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Seasonal Variation in the Physical Characteristics of the Copepod *Calanus finmarchicus* (Gunnerus) Along the North Atlantic

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Abstract: Physical oceanographic changes such as the North Atlantic Oscillation, which manifested in the 1990s, are said to affect the seasonal/stage dependent, vertical migrations and life cycle of *Calanus finmarchicus*. C4-C6 stages of *C. finmarchicus* collected during spring and summer in 2002 from the Irminger Sea, Greenland Sea, Iceland shelf and the Raykjanes Ridge were analysed microscopically for their prosome and total body lengths and gravimetrically for dry weights. Dry weight ranged from 60 µg individual⁻¹ in C4 to 326.6 µg individual⁻¹ in C6 stages. Total body lengths showed an increase with sample stage and season (2.10 mm in spring C4 to 3.39 mm in summer C6). Prosome lengths varied with stages and season showing small C4 stages with mean prosome lengths of 1.8 mm to larger female C6 with mean prosome lengths measuring up to 2.8 mm.

Key words: Body lengths, dry weights, *Calanus finmarchicus*, North Atlantic

INTRODUCTION

In recent times, there has been a decrease in the world's total fish supply per capita from 14.6 kg in 1987 to 13.1 kg in 2000 (FAO, 2004). This decrease is linked to environmental factors like the oscillations in 1994-1998 (e.g., *el-Nino*), as well as climatic changes, which affects the oceanic ecosystem. It is being recognised that sustainable use of the world's living aquatic resources can only be achieved if both the impacts of the ecosystem on the living resources and the impacts of the fishery on the ecosystem are explicitly identified and as far as possible understood. A simple linear feeding relationship (food chain) in the pelagic foodweb starts from the phytoplankton (diatoms, dinoflagellate), which are fed upon by the mesozooplankton (crustaceans etc.), which are further fed upon by the cetaceans (Shiel *et al.*, 2006).

The abundance of phytoplankton depends on the availability of nutrients and the water chemistry, which is affected by precipitation and flow of water, likewise the abundance or otherwise of commercially exploited fish is often linked to the availability of zooplankton, which they feed on. Hence, zooplankton are a critical link in the oceanic food chain. They transfer energy generated by phytoplankton to the higher trophic levels such as those of the commercially exploited fish (Burkhill *et al.*, 1995; NERC, 2004; Shiel *et al.*, 2006).

The calanoid copepod *Calanus finmarchicus* (Gunnerus) at times constitutes 70-80% of the zooplankton population biomass in the North Atlantic and is an important link in the food web between primary producers and many of the commercially exploited fish species around the North Atlantic (Heath *et al.*, 2000; Edvardsen *et al.*, 2006). According to Macauley *et al.* (1995) and Sundby (2000), *C. finmarchicus* is the main source of secondary energy to about 40-60,000 tons of red fish (*Sebastes mentella*), Baleen whales, squid and salmon. *C. finmarchicus* lifecycles and population dynamics interact with the physical oceanographic system they inhabit. The physical oceanography in the Irminger Sea has exhibited clear changes due to the North Atlantic oscillation index (Parsons and Lalli, 1998).

The Irminger and Labrador Seas are loci of high secondary production, which supports the major North Atlantic fisheries. Effects of the North Atlantic Oscillation Index (NAO), which manifest in the 1990s is said to affect fish stock, which depends mainly on the copepod *C. finmarchicus* as source of secondary production in the food web. It is being hypothesized that *C. finmarchicus* are sensitive to physical oceanographic changes, thus affecting their seasonal/stage-dependent, vertical migrations and life cycle.

This research was aimed at understanding how physical features like weight; prosome and total body

lengths in the zooplankton *C. finmarchicus* which are the main food for the commercially exploited fishes in the North Atlantic vary between depths and season which in turn affects the fish stock. This study was part of a research to investigate the changes in the study area after the *el-nino* in the 1990's.

MATERIALS AND METHODS

Sample collection: Zooplankton (*C. finmarchicus*) were collected during the discovery research vessel cruise between the months of April-May and July-August covering Spring and Summer in 2002 from the Irminger Sea, Greenland Sea, Iceland Shelf and Raykjanes ridge in the North Atlantic (Fig. 1). *C. finmarchicus* were collected using the Antarctic Reception Imagery for Environmental Studies (ARIES) sampling net with a mesh size of 200 μ m (Dunn *et al.*, 1993). Once on board the samples of *C. finmarchicus* were picked out immediately from the ARIES nets, sorted into sampling depth, stages of development i.e., copepodite stages 4, 5 and 6 and sex in sets of 10 over ice with a stereo dissecting microscope and then stored in cryo-vials flushed with nitrogen and immersed in liquid nitrogen. On return to shore the cryo-vials were stored in cryo-freezers (-170°C) until required for analysis (Webster *et al.*, 2006).

Measurement of total body and prosome length: Vials containing copepods are retrieved from cryo-freezers and allowed to thaw to refrigeration temperature gently over a period of 24 h. Five copepods were selected and placed onto 30 mm tin discs (Elemental Microanalysis Limited UK cat. No. D1066) which were solvent rinsed with Dichloromethane (DCM) followed by methanol using an entomology featherweight forceps (Bio Quip No. 4748). Tin discs containing copepods were transferred carefully into compartmentalised Petri dishes (Sterilin UK).

Determination of prosome and total body length: Vials containing copepods were retrieved from the cryo-store and allowed to thaw to refrigeration temperature gently over a period of 24 h. Solvent rinsed tin discs (30 mm) from elemental Microanalysis Limited (Ltd.), catalogue number D1066 were weighed and the weights in mg recorded; discs were then transferred to clean pre-labelled segmented Petri dishes. Approximately five copepods from each sample were transferred using a feather weight entomology forceps into the Petri dishes. This was then examined under the $\times 25$ objective of a stereomicroscope. Prosome and total body length for each copepod were measured using an eye piece graticule and recorded in eyepiece unit (EPU) and later converted to mm using the

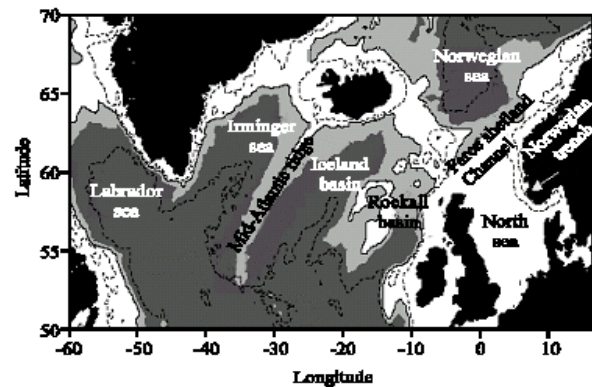


Fig. 1: Map showing the sampling areas covering the Irminger, Labrador, Norwegian Seas and Iceland Rockall basins with the Mid-Atlantic Ridge. Grey dashed contour, 250 m isobaths; black dashed contour, 3000 m isobaths, light grey shading, 1000-2000 m depth interval; dark grey shading, >2000 m depth

expression $\text{EPU} \times 0.0392 = \text{length in mm}$. This procedure was conducted in a controlled temperature room at $4-10^{\circ}\text{C}$.

Dry weight determination: The dry weights of individual copepods were determined gravimetrically following the method described by Ohman (1997) and modified for *C. finmarchicus* by Webster *et al.* (2006). Only intact animals were used and these were blotted against tissue to remove any excess water. Segmented Petri dishes containing pre-weighed tin discs with the individual copepods samples were transferred into drying oven set at 60°C . Samples were allowed to dry for 24 h, after which they are removed and allowed to cool to room temperature. The tin discs were reweighed and the dry weight calculated for each individual copepod expressed in μg per individual.

To prevent contamination gloves were worn throughout the analytical procedure and all ancillary equipments were solvent washed in DCM and iso-hexane, with the latter being allowed to evaporate before proceeding. Procedural blanks were also treated in the same way as samples and where necessary, accounted for in the results.

RESULTS

Prosome lengths: Mean prosome lengths (mm) are shown in Fig. 2 and 3 with relation to sample stage and sampling zones in summer and spring respectively. Along the study, area in summer (Fig. 2) females had the longest

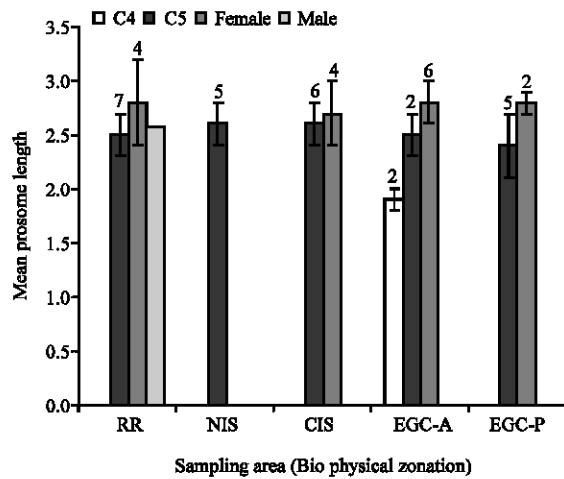


Fig. 2: Mean prosome length in C4, C5, C6 (females and males) stages in *C. finmarchicus* in summer along the sampling zones. Error bars represent ± 1 standard deviation from mean, numbers on bars represents number of measurements. RR = Raykjanes Ridge, NIS = North Irminger Sea, CIS = Central Irminger Sea, EGC-A and P = East Greenland with currents of Atlantic and Polar origin, respectively

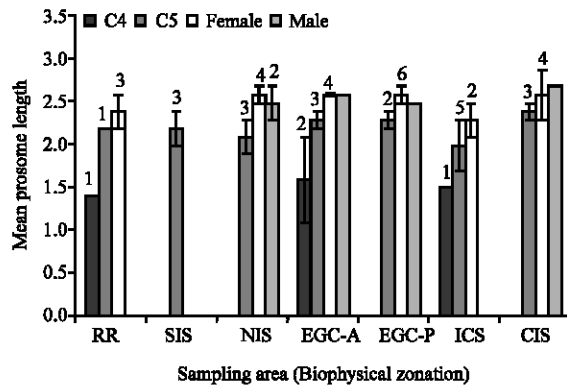


Fig. 3: Mean prosome length in C4, C5, C6 (females and males) stages in *C. finmarchicus* in spring along the sampling zones. Error bars represent ± 1 standard deviation from mean, numbers on bars represents number of measurements. RR = Raykjanes Ridge, NIS = North Irminger Sea, CIS = Central Irminger Sea, ICS = Iceland Shelf, EGC-A and P = East Greenland with currents of Atlantic and Polar origin, respectively

prosome length (2.7-2.8 mm). Smaller prosome lengths were observed in C4 along the East Greenland with characteristic current of Atlantic origin (EGC-A) with mean prosome 1.87 mm, the mean prosome length in C5 was 2.5 mm.

In spring (Fig. 3), the longest prosome lengths were in males found along the Central Irminger Sea (CIS) (2.7 mm), females had minimum prosome lengths of 2.3 mm in the Iceland Shelf (ICS). Much longer females, measuring 2.6 mm were found along the North Irminger Sea (NIS) Central Irminger Sea (CIS) and the East Greenland (EGC-P). *C. finmarchicus* in the CIS had the longest prosome in both C5 and C6 stages. There were no significant differences in prosome length with depth (ANOVA, $p > 0.05$), but there were significant differences in prosome length with season (ANOVA, $p < 0.05$).

Total body lengths: Table 1 shows the variation for total body lengths in mm for *C. finmarchicus* by sample stage and season. The mean total body lengths in spring C4 stage ranged from 2.12 mm in an April shallow water to 2.10 mm in May *C. finmarchicus*. There were no C4 stages collected from mid depth and deep water in spring, this was because in spring *Calanus* sp. are out of diapause and are found mainly in shallow water (Heath, 1999). In summer, C4 stages mean total body length was between 2.25 and 2.30 mm in a deep water *C. finmarchicus*. The mean total body length in C5 stages in spring from shallow water ranged from 2.58-2.80 mm. Mean total body length in C5 collected at mid depths during spring was 2.37-2.67 mm. In summer the mean body lengths for mid depth C5 stages were long (3.09 mm) and shorter in deep water (2.97 mm). In C6 stages spring samples have body lengths longer in mid depth (3.30 mm) and shorter in shallow water (2.95 mm). There was no significant difference in the total body length with depth (ANOVA, $p > 0.05$). However, total body length between sample stages exhibited a significant increasing trend with stage ($C4 < C5 < C6$; ANOVA, $p < 0.05$). This trend is expected because as the copepods develop from one stage to the other they increase in size.

Dry weights: Mean body weights are shown in Fig. 4 for sampling stage and season and Fig. 5 for sampling stage and sampling depth in $\mu\text{g individual}^{-1}$. The mean dry weight for C4 stages in spring ranged from 60.0-71.0 $\mu\text{g individual}^{-1}$ in the months of April and May from shallow water. While in summer, (July and August) the dry weight in a mid depth C4 stage was 90.0 $\mu\text{g individual}^{-1}$. Dry weights for C5 in spring shallow water ranged from 167.8-222.5 $\mu\text{g individual}^{-1}$, whereas in mid depth samples the mean dry weights were in the range 152.50-197.0 $\mu\text{g individual}^{-1}$. There were no C5 stages collected in spring from deep water. C5 *C. finmarchicus* collected in summer had mean dry weights between 197.5 $\mu\text{g individual}^{-1}$ in July up to about 254.6 $\mu\text{g individual}^{-1}$ in August. The mean dry weight in summer C5 stages collected from deep water in August was 243.0 $\mu\text{g individual}^{-1}$.

Table 1: Total body lengths in mm of *C. finmarchicus* C4, C5, C6 (females and males) presented as mean (± 1 standard deviation). Values represent averages for shallow (0-100 m) mid depth (101-1000 m) and deep (>1000 m) in April, May, July and August 2002. Dashes represent no samples collected

Depth sample stage	Shallow			Mid depth			Deep		
	C4	C5	C6	C4	C5	C6	C4	C5	C6
Total body lengths (mm)									
April (spring)	2.12 (n = 1)	2.58 \pm 0.4 (n = 4)	2.95 \pm 0.35 (n = 3)	-	2.37 (n = 1)	-	-	-	-
May (spring)	2.10 \pm 0.24 (n = 5)	2.8 \pm 0.22 (n = 7)	3.30 \pm 0.17 (n = 24)	-	2.67 \pm 0.3 (n = 7)	3.30 \pm 0.2 (n = 12)	-	-	-
July (summer)	-	2.90 \pm 0.2 (n = 4)	3.30 \pm 0.5 (n = 2)	-	2.65 \pm 0.15 (n = 2)	-	-	-	-
August (summer)	-	3.00 \pm 0.2 (n = 21)	3.13 \pm 0.34 (n = 4)	2.25 (n = 1)	3.09 \pm 0.21 (n = 36)	3.39 \pm 0.33 (n = 13)	2.30 (n = 1)	2.97 \pm 0.17 (n = 4)	3.19 \pm 0.09 (n = 4)

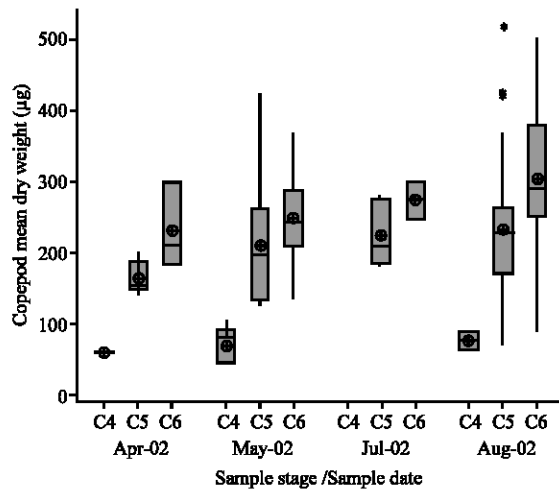


Fig. 4: Box and whisker plots of mean dry weights ($\mu\text{g individual}^{-1}$) of *C. finmarchicus* by sample stage, sampling dates (months). Circles represents the mean, horizontal lines in the centre represents the median, asterisks represent outliers (values lying 1.5 times away from the range C4, C5 and C6 represents copepodite stages in *C. finmarchicus*)

In spring, C6 females and males collected from shallow water dry weights were between 232.5-258.0 $\mu\text{g individual}^{-1}$. From mid-depth water C6 stages weighed 236.0 $\mu\text{g individual}^{-1}$. In summer, mean dry weights in shallow C6 stages were in the range 224.8-275.9 $\mu\text{g individual}^{-1}$ in the month of August and July. The mean dry weights in mid depth water for C6 in August was 326.6 $\mu\text{g individual}^{-1}$ with deep water C6 having mean dry weight up to 301.8 $\mu\text{g individual}^{-1}$. There was an observed increase in mean dry weights in all stages and sampling dates in spring (Fig. 4). In summer, there was an increase in dry weights in C5 and C6 stages. There was also an observed increase in dry weights with sampling depth (Fig. 5) for C5 and C6 stage, but not in C4 stages.

In general, variation in dry weights between sample stages, season and depth were significant (ANOVA, $p < 0.05$), with dry weights ranging from 60.0 μg

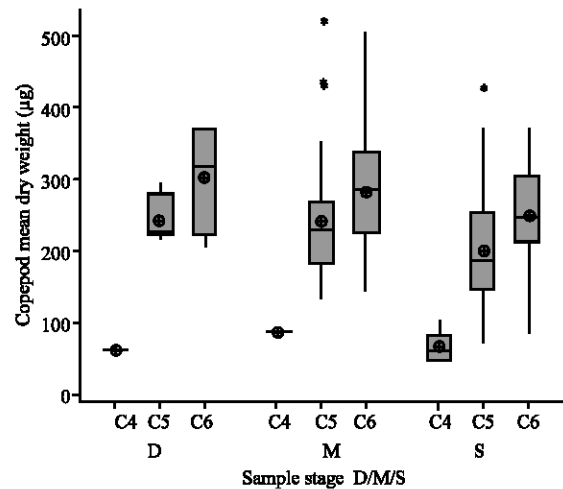


Fig. 5: Box and whisker plots of mean dry weights ($\mu\text{g individual}^{-1}$) of *C. finmarchicus* by sample stage and sampling depth. Circles represents the mean, horizontal lines in the centre represents the median, asterisks represent outliers (values lying 1.5 times away from the range), D, M and S stands for Deep (>1000 m), Mid depth (101-1000 m), Shallow (0-100 m) water layer, C4, C5 and C6 represents copepodite stages in *C. finmarchicus*

individual $^{-1}$ in C4 stages from shallow water in spring to 326.6 $\mu\text{g individual}^{-1}$ in C6 females from mid depth water in summer.

DISCUSSION

Prosome lengths in C4 stages found in this study fell within the ranges reported by Knutsen *et al.* (2001) when studying the mass density of marine copepods and their eggs in spring along the west coast of Norway, with reported range of 1.0-1.7 mm. However, longer prosome lengths in C5 stages of *C. finmarchicus* were previously reported by Knutsen *et al.* (2001) and Conway (2006) measuring up to 2.53 mm. This variation could be due to differences in the study area and or the sampling method

used, as Knutsen *et al.* (2001) used the Isaac-Kidd mid water Trawl (IKMT) which is use to collect samples from shallow waters. While the ARIES deep-water sampler was used for this study, which can sample up to depths deeper than 1000 m. Miller *et al.* (2000) reported prosome lengths in *C. finmarchicus* ranging from 1.9-2.7 mm in C5 stages which tallies with the findings here while studying the variability of oil storage along the Georges Bank using the MOCNESS hauls.

Prosome lengths in this study varied with season but not with sampling depth along the study area. This shows that copepod of the same stage are found within the same layer or depth (shallow, mid-depth and deep) further proving that the copepods ready to overwinter (diapause) in their C5 stages are likely to have longer prosome confirming Heath (1999) findings that they may be preparing to go into diapause to complete the life cycle later in spring.

Results obtained for total body lengths were slightly higher than the range of 1.0-3.0 mm reported by Dürbaum and Kunnerman (2004) and 1.6-2.70 mm documented for *C. finmarchicus* in Conway (2006). Klein (1982) also reported a total length of between 2.31-3.08 mm while studying *C. helgolandicus* (Claus) in the Celtic sea; *Undimula vulgaris* (Dana) from the Indian Ocean measured by Sewell (1929) were in the range of 1.43-3.14 mm. The longest individual in this study was a C6 from deep water in an August sample showing the longest lengths ever reported for *C. finmarchicus*, hence hypothesising that preference of this copepod to other zooplankton by marine fishes could be because of it sizes and its lipids reserves when coming out of diapause to complete the life cycle as suggested in Webster *et al.* (2006).

The results obtained for mean dry weights exhibited similar trends of an increase in dry weights with depths and stages of development as described by Mayzaud *et al.* (1998) while studying over wintering *C. sinmilimus* along the Atlantic Ocean. Jónasdóttir (1999) also observed an increase in dry weights in over wintering C5 stages of *C. finmarchicus* along the Faroe-Shetland between the upper 400 m and deep 400-1000 m. Dry weights between sample stages; season and depth were significant with dry weights ranging from 60.0-326.6 $\mu\text{g individual}^{-1}$ in C6 summer samples. This suggests an increase in weight with accumulation of lipid reserves in readiness for diapause and upon coming out of diapause in C6 before lipid reserves are utilised for other physiological activities. Yusuf (2004) reported the composition of lipid reserves (wax esters and triglycerides) in *C. finmarchicus* different life cycle (C4-C6) stages to be between 0.27-80.0% of their body weights.

Because of the importance of *C. finmarchicus* in a marine ecosystem it is therefore important to know how physical features like prosome and total body weights changes with season and depth. These and factors like the physical properties of the water could have influences on the behaviour of this copepod, most especially in their accumulation of lipid reserves prior to entering diapause stages in winter. Another assumption could be that, these physical features also help the copepod in determining the time and stage of the life cycle to enter diapause for the completion of the life cycle. This could be evident because not all stages enter into diapause as not all could accumulate enough lipids reserves to enter diapause. Hence it is evident that seasonal and diurnal variations affect the physical characteristics of *C. finmarchicus* and this in turn might affect fishes who prey upon this important copepod, thus reducing fish production in marine habitats.

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