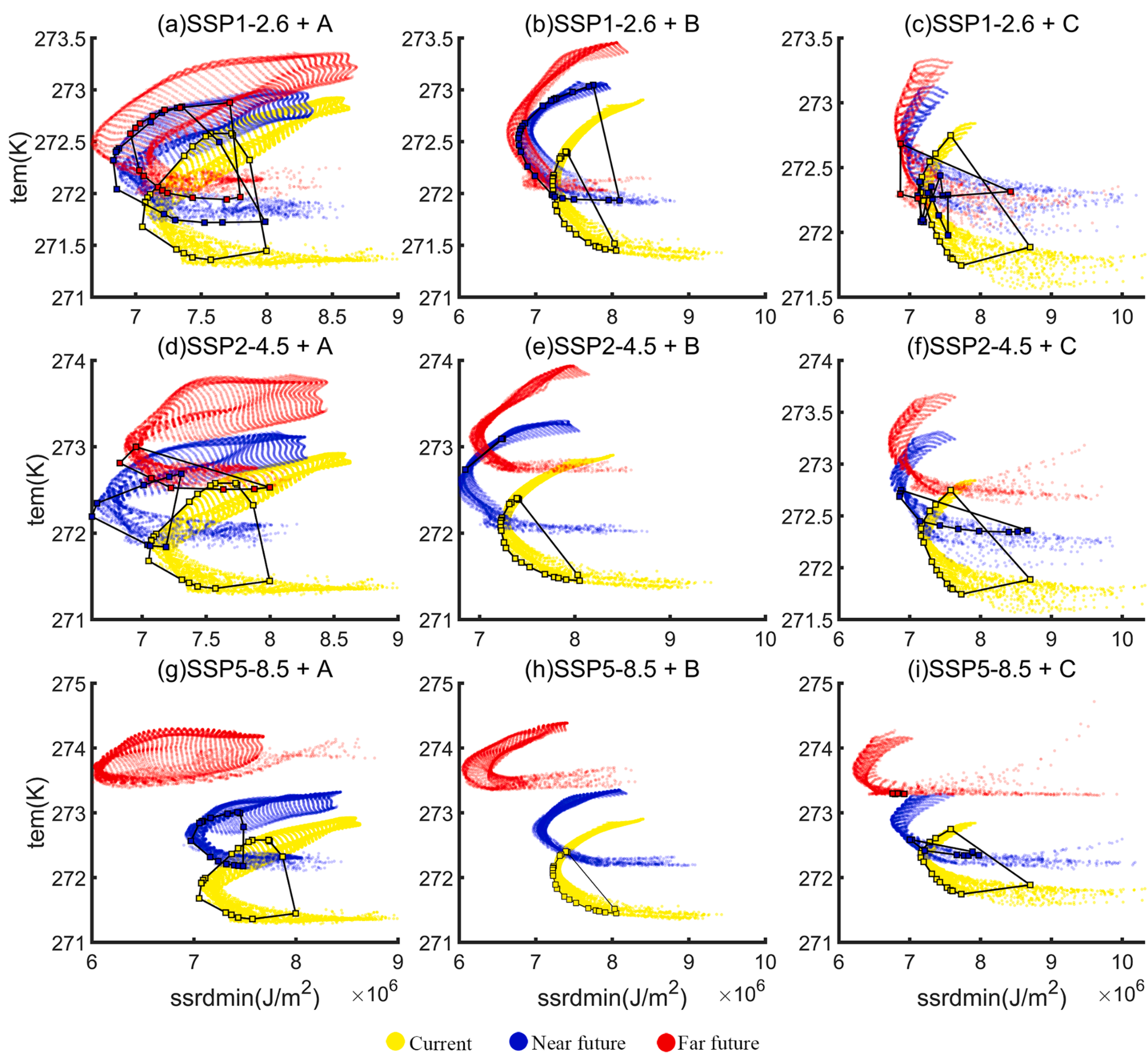

Fig. 9. Occupied environmental subspaces modeled for current, near future, and far future for krill. Background dots: environmental values present in the A, B, and C. Convex hulls delineate the environmental subspace of highly suitable area.

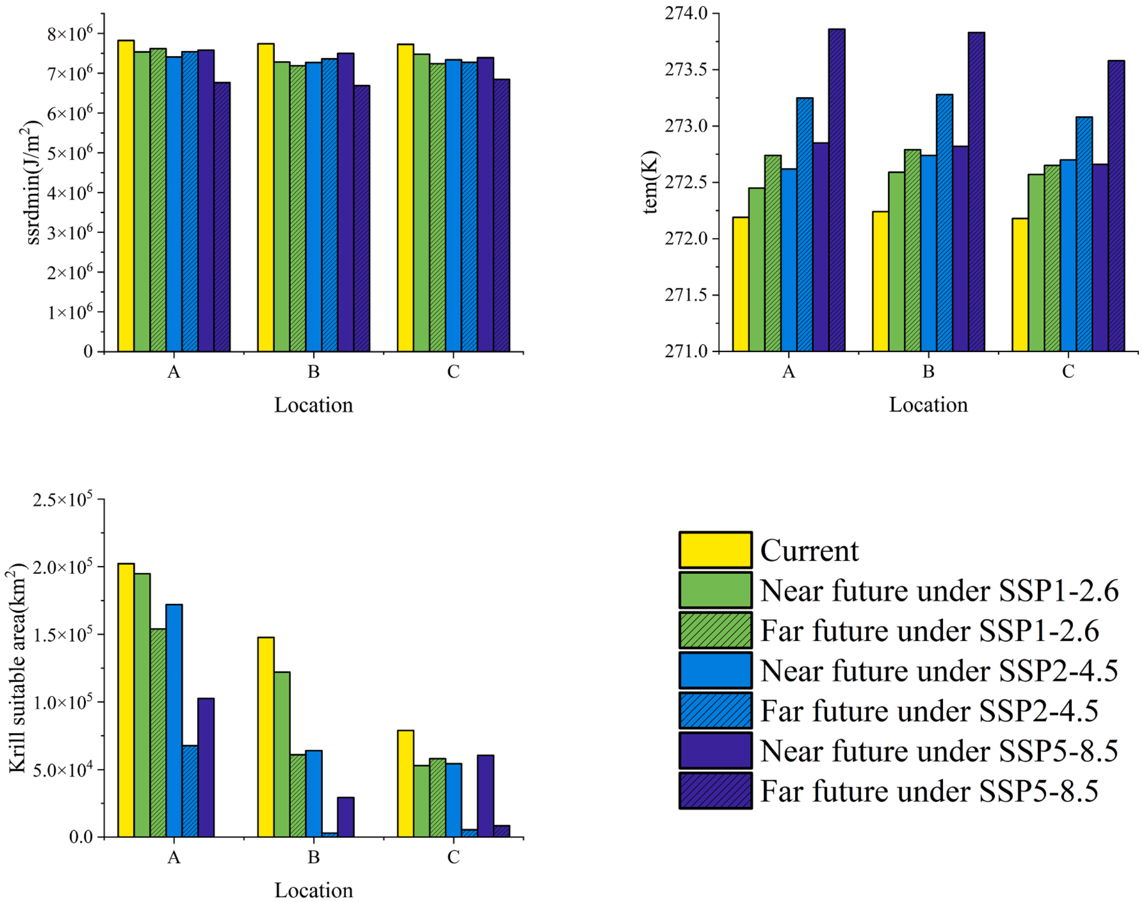

Fig. 10. The average value of *ssrdmin* and *tem* and potential suitable area for krill under different SSPs and periods in A, B, and C. Potentially suitable areas include marginally suitable areas, moderately suitable areas and highly suitable areas.

the high radiative forcing scenario (SSP5-8.5). The largest increase of *tem* from the present to the far future under SSP5-8.5 was 1.67 K. We observed that the suitable area of krill decreased faster from the near future to the far future than from the present to the near future.

4. Discussion

4.1. Reduction and poleward shift

A decreasing trend exists in the krill habitats in the Cosmonaut Sea under the different scenarios in the near future, and the southern region is much steady than the northern region. Our findings are consistent with global shifts in marine fishes under climate change. Previous research has predicted that in the 21st century, marine species would experience worldwide poleward shifts, with the rate being larger at high representative concentration pathways (RCPs) (Jones & Cheung, 2015; Morley et al., 2018; Worm & Lotze, 2016). Studies also indicated that differences also existed among marine species and in different regions (Hu et al., 2022; Perry et al., 2005; Zhu et al., 2020). Perry et al. (2005) discovered that warming caused boundary shifts in half of species with northerly or southerly range margins, with all but one species shifting northward. On the North American continental shelf, Pacific species exhibited a larger mean shift distance on the west coast (Morley et al., 2018). Hu et al., (2022) discovered in the North Sea that 20 fish species were anticipated to travel northward in the offshore areas of China, with species diversity diminishing at lower latitudes and rising at higher latitudes. Krüger et al. (2018) found that existing trends in southerly shifts in fisheries distributions in the Southern Ocean would continue at least until 2100 under climate change scenarios. The authors also determined that certain species would be affected by habitat loss in the future. Basher and Costello (2016) predicted a poleward shift in shrimp distribution from the present to the future in the Southern Ocean. Our findings were consistent with previous studies that analyzed the distribution of krill using empirical data over the past several years (Atkinson et al., 2019; Yang et al., 2021). As a result, we suggest that our findings are within reasonable bounds. The findings also serve as a warning, as the moderately and highly suitable habitat almost disappears under the SSP5-8.5 scenario at the end of 21st century.

4.2. Main environmental factors

The discrepancies in the shifts of marine species were considered related to variables such as sea surface temperature gradients, topography, currents, and chlorophyll-a concentrations (Krüger et al., 2018; Morley et al., 2018; Zhu et al., 2020). In our work, *ssrdmin*, *tem*, and *v* were the main factors affecting the habitat distributions of krill in the Cosmonaut Sea. Changes in solar radiation can impact on the amount of energy input into the ecosystem, as well as changes in sea ice concentration and sea surface temperature (SST). On the other hand, studies have indicated that krill are particularly vulnerable to Ultraviolet (UV) irradiation that reaches depths up to 10 m in Antarctic waters (Newman et al., 1999). The impacts of Ultraviolet B (UVB) on krill density may occur through physiological effects, behavioral reactions, declines in primary productivity, and changes in food-web structure (McBride et al., 2014; Newman et al., 2000; Newman et al., 2003). UV radiation, according to Flores et al. (2012), is anticipated to be an environmental stressor on krill and Antarctic ecosystems in future decades.

Krill is a cold-adapted, stenothermic species that is extremely sensitive to changes in water temperature, which might affect its physiological performance (Tao et al., 2011). Previous studies have already indicated that water temperature tends to be the main force for krill density (Trathan et al., 2003; Wiedenmann, 2010). Changes in SST can modify the depth of the mixed layer, affecting both the geographical distribution of primary production and the structure of phytoplankton communities. (Assmann et al., 2005; Holland et al., 2010). A negative relationship had already been observed between increasing SST and krill density in the Southern Ocean (Atkinson et al., 2019; Trathan et al., 2003). Individual development can be influenced by changes in SST. Krill grows through a succession of molts, with temperature influencing both the period between molts and the growth increase each molt (Atkinson et al., 2006; Bellard et al., 2012).

Krill is a type of plankton that lives in the upper layers of the ocean. Ocean currents substantially impact krill, both in the larval stage and throughout their life cycle (Mori et al., 2017). As larval and juvenile krill are unable to swim, they must rely on the prevailing ocean current to transport them. Although adult krill have good swimming abilities and can swim upstream, their movement is often determined by the flowing state surrounding individuals and swarms (Tarling & Thorpe, 2014). Previous research has suggested that the regional krill distribution and abundance on the shelf-slope regions can be explained by small-scale circulation patterns combined with active vertical and horizontal krill migrations (Ichii et al., 1998; Nicol et al., 2000). Consequently, advection is a crucial factor in determining the horizontal distribution of krill.

5. Conclusion

In this study, a MaxEnt model was used to anticipate the potential habitat distribution of krill in the Cosmonaut Sea under three future scenarios. At present, highly suitable krill habitats are mostly found in the western and central parts of the Cosmonaut Sea. Krill habitats will continue to diminish and migrate toward the Antarctic in the future, dropping more rapidly from the near future to the far future than from the present to the near future. Furthermore, krill habitat was reduced the least in the low radiative forcing scenario (SSP1-2.6) and the most in the high radiative forcing scenario (SSP5-8.5). The major cause of the loss of krill habitat was rising temperatures. We need to strongly promote renewable energy development while reducing greenhouse gas emissions in order to safeguard the long-term viability of the Cosmonaut Sea environment.

CRediT authorship contribution statement

Shiying Lin: Writing – original draft, Software. **Liang Zhao:** Methodology, Writing – review & editing. **Jianlong Feng:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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