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Review

## Water column stability and *Calanus finmarchicus*

Gabriel Reygondeau<sup>1</sup>, Grégory Beaugrand<sup>2,3</sup>

<sup>1</sup> IRD (Institut de Recherche pour le Développement)  
UMR EME 212, CRH (Centre de Recherches Halieutiques Méditerranéennes et Tropicales)  
av. Jean Monnet, B.P. 171, 34203 Sète cedex, FRANCE,  
E-mail: [gabriel.reygondeau@ird.fr](mailto:gabriel.reygondeau@ird.fr)

<sup>2</sup> Centre National de la Recherche Scientifique, Laboratoire d'Océanologie et de Géosciences'  
UMR LOG CNRS 8187, Station Marine, Université des Sciences et Technologies de Lille –  
Lille 1  
BP 80, 62930 Wimereux, France, E-mail: [Gregory.Beaugrand@univ-lille1.fr](mailto:Gregory.Beaugrand@univ-lille1.fr)

<sup>3</sup> Sir Alister Hardy Foundation for Ocean Science, Citadel Hill, the Hoe, Plymouth PL1 2PB,  
United Kingdom

\* To whom correspondence should be addressed. E-mail: [gabriel.reygondeau@ird.fr](mailto:gabriel.reygondeau@ird.fr)

## Abstract

Many authors have suggested that the abundance of the subarctic species *Calanus finmarchicus* can be influenced by the structure of the water column. Unfortunately to date, such a link has never been confirmed either experimentally or statistically. By using a macroecological approach, we investigated this hypothesis and showed that it varies with the developmental stage of the species. First, we implemented a new statistical procedure, based on an exponentially weighted moving average, to identify and quantify the depth and intensity of the thermocline. We applied the technique on 1,005,619 temperature profiles over the North Atlantic Ocean and provide a mapping of these two descriptors at a seasonal scale. Second, we studied the relationships between the depth and the intensity of the thermocline and *Calanus finmarchicus* using a biological dataset of 99,599 sampling stations. Our results suggested that the characteristics of the water column influence the spatial distribution of *C. finmarchicus*. The frequency in the occurrence of this species decreases when stratification rises. Our results further revealed that the effect is more pronounced for young copepodite stages. Such findings are of interest since, in a warmer world, water stratification is expected to increase, making more likely a reduction in the abundance of this key species in the North Atlantic.

**Key-words:** Exponentially Weighted Moving Average; *Calanus finmarchicus*; thermocline ; North Atlantic Ocean; Macroecology

## Introduction

The thermocline is often defined as a vertical zone of rapid temperature change in the water column located below the surface layer of rapid mixing (Kaiser et al., 2005). It can be seasonal or permanent. Seasonal thermoclines are located in extratropical regions, being shallow in spring and summer, deep at the beginning of the autumn, and disappearing in winter (Tomczak and Godfrey, 2003). In the tropics, winter cooling is not strong enough to destroy the seasonal thermocline, leading to a permanent thermocline called the tropical thermocline (Tomczak and Godfrey, 2003). In high latitudes, temperature profiles vary seasonally as a function of wind stress and ice cover. From spring to autumn, a dicothermal layer separates the upper from the deeper zones of the water column and in winter, the water column is homogenous (Pickard and Emery, 1990). Pickard and Emery (1990) described a depth range of seasonal and tropical thermoclines from 0 to 500 m. Below 500 m and up to 1000 m, the seasonal thermocline is known as the permanent or oceanic thermocline (i.e. transition zone from warm to cold waters of great oceanic depth). This type of thermocline is not considered in this paper (Tomczak and Godfrey, 2003). In the North Atlantic Ocean, both the depth and the intensity of the thermocline vary with the latitude and the local hydrodynamics (Longhurst, 1998).

Methods for estimating the depth of the thermocline from profile data fall into two broad categories of threshold methods (Thomson and Fine, 2003) (Table 1): 1) Methods using a depth-to-depth temperature or density difference (Defant, 1961; Kara et al., 2000, 2001; Wijffels et al., 1994), 2) Methods using a temperature or density difference between a reference depth and other depths in the profile (Lamb, 1984; Levitus, 1982; Monterey and Levitus, 1997; Sprintall and Tomczak, 1990; Weller and Plueddemann, 1996). For a long time, thermocline depth was considered as the *Mixed Layer Depth (MLD)* until Sprintall and

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2  
3 Tomczak (1990) showed that there was a difference between the two hydrodynamical features  
4  
5 (Levitus, 1982; Sprintall and Tomczak, 1990). However, due to a lack of salinity data, or  
6  
7 because salinity data tend to be noisier than temperature data, MLD is sometimes linked to a  
8  
9 steplike change in water temperature, with specified steps in the range 0.018–0.58°C  
10  
11 (Thomson and Fine, 2003).  
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14  
15 The structure of the water column influences the biodiversity of pelagic ecosystems  
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17 and related biogeochemical cycles (Bopp et al., 2005; Kara et al., 2000; Rutherford et al.,  
18  
19 1999; Sarmiento and Gruber, 2006). The stratification of the water column has an effect on  
20  
21 the spatial distribution of plankton and on the life cycle of many pelagic organisms (Beare  
22  
23 and McKenzie, 1999). For example, Rutherford et al. (1999) showed a strong relationship  
24  
25 between the diversity of foraminifera and the properties of the water column at a global scale.  
26  
27 *Calanus finmarchicus*, a subarctic oceanic species found north of the Oceanic Polar Front  
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29 (Dietrich, 1964), is among the most studied species of copepods in the world (Mauchline,  
30  
31 1998). The species plays a central role in transferring the primary production to high trophic  
32  
33 levels (Dickson and Brander, 1993). It is the prey of many young stages of fish and the  
34  
35 fluctuations of *Calanus* population have been linked to the variation in the stock of some  
36  
37 species of fish (Beaugrand et al., 2003). Some authors have suggested that the structure of the  
38  
39 water column could influence the vertical and horizontal distribution of the species (Helaouët  
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41 and Beaugrand, 2007; Williams and Lindley, 1980a; Williams and Lindley, 1980b; Williams  
42  
43 and Conway, 1980; Williams, 1985). Helaouët and Beaugrand (2007) used a proxy of water  
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45 turbulence induced by atmospheric forcing (i.e. the cube of the wind speed) and data from the  
46  
47 Continuous Plankton Recorder (CPR) survey (sampling between 0 and 10 m) to suggest a  
48  
49 possible influence of turbulence or of the the mixed layer depth on the abundance of *C.*  
50  
51 *finmarchicus* (Helaouët and Beaugrand, 2007). Williams (1980, 1985) supposed that at the  
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53 southern boundary of the species' spatial distribution, the stratification could stop the vertical  
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3 flux of organic particule and consequently increase the inter-specific competition for food  
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5 with *C. helgolandicus*. Williams (1985) concluded that it was likely that the survival rate of  
6  
7 *C. finmarchicus* located beyond the thermocline diminished due to food limitation.  
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12 The objectives of this paper were to investigate at a macroecological scale the  
13 influence of the structure of the water column (i.e. depth and intensity of the thermocline) on  
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15 *Calanus finmarchicus*. First, we implemented a new numerical procedure, based on a  
16  
17 technique used in statistical quality control and called Exponentially Weighted Moving  
18  
19 Average (EWMA) to identify and quantify the depth and intensity of the thermocline. Second,  
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21 the procedure was tested in neritic and oceanic regions. Third, this procedure was used on  
22  
23 more than 1 million temperature profiles, allowing us to map the seasonal variability of the  
24  
25 thermocline depth and intensity over the North Atlantic Ocean. Finally, the relationships  
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27 between the structure of the water column and the relative frequency of *C. finmarchicus* were  
28  
29 investigated from copepodite stage 1 to adults. Using a new database, monthly and inter-  
30  
31 annual changes were investigated to indicate the different ways in which thermocline  
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33 descriptors could affect *C. finmarchicus* population dynamics.  
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## 44 Method

### 45 *Biological data*

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47 Biological data used in this study were located in the northern part of the North Atlantic  
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49 Ocean and extended from 80 °W to 19.5 °E of longitude and 25.5 to 73 °N of latitude (Fig.  
50  
51 1a). Biological data came from different sources: the TASC programme (TransAtlantic Study  
52  
53 on Calanus; <http://tasc.imr.no>) from 1995 to 1998 ; the U. S Georges Bank programme  
54  
55 (http://globec.who.edu) from 1995 to 2000; the India survey (data provided by X. Irigoien)  
56  
57 from 1971 to 1975; the Norwestlant programme ([www.st.nmfs.noaa.gov/plankton](http://www.st.nmfs.noaa.gov/plankton)); Heath et  
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3 al. 2007) in 1963 ; the UK Marine Productivity project data held at BODC ([www.bodc.ac.uk](http://www.bodc.ac.uk),  
4  
5 Heath et al. 2007) from 2001 to 2002 ; the U. S Northeast continental shelf bongo survey  
6  
7 (data provided by Jack Jossi) from 1977 to 2006; Labrador data in 1997, 2001 and 2002.  
8  
9 Spatial distribution of the dataset is presented in Figure 1a and details of sampling methods  
10  
11 are shown in Supplementary Table 1.  
12  
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15 Chlorophyll-a data were gathered from the same surveys as the *C. finmarchicus*  
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17 database and completed by downloaded data from the World Ocean Database  
18  
19 ([www.nodc.noaa.gov](http://www.nodc.noaa.gov)). Chlorophyll-a from the upper five meters were retained and  
20  
21 integrated.  
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### 24 25 26 **Physical data**

27  
28 Physical data utilised in this work were located in the North Atlantic Ocean, extending  
29  
30 from 81.5 °W to 23.5 °E of longitude and 18.5 °N to 75 °N of latitude. Temperature and  
31  
32 bathymetric data came from different high resolution profile sources. Some were provided by  
33  
34 Conductivity-Temperature-Depth (CTD) data samples collected during the above biological  
35  
36 cruises. Others came from the National Oceanic and Atmospheric Administration (NOAA,  
37  
38 data provided by Maureen Taylor). Lastly, some data were downloaded from the World  
39  
40 Ocean Database ([www.nodc.noaa.gov](http://www.nodc.noaa.gov)) including Mechanical BathyThermograph (MBT),  
41  
42 eXpendable BathyThermograph (XBT) and Profiling Floats (PFL) data. Data encompassed  
43  
44 the period 1876-2008 (Fig. 1b). All profiles were taken from the surface to 500 m to focus on  
45  
46 seasonal thermocline. The main surface currents and frontal structures of the region covered  
47  
48 in this study are indicated in Fig. 1c.  
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### 53 54 55 **Analyses**

#### 56 57 58 ***Identification of intensity and depth of the thermocline*** 59 60



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3 The techniques used to identify the depth and intensity of the thermocline have  
4 generally been empirical in the past. In this study, we designed a new procedure, which is  
5 summarised in Fig. 2. The procedure was divided into 4 steps:  
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10 **Step 1:** for each profile, two tests were performed before estimating the thermocline. The first  
11 test measured the number of points in each profile. When the number of measures was strictly  
12 below 5 (threshold defined empirically in this paper), no estimation was made. The second  
13 test measured the resolution of the data. If the profile had a difference of more than 50 m and  
14 20 m between successive depths (threshold defined empirically) in oceanic and neritic regions  
15 respectively, the information was considered too scarce and the estimation of depth and  
16 intensity of the thermocline was not calculated.  
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27 **Step 2:** the temperature of the profile was linearly interpolated for each interval of 5 m from  
28 the original profile (in this study) (Lam, 1983). This interpolation was used to regulate the gap  
29 from one sample to another. No extrapolation was carried out here. Interpolation started at 2  
30 meters to minimise the influence of the diurnal fluctuation of the water temperature and the  
31 noise related to the instrument in the first few meters (de Boyer Montégut et al., 2004). The  
32 procedure ended at the maximal depth of the profile (maximum 500 m). The interpolation  
33 technique was applied because the use of the weighted moving average in Step 3 needed  
34 equally spaced data.  
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46 **Step 3:** a filtering technique, named Exponentially Weighted Moving Average (EWMA)  
47 (Montgomery, 1991), was applied on each temperature profile. This technique was chosen  
48 because it enables low or high persistent values to be better identified (Beaugrand and Ibanez,  
49 unpublished data). The technique is similar to the “*cumulative sums*”, another technique  
50 frequently used in statistical quality control (Ibañez et al., 1993). The technique was  
51 calculated by an iterative procedure and as follows:  
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$$E_z = \lambda.A_0 + (1 - \lambda).E_{z-1} \quad (1)$$

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Where  $E_z$  is the value of the moving average at depth  $z$ ,  $E_{z-1}$  is the value of the moving average at depth  $z-1$ ,  $A_0$  is the value of the initial dataset at depth  $z_0$  and  $\lambda$  is the filtering factor which is typically comprised between 0 and 1 and often fixed at 0.3 (Beaugrand and Ibanez, in preparation). The technique also enables a reduction of the noise inherent to this kind of data. The type of filtering is asymmetric contrary to most of the filtering methods (simple or weighted moving average, see Legendre & Legendre, 1998). This makes the method more sensitive to local variations.

**Step 4:** depth-to-depth absolute temperature difference  $d(T)$  was calculated every 5 meters as follows:

$$d(T) = |T_{Z_b} - T_{Z_a}| \quad (2)$$

Where  $T_{Z_b}$  is the temperature at depth  $Z_b$  and  $T_{Z_a}$  is the temperature at depth  $Z_a$ ,  $a$  and  $b$  ranging from 2 to 500m. The depth-to-depth temperature difference amplitude (i.e. the maximal minus the minimal difference in temperature calculated for each profile) was chosen to be the variable of the threshold method. This absolute difference amplitude marks a standardised increase or decrease of water temperature. In some cases, this variable can give the depth of the temperature inversions which occur at the base of barrier layers and in Polar Regions. When the depth-to-depth temperature difference amplitude was lower than a threshold (see Analysis 2), the thermocline intensity was fixed at the maximal difference of temperature and the thermocline depth was made equal to the maximal depth of the profile. In other cases, the thermocline intensity was fixed at the maximal value of  $d(T)$  and the depth of the thermocline was the depth at which the maximal value of  $d(T)$  was detected.

Before applying the procedure of identification of the depth and intensity of the thermocline (see previous analysis, step 4), it was important to select a threshold that allows

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2  
3 the numerical procedure described in this paper to distinguish between a homogenous and a  
4 stratified water column. The selection of the threshold was done by performing 3 analyses.  
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8 First, we examined monthly changes in the maximum depth-to-depth temperature  
9 difference (see Fig. 3) to evaluate the possible range of the different thresholds which could  
10 separate a homogenous from a stratified water column during a year, following descriptions in  
11 the literature (Longhurst, 1998; Pedlosky and Young, 1983). This analysis was conducted at a  
12 large-scale, covering the whole supratropical region of the North Atlantic and adjacent seas to  
13 consider the full range of conditions experienced by *C. finmarchicus*. We examined the  
14 interval of maximum annual variation (see Fig. 3) to temporarily select some thresholds for  
15 the next analysis in this interval.  
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27 Second, we tested the new procedure against two types of averaged thermal profiles.  
28 Two regions were chosen to observe bi-monthly changes in the depth and intensity of the  
29 thermocline (see Fig. 1 and 4). The first station (see Fig 4a) was located between 42°N and  
30 44°N and 66°W and 71°W and represented a neritic area of 132m mean depth. A total of  
31 17,846 profiles were considered in this area. The second area (see Fig. 4b) was located  
32 between 44°N and 46°N and 25°W and 30°W. The region represented an oceanic area of  
33 2620 meters mean depth. A total of 1,004 profiles were considered in this region.  
34 Temperature data were linearly interpolated every 5 meters for each profile from 2 meters to  
35 the maximal depth. A mean temperature was calculated for each depth and each two-week  
36 period. Mean bi-monthly depth and intensity of the thermocline were also calculated using the  
37 techniques of Levitus (1982) and Defant (1961). The Levitus (1982) method assesses the  
38 depth of the thermocline by calculating the differences between a reference point (here 0 m)  
39 and subsequent depths. A threshold of 0.5°C was selected by the author (Levitus, 1982). The  
40 Defant (1961) technique computes differences between successive depths with no prior  
41 transformation of the data. The threshold selected by the author was 0.015°C m<sup>-1</sup> (Defant,  
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3 1961). Our procedure was tested against these two techniques (see Analysis 1) but applied  
4 with different thresholds: 0.15, 0.25, 0.3, 0.4°C.5m<sup>-1</sup>. The threshold values were fixed per 5m  
5 because of the resolution of the profiles after interpolation, which corresponded to 0.03, 0.05,  
6 0.06, 0.08°C.m<sup>-1</sup>. For both regions, the analysis of the intensity of thermocline was used to  
7 quantify the period of restratification and destratification. Restrartification was considered as  
8 the first significant increase (i.e. increase of 5% from one point to the next) in the intensity of  
9 the thermocline. Destratification corresponds to the first significative decrease in the intensity  
10 of the thermocline (i.e. decrease of 5% from one point to the next). The Thresholds and  
11 methods were compared to the thermal profiles of the two regions.  
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25 Third, both depth and intensity of the thermocline were mapped and the different  
26 thresholds examined at a macro-scale (Fig. 5). For each geographical cell of 1° of longitude  
27 and 1° of latitude, median depth and intensity of the thermocline were mapped after  
28 application of the techniques on each profile between 17.5 °E and 80.5 °W and between 30.5  
29 and 72.5 °N. Spatial variation was computed using an isotropic variogram (Matheron, 1962)  
30 so as to compensate for gaps in the database, a kriging method based on the mgstat package of  
31 matlab ([www.mgstat.sourceforge.net](http://www.mgstat.sourceforge.net)) was used. The spatial scale at which these parameters  
32 were mapped was selected to compare characteristic features of the whole supratropical  
33 region detected by other procedures (e.g. the transition zone between permanently and  
34 seasonally stratified regions at 40°N). Mapping was realised in spring (from April to June),  
35 summer (from July to September), autumn (from October to December) and winter (from  
36 January to March), using the method of Levitus (1982) and the technique proposed in this  
37 paper with different thresholds (see Analysis 1; see Fig.5). Our results were then compared to  
38 existing knowledge on North Atlantic circulation (Fig 1c.). The maps of the selected  
39 thresholds for the depth of the thermocline are represented in Figure 6 and the intensity of the  
40 thermocline in Figure 7.  
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### *Relationships between the structure of the water column and *Calanus finmarchicus**

The objectives of these analyses were (1) to characterize the tolerance of each copepodite stage of *C. finmarchicus* to both the depth and the intensity of the thermocline and (2) to understand how the thermocline may affect the spatial distribution of the different copepodite stages.

Due to the variability in the sampling techniques among biological datasets (see Supplementary Table 1), a direct comparison based on abundance was likely to give biased results (Nichols and Thompson, 1991; Ohman, 2002). Therefore, we worked on relative frequency (Legendre and Legendre, 1998). To compute this index, the abundance data for each sampling sites and copepodite stages were integrated (BONGO and MOCNESS stratified dataset) on the whole water column sampled and converted into presence or absence. Then, for each geographical cell (spatial grid of 1° of longitude and latitude), month and year, the sum of the number of presences was divided by the total number of samples for each copepodite stage. Due to the likely overestimation or underestimation (mesh of 35-96 µm for early stages) of some specific copepodites by the different sampling techniques (Nichols and Thompson, 1991; Ohman, 2002), their potential influences were tested to estimate potential biases in the dataset. Relative presence was computed with and without all the different sampling techniques. No significant difference was observed between datasets, therefore the analyses presented in this article were performed with the whole database.

Physical observations (i.e. mean depth and intensity of the thermocline) were then integrated for each biological sample. Physical data were attributed to biological samples with the same month and year (at a temporal resolution of 15 days) and being at a maximum spatial distance of 0.2° of latitude or longitude. The first analysis characterised the tolerance of the species to the thermocline intensity and depth. The mean relative frequency of the

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3 different stages of the species as a function of the intensity of the thermocline was assessed  
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5 from 0 °C.5m<sup>-1</sup> to 2 °C.5m<sup>-1</sup> using a regular interval of 0.05°C.5m<sup>-1</sup>. A tolerance diagram was  
6  
7 also built to examine the relative presence of the different stages of *C. finmarchicus* as a  
8  
9 function of the depth of the thermocline from 0 m to 200 m by using a regular interval of 25  
10  
11 m. This procedure was applied for each every month and each copepodite stage (from stage 1  
12  
13 to adult) (see Fig. 8).  
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17 Secondly, correlations between the relative presence of *C. finmarchicus* and both the  
18  
19 intensity and depth of the thermocline were calculated at the scale of the North Atlantic Ocean  
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21 for the months between April and June (see Fig. 9). Prior to performing this analysis, the  
22  
23 relative presence of the species was averaged for categories of 0.05°C.m<sup>-1</sup> of thermocline  
24  
25 intensity ranging from 0 to 1.5°C.5m<sup>-1</sup> and for categories of 10m of depth between 0 and 200  
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27 m. Only intervals with an observation were considered when performing the linear regression.  
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32 Third, an average of thermocline intensity and depth was calculated for the whole  
33  
34 region where *C. finmarchicus* occurs at both monthly and year-to-year scales. The relative  
35  
36 presence of *C. finmarchicus* was reported on the graphs to examine potential relationships  
37  
38 between the species (copepodite stage 1, 5 and adults) and the mean characteristics of the  
39  
40 thermocline (see Fig. 10). The objective of this analysis was therefore to study the  
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42 relationships between the species and the thermocline by averaging the space and focussing  
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44 on time at both seasonal and year-to-year scales.  
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### 50 ***Relationships between C. finmarchicus and environmental parameters***

51  
52 To understand how stratification affects the relative frequency of the species, the  
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54 relation between thermocline (depth and intensity), surface chlorophyll-a and *C. finmarchicus*  
55  
56 was investigated. Data on relative presence of *C. finmarchicus* were averaged for categories  
57  
58 of chlorophyll-a of 0.075µg.l<sup>-1</sup> between 0 and 4.2µg.l<sup>-1</sup>. Then, correlations were calculated  
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3 between the relative presence of *C. finmarchicus* and the concentration of chlorophyll-a for all  
4 copepodite stages (see Fig. 11). Data of chlorophyll a were averaged for categories of  
5  
6  $0.05^{\circ}\text{C}\cdot\text{m}^{-1}$  of thermocline intensity ranging from 0 to  $1.5^{\circ}\text{C}\cdot 5\text{m}^{-1}$  and for categories of 10m  
7  
8 for the depth of the thermocline from 0 to 200 m in continental shelf regions and from 0 to  
9  
10 500 m in oceanic regions. Then, correlations were calculated between both the intensity and  
11  
12 the depth of the thermocline and the chlorophyll-a concentration (see Fig. 12).  
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## 20 Results

### 21 *Selection of a threshold to discriminate a homogeneous from a stratified water column*

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23 A fundamental step before running the technique for each thermal profile was to  
24  
25 choose a relevant threshold to discriminate between a homogeneous and a stratified water  
26  
27 column. This was done by performing three analyses. The first analysis used frequency  
28  
29 histograms of the depth-to-depth temperature difference amplitude (i.e. maximum depth-to-  
30  
31 depth temperature difference) found in each profile and each month (Fig. 3). Between  
32  
33 December and April when the water column was mainly homogeneous and June and  
34  
35 September when the water column was mostly stratified, pronounced changes (maximal  
36  
37 annual variation) were observed between  $0.1^{\circ}\text{C}\cdot 5\text{m}^{-1}$  and  $0.4^{\circ}\text{C}\cdot 5\text{m}^{-1}$  (Fig. 3). This analysis  
38  
39 enabled the selection of potential thresholds between  $0.1^{\circ}\text{C}\cdot 5\text{m}^{-1}$  and  $0.4^{\circ}\text{C}\cdot 5\text{m}^{-1}$  to  
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41 discriminate between a homogeneous and a stratified water column. Such a range of potential  
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43 thresholds coincided with values commonly found in the literature (Thomson and Fine, 2003).  
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54 The second analysis tested our procedure with different thresholds in the range determined  
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56 previously (see Fig. 3) against two other already published methods (Defant, 1961; Levitus,  
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58 1982) in a neritic (Fig. 4a) and an oceanic region (Fig. 4b). In the neritic region during the  
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60 winter mixing period from December to April, the method of Defant and Levitus and our

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3 procedure based on a threshold of  $0.15^{\circ}\text{C}\cdot 5\text{m}^{-1}$  localised the depth of the thermocline  
4 shallower than with other thresholds (Fig. 4a). The restratification period was detected in  
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6 April in the neritic region and at the end of May in the oceanic region with a significant  
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8 increase in the slope of the depth of the thermocline (Fig 4). This period was well identified  
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10 with all the techniques and thresholds except for the threshold of  $0.4^{\circ}\text{C}\cdot 5\text{m}^{-1}$  in the neritic  
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12 region (Fig 4a). In the oceanic region (Fig. 4b), the methods of Levitus and Defant and our  
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14 technique based on thresholds of  $0.15^{\circ}\text{C}\cdot 5\text{m}^{-1}$  localised the thermocline between April to  
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16 May. When thresholds of  $0.3^{\circ}\text{C}\cdot 5\text{m}^{-1}$  and  $0.4^{\circ}\text{C}\cdot 5\text{m}^{-1}$  were used, the technique identified the  
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18 establishment of the thermocline at the beginning of June. During the summer stratification  
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20 (strong stratification between June and September), the methods of Levitus and Defant  
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22 represented the depth of the thermocline shallower than our method. The destratification  
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24 period detected in September for both regions was well detected with all the procedures with  
25  
26 the notable exception of the technique of Levitus that localised the destratification in October.  
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28 Among all the techniques and thresholds, the results indicated that our procedure based on a  
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30 threshold of  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$  gave the closest match in term of depth. Furthermore, the intensity  
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32 assessed from our technique with a threshold of  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$  gave a satisfactory summary of  
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34 the structure of the water column (Fig. 4). Similar results were observed in the oceanic region  
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36 (Fig. 4b). Here also, the threshold of  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$  gave the best compromise between a too  
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38 conservative result (threshold of  $0.4^{\circ}\text{C}\cdot 5\text{m}^{-1}$ ) and too much sensitivity (Defant, followed by  
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40 Levitus). In all cases, the procedure of Defant was too sensitive and was therefore excluded  
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42 from the next analysis.  
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55 At a basin scale, the comparison of the Levitus technique with our method based on  
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57 the thresholds 0.25, 0.30 and  $0.40^{\circ}\text{C}\cdot 5\text{m}^{-1}$  showed a good correspondence in the spatial  
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59 changes in the depth of the thermocline (Fig. 5). However, some differences were observed at  
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3 the boundary between permanently and seasonally stratified regions. The Levitus method did  
4 not clearly detect this well-known boundary. The new technique gave the best contrast  
5 between both permanently and seasonally stratified regions (PSWW: permanently stratified  
6 water in winter, Fig. 1c) when the smallest threshold was used. We therefore selected the  
7 threshold of  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$  in the next analyses.  
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17 *Seasonal changes in the spatial distribution of the depth and the intensity of the*  
18 *thermocline*  
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24 Seasonal variability in the spatial distribution of the depth and the intensity of the  
25 thermocline were examined in the North Atlantic sector using our procedure with a threshold  
26 of  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$  (Fig. 6 and Fig. 7). Mapping of seasonal changes in the depth of the  
27 thermocline clearly located the Subtropical Convergence (PSWW and PSWS, Fig 1c). This  
28 front separates the permanently stratified regions of the North Atlantic Subtropical Province  
29 from the seasonally stratified extratropical provinces of the Atlantic Westerly Winds Biome  
30 as it was termed by Longhurst (1998). In the north of the Subtropical Convergence, deep  
31 mixing occurred and in most regions (e.g. the Subarctic Gyre) winter mixing was greater than  
32 500m in winter (Fig. 6). The meso-scale variability associated with the path of the Gulf  
33 Stream was particularly well detected in winter and the singularity of the South West  
34 European Basin clearly identified (Fig. 1b). A very interesting feature was the detection of the  
35 influence of the circulation around the Subarctic Gyre that increases the depth of the mixing  
36 in summer and autumn (Fig. 6c-d). The knowledge about the spatial distribution of *C.*  
37 *finmarchicus* (Heath et al., 2008; Helaouët and Beaugrand, 2007; Planque and Fromentin,  
38 1996) and the present results suggest that the species is predominantly present in those  
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3 oceanic regions characterised by deep winter mixing. This condition is important but sea  
4 surface temperature is another essential controlling factor (Helaouët and Beaugrand 2007).  
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8 Mapping of the seasonal changes in the intensity of the thermocline showed the  
9 contrast between the winter and summer on the one hand and coastal and oceanic regions on  
10 the other hand (Fig. 7). In summer, the strongest thermoclines were detected over continental  
11 shelves and in the Mediterranean Sea where maximal intensity values were greater than  
12  $1^{\circ}\text{C}\cdot 5\text{m}^{-1}$ . In oceanic regions, intensity values oscillated between 0 and  $0.3^{\circ}\text{C}\cdot 5\text{m}^{-1}$  in  
13 temperate and in subpolar regions and 0.3 and  $0.9^{\circ}\text{C}\cdot 5\text{m}^{-1}$  in subtropical regions north of the  
14 Subtropical Convergence. Local hydro-dynamic features such as the Ligurian Front and the  
15 Flamborough front were also detected (Fig. 7 and Fig. 1b). The impact of surface currents on  
16 the intensity of the thermocline was clear. For example, weaker values were observed in the  
17 path of the Gulf Stream and around the Subarctic Gyre (Fig. 7).  
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### 33 34 *Relationships between the structure of the water column and Calanus finmarchicus*

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38 To examine potential relationships between *C. finmarchicus* and the structure of the  
39 water column, we represented the relative frequency of the species as a function of the depth  
40 and the intensity of the thermocline (Fig. 8) for all the months from the copepodite stage 1 to  
41 the adult. The mapping of the relative frequency of the species as a function of the depth and  
42 intensity of the thermocline and the months revealed that young copepodite stages and  
43 especially copepodite stage 1 occurred in regions where the water column was not stratified  
44 (Fig. 8). Copepodite stage 1 individuals were less frequent in July. However, it was observed  
45 that a greater number of these stages were found in regions where the intensity of the  
46 thermocline was lower than 1 and the thermocline deeper than 50 m. Therefore, it is likely  
47 that copepodite stage 1 is less frequent during this month because it is not within its  
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3 environmental niche (Fig. 8) (Helaouët & Beaugrand, 2007). When the individuals become  
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5 older, stratification had much less influence and the species occurred in regions with both  
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7 shallow and stronger thermocline. Adult stages seemed however to have a less wide range of  
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9 habitats, than stage 5. The increase of tolerance to stratification occurring during the life  
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11 cycle of the species is not consistent with the seasonal course of the thermocline.  
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18 To investigate more deeply the potential link between *C. finmarchicus* and the  
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20 structure of the water column at a macroscale, we represented the mean relative frequency of  
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22 the species as a function of the depth and the intensity of the thermocline (Fig. 9) for the  
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24 months of maximum abundance. The results confirmed previous observations, showing a  
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26 negative relationship between the species and the intensity of the thermocline. This  
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28 relationship was especially high for copepodite stage 1. The negative relationship was not  
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30 detected in May for Stage 5 (Fig. 9a). The examination of the sensitivity of the relationship,  
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32 measured here by the strength of the correlation, indicated that adult stages were more  
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34 sensitive to thermocline intensity than stage 5 but less than stage 1. The same sensitivity was  
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36 found for all the stages when correlations were calculated between the relative presence of *C.*  
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38 *finmarchicus* and the thermocline depth (Fig. 9b). The positive relationship between the  
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40 relative presence of the species and the thermocline depth was however substantially lower  
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42 for stage 5 in June.  
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51 An analysis was performed to investigate the temporal relationships between both  
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53 thermocline depth and intensity and the relative presence of *C. finmarchicus* on both seasonal  
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55 and year-to-year scales (Fig. 10). The analysis revealed that the youngest stages had their  
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57 maximum relative presence just before the establishment of the thermocline (Fig. 10a). Stage  
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59 5 did not exhibit this relationship. On a year-to-year scale (period 1977-2005; n=28), the  
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3 relationship with the thermocline (intensity and depth) was significantly highly negative for  
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5 stage 1. No relationship was detected between thermocline intensity and the other stages (C5  
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7 and adult). Positive relationships between the relative presence of *C. finmarchicus* and the  
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9 depth of the thermocline were also detected for all stages.  
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### 12 13 14 15 ***Relationships between *C. finmarchicus* and chlorophyll a concentration***

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17 Positive and significant relationships were detected between chlorophyll a and the  
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19 relative presence of *C. finmarchicus* from stages 1 to 3. Then, the correlation became null for  
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21 stage 4 and significantly negative for C5 and adults.  
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### 26 27 ***Relationships between the structure of the water column and chlorophyll a concentration***

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29 The relationship between water column stratification and chlorophyll-a was examined in both  
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31 neritic (Fig. 12a) and oceanic (Fig. 12b) regions of the North Atlantic. Negative and  
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33 significant relationships between chlorophyll-a and both intensity and depth of the  
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35 thermocline were detected. Mean chlorophyll-a concentration was low in homogenous water  
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37 (intensity of the thermocline  $< 0.25 \text{ }^{\circ}\text{C}\cdot\text{m}^{-1}$  and deep thermocline depth) and slightly  
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39 increased when the intensity of the thermocline increased. Maximum chlorophyll-a  
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41 concentration was located in the interval between 0.2 to  $0.4 \text{ }^{\circ}\text{C}\cdot\text{m}^{-1}$  of intensity of the  
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43 thermocline and between 40 and 60m of depth of the thermocline in the neritic area and  
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45 between 100 and 230m in the oceanic area.  
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## 53 54 **Discussion**

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56 The technique proposed to determine the depth and intensity of the thermocline is a  
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58 gradient threshold method. This technique is usually considered to be a less consistent  
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60 estimator of the thermocline than the “*difference approach*” (Thomson et al. 2003). However,

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3 because of problems related to the instruments used to sample or the presence of rapid  
4 environmental variation over a short depth range, temperature profiles are often piecewise-  
5 linear rather than smoothing varying (Brainerd and Gregg, 1995). The use of EWMA  
6 (Montgomery, 1991; Beaugrand and Ibanez, in preparation) gave us the possibility to obtain  
7 sharp gradient-resolved temperature profiles. EWMA was chosen because (1) the technique  
8 reduces the noise associated with temperature profiles and (2) in contrast to classical moving  
9 average methods, it is more sensitive to local variations (rapid temperature change), which is  
10 an important property for an accurate detection of the depth of the thermocline.  
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25 In this article, a thermocline is defined as the depth of maximal temperature change in  
26 the water column (maximal temperature gradient) and the concept is used as an indicator of  
27 water column stability. A prerequisite to the use of the technique was to define a threshold to  
28 separate a stratified from a homogenous water column. Three analyses were performed on  
29 different time and space scales and compared to two already existing methods (Defant, 1961;  
30 Levitus, 1982) with different possible thresholds. The technique, applied to both neritic and  
31 oceanic regions (Fig. 4), revealed that the Defant method and our technique based on a  
32 threshold of  $0.15^{\circ}\text{C}\cdot\text{m}^{-1}$  were too sensitive because they overrated the depth of the  
33 thermocline during winter and identified restratification too early. De Boyer Montégut et al.  
34 (2004) noticed that the method of Levitus (1982) did not accurately localise the initiation of  
35 stratification (Fig. 4). The analysis performed at a macroscale (Fig. 5) and the comparison  
36 with profiles (see Fig. 4) showed that the general pattern of thermocline depth was respected  
37 in comparison to the Levitus technique. The comparisons with the profiles (see Fig. 4 and 5)  
38 showed that the threshold of  $0.25^{\circ}\text{C}\cdot\text{m}^{-1}$  gave the best results (see also the location of hydro-  
39 dynamic features in Fig 1c).  
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3 The spatial distribution and seasonal variation of the thermocline appear to be in  
4 agreement with the knowledge on water column characteristics across the North Atlantic  
5 Ocean (Beaugrand et al., 2001; Sarmiento and Gruber, 2006; Sprintall and Tomczak, 1990;  
6 Tomczak and Godfrey, 2003). In Atlantic central gyres, the thermocline is deep and rapidly  
7 increases across frontal structures or main surface currents. Major currents such as the Gulf  
8 Stream, the Labrador Current or the European Continental Shelf Current are identified in our  
9 results and seasonal frontal structures (Oceanic Polar Front or Flamborough Front, Iceland-  
10 Faroe Front) are well represented (Fig. 6 and 7). The general pattern proposed in this study  
11 respects the location and the seasonality of these currents, and the quantification of the  
12 intensity of the thermocline provides additional information. A comparison between the  
13 monthly changes in these two descriptors (Fig. 4) and the description of the change in the  
14 characteristics of the thermocline by Longhurst (1998) are in agreement. Nevertheless,  
15 examination of seasonal changes in the depth of the thermocline shows that our technique  
16 described a deeper thermocline than previous studies (Levitus, 1982; Sprintall and Tomczak,  
17 1990). Such a result can be explained either by the absence of consideration of the diurnal  
18 variation in the depth of thermocline in our analyses (de Boyer Montégut et al., 2004) or by  
19 the choice of the threshold of  $0.25^{\circ}\text{C}\cdot\text{m}^{-1}$ . Indeed, the greater the threshold, the less sensitive  
20 the method is regarding temperature change.  
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48 The present study used a new database on *C. finmarchicus* that can be complementary  
49 to the data collected by the Continuous Plankton Recorder (CPR) survey (Reid et al 2003).  
50 The present database is a compilation of several studies and surveys on the different  
51 copepodite stages of *C. finmarchicus* (supplementary Table 1.). This dataset has samples at  
52 different levels of the water column, information that cannot be obtained with CPR data  
53 (sampling at a constant depth of 7 m). Many authors have suggested an effect of stratification  
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3 on the life cycle or the spatial distribution of different types of planktonic organisms (Planque  
4 and Fromentin, 1996; Rutherford et al., 1999). While Planque & Fromentin (1996) suspected  
5 an effect of stratification on the spatial distribution of *Calanus finmarchicus* and *C.*  
6 *helgolandicus*, Rutherford et al. (1999) provide evidence of a positive influence of this  
7 parameter on foraminifera diversity at a global scale. At a higher trophic level, mechanisms  
8 by which the column stability affects fish (tuna, anchovy, sardines) have been widely studied  
9 and are relatively well understood (Beare et al., 2004; Bertignac et al., 1998; Block et al.,  
10 1997; Brill et al., 1999; Lehodey et al., 1997). Beare and colleagues (2004) have revealed that  
11 water column stability could affect nutrition of small pelagic fish and thereby alter their  
12 growth and mortality or delay their biological development. For many *Thunnidae*, the  
13 thermocline affects their vertical and horizontal distributions (Bertignac et al., 1998; Block et  
14 al., 1997; Brill et al., 1999) and many reports suggest that a change in the depth of the  
15 thermocline (for example due to the Niño effect) might change the catchability of these  
16 species (Lehodey et al., 1997). Williams (1980a, 1980 b, 1985) speculated that, at the  
17 southern edge of the spatial distribution of *C. finmarchicus*, the vertical position of the  
18 thermocline may affect the abundance and the location of the species. Williams (1980b) found  
19 that the vertical position of *C. finmarchicus* was altered when the thermocline was stronger.  
20 This author suggested that this phenomenon allows the species to be separated from its  
21 congeneric species *C. helgolandicus* located shallower in the water column. The author  
22 speculated that this difference was related to the warmer thermal preference of *C.*  
23 *helgolandicus*. Subsequently, Williams (1985) supposed that this mechanism may also affect  
24 the nutrition strategy of the two species which compete for phytoplankton.  
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58 The link between stratification and *C. finmarchicus* was examined in different ways to  
59 detect and better understand how the species might be influenced by the characteristics of the  
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3 water column stability. The macroecological study revealed a change in the environmental  
4 tolerance to stratification parameters occurring during the life cycle (Fig. 8). The results show  
5 that even if early life stages are found in different stratification conditions, they occurred more  
6 frequently (relative presence >0.5) in weakly stratified waters (0.1 and 0.3 C.5m<sup>-1</sup> of intensity  
7 of thermocline and >50 m of depth of the thermocline) (Fig. 8 and 9). Older developmental  
8 stages were less sensitive to stratification (Fig. 8 and 9). Weak conditions of stratification  
9 were found before the establishment of the thermocline (March to May) when, in parallel, an  
10 increase in the relative presence of all copepodite stages was detected (Fig 10). The  
11 restratification period was characterised by an increase of the intensity of the thermocline  
12 (ranging between 0.2 and 0.5°C.m<sup>-1</sup>) combined with a shallowing of the depth of the  
13 thermocline and exhibited an annual maximum of chlorophyll-a (Fig 12). Given the positive  
14 relationship between early stage and chlorophyll-a concentration (Fig 11) and the negative  
15 relationship between chlorophyll-a and the intensity of the thermocline (Fig. 12), it appears  
16 that the restratification period offers optimal environmental conditions for the species. Indeed,  
17 the results were in accordance with the observations made by Saumweber and Durbin (2006),  
18 who suggested that from March to May copepodite stages 5 emerged from diapause and  
19 became adults ready to spawn.

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22 In the Arctic and Subarctic pelagic domain, sea surface temperature and chlorophyll-a  
23 concentration were driven by the incoming solar radiation and water stratification (Longhurst,  
24 1998; Sverdrup, 1953). These two environmental parameters influence growth, nutrition,  
25 survival rate and therefore both temporal and spatial changes in the abundance of *C.*  
26 *finmarchicus* (Heath et al., 2008; Helaouët and Beaugrand, 2007). Furthermore, Cook et al.  
27 (2007) showed that early life stages were highly sensitive to both parameters suggesting that  
28 with low food concentration and high temperature conditions, young copepodites tended to  
29 disappear. Having said that, in winter and summer, the water column offers unsuitable  
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3 environmental conditions for early life stages of *C. finmarchicus*. During these periods,  
4 survival rates of young copepodite stages may decrease due to food limitation in winter or too  
5 higher temperature in summer. It is only during the restratification period when the  
6 thermocline shallows, that epipelagic water contains both high food concentration  
7 (phytoplankton bloom) and an optimal temperature range for the reproduction and  
8 development of naupliar and young copepodite stages (Helaouët and Beaugrand, 2007; Cook  
9 et al., 2007). Based on our results and on previous findings (Hirst and Kiørboe, 2002; Ohman  
10 et al., 2004; Plourde et al., 2009), we suggest that stratification affects the occurrence of this  
11 subarctic species via both food concentration and temperature.  
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27 Change in global air/sea temperature in the Northern Hemisphere are assumed to move the  
28 boundaries between permanently and seasonally stratified waters polewards but also to  
29 reinforce the stratification in high latitudes according to Atmosphere-Ocean General  
30 Circulation models (Intergovernmental Panel on Climate Change, 2007; Sarmiento et al.,  
31 2004). In addition, the seasonal timing in the establishment of the thermocline is also  
32 expected to shift (Walther et al., 2002). These alterations could affect phytoplankton blooms  
33 and all associated trophic webs (Edwards and Richardson, 2004; Gowen et al., 1995). The  
34 ecological-niche and ecophysiological models of *C. finmarchicus* suggest changes in the  
35 spatial distribution of the species in the next decades (scenario A2 and B2) without including  
36 explicitly the influence of stratification. Our results suggest that the intensification of  
37 stratification or changes in its seasonal progression could alter the survival rate of early life  
38 stages of *C. finmarchicus*. As a consequence, this effect might limit the expected northward  
39 movement if the temperature continues to warm in the North Atlantic sector. The contraction  
40 of the species range could have a significant impact for ecosystem functioning by bottom-up  
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3 or top-down propagation through the food web (Beaugrand et al. 2003) and have a potential  
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6 impact on some biogeochemical cycles (Beaugrand 2009).  
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For Peer Review

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For Peer Review

## Table Legends

**Table 1.** Selected equations for detecting the depth of the thermocline or mixed layer depth. Methods are sorted chronologically.  $T$  is temperature and  $\sigma_\theta$  is potential density.  $Z$  denotes the depth and  $\Delta Z$ ,  $\Delta T$  and  $\Delta\sigma_\theta$  denote respectively the difference in depth and temperature and density.

**Supplementary Table 1.** Characteristics of all databases used in this study.

## Figure Captions

**Figure 1.** (a) Spatial distribution of biological data (99 599 stations) .(b)Spatial distribution of temperature profile data (1,005,619 profiles).(c) Schematic representation of main surface currents over the North Atlantic based on Beaugrand et al. (2001) , Sarmiento and Gruber (2006) , Longhurst (2007), Tomczak and Godfrey ( 2001); Currents. CSC: Continental Shelf Current; EGC: East Greenland Current; FC: Faroe Current; IC: Irminger Current; LC: Labrador Current; NAD: North Atlantic Drift Current; NWAC: Norwegian Atlantic Current; WGC: Western Greenland Current. Frontal structures; FF: Flamborough Front; IFF: Iceland-Faroe Front; OPF: Oceanic Polar Front. Other abbreviations. NASG : North Atlantic Sub-tropical gyre; PSWW: Permanently Stratified Water in Winter; PSWS: Permanently Stratified Water in summer;

**Figure 2.** Sketch diagram of the procedure allowing the estimation of the intensity and the depth of the thermocline. The resolution, fixed by parameter  $x$  was equal to 5 meters in this study. Thresholds were fixed empirically.

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3 **Figure 3.** Frequency histograms of the maximal depth-to-depth temperature (in °C) difference  
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5 amplitude for each month over the regions covered by this study (see Fig. 1). The Interval of  
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7 maximum variance during the year is represented by a grey rectangle.  
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12 **Figure 4.** (a) *Upper figure:* Monthly changes in the thermal profile of the water column in the  
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14 neritic region area selected (between 42°N and 44°N and between 66°W and 71°W). The  
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16 depths of the thermocline as determined by different numerical procedures are superimposed  
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18 (solid red line for the Levitus' method; dash red line for the Defant method; solid green line,  
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20 solid blue line, solid black line, solid cyan line for our method with a threshold of 0.15; 0.25;  
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22 0.3; 0.4, respectively). *Bottom figure:* Monthly changes in the intensity (T.I) and depth of the  
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24 thermocline assessed by the numerical procedure for a threshold of 0.25. The grey boxes  
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26 represent a significant change in thermocline intensity highlighting the restratification period  
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28 or destratification period. (b) *Upper figure:* Monthly changes in the thermal profile of the  
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30 water column in the oceanic region area selected (between 44 to 46°N and 25 to 30°W). The  
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32 depths of the thermocline as determined by different numerical procedures are superimposed  
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34 (solid red line for the Levitus method; dash red line for the Defant method; solid green line,  
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36 solid blue line, solid black line, solid cyan line for our method with a threshold of 0.15; 0.25;  
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38 0.3; 0.4, respectively). *Bottom figure:* Monthly changes in the intensity (T.I) and depth of the  
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40 thermocline assessed by the numerical procedure for a threshold of 0.25. Grey boxes  
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42 represent a significant change in thermocline intensity highlighting the restratification period  
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44 or destratification period  
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55 **Figure 5.** Spatial changes in the mean depth of the thermocline for the period between  
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57 January and March using different methods and thresholds. (a) Levitus (b) the proposed  
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3 technique based on a threshold of 0.4 (c) 0.3 and (d)  $0.25^{\circ}\text{C}\cdot 5\text{m}^{-1}$ . Dashed grey line represent  
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5 the permanently stratified water in winter front.  
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10 **Figure 6.** Seasonal spatial changes in the mean depth of the thermocline for the period (a)  
11 January to March (b) April to June (c) July to September and (d) October to December.  
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17 **Figure 7.** Seasonal spatial changes in the mean intensity of the thermocline for the period (a)  
18 between January and March (b) April and June (c) July and September and (d) October and  
19 December.  
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27 **Figure 8.** Tolerance diagram of *C. finmarchicus* against the characteristics of the thermocline.  
28 Contour diagrams showing the relative frequency of the different copepodite stages of *C.*  
29 *finmarchicus* in relation to the intensity (a) and the depth (b) of the thermocline for all the  
30 months of the year. White indicates an area without data.  
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39 **Figure 9.** Relationships between both the intensity (a) and the depth (b) of the thermocline  
40 and the relative presence of the copepodites stages 1, 5 and adults of *C. finmarchicus* from  
41 April to June. Mean observation per interval of  $0.05^{\circ}\text{C}\cdot 5\text{m}^{-1}$  (a) or 10 m (b) are represented by  
42 black points. The grey line represents the trend. The coefficient of correlation  $r$  and its  $p$ -value  
43 are superimposed on each panel.  
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53 **Figure 10.** (a) Monthly changes in the intensity of the thermocline (in grey) and the relative  
54 presence of some copepodite stages (stages 1, 5 and adult) of *C. finmarchicus* (in black).(b)  
55 Monthly changes in the depth of the thermocline (in grey) and the relative presence of some  
56 copepodite stages (stages 1, 5 and adult) of *C. finmarchicus* (in black). (c) Year-to-year  
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3 changes in the intensity of the thermocline (in grey) and the relative presence of some  
4 copepodite stages of *C. finmarchicus* (black). The correlation and its probability are  
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6 superimposed. (d) Year-to-year changes in the depth of the thermocline (in grey) and the  
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8 relative presence of some copepodite stages of *C. finmarchicus* (black). The correlation and  
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10 its probability are superimposed.  
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17 **Figure 11.** Macroecological relationships between the relative frequency of copepodite stages  
18 and adults of *C. finmarchicus* and the chlorophyll a concentration. The correlation and its  
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20 probability are superimposed on each panel.  
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27 **Figure 12.** Macroecological relationships between both the intensity and the depth of the  
28 thermocline and the chlorophyll a concentration in (a) neritic regions and (b) oceanic regions.  
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30 The correlation and its probability are superimposed on each panel.  
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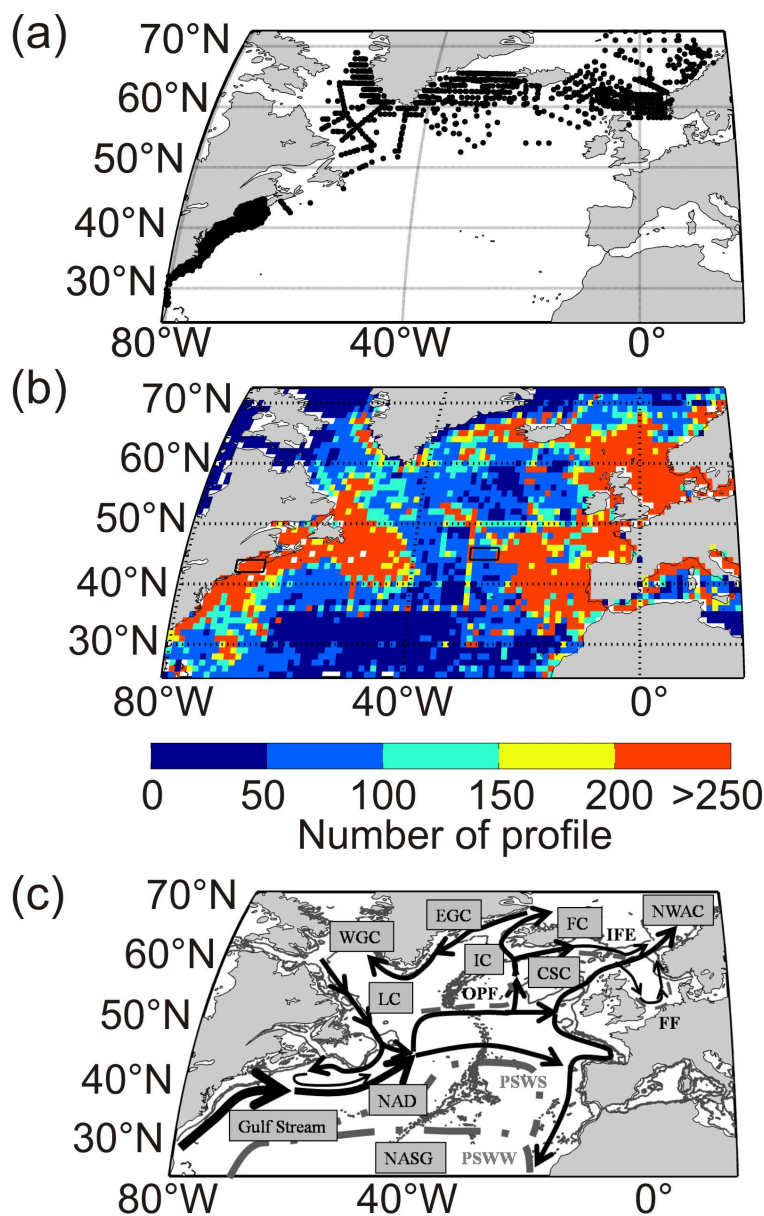


Figure 1. (a) Spatial distribution of biological data (99 599 stations) .(b)Spatial distribution of temperature profile data (1,005,619 profiles).(c) Schematic representation of main surface currents over the North Atlantic based on Beaugrand et al. (2001) , Sarmiento and Gruber (2006) , Longhurst (2007), Tomczak and Godfrey ( 2001); Currents. CSC: Continental Shelf Current; EGC: East Greenland Current; FC: Faroe Current; IC: Irminger Current; LC: Labrador Current; NAD: North Atlantic Drift Current; NWAC: Norwegian Atlantic Current; WGC: Western Greenland Current. Frontal structures; FF: Flammarion Front; IFF: Iceland-Faroe Front; OPF: Oceanic Polar Front. Other abbreviations. NASG : North Atlantic Sub-tropical gyre; PSWW: Permanently Stratified Water in Winter; PSWS: Permanently Stratified Water in summer; 135x215mm (300 x 300 DPI)

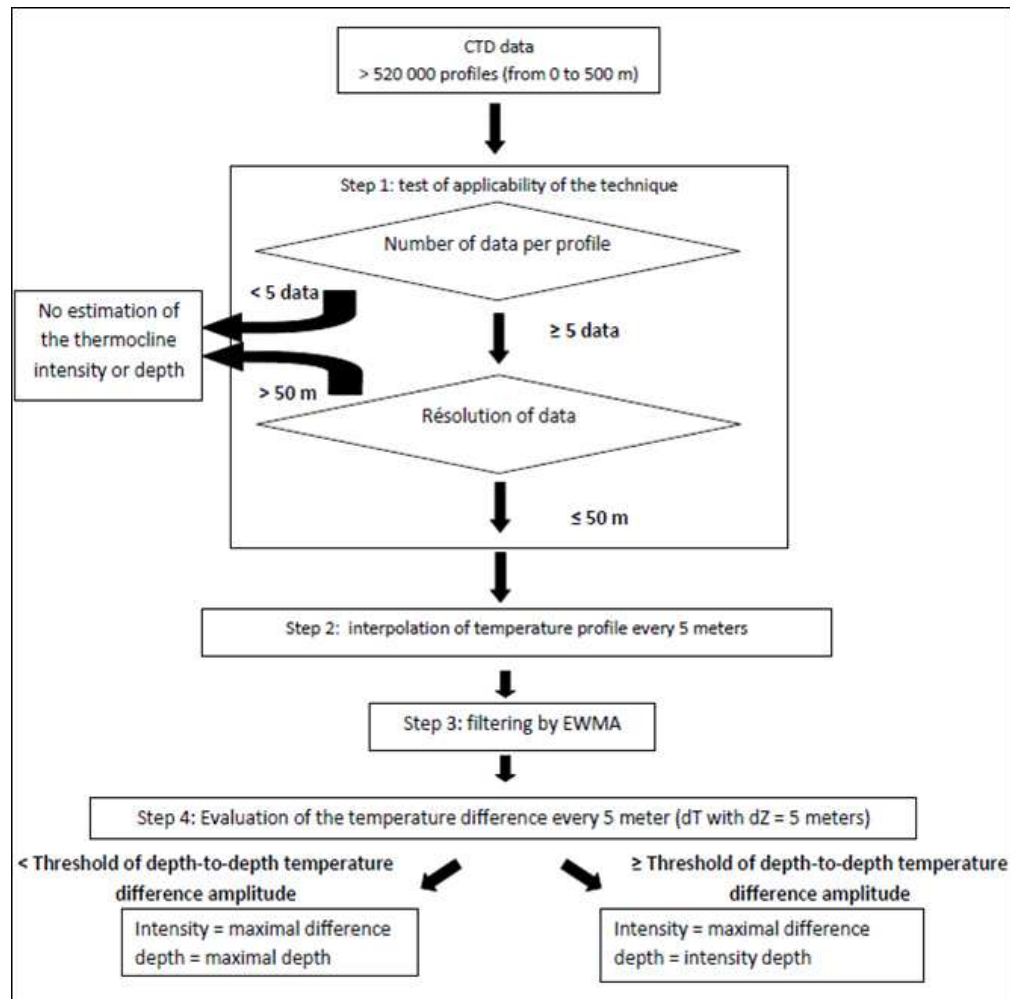


Figure 2. Sketch diagram of the procedure allowing the estimation of the intensity and the depth of the thermocline. The resolution, fixed by parameter  $x$  was equal to 5 meters in this study.

Thresholds were fixed empirically.

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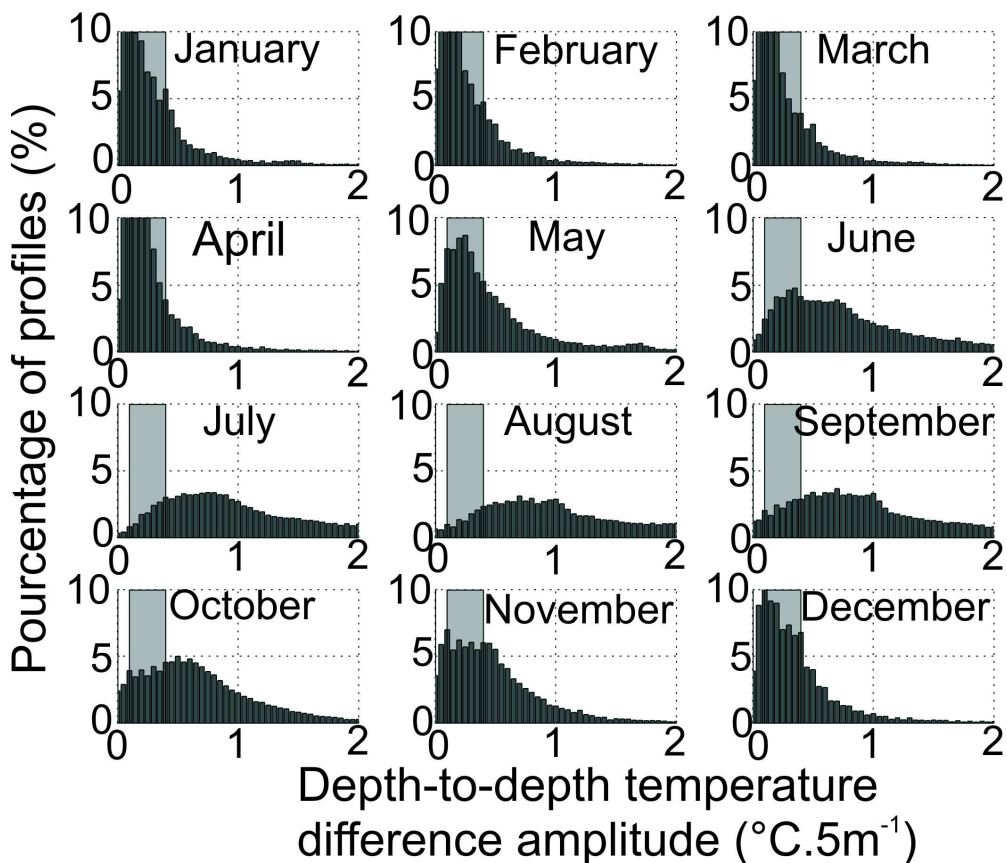


Figure 3. Frequency histograms of the maximal depth-to-depth temperature (in °C) difference amplitude for each month over the regions covered by this study (see Fig. 1). The Interval of maximum variance during the year is represented by a grey rectangle.  
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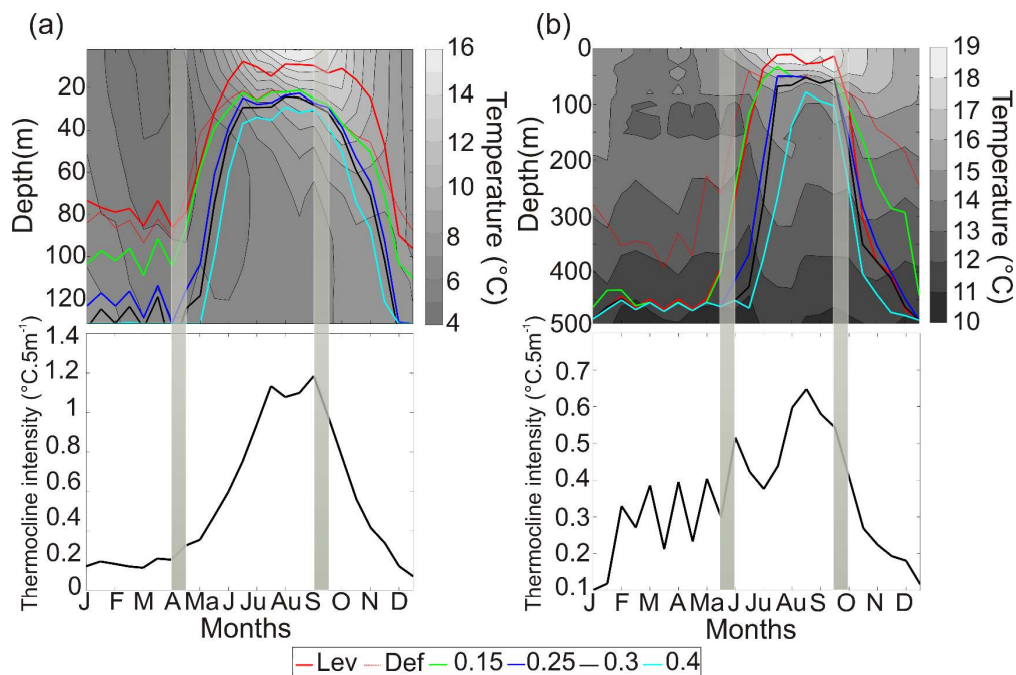


Figure 4. (a) Upper figure: Monthly changes in the thermal profile of the water column in the neritic region is selected area (between 42°N and 44°N and between 66°W and 71°W). The depths of the thermocline as determined by different numerical procedures are superimposed (solid red line for the Levitus' method; dash red line for the Defant's method; solid green line, solid blue line, solid black line, solid cyan line for our method with a threshold of 0.15; 0.25; 0.3; 0.4, respectively). Bottom figure: Monthly changes in the intensity (T.I) and depth of the thermocline assessed by the numerical procedure for a threshold of 0.25. The grey boxes represent a significant change in thermocline intensity highlighting restratification period or destratification period. (b) Upper figure: Monthly changes in the thermal profile of the water column in the oceanic region is the selected area (between 44 to 46°N and 25 to 30°W). The depths of the thermocline as determined by different numerical procedures are superimposed (solid red line for the Levitus' method; dash red line for the Defant's method; solid green line, solid blue line, solid black line, solid cyan line for our method with a threshold of 0.15; 0.25; 0.3; 0.4, respectively). Bottom figure: Monthly changes in the intensity (T.I) and depth of the thermocline assessed by the numerical procedure for a threshold of 0.25. Grey boxes represent a significant change in thermocline intensity highlighting restratification period or destratification period

291x193mm (300 x 300 DPI)

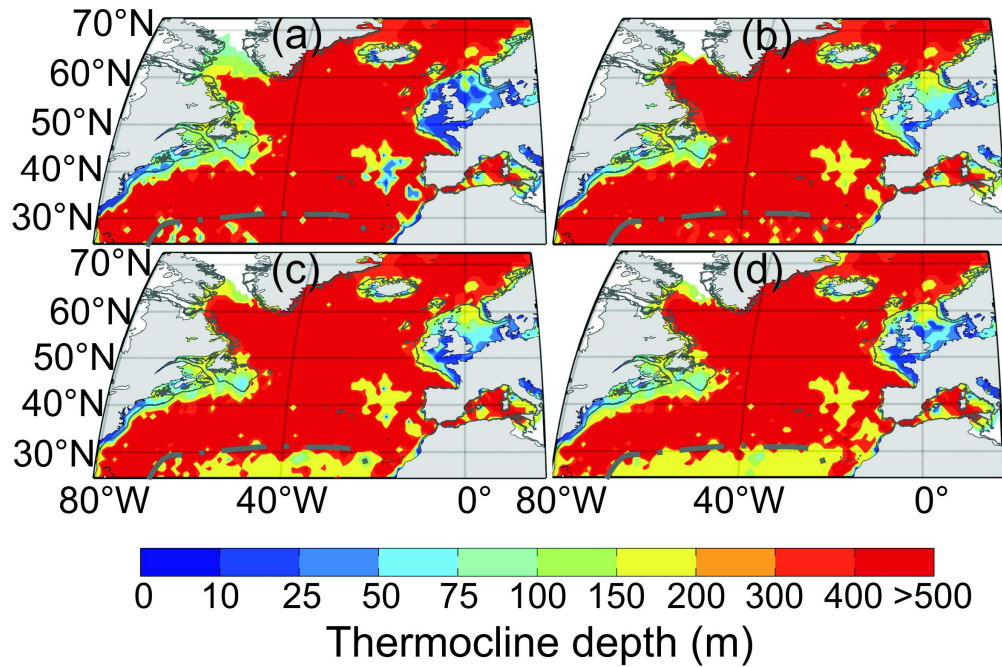


Figure 5. Spatial changes in the mean depth of the thermocline for the period between January and March using different methods and thresholds. (a) Levitus (b) the proposed technique based on a threshold of 0.4 (c) 0.3 and (d) 0.25°C.5m-1. Dashed grey line represent the permanently stratified water in winter front.

198x130mm (300 x 300 DPI)

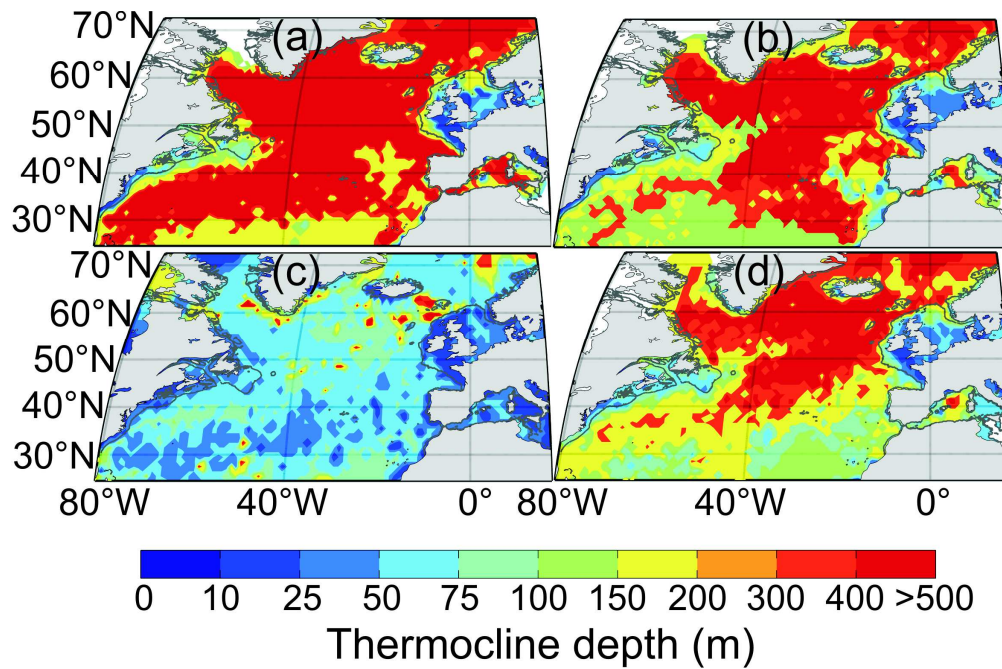


Figure 6. Seasonal spatial changes in the mean depth of the thermocline for the period (a) January to March (b) April to June (c) July to September and (d) October to December.  
198x130mm (300 x 300 DPI)

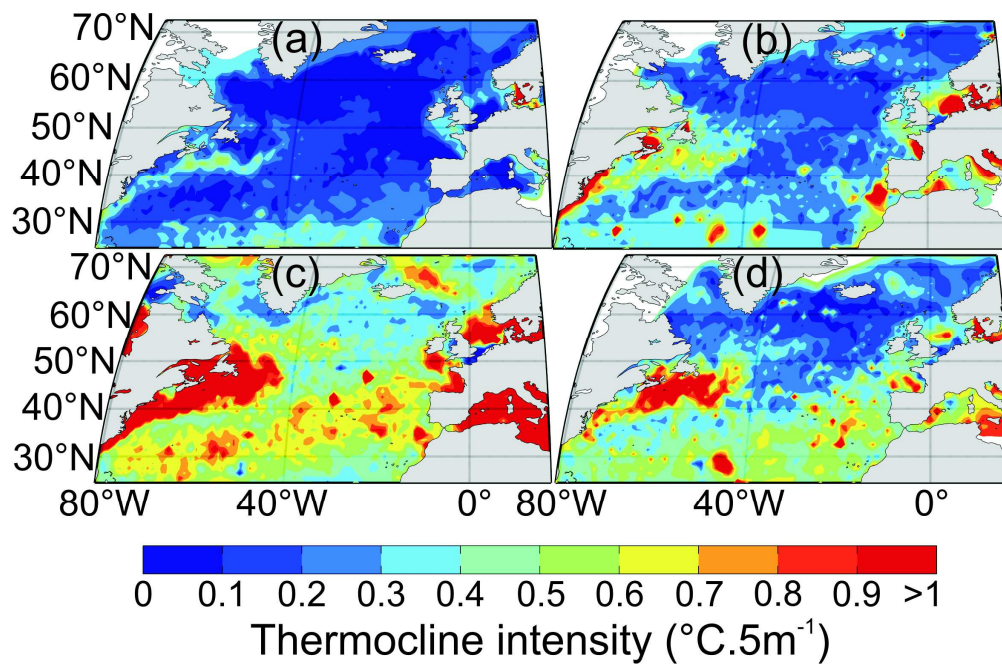


Figure 7. Seasonal spatial changes in the mean intensity of the thermocline for the period (a) between January and March (b) April and June (c) July and September and (d) October and December.

198x129mm (300 x 300 DPI)

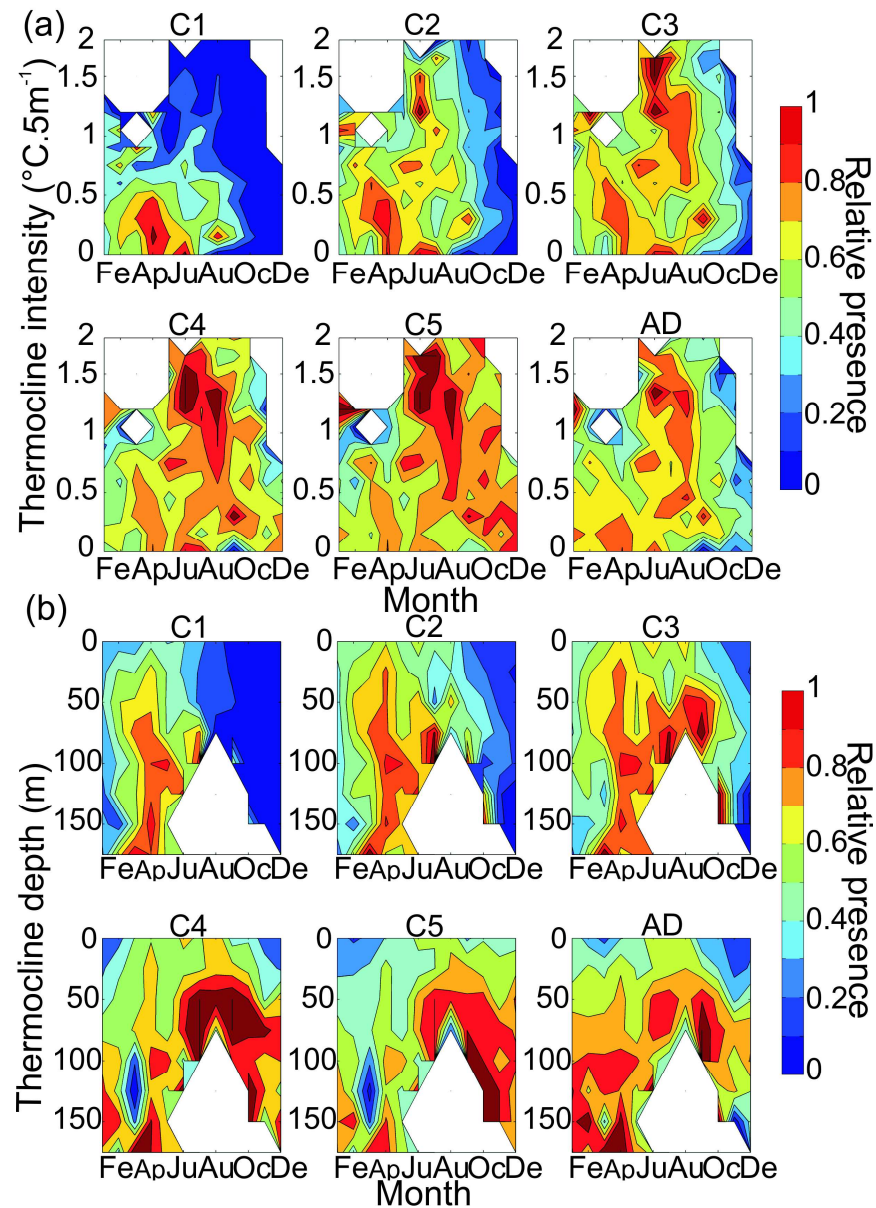


Figure 8. Tolerance diagram of *C. finmarchicus* against the characteristics of the thermocline. Contour diagrams showing the relative frequency of the different copepodite stages of *C. finmarchicus* in function of the intensity (a) and the depth (b) of the thermocline for all the months of the year. White indicates an area without data.  
208x291mm (300 x 300 DPI)

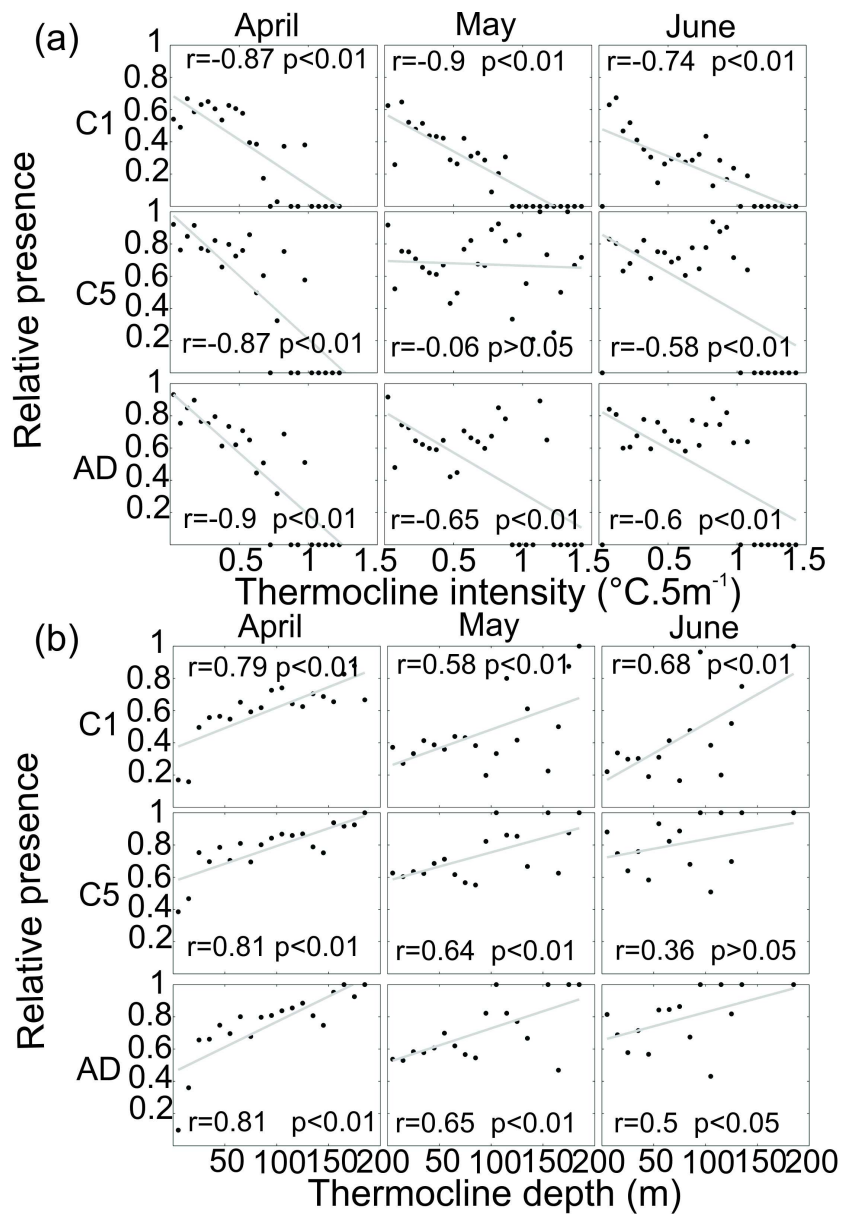


Figure 9. Relationships between both the intensity (a) and the depth (b) of the thermocline and the relative presence of the copepodites stages 1, 5 and adults of *C. finmarchicus* from April to June. Mean observation per interval of 0.05°C.5m<sup>-1</sup> (a) or 10 m (b) are represented by black points. The grey line represents the trend. The coefficient of correlation *r* and its *p*-value are superimposed on each panel.

191x272mm (300 x 300 DPI)

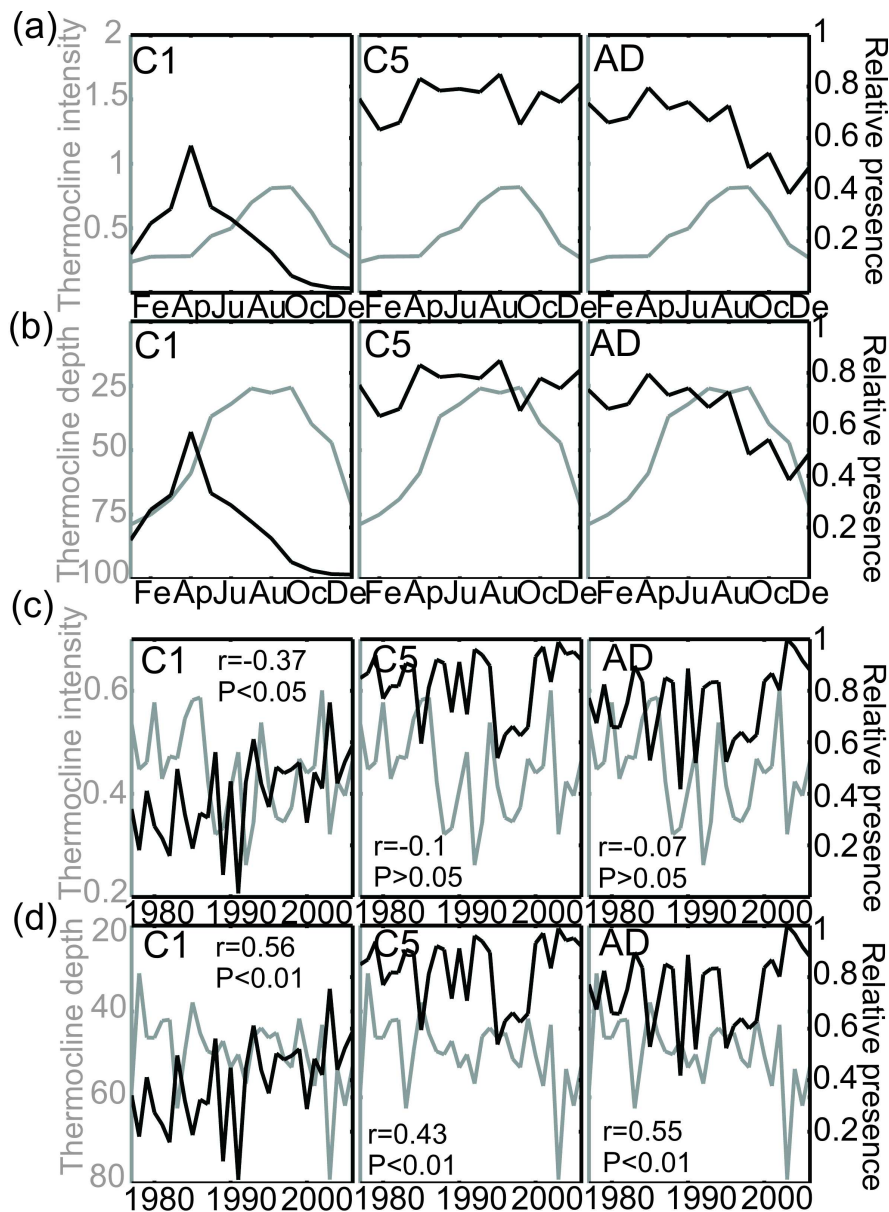


Figure 10. (a) Monthly changes in the intensity of the thermocline (in grey) and the relative presence of some copepodite stages (stages 1, 5 and adult) of *C. finmarchicus* (in black). (b) Monthly changes in the depth of the thermocline (in grey) and the relative presence of some copepodite stages (stages 1, 5 and adult) of *C. finmarchicus* (in black). (c) Year-to-year changes in the intensity of the thermocline (in grey) and the relative presence of some copepodite stages of *C. finmarchicus* (black). The correlation and its probability are superimposed. (d) Year-to-year changes in the depth of the thermocline (in grey) and the relative presence of some copepodite stages of *C. finmarchicus* (black). The correlation and its probability are superimposed.

199x271mm (300 x 300 DPI)

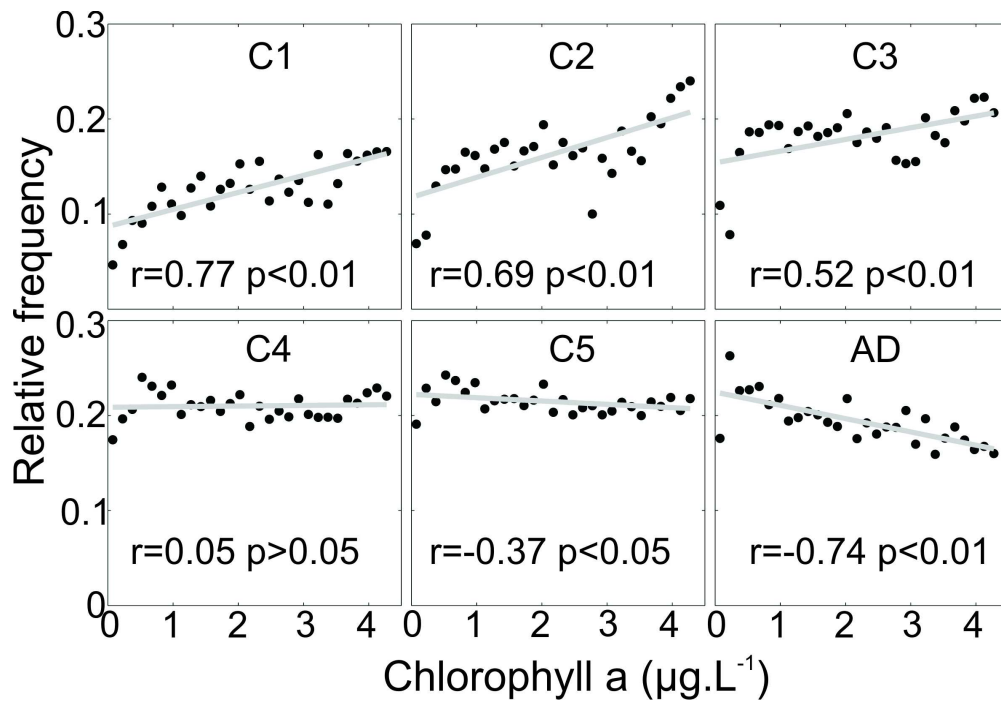


Figure 11. Macroecological relationships between the relative frequency of copepodite stages and adults of *C. finmarchicus* and the concentration in chlorophyll a. The correlation and its probability are superimposed on each panel.

200x138mm (300 x 300 DPI)



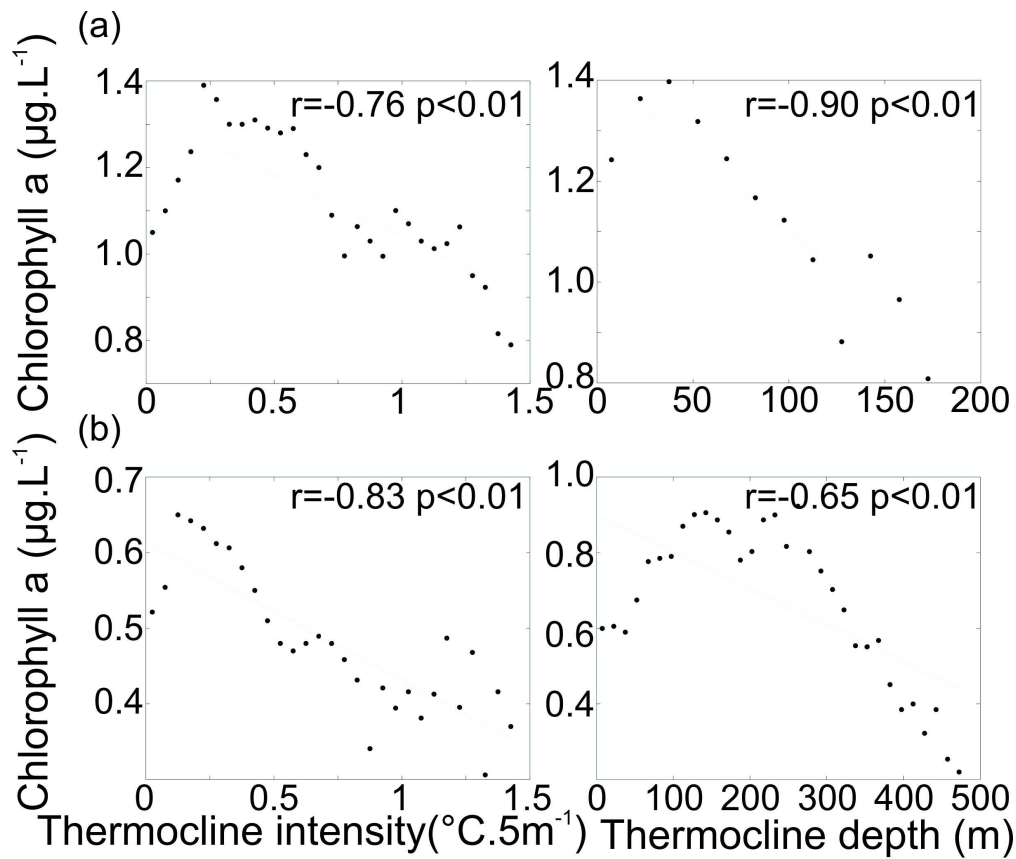


Figure 12. Macroecological relationships between both the intensity and the depth of the thermocline and the concentration in chlorophyll a in (a) neritic regions and (b) oceanic regions. The correlation and its probability are superimposed on each panel.

205x173mm (300 x 300 DPI)

source	reference depth	definition
Defant (1961)	$\Delta Z = 1\text{m}$	$\Delta T / \Delta Z = 0.015^\circ\text{C m}^{-1}$
Thomson (1976)	$Z = 0\text{m}$	$\Delta T = 0.2^\circ\text{C}$
Levitus (1982)	$Z = 0\text{ m}$	$\Delta T = 0.5^\circ\text{C}$
Lamb (1984)	$Z = 0\text{m}$	$\Delta T = 1.0^\circ\text{C}$
Martin (1985)	$Z = 0\text{m}$	$\Delta T = 0.1^\circ\text{C}$
Price et al. (1986)	$Z = 0\text{m}$	$\Delta T = 0.5^\circ\text{C}$
Sprintall and Tomczack (1990)	$Z = 0\text{ m}$	$\Delta T = 0.5^\circ\text{C}$
Wijffels et al. (1994)	$\Delta Z = 2.5\text{ m}$	$\partial\sigma_\theta / \partial z = 0.01\text{ kg.m}^{-4}$
Weller and Plueddemann (1996)	$Z = 10\text{ m}$	$\Delta\sigma_\theta = 0.15\text{ kg m}^{-3}$
Wagner (1996)	$Z = 0\text{m}$	$\Delta T = 1.0^\circ\text{C}$
Obata et al. (1996)	$Z = 0\text{m}$	$\Delta T = 0.5^\circ\text{C}$
Monterey and Levitus (1997)	$Z = 0\text{m}$	$\Delta T = 0.5^\circ\text{C}$
Kara et al. (2000)	$Z = 10\text{m}$	$\Delta T = 0.8^\circ\text{C}$
De Boyer Montégut et al. (2004)	$Z = 10\text{ m}$	$\Delta T = 0.2^\circ\text{C}$

Table 1.

Data base	Year	Study area	Mesh type	Mesh ( $\mu\text{m}$ )	Sample type
Trans Atlantic Study on <i>C. finmarchicus</i> (T.A.S.C)	1995 - 1998	32°W to 14,63°E and from 56,66°N to 72,52°N	PUP	68, 96 ,200	horizontal
			NANSEN	150	vertical
			Multinett	150, 180,200	stratified
			PUMP IFM	150	horizontal
			WPII	200	vertical
			MOCNESS	180,200	oblique
			ARIES	68, 200	stratified
			Bongo	200	oblique
U.S George Bank program	1995 - 2000	69,76°W to 65,64°W and from 40,27°N to 44,11°N	PUMP	35, 50	horizontal
			D35	35	stratified
			MOCNESS	150,333	oblique
			BONGO	200,333	oblique
Norwestlant	1963 - 1963	60,216°W to 21,91°W and from 51,73°N to 68,95°N	Hensen	333	vertical
Irminguer Sea campagne	2001 - 2002	42,29°W to 9,48°W and from 54,0°N to 65,34°N	ARIES	200	stratified
Labrador sea campagne	1997 - 2002	63,46°W to 44°W and from 42,53°N to 63,42°N	ARIES	200	stratified
India station	1971 - 1975	19°W and 59°N	Juday-Bogorov	330	vertical
U.S Northeast continental shelf bongo survey	1977 - 2006	81,13°W to 65,24°W and from 27,23°N to 44,77°N	BONGO	333	oblique

Supplementary table 1.