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Spatio-temporal analysis of summer salinity fronts in the Greenland Sea

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Abstract

Using daily average data from the global ocean eddy resolution reanalysis product (GLORYS12V1) from 1993 to 2018, sea surface salinity horizontal gradient is calculated to obtain the spatio-temporal distribution and the intensity characteristics of the salinity front in the Greenland Sea. Combined with the sea ice concentration data, the salinity front and sea ice relationship is also studied. There is a significant spatial relationship between the main position of the salinity front and the ice edge before the sea ice shrinks toward the continental shelf. In the climatological seasonal variation, the intensity of the salinity front beyond the continental shelf reaches its strongest (~ 0.22 psu/km) in July. The front area beyond the continental shelf reaches its peak value ($\sim 7.80 \times 10^4$ km²) in August. The interannual variation of sea ice extent averaged from July to August has a downward trend of 5.83×10^3 km²/year. Under the background of rapid change in sea ice, the intensity and area of the salinity front beyond the continental shelf are reducing at about 1.7×10^{-3} psu/km and 142 km²/year, respectively.

Introduction

The Greenland Sea, one of the main marginal seas in the Arctic Ocean, is located to the east of Greenland. Its shelf slope area is covered by sea ice all-year-round, and its dynamic thermal environment is affected by sea ice formation and melting. The Greenland cold current flows southward along the shelf break. The daily mean current on July 15, 2018 is shown in Fig. 1.

Figure 1. Topography of the Greenland Sea. The background color is the bathymetry, taken from ETOPO1¹. The black arrows are the geostrophic current field on July 15, 2018. The red line is the section selected for further analysis.

There are various complex mesoscale ocean-sea ice-atmosphere interactions in the marginal ice zone. The salinity front is one of the most significant marine phenomena in the Greenland Sea during Arctic summer². When the sea ice melts, the freshening seawater forms in the ice zone, and a strong horizontal surface salinity gradient appears along the marginal ice zone, forming a salinity/density front. From previous studies using observation data, there is a high temperature and salinity core of Mid Atlantic water along the polar front of East Greenland³, with significantly different currents on both sides of the front⁴. The wind stress above the front zone also changed rapidly^{5,6}.

Previous studies have shown a relationship between the position of the oceanic front and the ice edge location in the Pan-Arctic region^{7,8,9,10}. Based on a cruise observation in the Bering Sea in Spring 1982, the ice edge retreated at 6~38 cm/s. The

63 upper ocean front also moved fast and kept pace with the retreating ice edge, but the
64 deeper front was nearly stationary⁷. The ~3-day evolution of a density front located at
65 the ice edge in the Beaufort Sea was captured by an underway
66 conductivity-temperature-depth system. In the same period, the synthetic aperture
67 radar image also showed that the ice edge underwent concurrent evolution¹¹.

68 The formation and melting of sea ice play an important role in global climate
69 change^{12,13,14}. The sea ice in the Greenland Sea has been changing rapidly in recent
70 years, and this change also affects various ocean processes, including ocean fronts^{15,16}.
71 The ocean front is considered to be an important factor in the energy transfer chain
72 from global-scale circulation to small-scale phenomena¹⁷. It can affect the structure of
73 the ocean flow field, ocean heat exchange, material transport and air-sea interaction¹⁸.
74 In addition, various oceanic or atmospheric phenomena and processes are related to
75 the ocean front, such as high biological productivity, abnormal wind and waves,
76 dramatic changes in ocean color, strong vertical motion and local weather conditions.
77 Large-scale fronts can influence the weather and even the climate¹⁹. Therefore, the
78 variation of fronts under the background of the rapid change in sea ice is an important
79 point for research.

80 The horizontal gradient of the climatological sea surface salinity in the Nordic
81 Sea is not greater than 0.001 psu/km. Some researchers considered the spatial and
82 temporal variations of the oceanic front. They defined a salinity front threshold as
83 0.002 psu/km in the Nordic Sea to research the distribution characteristic of the
84 salinity front and its seasonal variation^{2,20}. Since an oceanic front is a mesoscale
85 phenomenon, the position and intensity of a front cannot be accurately defined using
86 climatology and low-resolution data.

87 In order to obtain the salinity front variation as accurately as possible, we use a
88 multi-year daily average reanalysis data to study the spatial distribution and intensity
89 characteristics of the salinity front beyond the continental shelf in the Greenland Sea
90 from July to August (JA). We also investigate the interannual variations of the salinity
91 front under the background of sea ice shrinking.

Results

As the sea ice melts in the Greenland Sea from June to August, the sea ice extent shrinks toward the continental shelf, and the salinity front moves and keeps pace with the ice edge. The spatial distributions of the ice edge and the horizontal gradient of the sea surface salinity in the Greenland Sea from June to August of 1993, 2007, and 2015 are shown in Fig. 2. The black line is the daily marginal ice line, and the purple line is the 330 m isobath and represents the shelf break.

On June 29, 1993 (Fig. 2a), the ice edge is located outside the shelf break. Its southernmost point reaches 68°N and the overall sea ice extent shrinks toward higher latitudes. On July 16, 1993 (Fig. 2b), the ice edge is near the continental shelf break. The sea ice continues to retreat northwestward while the ice edge meanders in the continental shelf. On the 31st of August (Fig. 2c), the sea ice extent is minimum and its southernmost point is at 69.6°N. In most years, the sea ice covers the continental shelf north of 77°N. Compared with 1993, the ice edge in 2007 (Fig. 2d-2f) and 2015 (Fig. 2g-2i) have a similar seasonal variation, but the sea ice extent shrinks more significantly.

When the ice edge is outside the shelf break (Fig. 2a, d, g), the strong salinity gradient is mainly concentrated at the ice edge. During the northward movement of the ice edge, the front moves and keeps pace with the ice edge. When the sea ice retreats toward the continental shelf, the front is limited to the shelf break (Fig. 2c, f, i), and the intensity and area of the front gradually decrease.

Figure 2. The spatial distributions of the ice edge and the horizontal gradient of the sea surface salinity in the Greenland Sea from June to August of 1993 (a-c), 2007(d-f), and 2015 (g-i). The black line is the daily marginal ice line, and the purple line is the 330 m isobath and represents the shelf break.

To clarify the relationship between the position of the salinity front and the ice edge in the Greenland Sea, we select a section (red line in Fig. 1) to analyze the relative position changes compared with the shelf-slope break. The daily variation of the salinity and horizontal salinity gradient along the section in 2007 is shown in Fig. 3. In June, when the sea ice concentration is lower, the seawater under the ice is fresher and a strong salinity gradient appears. The intensity of the salinity front strengthens from July to August. At the end of September, the salinity front gradually weakens.

When the sea ice (black dots in Fig. 3, which indicate the intersections of the ice edge line and the section) is beyond the continental shelf from June to August (solid

black lines in Fig. 3, which indicate the intersections of the section and shelf break), the salinity front is always distributed along the ice edge and keeps pace with the ice edge. When the sea ice shrinks back to the continental shelf (black dots below the solid black line), the salinity front is restricted to the vicinity of the shelf break due to the sufficient mixing of the seawater in the continental shelf. However, its intensity is gradually reduced.

Figure 3. Daily variation of (a) salinity and (b) sea surface salinity horizontal gradient (background color) along the section (red line) indicated in Fig. 1. The black dots are the daily variation of the intersections between the marginal ice line and the section line. The abscissa is the time for 2007 and the ordinate is the offshore distance along the section line. The solid black line in (b) is the position of the shelf break along the section line.

With global warming, sea ice melting has accelerated in the Pan-Arctic region^{21,22}. The sea ice concentration with the minimum sea ice area in selected years

is shown in Fig. 4a. The southern tip of the sea ice extent moves northward from 70°N to 75°N from 1995 to 2018. The monthly average sea ice area in the Greenland Sea from June to September of 1993-2018 shows that the sea ice area has a decreasing trend.

Based on the observed (reanalysis) data, the JA average sea ice area in the Greenland Sea from 1993-2018 (Fig. 4b) has a decreasing trend of 5.83×10^3 (4.36×10^3) km^2/year . The variations are almost the same between these two data. The climatological (1993-2018) seasonal variation in the Greenland Sea (black line in Fig. 4c) shows that the sea ice area decreases rapidly in May, shrinks to the continental shelf in July (the continental shelf area is about $2.70 \times 10^5 \text{ km}^2$, marked with the solid red line in Fig. 4c), and reaches its minimum ($7.58 \times 10^4 \text{ km}^2$) in September.

To explore the sea ice melting-induced changes in the Greenland Sea salinity front, we use two indices, the front area and the averaged front intensity. The front area is defined as the area occupied by a high salinity gradient greater than a threshold. The averaged front intensity is defined as the average value of the high salinity gradient greater than a threshold. In the analysis, this threshold is set to 0.1 psu/km.

In the climatological seasonal variation, the front area beyond the continental shelf increases rapidly in May, reaches its peak value of $7.80 \times 10^4 \text{ km}^2$ (solid blue line in Fig. 4c) and then decreases. The July-August surface front area is larger than in June and September (figure not shown). This is due to the rapid rate of sea ice melting in July and August, which results in a large influx of fresh water, thus inducing strong salinity gradients and increasing the frontal area.

In the Greenland Sea, the JA average front area beyond the continental shelf from 1993-2018 has a maximum of $1.03 \times 10^5 \text{ km}^2$ in 1996 and a minimum of $4.65 \times 10^4 \text{ km}^2$ in 1999 (solid blue line in Fig. 4d). The interannual variations of the upper front area with a strong gradient have a decreasing trend of $142 \text{ km}^2/\text{year}$ (dotted line in Fig. 4d). The decreasing trends of the monthly average front area are obvious in July and August, and are relatively flat in June and September (not shown).

The seasonal intensity of the salinity front beyond the continental shelf (Fig. 4c) increases rapidly in May. It reaches its strongest (0.22 psu/km) in July and then

decreases until April of next year. The lower intensity in September is due to the sea ice formation, which weakens the salinity gradient.

The interannual variation of the average intensity of the salinity fronts beyond the continental shelf in June and September increases year by year, and decreases in July and August (not shown). However, the amplitude of the front intensity has an overall decreasing trend of about 1.7×10^{-3} psu/km (dotted orange line in Fig. 4d). The JA average intensity reaches a maximum (minimum) value of 0.24 (0.18) psu/km in 1993 (2013).

Figure 4. (a) Sea ice concentration with the minimum sea ice extent in 1995, 2000, 2005, 2010, 2015 and 2018. (b) Interannual variations of the July-August averaged sea ice extent. The solid (dotted) line is the satellite observation (GLORYS12v1) data. (c) The seasonal variations of the front area and intensity beyond the continental shelf, the sea ice extent and the variation gradient of the sea ice area. The red line represents the continental shelf area. (d) Interannual variations of the July- August averaged front area and intensity beyond the continental shelf.

Conclusion and Discussion

Based on the daily average reanalysis data from 1993 to 2018, the spatio-temporal variations of salinity front in the Greenland Sea are analyzed. The results show a significant spatial relationship between the main position of the sea salinity front and the position of the marginal ice edge before the sea ice shrink to the shelf break. In summer, the solar short-wave radiation increases, leading to a rise in air and seawater temperature. With the sea ice melting, the cold and fresh seawater meet with the warm

198 and salty seawater in the open sea area and produce the salinity front. The front area
199 with a strong salinity gradient is mainly distributed near the ice edge.

200 Affected by the formation and melting of the sea ice, the intensity and area of
201 the salinity front show seasonal variations. The sea ice extent begins to decrease
202 rapidly from May, while the average intensity and area of the salinity front begin to
203 increase rapidly. When the sea ice extent shrinks to the continental shelf in July, the
204 intensity of the salinity front reaches its strongest (~ 0.22 psu/km). The sea ice
205 continues to melt in the continental shelf. But due to the strong mixing effect of the
206 seawater in the continental shelf area, the front is restricted to the continental shelf
207 break. At this time, the maintaining mechanism of the strong salinity gradient steadily
208 weakens in the shelf break, and the salinity front intensity begins to decrease.
209 However, although the front intensity weakens due to the horizontal diffusion and
210 mixing, the salinity front area is still expanded and reached its peak value ($\sim 7.80 \times$
211 10^4 km²) in August. After reaching the minimum value in early September, the sea ice
212 extent increases rapidly until January of the next year, and then has a slight change
213 from February to April. In the same period, the intensity and area of the salinity front
214 beyond the continental shelf decrease from September to April of the next year.

215 In terms of interannual variation, the monthly average intensity of salinity front
216 beyond the continental shelf increases in June and September and decreases in July
217 and August. But overall, the amplitude of the front intensity has a decreasing trend of
218 about 1.7×10^{-3} psu/km. The monthly average front area beyond the continental shelf
219 also decreases year by year from June to September. It has a decreasing trend of about
220 142 km²/year.

221 The sea ice extent from July to August dramatically decreases and has a
222 decreasing trend of 5.83×10^3 km²/year in the Greenland Sea. But the background
223 surface salinity increases slightly. It may be the reason for the weakening of the
224 salinity front gradient and the decreasing of the average intensity and area. The
225 variation of the salinity front influences other oceanic processes, such as frontal
226 eddies. Therefore, it is necessary to analyze the salinity budget and the variations in
227 the oceanic processes related to the salinity front in the Greenland Sea.

228

229 **Data and Method**

230 **Satellite data.** The sea ice concentration data from the Operational Sea Surface
 231 Temperature and Ice Analysis (OSTIA) reprocessed product²³ is used in this study. It
 232 has a horizontal resolution of 1/20° and the time range is from 1981 to 2020. The
 233 geostrophic current data is from the Archiving Validation and Interpretation of
 234 Satellite Oceanographic (AVISO). It has a horizontal resolution of 1/4° and spans
 235 from 1993 to 2019. Both datasets are distributed by the Copernicus Marine
 236 Environment Monitoring Service (CMEMS; <https://marine.copernicus.eu/>).

237 **Reanalysis data.** The salinity data, a global ocean eddy resolution reanalysis
 238 product GLORYS12V1, also distributed by CMEMS, is used. It has a horizontal
 239 resolution of 1/12° and 50 vertical layers. The time range of the data is from 1993 to
 240 2018.

241 **Methods.** Some studies use the isobath of temperature, salinity or density to
 242 determine the existence of a front^{24,25,26}. This method is suitable for the frontal
 243 analysis of profile data. In this paper, we use a front detection algorithm proposed by
 244 Belkin et al. (2009)²⁶. The horizontal gradient field is calculated to determine the
 245 position and intensity of the salinity front.

246 First, we calculate the distance between every two grid points (equation (1)):

$$247 \quad dis = 2 \arcsin \sqrt{\sin^2 \frac{a}{2} + \cos(Lat1) \times \cos(Lat2) \times \sin^2 \frac{b}{2}} \times R \quad (1)$$

248 where a is the latitude difference $Lat1 - Lat2$, b is the longitude difference
 249 $Lon1 - Lon2$ and R is the Earth radius 6378.137 km. Then, we use the Sobel
 250 operator's convolution kernels GX and GY (GX rotated by 90°) to calculate the
 251 gradients (G_x , G_y) in the X and Y directions, respectively. The calculation formula
 252 is as follows (equation (2)):

$$253 \quad GX = \begin{bmatrix} +1 & +2 & +1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \quad GY = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \quad (2)$$

254

$$255 \quad G_x = \frac{1}{4} * GX * A / (2 * dis_x) \quad G_y = \frac{1}{4} * GY * A / (2 * dis_y)$$

where dis_x is the distance in X direction between two grid points and dis_y is the distance in Y direction. A is the original salinity data. So, the gradient value G is obtained by the square root of the gradient in the X and Y direction (equation (3)).

$$G = \sqrt{G_x^2 + G_y^2} \quad (3)$$

The value G is used to determine the position and intensity of the salinity front. The intensity of the front varies in different seas. In this paper, we choose 0.1 psu/km as the threshold value to define the salinity front in the Greenland Sea. In addition, we use two indices, the front area and the mean intensity, to describe the salinity front. The front area S_g of the front is calculated as follows (equation (4)):

$$S_i = dis_{xi} * dis_{yi} \quad (4)$$

$$S_g = \sum_{i=1}^n G_{mask} \times S_i$$

where dis_{xi} and dis_{yi} are the distances between two adjacent grid points in the horizontal and vertical directions, respectively. S_i is the grid area. G_{mask} is a matrix, in which the part corresponding to G greater than 0.1 psu/km is set to 1, and the rest is set to 0. The average intensity of the front is defined as equation (5):

$$\bar{G} = \frac{\sum_{i=1}^n G_{mask} \times G_i \times S_i}{\sum_{i=1}^n G_{mask} \times S_i} \quad (5)$$

The above front area calculation method is affected by the resolution of the data grid, but the average intensity is not. In this paper, we use the average intensity and front area to analyze the variation of the salinity front in the Greenland Sea.

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Author Contributions

J.W. and Y.L. initiated the idea, designed the study, analyzed the data and contributed to the writing of the manuscript. G.H., X.L. and G.Y. contributed to the revision of the manuscript.

Additional Information

Competing Interests: The authors declare that they have no competing interests.