Abstract This chapter investigated the relationships between phytoplankton biomass, measured using chlorophyll a (CHL), sea-ice cover (ICE), and North Atlantic Oscillation (NAO) in the Greenland Sea in 20°W–10°E, 65–85°N during the period 2003–2012. Remote-sensed satellite data were used to do correlation analysis. Enhanced statistics methods (such as unit root checking, lag regression, and co-integration analysis methods) are used for correlation analysis. Results show that the melting ice (MI) played a significant role on promoting the growth of CHL. In general, ICE reached peak (in March) 3 months ahead of CHL (peaked in June), and CHL was higher in south and lower in north. CHL increased around 10 % in spring and early summer during last 10 years in 75°N–80°N. Moreover, CHL was higher in 75°N–80°N region where ice melted more and the water column was more stable. The peak of CHL in 2012 was 1 month later than the other years. The CHL peak in 2011 was highest, and there were two peaks in 2010. The peaks of CHL came later in 2012 and 2008. The early and higher peaks of CHL in year 2010 was due to the more MI happened in that year. Other reasons including the stronger wind speed in spring and special wind direction from southeast changed to southwest, plus lower SST and PAR in summer and negative NAO through the year. The research shows that CHL, ICE, and NAO were correlated with a time lag. CHL and ICE had long-term equilibrium relationship. The NAO and MI had a negative correlation. NAO affected the MI and its peak was 3 months ahead of the MI. The CHL and NAO also had negative correlations. With NAO reached to its peak, CHL almost reached to its valley at the same time.

Keywords Chlorophyll a (CHL) · Ice cover (ICE) · Melting ice (MI) · North Atlantic Oscillation (NAO) · Peak · Coupling
2.1 Introduction

2.1.1 Sea Ice and the Phytoplankton Biomass

Sea ice provided a significant amount of habitat for productive microbial communities (including algae, bacteria, archaea, heterotrophic protists, and viruses) (Horner et al. 1992). In terms of biomass, the communities were dominated by algae, particularly diatoms during bloom period (Vancoppenolle et al. 2013). There are many protist species in Arctic sea ice, with diatoms dominated, other species such as dinoflagellates and chrysophytes. Ice algae also provided early-season high-quality food source for pelagic herbivores (Soreide et al. 2010).

There are numerous studies on the MI and its contribution to the phytoplankton concentrations (Matrai and Vernet 1997; Wassmann et al. 1999; Olli et al. 2002; Qu et al. 2006; Pabi et al. 2008; Leu et al. 2011). It was suggested that the decreasing of sea ice and increasing of light result in increasing of phytoplankton biomass. What is the effect of phytoplankton to ice cover properties? Early study from Ericken et al. (1991) suggested that high phytoplankton biomass may accompany with low ice strengths. The reason is ice algae may speed ice deterioration and increase porosity via solar radiation absorption.

2.1.2 The Light Effect on Phytoplankton Biomass

Phytoplankton would decrease with the increase of light intensity in summer. There is an optimal light intensity for growth of phytoplankton. Algae under ice receive much less light than in open area. The question is, how much light is least required for growth of phytoplankton and how much nutrients required as well? Jassby and Platt (1976) obtained a mathematical formula of the relationship between photosynthesis and light for phytoplankton. They derived the following formula:

\[ PB = \alpha I - RB \]  
(1.1)

where \( PB \) is the primary production per unit chlorophyll biomass, \( I \) is irradiance, and \( \alpha \) is the slope of the light-saturation curve at low light levels. Light-independent respiration loss \( RB \) (mgC[mgChla]^{-1}h^{-1}) is

\[ RB = P_{B\text{gross}} - P_{B\text{net}} \]  
(1.2)

It is interesting to know that the phytoplankton in Arctic Ocean can survive without irradiance (Parsons et al. 1984). Melting water generates more nutrients, although the dilution decreased salinity and surface temperature and also brings lower light penetration, these could have negative effect on the growth of phytoplankton (Cui et al. 2012).
In Arctic Ocean, light is very important factor controlling phytoplankton biomass. Compared to the ice-covered region, polynyas received much earlier light in the year. Hence, earlier CHL appeared in the polynyas region. The Arctic water flows from northeast and formed upper layer waters, while North Atlantic water flows from South and into deep layer waters. With the phytoplankton biomass increased, the nutrient concentrations decreased. Lara et al. (1994) found that diatom appeared often in open water and in the starting production period. In late spring (April) in northern part of Greenland Sea, most of species forming the spring bloom are located under the ice. They are both diatoms and flagellates. Phytoplankton biomass growth until nutrients depleted. Phytoplankton advected from north to south by anticyclonic pattern (Schneider and Budeus 1994).

The different stages of ice melting would add different amount of ice algae to the community. The process is complicated due to many effects. The detailed study on ice melting and its relationship with phytoplankton biomass and other effects of decline ice is expected to carry out. This chapter is focused on the effect of ice melting on the phytoplankton biomass (CHL) and their relationship with NAO based on the most recent 10 years data in Greenland Sea.

2.2 Data and Methods

Our study region is in Greenland Sea 20°W–10°E, 65–85°N (highlighted box in Fig. 1.1), for the period of 10 years: 2003–2012. Due to the special condition in Arctic (half year darkness from October to February) and satellite data only valid within March to September, we choose MODIS satellite afternoon (Aqua), 8-day, 4-km, level-3 mapped data for retrieving global chlorophyll a (CHL), aerosol optical depth (AOD) data. MODIS Web site is located in http://modis.gsfc.nasa.gov/. Photosynthetically active radiation (PAR) was derived from SeaWiFs, 8-day mapped data (http://oceandata.sci.gsfc.nasa.gov/seawifs). The image analysis package SeaWiFS Data Analysis System (SeaDAS 6.4) (http://seadas.gsfc.nasa.gov/) was then used to get subset data for our focused study region.

Global sea ice weekly data were obtained from NOAA (ftp://sidads.colorado.edu/pub/DATASETS). Ice cover is calculated from http://iridl.ldeo.columbia.edu/SOURCES/Wind speed, wind directions, and sea surface temperature (SST) were calculated from www.remss.com/windsat. Daily data were downloaded for calculating weekly and monthly mean. Cloud cover (CLD) is from http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/.

Enhanced statistics methods, such as lag regression method and co-integration analysis method, are used for correlation analysis and long-term equilibrium relationship between two variables.
2.3 Results

2.3.1 CHL Distributions

8-day mean time series of CHL in the study region averaged for the 10 years (2003–2012) is shown in Fig. 2.1. With gradually increased CHL from March and reached to peak in day 160 (early May), then decreased toward the end of September, there was little lump after June.

Looking in detail for different years, we divide the region into 4 subregions with 5-degree zonal difference for each subregion (Fig. 2.2).

In 65°N–70°N (Fig. 2.2a), year 2011 showed the early peak around day 128 (early April) although some missing values after day 128. Year 2003 had the highest peak on day 136 (middle of April) and the second peak was on day 152 (early May). The Russian 2003 fire could be the cause (Serreze et al. 2000). Further north, there was no such high peak in year 2003. Year 2010 had longer peak period from day 144–152 (late April–early May), and highest autumn peak on day 232 (late July). Year 2006 had late peak on day 192 (middle of June).

In 70°N–75°N (Fig. 2.2b), year 2007 had highest peak around day 160 and 2006 had second high peak around day 168 (mid of May). Year 2011 had early rising in April but had some missing data after middle of April. It had the third highest peak around day 160. Year 2008 had double peaks in day 152 and day 168, while 2012 had the latest peak in day 192 (middle of June). The CHL reduced greatly after day 208 (early July).

In 75°N–80°N (Fig. 2.2c), CHL had early peak (in day 128, middle of April) in year 2010 and also had second even higher peak (day 184, early June). Year 2011 had the highest peak in day 160, while 2008 and 2012 had late peak in day 192 (middle of June) with year 2008 much higher than year 2012. We noticed with the
latest peak in 2012 and lasted for 8 more days, it had highest autumn peak in day 240 (early August).

In 80°N–85°N (Fig. 2.2d), due to its darkness, CHL started later than southern regions. The satellite data are only valid from April to August. The highest peak was in year 2008 (day 224, middle of July), and year 2004 had early peak in day 136, followed the second peak in day 160–168, then the third peak was in day 224 (middle of July). Year 2006 had early rising of CHL (day 120 early April) and reached to second peak on day 136 and then decreased significantly, increased sharply to reach to its peak on day 152. The rising of CHL in spring of 2006 is interesting and could relate to the patterns of MI. Day 224 had several peaks for years 2003, 2004, 2005, 2008, and 2012. The reasons are worth to find out.
The general trends of CHL increased from north to south, up to 70°N. However, CHL in 65°N–70°N was lower than 70°N–75°N, as there was no ice cover in 65°N–70°N. The average peak time was shifted ahead from day 152 in the south to day 224 in the north (Table 2.1). The time lag was about two and half months.

The detailed peak times for different years in the different subregions are also calculated (Table 2.2). In southern region 65°N–70°N, CHL was gradually shifted ahead from year 2006. In other subregions, CHL peak times in years 2012 and 2008 were much later than other years. However, the first peak time in year 2010 was much earlier. In 75°N–80°N, years 2006, 2008, and 2012 had much late peak time.

**Table 2.1** The average CHL peak time during years 2003–2012 for different subregions

<table>
<thead>
<tr>
<th></th>
<th>80°N–85°N</th>
<th>75°N–80°N</th>
<th>70°N–75°N</th>
<th>65°N–70°N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak time (day)</td>
<td>224</td>
<td>184</td>
<td>160</td>
<td>152</td>
</tr>
</tbody>
</table>

The general trends of CHL increased from north to south, up to 70°N. However, CHL in 65°N–70°N was lower than 70°N–75°N, as there was no ice cover in 65°N–70°N. The average peak time was shifted ahead from day 152 in the south to day 224 in the north (Table 2.1). The time lag was about two and half months.

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2.3 Results

Table 2.2  CHL peak time in different years and different subregions

<table>
<thead>
<tr>
<th>Year</th>
<th>65°N–70°N</th>
<th>70°N–75°N</th>
<th>75°N–80°N</th>
<th>80°N–85°N</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>120</td>
<td>152</td>
<td>144</td>
<td>224</td>
</tr>
<tr>
<td>2004</td>
<td>160</td>
<td>192</td>
<td>160</td>
<td>136</td>
</tr>
<tr>
<td>2005</td>
<td>136</td>
<td>184</td>
<td>184</td>
<td>224</td>
</tr>
<tr>
<td>2006</td>
<td>192</td>
<td>168</td>
<td>200</td>
<td>152</td>
</tr>
<tr>
<td>2007</td>
<td>152</td>
<td>160</td>
<td>168</td>
<td>184</td>
</tr>
<tr>
<td>2008</td>
<td>144</td>
<td>152</td>
<td>192</td>
<td>224</td>
</tr>
<tr>
<td>2009</td>
<td>136</td>
<td>160</td>
<td>160</td>
<td>208</td>
</tr>
<tr>
<td>2010</td>
<td>152</td>
<td>152</td>
<td>184</td>
<td>144</td>
</tr>
<tr>
<td>2011</td>
<td>128</td>
<td>160</td>
<td>160</td>
<td>200</td>
</tr>
<tr>
<td>2012</td>
<td>128</td>
<td>192</td>
<td>192</td>
<td>224</td>
</tr>
</tbody>
</table>

Fig. 2.3  CHL variation along latitude for years 2003–2012

2.3.2 The Reason of the High CHL Peaks in Northern Region

Figures 2.3 and 2.4 are the mean CHL along latitude and longitude for the 10 years. Generally, CHL was higher down south and lower up north. Year 2010 had unusual high peak near 79°N, the magnitude was even greater than southern region. Along longitude, CHL was also higher in year 2010, especially between 18°W–12°W and 2°E–8°E, where East Greenland current and West Greenland current plus Norwegian Sea current located. Year 2004 had least CHL along latitude and year 2003 had least CHL along longitude. Generally, CHL has less variability along longitude for each year.

Figure 2.5 is the mean distribution of CHL in the study region in year 2010. The peak value appeared near 79°N. It is unusual that summer peaks in northern region (near 80°N) were even lower than spring peak.

Generally, CHL distributed higher down south and lower up north in Arctic Ocean (Qu et al. 2006, 2014). However, in our study region, there was a high peak
Mean CHL along longitude in the study region (65°N-85°N, 20°W-10°E)

**Fig. 2.4** CHL variation along longitude for years 2003–2012

**Fig. 2.5** Mean CHL distribution in 2010 in the study region

Mean CHL (mg/m³) in 2010 in the study region

of CHL near 79°N. The reasons causing such a higher northerly peak are unusual. We need to look into several factors in the region.

Lara et al. (1994) did detailed research on the mechanisms of nutrients supply and influence factors on phytoplankton distribution in northeast water of Greenland Sea (78°N–82°N, 20°W–0). They found the vertical stability in their study region was much better than south of the study region. The reason could be the input of melting water and solar heating. The melting water caused lower salinity and higher CHL production. The salinity was lower near 79°N–80°N and higher in both south
of 79°N and north of 80°N. Hence, more melting waters from various sites and the land runoff from east of Greenland are the two main factors. Those introduced vertical stability and more iron content, which favored phytoplankton biomass.

Several researchers studied the phytoplankton density near Fram Strait in Greenland Sea and found that the phytoplankton biomass in northeastern of Fram Strait (78°N–81°N) was higher due to the enhanced water–column stability (Gradinger and Baumann 1991). Cherkasheva et al. (2014) did study on Fram Strait area (76°N–84°N, 25°W–15°E). They found the late ice retreat leads to a late ice-associate bloom in the northern region. The stratification of the surface water due to solar radiation (considered is the first reason) and ice melting (the second reason) in the relative sallower surface layer is correspondent to the highest CHL. The water salinity was not much related to CHL. Here, the key parameter for surface stratification is the surface temperature.

Cherkasheva et al. (2014) found that there is no significant relationship between the stratification and CHL variability in coastal water. In coastal water, CHL is higher when absence of ice. This indicating CHL related more to the nutrients rather than light limitation in coastal water. NAO, air temperature, and wind speed could have more impact on marine organism productivity. They also found the phytoplankton blooms would start when the depth of the stratified layer is at its maximum. The later summer months in Fram Strait, CHL concentration decreasing could be due to the limitation of light, stratification, and intense grazing pressure by small copepods and protozooplankton.

The surface melting water south of 79°N and north of 80°N may be depleted from nutrients and lacked vertical stability in the water column due to the different geographic positions.

### 2.3.3 Ice Cover Distributions

The profile of mean ICE in the 10 years in the study region was generally higher in March and decreased through summer and reached to the valley in September and then increased again after September (Fig. 2.6). Figure 2.7 shows the mean ICE in different subregion (20°W–10°E). There was a dip in year 2009 in spring in northern regions (Fig. 2.7c, d). More ICE happened in spring and summer of 2012 down south. Higher ICE occurred in spring and early summer in 2010 down south. Less ICE occurred in 2004 and 2003 in late summer and early autumn up north.

Figure 2.8 is MI in 75°N–80°N region. We calculated the MI by subtract the ice cover from this week to last week. We are more interested in those higher CHL peak times (Fig. 2.3).

The first CHL peak of 2010 happened in middle of April, while MI started increasing (blue line). The early high March melting in that year contributed relative amount of ice algae to this peak. The second peak of 2010 also happened when MI increased. However, the timing of the two 2010 CHL peaks all happened only one more weeks after MI increasing. The further melting of ice did not contribute more ice algae to the plankton production. The previous MI could contribute to its
second CHL peak. The time span between the two peaks was one more month. Year 2011 had its highest CHL peak in middle of May, and it was not on the MI period, but happened just when the MI stopped decreasing. More MI happened in late March and early April in year 2011. This could be partly the cause of peak of

---

**Fig. 2.6** Monthly mean ICE for 10 years in the study region

**Fig. 2.7** Weekly mean Ice Cover time series in years 2003–2012
### 2.3 Results

**Fig. 2.7** (continued)

**c)** Mean ICE in the region (75°N–80°N)

**d)** Mean ICE in the region (80°N–85°N)

**Fig. 2.8** MI profiles for 75°N–80°N in the research area for years 2003–2012
CHL in 2011 in middle of May. However, lower PAR and positive NAO could be the other reasons causing the peak of CHL in 2011. Year 2008 had late CHL peak in early July. The relative low SST could be the reason for the late peak of 2008.

### 2.3.4 SST, PAR, ICE, and Wind in the 75°N–80°N Region

In our study region, SST had quite strong positive relationship with PAR (Fig. 2.9 for region 75°N–80°N) with PAR 2 months ahead of SST. However, year 2009 had strong negative relationship between PAR and SST.

Looking at 10 years SST profiles in the 75°N–80°N region (Fig. 2.10), the temperature was low in March and gradually increased until July reached to its peak and then started to drop. Year 2003 had the lowest SST during spring and summer. Year 2010 had relative mild SST, while year 2012 had relative higher SST during ice-melting season. Generally, there is an inverse relationship between phytoplankton

![Time Series for PAR and SST in 75°N-80°N](image)

Fig. 2.9 Monthly time series of PAR and SST for the years 2003–2012 in 75°N–80°N

![SST for 75°N-80°N](image)

Fig. 2.10 Weekly mean SST in 75°N–80°N for 2003–2012
biomass and SST (Jutla et al. 2009). PAR inter-annual profile for the 10 years in the study region is shown in Fig. 2.11. Year 2009 had highest PAR in summer (although had some missing values), and Year 2011 had summer peak in June. Year 2010 had a dip in middle May. The lower PAR and relative low SST appeared in middle of May favoured growth of phytoplankton biomass in year 2010.

Wind speed in middle of March in 2010 was much higher than other years (Fig. 2.12a). Wind direction generally was southeast direction (Fig. 2.12b). Wind direction in the early spring of 2010 changed from southeast to southwest direction (Fig. 2.12b). That possibly brought MI water from south to north and brought runoff melting water from the east coast of Greenland up to north (79°N–80°N). Year 2010 had relative higher wind speed, and year 2011 had second higher wind speed in spring. Spring wind direction in the both years changed from southeast to southwest with year 2010 changed earlier, and year 2011 changed later but stayed longer in southwest direction. That could explain the Fig. 2.3 that higher CHL peak came earlier in year 2010 and later in year 2011. With year 2011, CHL peak higher than year 2010 within May and June could be due to the longer period of wind direction from southwest.

Yearly MI is calculated in the study region (Fig. 2.13). The positive value shows the MI, and the negative value shows the ice was increasing. The hollow dot line is purely total MI for the year (ignoring the ice increasing amount). The solid dot line includes the MI (positive value) and increasing ice (negative value). Year 2004 had the largest MI through the year. The second largest MI is year 2003. Year 2009 had the least MI and more increased ice. Year 2010 had relative more MI in recent years. In recent 3 years, year 2010 had more MI and 2011 through 2012 had less MI. Table 2.3 lists the weekly ICE trends in different region for the 10 years (March to September). The increasing rate of ICE is insignificant.

Figure 2.14 is the 10 years MI and ice cover for the first half year from day 72–160 (middle of March to middle of May) in the study region. The hollow dot
Fig. 2.12 Wind speed and direction in 75°N–80°N for years 2003–2012

Fig. 2.13 Yearly MI amount for years 2003–2012
The regression equations of mean ice cover for different subregions:

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>65°N–70°N</td>
<td>( y = 0.00002x + 4.4928 )</td>
</tr>
<tr>
<td>70°N–75°N</td>
<td>( y = 0.0005x - 5.7024 )</td>
</tr>
<tr>
<td>75°N–80°N</td>
<td>( y = 0.0022x - 38.388 )</td>
</tr>
<tr>
<td>80°N–85°N</td>
<td>( y = 0.0015x + 31.066 )</td>
</tr>
</tbody>
</table>

2.3 Results

The general trend of MI in the study region was decreasing in the last 10 years, while ICE increased in general for the spring and early summer.

2.3.5 The Correlation and Regression Analysis Between CHL and ICE

CHL actually increased 1.75 % from 2003 to 2012 in 75°N–80°N region. If only consider the spring and early summer (March to middle of May, up to day 168), the tendency line of CHL is: \( \text{CHL} = 0.1078x \), where \( x \) is time (see Fig. 2.15). That means in the last 10 years in the region 75°N–80°N, CHL increased 10 % during spring and early summer.

Figure 2.16 is the 10 years mean monthly CHL and ICE in 75°N–80°N region. The general trends of CHL and ICE are as follows: with the decreasing of ICE, CHL was increasing during spring and early summer and reached to its peak in May (for years 2003 and 2010) and in June (for years 2004, 2005, 2006, 2007, and 2011) and in July (for years 2008, 2009, and 2012). In the first 2 months, MI contributed the algae ice to the production of CHL, but after 2 months, the MI water usually did not have significant contribution to the CHL production. Ice did
not melt until May in years 2007, 2008, 2009, and 2012. However, year 2010 had consistent MI from April to August, and CHL was higher in spring in 2010 for monthly data.

Table 2.4 is the correlation coefficient for the CHL and ICE for the years 2003–2012. Generally, they had negative correlations in year 2009 and much significant than other years.

The peak of CHL was about 2 months behind of ICE in 65°N–70°N region, and CHL was about 3 months behind of ICE in other northern regions. Generally, with ice decreasing, CHL would increase from April to its peak in June or July (years 2006, 2008, 2009, and 2012). Year 2010 was quite special with CHL reached to its peak one month earlier in May.

If we shifted ICE 3 months back and aligned with the peak of CHL, there would be quite strong positive coefficient (from 0.51 to 0.68). The correlations of CHL and ICE before and after shifting are shown in Table 2.5.

**Table 2.4** The correlation coefficient for CHL and ICE in the 10 years

<table>
<thead>
<tr>
<th>Year</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.03</td>
<td>−0.21</td>
<td>−0.20</td>
<td>−0.33</td>
<td>0.11</td>
<td>0.07</td>
<td>−0.53</td>
<td>−0.10</td>
<td>0.05</td>
<td>−0.43</td>
</tr>
</tbody>
</table>
After shifting the CHL 3 months back, the regression analysis and F-statistic checking in 75°N–80°N are shown in Table 2.6. The correlation analysis for CHL and MI is shown in Fig. 2.17. Different from ICE and CHL had 3 months time lag, MI and CHL had no time lag and their correlation coefficient is 0.4. With MI increasing, the CHL would increase up to its peak. Year 2010 was different. The CHL reached to its peak 2 months before MI. The second peak of MI reached to the same time with the CHL peak. CHL in year 2011 reached to its peak 1 month ahead of MI peak.

Eviews statistics software (Pang 2007) is used to do regression analysis between CHL and ICE.

The regression equation for CHL and ICE is as follows:

\[
CHL = -0.045 + 0.0145\text{ICE} \quad (75°N–80°N)
\]

(2.1)

The goodness of fit \( R^2 = 0.254 \) is not a very good fit. Under given significance level \( \alpha = 0.05 \), \( t \) value rejects the hypothesis. The \( P \) value in the Table 2.6 shows very good significance. By inspection, we found out that \( F \) value is 19.07 > 4.00 (critical

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. error</th>
<th>( t )-statistic</th>
<th>( P ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (C)</td>
<td>-0.0447</td>
<td>0.1659</td>
<td>-0.2692</td>
<td>0.7888</td>
</tr>
<tr>
<td>ICE</td>
<td>0.0145</td>
<td>0.0033</td>
<td>4.3668</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Dependent variable: CHL

\( R^2 = 0.254 \)

\( F \)-statistic: 19.069

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![Mean CHL and Melting Ice in the study region (75°N-80°N)](image_url)

**Fig. 2.17** Monthly mean time series for CHL and MI in 75°N–80°N
value, not shown in the table). That means the regression equation is significant. The regression analysis for CHL and ICE in other regions is shown in Table 2.7.

The goodness of fit $R^2$ is better in region 65°N–70°N and worse in northern region. We use EViews set up a distributed lag model.

Table 2.8 shows the ICE(-3) has lowest $P$ value (0.0003) for CHL regression coefficient test. That means when ICE lagged 3 months behind, ICE had the most significant influence on CHL. This is consistent with the previous results.

The unit root-test is in Table 2.9.

Unit root-test for CHL (Table 2.8) shows that under 1, 5, and 10 % three significant levels, the Mackinnon critical values of unit root-test are $-3.5402$, $-2.9092$, and $-2.5922$, respectively. The $t$ test statistical value ($-1.5844$) is greater than the critical values; hence, we cannot refuse original hypothesis. This shows CHL had unit root which was non-stationary sequence. We then do unit root-test for the first-order differential sequence.

Table 2.10 shows that $t$ test statistical value $-8.8268$ is less than all critical values; hence, it can refuse original hypothesis. This shows first-order differential sequence of CHL has no unit root, and it is stationary sequence. Hence, CHL sequence is an integrated of order.

<table>
<thead>
<tr>
<th>Table 2.7</th>
<th>Regression analysis for CHL and ICE after shifting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression equation</td>
<td>$F$ value</td>
</tr>
<tr>
<td>65°N–70°N CHL</td>
<td>$-0.22 + 0.16$ICE</td>
</tr>
<tr>
<td>70°N–75°N CHL</td>
<td>$0.12 + 0.03$ICE</td>
</tr>
<tr>
<td>75°N–80°N CHL</td>
<td>$-0.24 + 0.01$ICE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2.8</th>
<th>Distributed lag regression analysis result for CHL and ICE (20°W–10°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>Coefficient</td>
</tr>
<tr>
<td>C</td>
<td>$-0.8824$</td>
</tr>
<tr>
<td>ICE(-1)</td>
<td>0.01035</td>
</tr>
<tr>
<td>ICE(-2)</td>
<td>0.01065</td>
</tr>
<tr>
<td>ICE(-3)</td>
<td>0.00159</td>
</tr>
<tr>
<td>ICE(-4)</td>
<td>$-0.0062$</td>
</tr>
</tbody>
</table>

Dependent variable: CHL

$R^2 = 0.59$

$F$-statistic: 21.9454

Prob ($F$-statistic): 0.0000

<table>
<thead>
<tr>
<th>Table 2.9</th>
<th>Unit root-test for CHL (Null hypothesis: CHL has a unit root)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$-statistic</td>
<td>Prob.</td>
</tr>
<tr>
<td>Augmented Dicky-Full test statistic</td>
<td>$-1.5844$</td>
</tr>
</tbody>
</table>

Test critical values

1 % level $-3.5402$

5 % level $-2.9092$

10 % level $-2.5922$
Using the same method, we also found first-order differential sequence of ICE D(ICE) is also a stationary sequence (Table 2.11). Hence, ICE sequence is an integrated of order.

Next is finding if CHL and ICE had co-integration relationship? We do the regression analysis for the two variables: CHL and ICE, then check the smoothness of the regression residuals.

Table 2.12 shows that t test statistical value is $-5.2406$, less than the correspondent critical value. It shows the residuals sequence does not have unit root, it is stationary sequence. That is, CHL and ICE had co-integration relationship, that means CHL and ICE had long-term equilibrium relationship.

### 2.3.6 The Correlation Analysis Between NAO and CHL

Monthly NAO from years 2003 to 2012 is shown in Fig. 2.18.

NAO had inter-annual variations. Apart from year 2010 where NAO was negative throughout the year, NAO in other years had more fluctuations through one year. The negative NAO indicated the cold air in European and milder in Greenland. The mild Greenland air would lead more MI from the east coast of Greenland to Greenland Sea. That explains more MI happened in year 2010, and hence, higher and earlier CHL blooms occurred.
Figure 2.19 is the 20 years’ time series of CHL and NAO in region 75°N–80°N. In general, CHL had negative relationship with NAO. The correlation coefficient for the 10 years is $-0.43865$.

We still use Eviews to do regression analysis for CHL and NAO. Table 2.13 is the regression analysis for CHL and NAO in 75°N–80°N region (Table 2.14).

The regression equation between CHL and NAO is:

$$\text{CHL} = 0.19 - 0.16 \text{NAO} \quad (75°\text{N–}80°\text{N}) \quad (2.2)$$

![Fig. 2.18](image1)

**Fig. 2.18** NAO monthly mean for years 2003–2012

![Fig. 2.19](image2)

**Fig. 2.19** Monthly mean CHL and NAO in years 2003–2012 in 75°N–80°N

**Table 2.13** Regression analysis for CHL and NAO in different sub-region

<table>
<thead>
<tr>
<th>Region</th>
<th>Regression equation</th>
<th>$F$ value</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>65°N–70°N</td>
<td>CHL = 0.60–0.07NAO</td>
<td>4.64</td>
<td>0.06</td>
</tr>
<tr>
<td>70°N–75°N</td>
<td>CHL = 0.52–0.10NAO</td>
<td>3.70</td>
<td>0.05</td>
</tr>
<tr>
<td>80°N–85°N</td>
<td>CHL = 0.39–0.01NAO</td>
<td>0.18</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Giving significant level $\alpha = 0.05$, after $t$ test and $F$ test, $P$ value is smaller than $\alpha$ ($P$ value = 0.0005). Hence, the regression equation is significant. Other regression equation is listed in Table 2.13. The small value of $R^2$ could be due to the different cycle of the two parameters.

### 2.3.7 Correlations of MI and NAO

It is found MI had better correlation with NAO rather than ICE and NAO. In region 75°N–80°N, the 10 years monthly MI and NAO time series is shown in Fig. 2.20. There was a positive correlation relationship in some time period, although it was not consistently always positive. It is noticed that NAO was 3 months ahead of MI. This result is confirmed by Eviews. Figure 2.21 is the weekly two time series for year 2010 in the same region. The detailed time series shows there was obvious correlation between the two (Fig. 2.21a). If we shift MI 3 weeks ahead, the MI and NAO were negatively correlated (Fig. 2.21b). The correlation coefficient is $-0.57$. It means with the increase of NAO, MI would decrease. On the other hand, with decrease of NAO, MI would increase.

**Table 2.14** Regression analysis for CHL and NAO (75°N–80°N)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. error</th>
<th>$t$-statistic</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (C)</td>
<td>0.5965</td>
<td>0.0456</td>
<td>13.0827</td>
<td>0.0000</td>
</tr>
<tr>
<td>NAO</td>
<td>$-0.158$</td>
<td>0.0425</td>
<td>$-3.7174$</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

$R^2 = 0.1924$  
$F$-statistic: 13.8189

Dependent variable: CHL

![Graph](image_url)  
**Fig. 2.20** 10 years NAO and MI time series in 75°N–80°N
If considering the positive correlations for monthly data, the time lag is much larger. For years 2011 and 2012, the time lag between MI and NAO is 3 months. After shifting MI 3 months ahead, the high positive correlation is shown in the two figures (Fig. 2.22). The correlation coefficients for these two years are 0.81 and 0.84, respectively, for 2011 and 2012.

### 2.3.8 The Correlation Analysis Among CHL, MI, and NAO

We still study the correlation among CHL, NAO, and MI in 75°N–80°N region (Table 2.15).

We have the regression equation:

\[
\text{CHL} = 0.054 - 0.111 \text{NAO} - 0.012 \text{ICE}(-3)(75°\text{N–80°N})
\]

(2.3)

Table 2.16 confirmed ice and NAO had 3 months’ time lag with NAO 3 months ahead of MI. The regression equation is significant. That means NAO and MI
2.3 Results

had significant influence on CHL. The southern region had the more correlated correlations.

![Melting ICE and NAO in 2011 (75°N-80°N) after shifting](image)

![Melting ICE and NAO in 2012 (75°N-80°N) after shifting](image)

**Fig. 2.22** Month mean MI and NAO after shifting in 75°N–80°N for years 2011 and 2012

**Table 2.15** Regression analysis for CHL, NAO, and MI/(ICE) (Dependent variable: CHL)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Std. error</th>
<th>t-statistic</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant (C)</td>
<td>−0.0544</td>
<td>0.1659</td>
<td>0.3368</td>
<td>0.7375</td>
</tr>
<tr>
<td>ICE(−3)</td>
<td>0.0116</td>
<td>0.0033</td>
<td>3.5066</td>
<td>0.0009</td>
</tr>
<tr>
<td>NAO</td>
<td>−0.1118</td>
<td>0.0412</td>
<td>−2.7092</td>
<td>0.0090</td>
</tr>
</tbody>
</table>

$R^2 = 0.3419$  
F-statistic: 14.2838

**Table 2.16** Regression analysis for CHL, NAO, and melted ice in different subregions

<table>
<thead>
<tr>
<th>Reg. equation</th>
<th>F value</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>65°N–70°N CHL = −0.227 + 0.005NAO + 0.158ICE(−2)</td>
<td>46.63</td>
<td>0.59</td>
</tr>
<tr>
<td>70°N–75°N CHL = 0.266 − 0.054NAO + 0.021ICE(−3)</td>
<td>6.31</td>
<td>0.16</td>
</tr>
<tr>
<td>80°N–85°N CHL = −0.177 − 0.035NAO + 0.006ICE(−3)</td>
<td>5.69</td>
<td>0.22</td>
</tr>
</tbody>
</table>

had significant influence on CHL. The southern region had the more correlated correlations.
2.4 Conclusions

The distributions and correlation analysis between CHL and ICE, CHL and MI, NAO and ICE, NAO and MI, and CHL and NAO are all studied. The MI played a significant role on promoting the growth of CHL. We are more focused on the northern region (75°N–80°N), where ice melted more. It was unusual to find CHL was higher near 80°N in the study region due to the enhanced water column stability and more MI, less salinity in this region. The peaks of CHL in 2010 happened very early and much higher than other year (in the same time). We tried to find the reason for that. The first high peak in early spring could be due to the higher wind speed. Spring wind direction in the year changed from southeast to southwest direction brought more MI water in the northern region, hence promoting the CHL concentrations. MI in year 2010 was much more than other recent years. Moreover, when temperature was warm in middle of May, the relative mild SST and lower PAR profile in year 2010 favoured the growth of phytoplankton biomass.

The peak of CHL was about 2 months behind of ICE in 65°N–70°N region, and 3 months behind of ICE in other northern regions. After shifting ICE 3 months back, the correlation between CHL and ICE was 0.68. That means ICE influenced CHL and had positive correlations with CHL.

NAO had almost negative index in year 2010, and it refers the mild Greenland air would lead to more MI in that year. NAO had negative correlations with CHL; with lower NAO, stronger CHL would appear. MI had better correlations with NAO than Ice cover with NAO. In year 2010, MI and NAO were negatively correlated with NAO 3 weeks ahead of MI. If shifted NAO 3 months behind, there would be higher correlation coefficients (0.81 and 0.84) between NAO and MI in years 2011 and 2012, respectively.

We focus the region in 75°N–80°N for correlation analysis and found out that NAO and MI had significant influence on CHL.

References


References


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