The North Atlantic Ocean as habitat for *Calanus finmarchicus*: Environmental factors and life history traits

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**A B S T R A C T**

Here we present a new, pan-Atlantic compilation and analysis of data on *Calanus finmarchicus* abundance, demography, dormancy, egg production and mortality in relation to basin-scale patterns of temperature, phytoplankton biomass, circulation and other environmental characteristics in the context of understanding factors determining the distribution and abundance of *C. finmarchicus* across its North Atlantic habitat. A number of themes emerge: (1) the south-to-north transport of plankton in the northeast Atlantic contrasts with north-to-south transport in the western North Atlantic, which has implications for understanding population responses of *C. finmarchicus* to climate forcing, (2) recruitment to the youngest copepodite stages occurs during or just after the phytoplankton bloom in the east whereas it occurs after the bloom at many western sites, with up to 3.5 months difference in recruitment timing, (3) the deep basin and gyre of the southern Norwegian Sea is the centre of production and overwintering of *C. finmarchicus*, upon which the surrounding waters depend, whereas, in the Labrador/Irminger Seas production mainly occurs along the margins, such that the deep basins serve as collection areas and refugia for the overwintering populations, rather than as centres of production, (4) the western North Atlantic marginal seas have an important role in sustaining high *C. finmarchicus* abundance on the nearby coastal shelves, (5) differences in mean temperature and chlorophyll concentration between the western and eastern North Atlantic are reflected in regional differences in female body size and egg production, (6) regional differences in functional responses of egg production rate may reflect genetic differences between western and eastern populations, (7) dormancy duration is generally shorter in the deep waters adjacent to the lower latitude western North Atlantic shelves than in the east, (8) there are differences in stage-specific daily mortality rates between eastern and western shelves and basins, but the survival trajectories for cohort development from CI to CV are similar, and (9) early life stage survival is much lower in regions where *C. finmarchicus* is found with its congeners, *C. glacialis* and/or *C. hyperboreus*. This compilation and analysis provides new knowledge for evaluation and parameterisation of population models of...
Introduction

The northern North Atlantic Ocean is characterised by its circulation and water mass distribution, its extensive latitudinal expanse (from roughly 40 to 75°N) and topography, and its seasonally and geographically varying wide ranges of temperature, salinity and light conditions, which provide a variety of habitats for its biota. Regional differences in physical features lead to differences in the timing and intensity of the annual cycles of primary production, and in the distributions, abundances and seasonal cycles of planktonic grazers and their predators. The distribution of any zooplankton species in the North Atlantic is the manifestation of its ability to maintain itself within this range of conditions, from sub-optimal to optimal, that constitute its habitat.

One approach to understanding the distribution of a species is to examine and define its ecological niche in terms of its range of tolerance based on a series of environmental factors (e.g. Helaouët and Beaugrand, 2009). Advances in statistical and numerical techniques, such as generalised linear models (GLM) and geographic information systems (GIS), have been applied to quantify species distributions, in species distribution models (Elith and Leathwick, 2009), habitat distribution models (Guisan and Zimmermann, 2000) and habitat suitability models (e.g. Hirzel et al., 2002). Extrapolation to future distribution patterns resulting from habitat change, however, confronts the statistical and ecological assumptions of these models (Elith and Leathwick, 2009). To gain predictive insight into the consequences of habitat change on the abundance of a species and on shifts in its range and biogeographic boundaries, it is also necessary to understand, at the species level, processes determining population dynamics and life history in relation to environmental changes that affect both physiological and behavioural responses to changes in environmental conditions. Our overall objective is to provide parameter values and new knowledge of C. finmarchicus life history characteristics on a North Atlantic basin scale and, thus to further the development of habitat and basin-scale dynamic models that can be used to predict the effects of climate change on C. finmarchicus populations.

The North Atlantic habitat

Ocean circulation is fundamental to the dynamics of a planktonic species’ habitat. The North Atlantic surface circulation system is made up of a series of gyres, encircled by strong boundary currents (Fig. 1a). In the west, the Northwest Atlantic Subpolar Gyre, commonly referred to as the Subpolar Gyre, includes the Labrador and Irminger Seas and is defined by bathymetry to the north and the North Atlantic Current to the south. In the east, the Southern Norwegian Sea Gyre, a cyclonic gyre over the Norwegian Basin of the southern Norwegian Sea, is bounded by bathymetry to the north and by the North Atlantic Current to the south. These two gyres are interconnected, however, and together can be regarded as one basin-scale North Atlantic Subpolar Gyre system, throughout which organisms, including plankton, can be broadly distributed over appropriate time scales, but which nevertheless shows regional differences in ecological characteristics due to the responses of individual species to local conditions.

The Gulf Stream System transports warm and saline water from west to east in the North Atlantic at a latitude of about 40°N in the west (e.g. Reverdin et al., 2003). At about 54°W, the Gulf Stream splits into two branches, a northern branch connected to the North Atlantic Current and a southern branch connected to the Azores Current. The Azores Current and the southward flowing Canary Current limit the Subtropical Gyre to the north and east. The North Atlantic Current flows to the northeast, with branches flowing into the Icelandic basin and Irminger Sea before the main body enters the Norwegian Sea as the Norwegian Atlantic Current. Thus, the Northeast Atlantic is strongly influenced by northward flowing warm and saline water. Warmer water of Atlantic origin also circulates clockwise around Iceland. Cold Arctic water enters the system from the Arctic Ocean through the Fram Strait as the East Greenland Current and east of Baffin Island as the Baffin Island Current. North of Iceland, the East Icelandic Current separates from the East

C. finmarchicus and their responses to climate change in the North Atlantic. The strengths and weaknesses of modeling approaches, including a statistical approach based on ecological niche theory and a dynamical approach based on knowledge of spatial population dynamics and life history, are discussed, as well as needs for further research.

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Greenland Current, bringing Arctic water eastward into the western Norwegian Sea. The East Greenland Current itself continues southward and meets the warmer Atlantic water of the Irminger Current, with both turning around the southern tip of Greenland and entering the Labrador Sea. This northwesterly flow has a cold water shelf component (the West Greenland Current) and a warmer, deeper offshore component (identified as the Irminger Current), which provides a major warm water input to the Labrador Sea. The main sources of water to the Labrador Shelf and Slope are the outflows from the Arctic via Hudson Strait and the Baffin Island Current, and the branch of the slope water current that follows the bathymetry westward across the mouth of Davis Strait. These water masses mix off Hudson Strait together forming the inshore (shelf) and offshore (slope) branches of the Labrador
Current moving southwards. Part of the inshore branch enters the Gulf of St. Lawrence through the Strait of Belle Isle, and part continues on to the Newfoundland Shelf and turns around the southeast tip of Newfoundland. A substantial portion of the offshore branch turns to the northeast at the Tail of the Grand Bank to join the North Atlantic Current, but a portion also flows around the Tail of the Grand Bank and along the edge of the Scotian Shelf and Georges Bank (Fratantoni and MacCartney, 2010; Loder et al., 1998). Cross-shelf transport of slope water at the Laurentian Channel, Scotian Gulf, and Northeast Channel influences the deep water properties of the Gulf of St. Lawrence, western Scotian Shelf, and Gulf of Maine, and variability in the slope water source, e.g. cold Labrador Slope water vs. warm Atlantic slope water, can drive substantial changes in deep water temperatures on the western Scotian shelf and in the northwest Atlantic marginal seas (Bugden, 1991; Petrie and Drinkwater, 1993; Gilbert et al., 2005). Cross-shelf transport of slope water at the Laurentian Channel, Scotian Gulf, and Northeast Channel influences the deep water properties of the Gulf of St. Lawrence, western Scotian Shelf, and Gulf of Maine, and variability in the slope water source, e.g. cold Labrador Slope water vs. warm Atlantic slope water, can drive substantial changes in deep water temperatures on the western Scotian shelf and in the northwest Atlantic marginal seas (Fratantoni and MacCartney, 2010; Loder et al., 1998). Cross-shelf transport of slope water at the Laurentian Channel, Scotian Gulf, and Northeast Channel influences the deep water properties of the Gulf of St. Lawrence, western Scotian Shelf, and Gulf of Maine, and variability in the slope water source, e.g. cold Labrador Slope water vs. warm Atlantic slope water, can drive substantial changes in deep water temperatures on the western Scotian shelf and in the northwest Atlantic marginal seas (Fratantoni and MacCartney, 2010; Loder et al., 1998).

In contrast to the northeast Atlantic, the western Atlantic shelf and slope waters are therefore strongly influenced by southerly flowing cold and low salinity water of Arctic origin. As we discuss later, this contrast in physical regime has implications for understanding east–west differences in effects of climate forcing on species distribution.

The topography of the North Atlantic is characterised by several deep basins: the Labrador Sea basin, the Iceland basin and Irminger Sea, the Norwegian Sea basin in the southern Norwegian Sea, the Lofoten basin in the Northern Norwegian Sea and the Greenland Sea basin. More or less well defined cyclonic gyres are located over these deep basins, which thus offer reduced dispersal for animals within the gyres and possibilities for deep overwintering or deep diurnal migration. In addition to these deep basins are the Norwegian deep fjords (up to 1300 m deep) and basins or troughs (200–400 m depth) in the northwest Atlantic marginal seas (Gulf of Maine and Gulf of St. Lawrence).

The geographical pattern of sea surface temperature (SST) in the North Atlantic is strongly related to light conditions and SST, but also to nutrient supply, and to mechanisms of water column vertical stabilisation and grazing. The northeast Atlantic is a typical spring bloom system, although the seasonal cycle of PP differs between deep basins and shelves. In the deep Norwegian Sea basin the pattern of seasonal phytoplankton production has been shown to comply with Sverdrup’s concept of critical depth (Sverdrup, 1953), although newer publications indicate that the controlling mechanisms may be more complex or at least regionally different (e.g. Behrenfeld, 2010; Mahavedan et al., 2012). According to the critical depth concept, production will occur when the mixing depth of algal cells is less than a critical depth such that net production is positive. This usually occurs in March–April and the bloom starts in May–June when the pycnocline approaches the upper 30–40 m (Rey, 2004; Bagoeien et al., 2012; Zhai et al., 2012). The timing of the bloom may vary by more than a month among years (Rey, 2004) and the chlorophyll concentration of the upper mixed layer is on average less than 3 mg m$^{-3}$ (Bagoeien et al., 2012). On the Norwegian shelf the water column is permanently stratified by a near surface layer of fresh (light) coastal water or is restricted by shallow bottom depths, so that pre-bloom production and

![Fig. 2](image-url) (A) Annual average sea surface temperature (SST: °C). (B) Annual average phytoplankton colour index from Continuous Plankton Recorder data collected between 2000–2009.
blooms tend to start earlier and to some extent are more intense, providing relatively high chlorophyll concentrations in the water column (Rey, 2004). During the bloom diatoms are the main algal group (Rey, 2004). The post-bloom period lasts until September and is characterised by flagellates, utilising re-cycled nutrients. It has been suggested that pre-bloom levels of phytoplankton are lower than might be expected in the Norwegian Sea due to the grazing activity of the large overwintering population of *C. finmarchicus*, which returns to the surface at this time, and that the intensity of the spring bloom itself is kept low by grazing by the offspring of the overwintered *C. finmarchicus* (Rey, 2004).

In the Irminger Sea, spatial variability in the timing and magnitude of the spring bloom is considerable, reflecting differences in the seasonal timing of stratification of the surface waters (Henson et al., 2006; Waniek and Holliday, 2006; Gudmundsson et al., 2009; Mahavedan et al., 2012; Zhai et al., 2012). On the Iceland and Greenland shelves fringing the Irminger Sea, the growth of phytoplankton usually starts in late April culminating in June and July, whereas in the central region of the Irminger Sea growth usually starts in early May with a maximum in June. As in the northeast Atlantic, timing of the start of the bloom is patchy and may vary interannually by as much as one month, influenced by storms and mixed layer eddy restratification (Mahavedan et al., 2012).

In the northwest Atlantic regions, the timing of spring bloom initiation generally varies with latitude, but there can be substantial departures from this trend among shelf areas due to local or regional processes (O'Reilly and Zetlin, 1998; Platt et al., 2010). Spring and fall blooms tend to start earlier in shallow water, and spring blooms tend to be longer in shallow water (O'Reilly et al., 1987). Interannual variability in bloom timing can be high in the northwest Atlantic (Thomas et al., 2003; Platt et al., 2010). In the Gulf of Maine/Georges Bank region, the spring bloom starts earliest in the shallow coastal areas (January–March), later over Georges Bank (March–April), and latest in the deep basins of the Gulf of Maine and off the shelf edge (April–May) (O'Reilly et al., 1987). On the western and eastern Scotian Shelf, the spring bloom starts in March or April and peaks after about a month, while in the Scotian Slope waters it starts in February or March and peaks in May (Zhai et al., 2011). In the Gulf of St. Lawrence, the spring bloom is earlier in the northeast and southern Gulf (April–May) than in the lower St. Lawrence Estuary (June–July) (reviewed by Zhi-Ping et al., 2010). On the Grand Bank and Flemish Cap, the spring bloom starts in late March or April and peaks after about a month, while on the Labrador Shelf it starts in May (Fuentes-Yaco et al., 2007). The spring bloom starts relatively late (April–June) in the central Labrador Sea, but slightly earlier (April–May) in the northern Labrador Sea, where early stratification is driven by offshore flow of relatively freshwater from the West Greenland Shlef (Frajka-William and Rhines, 2010). Estimates of annual primary production from satellite ocean colour and temperature from 1998–2004 indicate that the highest offshore production in the northwest Atlantic occurs on Georges Bank and in the outflow from the Hudson Strait (ca. 275–325 gC m$^{-2}$ y$^{-1}$), while the lowest production occurs in the Labrador slope waters (ca. 150 gC m$^{-2}$ y$^{-1}$) and southern Labrador Sea (ca. 175–200 gC m$^{-2}$ y$^{-1}$) (Carla Caverhill, pers. comm., Platt et al., 2008).

*Calanus finmarchicus*

The copepod *C. finmarchicus* is the main contributor to mesozooplankton biomass throughout the North Atlantic. Population centres, defined as regions where overwintering populations exceed 15,000 m$^{-2}$, have been identified in the Labrador Sea, northern Irminger Basin, northern Iceland Basin, Faroe-Shetland Channel, eastern Norwegian Sea and Norwegian Trench (Heath et al., 2004). Based on this criterion, slope waters off the Grand Bank of Newfoundland, the Laurentian Channel of the Gulf of Saint Lawrence, deep basins in the Gulf of Maine, and slope waters of the western Scotian Shelf are also population centres (Plourde et al., 2001; Head and Pepin, 2008; Maps et al., 2012). *C. finmarchicus* makes up >80% of large copepods by abundance in the central Labrador Sea in spring and summer (Head et al., 2003, sampled with a 200 μm mesh net, which in this cold region catches all *Calanus* copepodite stages), about 40–70% of the mesozooplankton community on Flemish Cap, east of the Grand Bank of Newfoundland (Anderson, 1990, sampled with 333–505 μm mesh nets, which excludes the youngest copepodite stages as well as smaller copepod species), and 40–90% of the zooplankton community by abundance in waters around Iceland in summer (Gislason and Astthorsson, 2000, sampled with a 200-μm mesh net which here excludes some of the smaller stages). There are apparently two major overwintering areas, which serve as population reservoirs and distribution centres, in the two subpolar gyres; one in the Labrador/Irminger Seas and the other in the southern Norwegian Sea (Conover, 1988; Planque et al., 1997; Head et al., 2003; Melle et al., 2004; Heath et al., 2008, Broms et al., 2009). These cyclonic gyres are centred over deep ocean basins, so that they can retain populations as they are overwintering at depth, a necessity for *C. finmarchicus* to close its life cycle both spatially and inter-annually (Heath et al., 2004, 2008). From these distribution centres *C. finmarchicus* is transported to the surrounding shelves and shallow seas (e.g. the Labrador, Newfoundland shelves; North and Barents seas) and ultimately to more distant regions (e.g. Scotian Shelf, Gulf of Maine) (Speirs et al., 2006; Heath et al., 2008). There is evidence from genetic analysis that there are two to four distinct *C. finmarchicus* populations, with greatest differences occurring between the northwest-central North Atlantic and northeast Atlantic (Oulad and Bucklin, 2010). Toward the Arctic domain, *C. finmarchicus* co-occurs with its larger congeners, *C. hyperboreus* and *C. glacialis*, while in the southeast it co-occurs with the temperate water species, *C. helgolandicus* (Conover, 1988; Hirche, 1991; Head et al., 2003; Melle et al., 2004; Bonnet et al., 2005; Hop et al., 2006; Broms et al., 2009).

Throughout its biogeographic range, *C. finmarchicus* is a dominant grazer and the main prey for numerous planktivorous fish, including herring, mackerel, capelin and young blue whiting and salmon (e.g. Dalpadado et al., 2000; Darbyson et al., 2003; Domnasnes et al., 2004; Skjoldal, 2004; Overholtz and Link, 2007; Smith and Link, 2010; Langley et al., 2012). The larvae of many fish species also feed, sometimes almost exclusively, on the eggs and nauplii of *C. finmarchicus*, and copepodite stages are important food for the juvenile fish in shelf and shallow sea nursery areas (Runge and de Lafontaine, 1996; Heath and Lough, 2007).

During its life cycle from egg to adult (females, CV1 to NI–NVI and five copepodite stages (CI–CV)). The first two naupliar stages do not feed. The life cycle of *C. finmarchicus* is annual in its main distributional area (Conover, 1988; Heath et al., 2000a, 2008; Irigoien, 2000; Hirche et al., 2001; McLaren et al., 2001; Broms et al., 2009; Bagoeien et al., 2012; Head et al., 2013b). In regions influenced by Arctic outflow, however, where water temperatures are low, development rates are reduced and young copepodes (CI–CIII) are found among the older overwintering stages (Broms and Melle, 2007; Heath et al., 2008), suggesting that there is either a multiannual life cycle or an inability to reach stages that can survive the winter within the first season, leading to expatriation (Melle and Skjoldal, 1998). Although there is only one generation per year within the main distributional area within the subpolar gyre (e.g. Labrador Sea, Northern Norwegian Sea) farther south (e.g. Georges Bank) there may be up to three generations per year (Irigoien, 2000; Hirche et al., 2001; McLaren et al., 2001; Plourde et al., 2001; Head et al., 2013b). The number of generations may...
vary among years at the same location (Irigoin, 2000) and in some areas (e.g. Newfoundland Shelf) distinct generations are not evident.

The main overwintering stage is the pre-adult CV (Conover, 1988). In the deep basins, C. finmarchicus CVs spend most of the year at depths below 400–1000 m (Heath et al., 2000b, 2004; Melle et al., 2004). In the northern Norwegian Sea, overwintering C. finmarchicus are most abundant between about 600 and 1200 m, at temperatures less than 2 °C (Edvardsen et al., 2006). In the Iceland Basin, overwintering C. finmarchicus reside between about 400 m and the bottom (>2000 m) at temperatures about 3–8 °C, while in the Inerminger Basin, they reside between about 200 and 1800 m at temperatures of 3–6 °C (Gislason and Astthorsson, 2000). In the northwest Atlantic, overwintering C. finmarchicus occupy a broad and spatially variable depth range, in temperatures ranging from 1 to 10 °C (Head and Pepin, 2008). Overwintering depths are shallowest in Gulf of Maine basins, the Laurentian Channel and in eastern Scotian slope waters (ca. 100–400 m) and deeper in western Scotian slope water (400–950 m) and in Newfoundland slope waters (400–1500 m). In the western part of the central Labrador Sea overwintering depths are variable, but generally <1000 m, while in the eastern Labrador Sea near the Greenland shelf, C. finmarchicus overwinters at greater depths, similar to those in the Inerminger Sea (Head and Pepin, 2008). Individual C. finmarchicus enter dormancy in summer and fall (Hirche, 1996a), carrying with them lipid stores that make up most of their body weight. These lipid stores sustain metabolism during overwintering and subsequent molting and partial development of gonads in mid-late winter (Rey-Rassat et al., 2002). Dormant copepodes are characterised by reduced metabolism and arrested or slowed development (Saumweber and Durbin, 2006). In many locations there is evidence that fourth stage copepodes (CIVs) enter dormancy, with higher proportions of dormant CIV copepodes observed in the northeast Atlantic than in the northwest Atlantic (Heath et al., 2004; Melle et al., 2004; Head and Pepin, 2008). The implications of CIV dormancy have not been rigorously examined, although it is unlikely that CIVs can molt to CVs without feeding since they are significantly smaller. The descent to overwintering depths at Weather Station India occurred during at least two pulses towards the end of each of two cohorts (Irigoin, 2000), whereas elsewhere individuals from different generations may descend over several months (e.g. Johnson et al., 2008).

Arousal from the winter diapause generally occurs in mid-late winter, when most CVs leave dormancy, molt into adults and mate upon returning to the surface (e.g. Melle et al., 2004). Females then lay eggs in response to food levels, for which chlorophyll a concentration is a useful proxy (Runge et al., 2006). The arctic species, Calanus hyperboreus, uses internal body stores including lipids to produce eggs without any external food supply (Conover, 1988), but the extent to which internal body stores contribute to egg production for C. finmarchicus is still unresolved. In many populations, not all CVs from the new year’s generation enter dormancy; some molt on to adulthood, so that reproduction can occur throughout the year (e.g. Durbin et al., 1997; Heath et al., 2008).

In the Norwegian Sea, studies have demonstrated that spawning occurs at relatively low food concentrations and low individual rates before the spring bloom. However, population egg production rates were higher during the pre-bloom period than during the bloom itself, due to the higher abundance of females (Niehoff et al., 1999; Richardson et al., 1999; Stenevik et al. 2007; Debes et al., 2008). Regional differences in the timing and intensity of C. finmarchicus reproduction have been observed (e.g., Plourde et al., 2001; Runge et al., 2006; Stenevik et al., 2007; Head et al., 2013a, 2013b), reflecting regional variations in the timing and intensity of spring blooms. These results are mainly based on individual studies that have usually been limited to one or a few regions; whether responses of females to environmental conditions can be generalised throughout the North Atlantic has not been addressed.

The maximum abundance of CIs of the first generation has often been observed to occur during the peak of bloom or just after (Hirche et al., 2001; Melle et al., 2004; Bagoein et al., 2012), and these CIs must have arisen from eggs spawned before the bloom. On the other hand, during the pre-bloom period, mortality rates are thought to be high due to starvation of first feeding nauplii and/or predation on eggs during the pre-bloom phase, which may include predation by the females themselves (e.g. Ohman and Hirche, 2001; Plourde et al., 2001; Heath et al., 2008). The CIs–CIIIs are found exclusively in the upper mixed layer or in the pycnocline, if a subsurface chlorophyll maximum develops during the post-bloom phase (Melle and Skjoldal, 1989; Irigoien, 2000; Melle et al., 2004).

Mortality and survival are key parameters in C. finmarchicus population dynamics. In the early stages (eggs, nauplii) they are especially important in determining overall recruitment success (i.e., Ohman and Hirche, 2001; Ohman et al., 2002; Plourde et al., 2009b). Survivorship of C. finmarchicus is mainly governed by temperature, food availability and/or con-specific abundance, which results in marked seasonal and regional differences in stage-specific mortality patterns (Ohman and Hirche, 2001; Ohman et al., 2002, 2004; Heath et al., 2008; Plourde et al., 2009b). In the northwest Atlantic, the integration of stage-specific daily mortality rates over the entire cohort developmental period revealed significant differences in survival trajectories among seasons and sub-areas, associated with differences in environmental conditions (Plourde et al., 2009b). The use of mortality formulations corresponding to different sets of environmental conditions have enabled modeling of region-specific C. finmarchicus population dynamics, a significant step forward in basin-wide biological modeling for the species (Runge et al., 2005; Neuheimer et al., 2010; Maps et al., 2010, 2011).

In the Norwegian Sea studies of predation mortality for C. finmarchicus copepode stages have been conducted to evaluate feeding conditions for pelagic fish stocks and to investigate top down versus bottom up processes in the ecosystem. Analysis of stomach samples have shown herring, mackerel and young blue whiting to be important predators on C. finmarchicus copepodes (Dalpadado et al., 2000; Gislason and Astthorsson, 2002; Prokopchuk and Sentyabov, 2006). Consumption by herring has been estimated at about 20–100% of the annual C. finmarchicus production (Dommasnes et al., 2004; Skjoldal et al., 2004; Utne et al., 2012). Other potential predatory taxa in the Norwegian Sea are krill, amphipods, ctenidians, chaetognaths, large copepods and mesopelagic fishes. For these taxa reliable estimates of biomass, diet and stomach evacuation rates are generally not known, making their predatory impact hard to estimate. Nevertheless, it is clear that these taxa may also be important predators of C. finmarchicus copepodes (Melle et al., 2004; Skjoldal et al., 2004).

Materials and methods

Hydrography and chlorophyll measurements and analyses

CTD probes were used to collect hydrographic data (temperature and salinity) at all sampling stations (Fig. 1b and c). Water samples for measurements of chlorophyll-a concentration were collected using water bottles on a rosette on the CTD or on a hydro-wire. At most sites the hydrographic and chlorophyll samples were taken in concert with the zooplankton net samples. CTD profiling depths and water bottle depths varied among sampling sites. Methodologies for determination of chlorophyll a
concentrations are described in publications or can be retrieved from the data provider associated with each station as shown in Tables 1 and 2. Temperatures (°C) were averaged over various depth ranges, while chlorophyll concentrations were either integrated (mg m⁻²) or averaged (mg m⁻³) over various depth ranges, as indicated in figure captions. At each site where time series measurements were made, temperatures and chlorophyll concentrations were first averaged over 2-week periods within a given year and then over the 2-week periods for all years.

The basin scale distribution of Sea Surface Temperature (SST, °C) was calculated from data available from the British Atmospheric Data Centre (BADC); [HadISST 1.1 dataset (http://badc.nerc.ac.uk/home)]. Monthly SST records (1 degree by 1 degree) or the years 2000–2009 were firstly averaged by year and then used to produce the overall average SST map for the period of reference.

### Mapping of Calanus finmarchicus distribution at the basin scale

The CPR survey is an upper layer plankton monitoring program that has regularly collected samples (ideally at monthly intervals) in the North Atlantic and adjacent seas since 1946 (Warner and Hays, 1994). Water from approximately 6 m depth (Batten et al., 2003a) enters the CPR through a small aperture at the front of the sampler and travels down a tunnel where it pass through a silk filtering mesh of 270 μm before exiting at the back of the CPR. The plankton filtered on the silk is analysed in sections corresponding to 10 nautical miles (approx. 3 m² of seawater filtered) and the plankton microscopically identified (Jonas et al., 2004). In the present study we used the CPR data to investigate the current basin scale distribution of C. finmarchicus (CV–CVI). Monthly data collected between 2000 and 2009 were gridded using the inverse-distance interpolation method (Isaaks and Srivastava, 1989), in which the interpolated values were the nodes of a 2 degree by 2 degree grid. The resulting twelve monthly matrices were then averaged within the year and the data log-transformed (i.e. \( \log_{10}(x + 1) \)). The Phytoplankton Colour Index (PCI), which is a visual assessment of the greenness of the silk, is used as an indicator of the distribution of total phytoplankton biomass across the Atlantic basin (Batten et al., 2003b; Richardson et al., 2006).

### Seasonal dynamics of Calanus finmarchicus

Seasonal abundance cycles of C. finmarchicus were derived from samples taken at sites across the North Atlantic (Table 1, Fig. 1b). The sampling sites include both coastal and oceanic stations and vary from relatively cold to warm water locations. Sampling frequency also differs among sites; the more easily accessed coastal sites were generally visited more frequently than the offshore sites. An overview of sampling sites characteristics, sampling gear and methods is provided in Table 1. Temperatures and chlorophyll concentrations are provided for all sites and details on depth ranges and units are given in Appendix Figs. 1–6.

### Dormancy

Dormancy timing was calculated using metrics developed by Johnson et al. (2008). Briefly, entry to dormancy was determined as the date when the CV portion of the total composition of the copepodites and adults comprised 50% of the overall maximum CV proportion, calculated using all years of data at a station. In other words, if the maximum CV proportion was 90% at a given station, the date at which the proportion of CVs was greater than 45% of the total number of copepodites and adults would be the dormancy start date. The end of dormancy was calculated as the first date at which adults constituted more than 10% of all copepodites and adults in a given year for three consecutive dates. This was done to alleviate spurious estimates of dormancy end that may result from transient increases in the proportion of adults in the population.

Data (see Table 1) were gathered from the AZMP dataset (Johnson et al., 2008; Pepin, Plourde, Johnson, Head, pers. comm; http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html), the TASC time series dataset (Heath et al., 2000a: http://tasc.imr.no/tasc/reserved/cruiseact/timeseries.htm), the Svinoy Section and Station M datasets (Melle, pers. comm.) and the Gulf of Maine PULSE and REACH time series datasets (Runge, pers. comm.).

### Egg production

Observations of egg production rates (EPR) for female C. finmarchicus were compared for different regions of the North Atlantic (Fig. 1c). The regions were diverse in size and sampling frequency, ranging from a fixed time series station in the Lower St Lawrence Estuary, off Rimouski (RIM), where nearly 200 experiments were carried out between May and December from 1994 to 2006 (RIM), to a large-scale survey in the Northern Norwegian Sea (NNWS), where about 50 experiments were carried out between April and June from 2002 to 2004 (NNWS). For this analysis the stations were grouped mostly along geographic lines, with only limited attention being paid to oceanographic features. There is some overlap between regions, however, where stations were sometimes kept together when they were sampled on the same cruise. As well, although not shown in Fig. 1c, some stations other than RIM were occupied more than once during different years and/or in different seasons. An inventory of the experiments used in this synthesis and of the data contributors is presented in Table 2. Some of the data included here have appeared in published papers and the citations are included. Previously unpublished data were also provided by C. Brooks, E. Gaard, A. Gislason, E. Head and S. Jónasdóttir.

Egg production in C. finmarchicus occurs in spawning bouts, which are of relatively short duration and may occur once or more per day (Marshall and Orr, 1972; Hirche, 1996b). While there is evidence for diel spawning periodicity in the sea (Runge, 1987; Runge and de Lafontaine, 1996), females incubated in dishes for the first 24 h after capture do not always show a consistent night time release of eggs, as they did for Calanus pacificus (Runge and Plourde, 1996; Head et al., 2013a). Because of the potential for diel egg-laying behaviour, the vast majority of egg production experiments have been carried out by incubating freshly caught females for 24 h. It has been shown that female Calanus that are kept and fed in vitro and then transferred to an incubation chamber lay the same number of eggs over the next 24 h whether or not they are fed (Plourde and Runge, 1993; Laabir et al., 1995). Thus, it has been assumed that average egg production rates of freshly caught females are the same during the 24 h following capture as they would have been in situ (Runge and Roff, 2000). In this study we include only results from such 24 h incubation experiments, and we term the eggs laid during these 24 h periods “clutches”, even though they may originate from more than one spawning bout, and the number of eggs laid by one female during a 24 h period as the clutch size (CS). In most experiments 20–30 females were incubated individually in separate chambers, and the proportion of females that laid eggs over 24 h is referred to as the “spawning frequency” (SF), which is here expressed as a percentage per day. Egg production rates (EPRs) reported here were calculated by individual contributing investigators either simply as the sum of all of the eggs produced in an experiment divided by the number of females incubated and the average incubation time (generally 1 day), or as the average of the EPRs calculated for each experimental female individually, which takes
<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Site No.</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Bottom depth (m)</th>
<th>Water mass</th>
<th>Shelf</th>
<th>Mesh size (µm)</th>
<th>Max. sampling depth (m)</th>
<th>Gear</th>
<th>Mesh</th>
<th>Years</th>
<th>No. Stations</th>
<th>Analyses</th>
<th>Data provider</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeffrey’s Ledge</td>
<td>1</td>
<td>Gulf of Maine</td>
<td>42.83 N</td>
<td>70.31 W</td>
<td>50</td>
<td>Coastal</td>
<td>Shelf</td>
<td>45</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>2003–2008</td>
<td>1</td>
<td>M/D</td>
<td>BCO-DMO, USA</td>
<td></td>
</tr>
<tr>
<td>Wilkinson Basin</td>
<td>2</td>
<td>Gulf of Maine</td>
<td>42.86 N</td>
<td>69.86 W</td>
<td>250</td>
<td>Coastal</td>
<td>Shelf</td>
<td>240</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>2005–2008</td>
<td>1</td>
<td>M/D/S</td>
<td>BCO-DMO, USA</td>
<td></td>
</tr>
<tr>
<td>AZMP lines</td>
<td>3</td>
<td>Gulf of St. Lawrence, Scotian Shelf, Newfoundland Shelf</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Coastal/Atlantic</td>
<td>Shelf</td>
<td>250</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2009</td>
<td>108</td>
<td>M</td>
<td>DFO, Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Prince</td>
<td>4</td>
<td>Bay of Fundy</td>
<td>44.93 N</td>
<td>66.85 W</td>
<td>95</td>
<td>Coastal</td>
<td>Shelf</td>
<td>80</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2009</td>
<td>1</td>
<td>D</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Halifax 2</td>
<td>5</td>
<td>Scotian Shelf</td>
<td>44.27 N</td>
<td>63.32 W</td>
<td>155</td>
<td>Coastal</td>
<td>Shelf</td>
<td>80</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2009</td>
<td>108</td>
<td>M</td>
<td>DFO, Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Rimouski Station</td>
<td>6</td>
<td>Lower St. Lawrence Estuary</td>
<td>48.67 N</td>
<td>68.58 W</td>
<td>340</td>
<td>Coastal</td>
<td>Shelf</td>
<td>320</td>
<td>1-m or 0.75-m Ring net</td>
<td>200</td>
<td>1994–2008</td>
<td>1</td>
<td>M/D/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Anticosti</td>
<td>7</td>
<td>Northwest Gulf of St. Lawrence</td>
<td>49.72 N</td>
<td>66.25 W</td>
<td>340</td>
<td>Coastal</td>
<td>Shelf</td>
<td>320</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2003</td>
<td>1</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Gaspé</td>
<td>8</td>
<td>Northwest Gulf of St. Lawrence</td>
<td>49.24 N</td>
<td>66.20 W</td>
<td>185</td>
<td>Coastal</td>
<td>Shelf</td>
<td>180</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2003</td>
<td>1</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Shediac</td>
<td>9</td>
<td>Southern Gulf of St. Lawrence</td>
<td>47.78 N</td>
<td>64.03 W</td>
<td>84</td>
<td>Coastal</td>
<td>Shelf</td>
<td>80</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2009</td>
<td>1</td>
<td>D</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>AZMP Station 27</td>
<td>10</td>
<td>Newfoundland Shelf</td>
<td>47.92 N</td>
<td>52.98 W</td>
<td>175</td>
<td>Coastal/Atlantic</td>
<td>Shelf</td>
<td>175</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>2000–2009</td>
<td>1</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Labrador Shelf</td>
<td>11</td>
<td>Labrador Shelf</td>
<td>54.22 N</td>
<td>50.04 W</td>
<td>140–200</td>
<td>Arctic</td>
<td>Shelf</td>
<td>100</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1995–2006</td>
<td>1–7</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Labrador Slope</td>
<td>12</td>
<td>Labrador Slope</td>
<td>59.07 N</td>
<td>150.00 W</td>
<td>1000–3000</td>
<td>Arctic</td>
<td>Slope</td>
<td>100</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1995–2006</td>
<td>&lt;7</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Central Labrador Sea</td>
<td>13</td>
<td>Labrador Sea</td>
<td>55.37 N</td>
<td>0.00 W</td>
<td>3000–3700</td>
<td>Arctic</td>
<td>Oceanic</td>
<td>100</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1995–2006</td>
<td>0–13</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Eastern Labrador Shelf</td>
<td>14</td>
<td>Labrador Sea</td>
<td>58.00 N</td>
<td>280.00 W</td>
<td>3600–4000</td>
<td>Arctic</td>
<td>Oceanic/Shelf</td>
<td>100</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1995–2006</td>
<td>&lt;5</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>West Greenland shelf</td>
<td>15</td>
<td>West Greenland</td>
<td>60.51 N</td>
<td>48.30 W</td>
<td>185</td>
<td>Coastal</td>
<td>Shelf</td>
<td>185</td>
<td>0.75-m Ring net</td>
<td>200</td>
<td>1999–2003</td>
<td>1</td>
<td>M/S</td>
<td>Canada</td>
<td></td>
</tr>
<tr>
<td>Faroe Shelf station</td>
<td>20</td>
<td>Faroese Shelf</td>
<td>62.05 N</td>
<td>6.62 W</td>
<td>55</td>
<td>Toilet</td>
<td>Oceanic</td>
<td>50</td>
<td>WP–2/Bongo</td>
<td>100</td>
<td>1994–2004</td>
<td>1</td>
<td>M/D/S</td>
<td>Faroes, FAMRI</td>
<td></td>
</tr>
<tr>
<td>Svinøy section</td>
<td>23</td>
<td>Central Norwegian Sea</td>
<td>64.51 N</td>
<td>0.36 E</td>
<td>2932</td>
<td>Arctic</td>
<td>Oceanic</td>
<td>200</td>
<td>WP2</td>
<td>180</td>
<td>1996–2006</td>
<td>1–2</td>
<td>M/S</td>
<td>Heath et al. 2000</td>
<td></td>
</tr>
<tr>
<td>Svinøy section</td>
<td>24</td>
<td>Eastern Norwegian Sea</td>
<td>63.52 N</td>
<td>2.66 E</td>
<td>1453</td>
<td>Arctic</td>
<td>Oceanic</td>
<td>200</td>
<td>WP2</td>
<td>180</td>
<td>1996–2006</td>
<td>7–8</td>
<td>M/S</td>
<td>MRI, Norway</td>
<td></td>
</tr>
<tr>
<td>Saltenfjorden</td>
<td>27</td>
<td>Northern Norwegian Shelf</td>
<td>67.23 N</td>
<td>13.65 E</td>
<td>400</td>
<td>Coastal</td>
<td>Shelf</td>
<td>370</td>
<td>WP2</td>
<td>200</td>
<td>1997–1998</td>
<td>1</td>
<td>M/S</td>
<td>MRI, Norway</td>
<td></td>
</tr>
</tbody>
</table>
As batches of eggs are released into the water column \textit{in situ}, they may hatch and develop, or they may be consumed by local predators, including female \textit{C. finmarchicus} themselves, which are sometimes the most abundant potential predators (Basedow and Tande, 2006). To avoid cannibalism, incubations are generally set up so as to minimise contact between the females and the eggs they are laying. This has been done by the investigators contributing to this work using one of five techniques (see Table 2). In Method A females are incubated individually in 45–50 ml of seawater in 6–10 cm diameter petri dishes. The eggs sink rapidly to the bottom surface, where they are unlikely to be caught up in the females’ feeding currents. Method B involves incubating females individually in similar but smaller “Multi-well” chambers, which have a volume capacity of 10–15 ml. In Method C females are placed individually (or in groups of 2 or 3) in cylinders, fitted with mesh screens on the bottom, which are suspended in beakers of 400–600 ml capacity (Gislason, 2005). The eggs sink through the mesh and are thus separated from the females. Method D represents a modification of Method C, in which there is flow of seawater through the chamber (White and Roman, 1992). Finally, in Method E, individual (or groups of 2 or 3) females are incubated in bottles or beakers (up to 1 l capacity), without screening (Jónasdóttir et al., 2005). For Method E the vessels are kept upright and it is assumed that the eggs will sink out and become unavailable to the females relatively rapidly.

There have been relatively few comparisons of these different experimental methods. Cabal et al. (1997) found that female \textit{C. finmarchicus} from the Labrador Sea incubated individually in 50 ml petri dishes (Method A) or 80 ml bottles (Method E) produced similar numbers of eggs after 3 days, although only three experiments were done and over the first 24 h CSs were larger for Method A. They also found that over 24 to 72 h periods groups of females in screened cylinders within large volume chambers (Method C) gave higher egg production rates than did those in chambers without screens (Method E). Runge and Roff (2000) reported egg laying in dishes (Method A) yielded similar egg production rates to those for groups of 10–15 females incubated in 1.5 l screened beakers (Method C). However, the beaker egg production estimates declined dramatically relative to dish estimates in rough weather, presumably due to increased mixing in beakers and therefore higher loss due to cannibalism. More recently, Plourde and Joly (2008) found that suspending a mesh screen within petri dishes 2 mm above the bottom made no difference to the number of eggs produced by female \textit{C. finmarchicus} over 24 h, although it did increase the number of eggs recovered from \textit{Metridia longa} females, which could be seen swimming actively and sweeping the bottom with their mouthparts in the unscreened dishes. In the Northeast Atlantic, at Ocean Weather Station M (included in our Southern Norwegian Sea (SNWS) region), B. Niethoff (pers. comm.) found that females incubated for 24 h in Multi-wells (Method B) had similar CSs to those incubated according to Method C. None of these studies compared all methods and the fact that the NW Atlantic groups have used Method A, while the central and NE Atlantic groups have used mainly Methods C, D or E introduces a question as to whether methodological differences might have contributed to the differences found among the CSs and EPRs in the different regions. Such an analysis is not possible based on the data currently available, however, and the topic will not be considered further in this work, although it merits further attention.

### Table 2: Summary of Experimental Methods

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Water mass</th>
<th>Bottom depth (m)</th>
<th>Water temperature</th>
<th>Chamber capacity (%)</th>
<th>Egg production rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stonehaven</td>
<td>North Sea, Scotland Shelf</td>
<td>Coastal</td>
<td>47</td>
<td>1.67 E</td>
<td>45</td>
<td>Method A (50 ml)</td>
</tr>
<tr>
<td>Murchinson</td>
<td>North Sea</td>
<td>Atlantic</td>
<td>170</td>
<td>2.45 E</td>
<td>60</td>
<td>Method B (60 ml)</td>
</tr>
<tr>
<td>Arendal st. 2</td>
<td>Southern Norway Shelf</td>
<td>Coastal</td>
<td>105</td>
<td>8.82 E</td>
<td>100</td>
<td>Method C (500 ml)</td>
</tr>
<tr>
<td>Station India</td>
<td>Northeast ATL</td>
<td>Atlantic</td>
<td>2000</td>
<td>1.9 W</td>
<td>2000</td>
<td>Method E (200 ml)</td>
</tr>
</tbody>
</table>

| Number of stations out of a total of 12 based on watermass distribution. |

- M = Mortality, D = Dormancy, S = Seasonal dynamics.

---

### Table 1: Sampling Site Locations

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Site Location</th>
<th>Location</th>
<th>Water mass</th>
<th>Bottom depth (m)</th>
<th>Water temperature</th>
<th>Chamber capacity (%)</th>
<th>Egg production rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stonehaven</td>
<td>North Sea, Scotland Shelf</td>
<td>Coastal</td>
<td>47</td>
<td>1.67 E</td>
<td>45</td>
<td>Method A (50 ml)</td>
<td></td>
</tr>
<tr>
<td>Murchinson</td>
<td>North Sea</td>
<td>Atlantic</td>
<td>170</td>
<td>2.45 E</td>
<td>60</td>
<td>Method B (60 ml)</td>
<td></td>
</tr>
<tr>
<td>Arendal st. 2</td>
<td>Southern Norway Shelf</td>
<td>Coastal</td>
<td>105</td>
<td>8.82 E</td>
<td>100</td>
<td>Method C (500 ml)</td>
<td></td>
</tr>
<tr>
<td>Station India</td>
<td>Northeast ATL</td>
<td>Atlantic</td>
<td>2000</td>
<td>1.9 W</td>
<td>2000</td>
<td>Method E (200 ml)</td>
<td></td>
</tr>
</tbody>
</table>

| Number of stations out of a total of 12 based on watermass distribution. |

- M = Mortality, D = Dormancy, S = Seasonal dynamics.
Another point on which investigators differed is how they dealt with small clutches. For the Georges Bank (GB), Rimouski station (RIM) and Scotian Shelf (SS) regions and for the Labrador Sea (LS) data provided by R. Campbell, clutches of <6 eggs were routinely included by all investigators in their calculations of EPRs. This was in the SNWS region (data from Ocean Weather Station M), for which average female prosome lengths were determined for groups of females that had not been used in experiments, but that had collected on the same day. In addition, there were no measurements of prosome lengths for some data from the region “Between Scotland and Iceland” (BIS) and the SNWS and NNWS regions. As well, prosome lengths were not measured for all clutch sizes enumerated at RIM. Egg production rates for the experiments carried out within a given region were averaged seasonally (Table 2). The rationale for the grouping of months into seasons within each region was based partly on observations of seasonal cycles of temperature and chlorophyll concentration, partly on what could be ascertained from the literature about the timing of the appearance of females at the surface after over-wintering, and partly on the availability of data. The spring months cover the period when water temperatures at the surface after over-wintering, and partly on the availability of data. The spring months cover the period when water temperatures are generally low (see section ‘Seasonal dynamics in situ temperature and chlorophyll concentration’).

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of egg production experiments</th>
<th>Investigator(s)</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB (Mar-Apr)</td>
<td>48</td>
<td>-</td>
<td>18</td>
<td>JR</td>
</tr>
<tr>
<td>SS (Apr-May)</td>
<td>27</td>
<td>(Jul)</td>
<td>8</td>
<td>RC</td>
</tr>
<tr>
<td>RIM (May-Jul)</td>
<td>110</td>
<td>(Oct-Nov)</td>
<td>3</td>
<td>SP</td>
</tr>
<tr>
<td>LS (May)</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>RC</td>
</tr>
<tr>
<td>WGBB (Late Apr-May)</td>
<td>21</td>
<td>(Jun-Jul)</td>
<td>6</td>
<td>TGN, RS, SM</td>
</tr>
<tr>
<td>IRM (May-Jun)</td>
<td>52</td>
<td>-</td>
<td>6</td>
<td>AG</td>
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<tr>
<td>ICE(N) (May-Jun)</td>
<td>16</td>
<td>-</td>
<td>7</td>
<td>MH</td>
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<td>ICE(S) (Apr-Jun)</td>
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<td>-</td>
<td>9</td>
<td>AG</td>
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<td>BIS (Apr-May)</td>
<td>16</td>
<td>(Oct)</td>
<td>-</td>
<td>SJ</td>
</tr>
<tr>
<td>SNWS (Apr-May)</td>
<td>38</td>
<td>-</td>
<td>4</td>
<td>SJ</td>
</tr>
<tr>
<td>NNWS (May)</td>
<td>36</td>
<td>(Jun)</td>
<td>4</td>
<td>WM</td>
</tr>
<tr>
<td>NS (Mar-May)</td>
<td>56</td>
<td>(Jul-Aug)</td>
<td>4</td>
<td>SJ</td>
</tr>
</tbody>
</table>

References to published data are as follows: 1, Runge et al. (2006); 2, Campbell and Head (2000); 3, Plourde and Runge (1993)+unpubl. data; 4, Head et al. (2013a); 5, Nielsen and Hansen (1995); 6, Arendt et al. (2010); 7, Munk et al. (2003); 8, Madsen et al. 2008; 9, Swalethorp et al. (2011); 10 Gislason et al. (2003); 11, Gislason (2005); 12, Gislason et al. (2008); 13, Heath et al. (2008); 14, Jónasdóttir et al. (2002); 15, Richardson et al. (1999); 16, Jónasdóttir et al. (2008)+unpubl. data; 17, Niehoff et al. (1999); 18, Stenevik et al. (2007); 19, Head et al. (2013b); 20, Jónasdóttir et al. (2005); 21, Jónasdóttir and Koski (2011).
concentrations integrated to 30 m in this study. Not all data were provided in this form, however. For example, in some datasets temperature data were surface values or 0–10 m or 0–20 m averages and chlorophyll concentrations were sometimes values integrated to 50 m. In Fig. 3 the data were standardized to a comparable format by assuming that surface, 0–10 m or 0–20 m average temperatures were the same as 5 m temperatures, and that the chlorophyll concentrations were uniform throughout the 0–50 m depth range. These assumptions are likely to be most appropriate in spring and winter, when mixed layers are relatively deep.

Mortality and survival estimation

Data were obtained from sampling programs in different regions of the northeast Atlantic and northwest Atlantic, for which there is sampling at fixed stations sampled at least once a month (sometimes 3–4 times a week, e.g., Station M) or along sections once or a few times per year (Table 1, Fig. 1b). In the northwest Atlantic suitable data were collected in the Gulf of Maine (GoM), on the Scotian Shelf (SS) and the Newfoundland Shelf (NLS), in the Gulf of St Lawrence (GSL) and in the Labrador Sea (LS). In the northeast Atlantic appropriate data were available in areas to the south and north of Iceland (the former including Station India), to the north of the Faroe Islands, in the Norwegian Sea (NWS), and in the Skagerrak (Table 1). Data collected during the TASC and MarProd programmes were also included (Heath et al., 2000a, 2008). Sampling in the northeast Atlantic (with the exception of TASC and MarProd) and in the Labrador Sea targeted the active part of the C. finmarchicus population, with sampling in the near-surface layers (different depth ranges at different sites) whereas sampling in the GoM and in the AZMP region (SS, GSL, NLS) in the northwest Atlantic was over the entire water column, potentially including dormant individuals at depth (Table 1). This difference had to be accounted for before using the VLT method (see below). Because several of the programs did not sample the diapausing component of the population, mortality and survival during the overwintering period were not addressed. Temperature and chlorophyll a biomass were estimated for the region-specific surface layer, which was generally shallower on the northwest Atlantic shelves than in other regions.

We adopted the approach of Plourde et al. (2009b) using the Vertical Life Table (VLT) method to estimate mortality and survival for the following stage pairs egg–CI (which actually includes all of the naupliar stages), CI–CII, CIII–CIV, CIV–CV, CV–CVI. The VLT uses the ratio in abundance of adjacent stages, except for eggs, for which female population egg production rate is used rather than abundance. This method is thought to be relatively robust except in highly dynamic or advective environments (Ohman, 2012; Gentleman et al., 2012). In order to minimize biases due to advection and insufficient sampling, which are likely to induce violations to the assumptions associated with VLT, we averaged stage abundances and environmental data for each month at fixed stations (e.g. Halifax 2) or along transects (AZMP) or for oceanographic domains (e.g. LS, NWS, Arctic vs. sub-arctic waters) sampled during each survey. This approach resulted in more robust input data.

Table 3

Inventory of measurements of female prosome length (PL) and clutch size (CS) of more than 5 eggs included in this study. Regions and investigators are as in Table 2. Clutch sizes for WGBB from experiments run for 24 h (8 in spring, 7 in summer).

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of measurements</th>
<th>Investigator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spring</td>
<td>Summer</td>
</tr>
<tr>
<td>GB</td>
<td>(Mar-Apr)</td>
<td>(May-Jun)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>335/655</td>
<td>323/930</td>
</tr>
<tr>
<td>SS</td>
<td>(Mar-Apr)</td>
<td>(Jun)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>773/435</td>
<td>250/131</td>
</tr>
<tr>
<td>RM</td>
<td>(May-Jul)</td>
<td>(Aug-Sept)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>1989/</td>
<td>1332/</td>
</tr>
<tr>
<td>LS</td>
<td>(May)</td>
<td>(Jun-Jul)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>2691/1689</td>
<td>1280/632</td>
</tr>
<tr>
<td>WGBB</td>
<td>(May)</td>
<td>(Jun-Jul)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>318/61</td>
<td>188/39</td>
</tr>
<tr>
<td>IBM</td>
<td>(May-Jun)</td>
<td>-</td>
</tr>
<tr>
<td>PL/CS</td>
<td>782/407</td>
<td>-</td>
</tr>
<tr>
<td>ICE(N)</td>
<td>(May-Jun)</td>
<td>-</td>
</tr>
<tr>
<td>PL/CS</td>
<td>2074/1395</td>
<td>-</td>
</tr>
<tr>
<td>ICE(S)</td>
<td>(Apr-June)</td>
<td>-</td>
</tr>
<tr>
<td>PL/CS</td>
<td>2009/1198</td>
<td>-</td>
</tr>
<tr>
<td>BIS</td>
<td>(Apr-May)</td>
<td>(Sep-Oct)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>448/200</td>
<td>30/5</td>
</tr>
<tr>
<td>SNWS</td>
<td>(Apr-May)</td>
<td>(Jun)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>872/1484</td>
<td>54/40</td>
</tr>
<tr>
<td>NNWS</td>
<td>(May)</td>
<td>(Jun)</td>
</tr>
<tr>
<td>PL</td>
<td>630/337</td>
<td>106/40</td>
</tr>
<tr>
<td>NS</td>
<td>(Mar-May)</td>
<td>(Jul-Aug)</td>
</tr>
<tr>
<td>PL/CS</td>
<td>767/329</td>
<td>262/166</td>
</tr>
</tbody>
</table>

Fig. 3. (A) Surface layer average temperature (°C) and (B) chlorophyll a biomass (mg m⁻²) averaged over the surface 50 m in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean ± standard error.

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reducing the proportion of discontinuous stage structures (stage abundance = 0) or negative mortality estimates that may be caused by patchy plankton distributions or violations of the VLT assumptions (Plourde et al., 2009b). Thus, our meta-analysis was based on duplicates of robust averaged stage abundances and environmental data. Only the data collected in Icelandic waters were not averaged because they were collected over only two years. Overall, our data set includes 1233 monthly or transect/regional averages (total $n = 1334$, including Icelandic data), and C. finmarchicus shows markedly different phenology across its distributional range (see Figs. Appendix 1–6). We established a common metric to define phases of the population dynamics so that we could compare C. finmarchicus populations at the same stage of their seasonal cycles (pre-growth, growth and post-growth periods, see Plourde et al., 2009b), and limit potential biases in our large scale analysis (Gentleman et al., 2012). We chose to restrict our analysis to the population growth period because all development stages should be actively developing and because several sampling programs target the active component of the population in the surface layer, both factors being optimal for the use of the VLT method (Table 1) (Plourde et al., 2009b). We estimated egg production rates per female (EPR) using functional relationships between EPR and chlorophyll $a$ that have been reported for each region (Gislason, 2005; Runge et al., 2006; Plourde and Joly, 2008; Head et al., 2013a). EPRs were then combined with the monthly climatology for CVI abundance for each region (location) to calculate the population EPR per square metre. The region-specific population growth period was defined as months with population EPR greater than 15% of the regional seasonal maximum. Using this metric, the population growth period was, for example, from January to August on the SS and from May to September off southern Iceland (not shown). Overall, 57% of all data were collected during the population growth period ($n = 757$).

As in Plourde et al. (2009b), we used the developmental parameters of Corkett et al. (1986) to estimate stage-specific development times (DT) in regions with relatively cold ($<6^\circ C$) near-surface temperatures during the population growth period, and those of Campbell et al. (2001) for regions that were relatively warm ($>6^\circ C$). We chose $6^\circ C$ because this represents the lower limit of the optimal thermal habitat for C. finmarchicus (Helouët and Beauprã©, 2007). In the northwest Atlantic, only the GoM was considered to be a warm habitat, while in the central and northeast Atlantic Corkett’s parameters were used for transects/regions located in Arctic water masses north of Iceland, the Faroe Islands and on the part of the Svinoy section where near-surface temperatures were $<6^\circ C$.

Because our dataset was large, we were able to statistically exclude mortality and survival data that gave unrealistic results which indicated violations of the assumptions and conditions for the application of the VLT method (Plourde et al., 2009b). Based on the cumulative percentile distribution of all mortality and survival values, we determined that mortality values lower than the 5th percentile and survival values greater than the 85th percentile were anomalous, and therefore excluding mortality rates $< -0.20$ d$^{-1}$ and survival $>2$. Application of this procedure allowed us to objectively exclude between 0% (egg–CI) and 20% (CI–CII, CIII–CVI) of the mortality values (depending on the location), and between 5% and 35% of survival values.

The data originated from sampling programs with different sampling strategies and from regions showing markedly different environmental conditions (temperature, food), both being potential vectors of bias in estimating stage-specific abundance and development time (stage duration, DT) and using VLT (Ohman, 2012; Gentleman et al., 2012). We standardized the data in order to minimize these potential biases. Here, we summarize these operations and their rationale as follows:

- We corrected the data for the presence of overwintering stages in the GoM, GSL, on the SS and NLS (northwest Atlantic), which could cause problems with the mortality estimates in stage pairs CV–CV and CV–CIV (Plourde et al., 2009b). We adapted the seasonal climatology in the activity index (proportion of abundance in 0–100 m/0–bottom) at RIM in the GSL based on the phenology (timing of diapause) in different regions (Plourde, unpublished data, Johnson et al., 2008). This correction had a stronger impact during the early and late phases of the population growth period by decreasing the observed CIV–VI abundance. This adjustment made the abundances of late development stages in the GoM and AZMP comparable with those found in the LS and in the northeast Atlantic where sampling, which was in the upper 0–100 or 0–200 m, and which would have excluded most of the overwintering stages (Østvedt, 1955; Gislason and Astthorsson, 2000; Gislason et al., 2000; Heath et al., 2000b; Melle et al., 2004).

- Sampling the 0–50 m layer along the line off northern Faroe Island and in the Skagerrak likely underestimated total C. finmarchicus abundance, especially the late development stages CV and CIV (Gaard and Hansen, 2000). This bias would probably have been even more important later on during the population growth period, when surface temperatures are higher (Williams, 1985; Bonnet et al., 2005; Jónasdóttir and Koski, 2011). Thus, at these locations, we excluded mortality and survival values of stage pairs for the following stages: egg–CI, CIV–CV and CV–CVI.

- We found differences in temperature regimes and phytoplankton biomass among sampling sites and regions, both parameters being important in the determination of DT for most stages in C. finmarchicus (Campbell et al., 2001). In the absence of stage-specific parameters for the effect of food limitation on DT, we transposed to C. finmarchicus results of an exhaustive study of the effect of food and temperature on development and growth of C. pacificus (Vidal, 1980). This study, which included temperatures representative of the whole distributional range of C. pacificus ($8^\circ C$, $12^\circ C$, $16^\circ C$), showed that the effect of food limitation on DT increased with temperature and developmental stage. We applied these results to C. finmarchicus, separating its temperature range into three categories: $<6^\circ C$, 6–11 °C, >11 °C. These temperature limits were chosen because based on CPR observations (Helouët and Beauprã©, 2007), the optimal thermal habitat for C. finmarchicus CV–CIV in the North Atlantic is at surface temperatures between 6 and $11^\circ C$. Overall, the impact of this food limitation formulation was greater at chlorophyll $a$ concentrations <25 mg m$^{-2}$ in the upper 50 m (or 0.5 mg m$^{-3}$) and at temperatures above $6^\circ C$. This effect was therefore more prominent in the northeast Atlantic where conditions during the population growth period were generally warmer (greater proportion of temperatures $>6^\circ C$) (Fig. 17). The northeast Atlantic also showed a greater proportion of stations with chlorophyll $a$ concentrations <20 mg m$^{-2}$, while concentrations $>100$ mg m$^{-2}$ were more frequently observed in the northwest Atlantic. Under these conditions, the DT for CIVs at temperature in the 6–11 °C range with a chlorophyll $a$ concentration <20 mg m$^{-2}$ would be 3–4 times longer than under non-limiting food conditions. This adjustment diminished the proportion and amplitude of negative mortality estimates for several stage pairs.

- Different temperature regimes might also affect the size of C. finmarchicus, which could influence the sampling efficiency for CI, CII and CIII, depending on the net mesh size (Nichols and Thompson, 1991). We used field data collected in the GSL and on SS to establish a relationship between prosome length (PL) of early stages and surface temperature (Plourde, Head, unpublished). PL of both stages decreased significantly with increasing
temperature. We used this relationship to predict PL from surface temperature in our data set, determining a minimal PL above which increasing temperature had no effect (Conway, 2006; Plourde, unpublished). PL was then used to estimate the prosome width necessary to estimate sampling efficiency (Nichols and Thompson, 1991; Conway, 2006). Again, the bias was likely more important in warmer conditions late in the growth period, i.e. generally in the northeast Atlantic. For example, the sampling efficiency for CI and CII with a 200-μm mesh rapidly diminishes between 4–12 °C, with less than 75% and 50% of CI and CII being sampled at temperatures equal to or higher than 12 °C (no effect on CII). This adjustment reduced the proportion and amplitude of negative mortality estimates in early stage pairs (CI–CII, CII–CIII), and the absolute mortality for the egg to CI transition.

Non-parametric statistical tests (Mann–Whitney to contrast between two groups; Kruskal–Wallis for more than two groups) were used to contrast mortality and survival estimates among different groups (see text below). We used non-linear regression models to describe the relationships between mortality estimates in all stage pairs and temperature, and linear multiple regression models to describe the relationships between mortality in early stages (egg–CI) and temperature, phytoplankton biomass and CVI female (CVIF) abundance.

We contrasted stage-specific mortality and survival among offshore (>1000 m, deep basins) and shelf (<1000 m) domains in the northeast and northwest Atlantic regions. We note, however, that the offshore domain (n = 44) was under-represented relative to the shelf (n = 357) in the northwest Atlantic, whereas both domains were reasonably covered in the northeast Atlantic (offshore = 146, shelf = 210).

Late stages of sub-Arctic and temperate Calanus species and other suspension feeding copepods can ingest their own eggs and nauplii at high rates (see Landry, 1981; Bonnet et al., 2004; Basedow and Tande, 2006), with sizeable consequences on the recruitment patterns (i.e., Ohman and Hirche, 2001; Ohman et al., 2008; Plourde et al., 2009a). Feeding experiments have shown that the large Arctic species C. hyperboreus can clear up to 5 1 d−1 when fed with C. finmarchicus eggs at realistic field concentrations (Plourde unpublished data), suggesting a potential for a high impact of Arctic Calanus species on C. finmarchicus population dynamics. Therefore, we contrasted stage-specific mortality and survival of C. finmarchicus in different ‘habitats’ defined on the basis of local temperature and on the likelihood of high abundance of C. glacialis and C. hyperboreus in the surface waters, both indicative of regions being under the influence of cold Arctic water. In the northwest Atlantic C. hyperboreus and C. glacialis are generally abundant on the shelves and slopes of the Labrador Sea, on the NLS, in the GSL and part of the SS (Head et al., 1999, 2003; Plourde et al., 2003). In the central and northeast Atlantic, these species are important in the Arctic/polar waters off the north coast of Iceland and the Faroe Islands and in the northwestern Norwegian Sea (Asthorsson and Gislason, 2003; Broms et al., 2009; Gislason et al., 2009). These Arctic species are generally active in the surface layer from mid-winter (SS) or early spring (GSL, NLS) to June (SS) or July (GSL, NLS), the end of their active phase in surface waters corresponding roughly to when temperatures reach 6 °C (Plourde et al., 2009a, 2009b; Head and Pepin, 2010; Plourde, unpublished). In the northeast Atlantic, C. hyperboreus and C. glacialis are present in surface waters from April to July, a pattern similar to the one observed for the GSL and NLS (Hirche, 1997; Melle and Skjoldal, 1998; Astthorsson and Gislason, 2003). In this analysis, we therefore combined these spatial and seasonal patterns to classify our data into the following ‘habitats’: (1) ‘habitats’ with temperatures <6 °C with high (n = 235) or low (n = 150) likelihood for C. finmarchicus to co-occur with C. hyperboreus and C. glacialis, and (2) ‘habitats’ with low abundance of C. hyperboreus and C. glacialis with temperatures 6–11 °C (n = 272) or 11–16 °C (n = 97). Given the importance of mortality and survival during the egg and naupliar stages in determining the overall cohort development success (Plourde et al., 2009b), this analysis primarily focused on stage pair egg–CI.

Results

Basin scale habitat characteristics: hydrography and chlorophyll

The 15 °C surface isotherm, from approximately 40° latitude (south of Long Island, New York) in the west and at about 47° latitude in the east (south of Brittany, France), delimits the southern edge of the northern North Atlantic (Fig. 2a). The coldest surface temperatures occur in the Labrador Sea and off the east coast of Greenland. The 11–15 °C annual average surface temperature occurs in a narrow band between southern New England and Long Island in the west, expanding in the drift path of the Gulf Stream, to include a large area of the deep North Atlantic basin south of Iceland, the North Sea, and coastal shelves of Great Britain.

The annual phytoplankton colour index (i.e. PCI, Fig. 2b), a relative index of phytoplankton biomass as sampled by the silk mesh in the CPR, shows no obvious correspondence with the annual pattern of sea surface temperature in the northern North Atlantic. Instead, it indicates that the areas of highest phytoplankton biomass occur at the shelf margins, including the Gulf of Maine, Grand Bank, North Sea and the shelf north and west of the British Isles. Higher phytoplankton biomass is also indicated in Denmark Strait. In general, surface phytoplankton biomass is lower in the deep, central North Atlantic basin, with the exception of the deep water south of Iceland.

Phytoplankton data from the Calanus sampling stations generally corroborate the annual patterns of PCI shown in the CPR data, although they indicate that phytoplankton biomass is lower in the northeast Atlantic than in the northwest, except in the northern Norwegian Sea. Two independent regional analyses of the environmental data were carried out. For the first, surface layer averaged temperature and chlorophyll a biomass during the C. finmarchicus population growth period (Fig. 3) were calculated for the stations used in the analyses of mortality and survival. Surface layer temperatures were significantly higher in the northeast Atlantic than in the northwest (Mann–Whitney test, p < 0.0001), but similar in offshore and shelf habitats within the northeast and northwest Atlantic habitats (Mann–Whitney test, p > 0.05). On the other hand, chlorophyll a biomass was greater in both offshore and shelf habitats in the northwest Atlantic than in the northeast (Kruskal–Wallis test, p < 0.0001). For the second analysis, near surface temperatures and integrated chlorophyll standing stocks (0–30 m) were calculated by season using data from stations where C. finmarchicus egg production rates were measured (Fig. 4). Average 5 m temperatures were highest in summer within each region, and in all seasons and regions they were generally between 4 and 10 °C although they were below 4 °C four regions: the Scotian Shelf (SS), Labrador Sea (LS) and West Greenland Baffin Bay (WGBB) in spring, and Rimouski (RIM) in winter, and above 10 °C at one
station the North Sea (NS) in summer and autumn. Most regions were not sampled in every season, but where data are available, integrated chlorophyll concentrations were highest in spring or summer, with the spring months coinciding with the early to mid–bloom period, and the summer months to the mid- to post bloom period. The highest average springtime chlorophyll concentration was near Iceland, north of 65°C (ICE(N)) where the average 0–30 m value was 4.6 mg m⁻², the lowest was in the southern Norwegian Sea region, where it was 1.1 mg m⁻². Chlorophyll concentrations were generally low in autumn and winter. The Georges Bank (GB) region, located relatively far south with high winter light levels, was anomalous in that integrated chlorophyll concentrations were relatively high in winter (Jan–Feb).

**Distribution of Calanus finmarchicus by CPR sampling**

The spatial distribution of the log-transformed mean annual abundance for *C. finmarchicus* from CPR collections between 2000 and 2009 is shown in Fig. 5. The abundance of *C. finmarchicus* is highest in the western part of the Atlantic basin particularly off the Scotian Shelf, the southern Labrador Sea, south of Greenland and in the Irminger Basin. The data show lower abundance in the eastern Atlantic, where it is restricted mainly to northern regions.

**Seasonal dynamics of Calanus finmarchicus in relation to chlorophyll and temperature**

Detailed descriptions of the seasonal cycle and associated environmental variables at the sampling stations compiled in Table 1 are provided in the appendix (Figs. A1–A6). Here we explore general demographic patterns (abundance, recruitment timing and dormancy timing) of *C. finmarchicus* populations across the North Atlantic.

Two indices of abundance at the study sites across the North Atlantic were calculated. The annual maximum abundance of all copepodite stages combined (Fig. 6) was highest...
(135–265 × 10^3 m^−2) at the southern and eastern Norwegian Sea, southern Iceland shelf and eastern Labrador Sea stations. Differences in abundance could not be simply explained by location on shelves or over deep ocean basins. The relatively high abundance observed at Foinaven is likely due to the fact that here sampling was down to the bottom (500 m), where dormant copepodites would have been captured. The autumn and winter mean annual maximum abundance of stage CV (Fig. 7) shows much higher abundances (on average 10–30 × 10^3 m^−2) along the western North Atlantic shelves and at a Norwegian fjord station. Abundances in Wilkinson Basin in the Gulf of Maine are notably higher than at any other shelf site and are similar to abundances of stage CV found at depth in the Norwegian and Irminger Seas (Heath et al., 2004). These high shelf abundances represent overwintering stage CVs in areas where the sea is deep enough to allow overwintering to occur. Other sites in the central and eastern Atlantic are either too shallow (e.g. Arendal, Stonehaven) for overwintering, or are very deep (e.g. Station Mike), in which case the overwintering stage CVs were deeper than the depths sampled at sites used in this study. Data from the overwintering period in the Labrador Sea are not shown here, but there individuals would have been at depths greater 0–100 m, which is the depth range that was used for the Labrador Sea data presented here (Head and Pepin, 2008; Head et al., 2013b).

Maximum abundances of *C. finmarchicus* showed a positive relationship with the annual maximum temperature in the surface layer (see axes labels in Appendix Figs. 1–6 for actual depth range of temperature measurements, Fig. 8). Maximum temperature gives a measure of habitat suitability if there is an upper temperature limit above which population growth, reproduction or survival are hampered. Abundances were both high and low at higher maximum temperatures and invariably low at lower maximum temperatures. If the very near shore and shallow stations of the North Sea and Faroes are excluded, the maximum abundance of *C. finmarchicus* increased exponentially for all maximum temperatures measured at the sites included here.
The timing of recruitment to stages CI–III of the first generation (G1) was investigated by plotting the time of maximum abundance of CI–CIII versus the maximum annual water temperature in the surface layer and the time of maximum chlorophyll concentration (Fig. 9). At all sites, except at the Faroe and Rimouski stations, maximum number of CI–CIII occurred during or after the peak in chlorophyll concentration. There was a weak positive correlation between the times of occurrence of the chlorophyll and CI–CIII maxima (Fig. 9) and a strong, positive relationship between temperature and the timing of recruitment to CI–CIII, so that recruitment at the western North Atlantic sites was up to 3.5 months later than at the eastern Atlantic sites. The sites that showed delayed timing of CI–CIII recruitment relative to the timing of the bloom (sites in upper left corner of Fig. 9, upper panel), were sites with low temperatures, suggesting that low temperature may cause a mismatch between *C. finmarchicus* recruitment and the bloom (Broms et al. 2009) (but see also section ‘Mortality and survival of *Calanus finmarchicus* for potential effects of *Calanus* congeners on survival of *C. finmarchicus* early stages). There was no apparent relationship between temperature and the timing of the bloom (not shown).

**Dormancy**

Considerable variability in the timing of dormancy across the range of *C. finmarchicus* has been recorded (e.g. Planque et al., 1997; Hind et al., 2000; Johnson et al., 2008). Using the dormancy timing metrics described by Johnson et al. (2008), we calculated dormancy entry and exit dates of *C. finmarchicus* for 15 time series data sets throughout the North Atlantic (Fig. 10a and b). In general, the start date of dormancy was more variable than the end date, and the northwest Atlantic had more variability in timing than the northeast Atlantic over similar spatial scales. The dormancy metrics indicated that *C. finmarchicus* enters dormancy later at the northwest Atlantic sites but that the timing of arousal occurs over a relatively short period in late winter (20–60 d) across all stations. In the northwest Atlantic, the major exceptions are the Rimouski and Shediac stations in the Gulf of St. Lawrence, but these may be skewed by the absence of sampling in late winter due to the presence of ice cover. In the northeast Atlantic, the very late exits from dormancy at Foinhaven and Vestfjorden (10 and 15 in Fig. 10) are likely due to local effects on the calculation of dormancy exit times, involving the possible inclusion of a high number copepods that may have been *C. helgolandicus* or the short length of the time series (<2 yr). Inclusion of *C. helgolandicus* will be a general problem in time series from the North Sea and south of the Norwegian Sea, unless *C. helgolandicus* have been identified (Bonnet et al., 2005). Around Iceland and farther west the numbers of *C. helgolandicus* are small. The data suggest that duration of dormancy, from time of entry to time of exit, is shorter in the western North Atlantic than in the eastern North Atlantic. Our estimate of the median duration of dormancy is 200 d in the northwest Atlantic and 250 d in the northeastern Atlantic (270 d if two outliers, Iceland and Faroes, are excluded). There are no time series with sufficient temporal resolution to make these calculations in the middle of the Atlantic (e.g. in the Irminger and Labrador Seas).

**Egg production**

Broad-scale regional differences in egg production rate (EPR), clutch size (CS), spawning frequency (SF) and prosome length (PL) were examined by averaging all observations carried out within a given region during a given season (Fig 11). Average female egg production rates were generally highest in spring and summer within regions, and the spring and summer rates were generally higher west of the Irminger Sea (in the GB, SS, RIM and LS regions) and in the ICE(N) region than in the Irminger Sea (IRM) or farther east. One exception to this east–west pattern was the WGBB region, where rates were lower than in other western regions, particularly in spring, when chlorophyll concentrations were very high and temperatures, very low (Fig. 4). Egg production rates were relatively high in winter on GB, but no females laid eggs in experiments carried out during winter in the RIM, IRM and SNWS regions. Average experimental clutch sizes were highest at RIM and in the LS. Spawning frequencies were generally lower in autumn and winter than in spring and summer, but relatively high for GB and NWNS (73% d\(^{-1}\) and 78% d\(^{-1}\) in winter and low (13% d\(^{-1}\)) for SNWS in summer. The highest average female prosome lengths were in the SS, RIM, LS and IRM regions and the lowest, in the North Sea (NS).

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1 For identification of acronyms, see Fig. 4.
Clutch size (eggs female$^{-1}$) increased with increasing prosome length in all regions and seasons, except in the WGBB region, where the two were not related. Most points fell below a line that has been suggested to define the upper limit to clutch size ($CS_{\text{max}}$) per unit length (Jónasdóttir et al., 2005; Fig. 12). One factor that contributes to variations in CS is food availability (Niehoff, 2004; Runge et al., 2006; Jónasdóttir et al., 2008; Head et al., 2013a). Runge et al. (2006) reported a linear relationship between CS and log transformed integrated chlorophyll concentration for females from the GB region. Plots of average experimental CS versus integrated chlorophyll concentration (Intchl) in other regions where the range of chlorophyll concentrations was large enough showed a rapid increase in CS at low chlorophyll concentrations, reaching an upper limit at high concentrations (Fig. 13). The degree of food limitation was investigated on a regional basis by comparing regional average values of CS/$CS_{\text{max}}$, using the Jónasdóttir et al. (2005) relationship to estimate $CS_{\text{max}}$. Including data from all seasons, or from spring alone (Table 4). In spring, the average CS/$CS_{\text{max}}$ values were correlated with average integrated chlorophyll concentrations across all regions ($P < 0.05$), if the anomalous WGBB region was omitted, although the highest CS/$CS_{\text{max}}$ value (58% at RIM) was not in the region with the highest average chlorophyll concentration (ICE(N)). Despite the effect of chlorophyll concentration on CS, experimental averages for CS and PL were significantly correlated in the six of twelve regions (GB, SS, RIM, LS, ICE(S), NS), although not in the others.

Relationships between experimental spawning frequency and integrated chlorophyll concentration (Intchl) showed patterns similar to those shown for CS versus Intchl (Fig. 13), except in the WGBB. CS and SF were significantly correlated in most regions including the WGBB, the exceptions being ICE(S), NNWS and NS [Fig. 14]. As some of the scatter might have been due to the dependency of CS on female size, CS/$CS_{\text{max}}$ values were plotted against SFs. The $r^2$ values for these relationships were generally slightly higher than those for CS vs. SF, and in the NS, the correlation between CS/$CS_{\text{max}}$ and SF was significant ($r^2 = 0.12$) whereas the correlation between CS and SF was not (Fig. 14). Thus, females that are producing large clutches produce them more frequently and in most regions these increases seem to be related to increasing food intake, due to increasing chlorophyll concentration. In the WGBB region, however, the low spring temperatures may limit egg production, despite the high chlorophyll concentrations (Swalethorp et al., 2011; Kjellerup et al., 2012).

Egg production rates generally increased with integrated chlorophyll concentration to a saturating level (Figs. 15 and 16), showing patterns that resemble those for CS and SF vs. Intchl. Elsewhere (e.g. Runge et al., 2006; Head et al. 2013a) the relationship between EPR and Intchl has been fitted to an Ivlev function of the general form.

$$y = y_0 + a(1 - e^{-bx})$$

where $y$ is the EPR at chlorophyll concentration $x$, $y_0$ is the EPR when the chlorophyll concentration is zero (for positive $y_0$ values), or indicates the threshold below which EPR is zero (for negative $y_0$ values), and $a$ and $b$ are constants. Since spring was the only season for which there were measurements in all regions, and in order to increase comparability among the datasets, only spring data were used to examine the relationship between EPR and integrated chlorophyll standing stock. The three parameter equation was fitted to all datasets, but in all regions a two parameter equation, where $y_0$ was equal to zero, gave an equally good fit to the data. There was
always a great deal of scatter about the Ivlev curves (Figs. 15 and 16, Table 5). The $r^2$ values for the Ivlev function were >0.2 in two of five regions in northwest Atlantic and in two of four regions in the northeast Atlantic, but <0.2 for all three regions in the central North Atlantic.

Two of the factors that might be expected to contribute to this scatter are female size and temperature. Female size has a direct effect via its influence on CS, and temperature could have either a direct effect, as it does on most physiological rates, or an indirect effect via its influence on female size, which varies with long-term food and temperature conditions (e.g. Campbell et al., 2001). A direct effect of temperature on spawning frequency has been demonstrated when groups of females from a common source population are brought into the laboratory and experimental incubations are run at different temperatures (Runge and Plourde, 1996; Hirche et al., 1997). In the sea, however, for Georges Bank (January–June: Runge et al., 2006) and the NW Atlantic sub-polar gyre (January–June: Gislason, 2005; May–June: Head et al., 2013a) there was no observable effect. In order to see whether either of these factors was contributing to the variability in the expected EPR versus Intchl relationships, the residuals (i.e. the EPR values observed – the EPR values predicted by the Ivlev fits) were plotted against the average experimental female prosome length, or the ambient near-surface (and experimental) temperature within each region. In three regions (GB, RIM, LS) the residuals were positively correlated with prosome length, although the correlations were weak ($r^2 = 0.12–0.20$) (Table 6). Temperature was also positively correlated with the residuals in three regions (GB, RIM, ICE(N)), but in one (IRM) there was a negative correlation, and in all cases the proportion of the variance accounted for was low ($r^2 = 0.12–0.21$). Multiple regression analysis did not improve these results.

Fig. 11. Regional averages, by season, of C. finmarchicus egg production rates, clutch sizes, spawning frequencies and female prosome (body) lengths. Clutch sizes and prosome lengths were determined using experimental (i.e. station) averages. Horizontal lines, boxes, whiskers and points as in Fig. 4.
Even though temperature could not explain the scatter in the Ivlev plots, suggesting that it has no substantial impact on egg production rate in most regions in spring, the very low springtime temperatures in the WGBB region do appear to reduce EPRs since here, despite high chlorophyll concentrations, the upper limit for EPR was 11 eggs $f^{-1} d^{-1}$ (Table 5). As well, maximum EPRs measured during summer at higher temperatures were generally much higher than those found in spring at similar chlorophyll concentrations (Figs. 4 and 15).

Attempts were also made to reduce the scatter of the Ivlev plots by scaling the EPR values to female size. Both EPR/PL and EPR/CS$_{\text{max}}$ transformations were used, but neither led to any appreciable increases in $r^2$ values for the Ivlev curve fits. Elsewhere, EPR values have been scaled to female body size in terms of body carbon (C) or body nitrogen (N) content, and EPRs have been expressed as % female body C (or N) $d^{-1}$, using literature values for egg C and N content (Runge and Plourde, 1996). Runge et al. (2006) found that Ivlev curve fits to Intchl vs. EPR data, where the EPRs were expressed in this way, measured between January and June, tended to maximum values of 8.5% body C $d^{-1}$ and 7.7% body N $d^{-1}$ in the GB region. The $r^2$ value they report ($r^2 = 0.42$) was lower than the value reported here ($r^2 = 0.47$) for EPR expressed as eggs $f^{-1} d^{-1}$ derived using only data from April and May. Head et al. (2013a), using experimental data collected between May and July in the central basin of the Labrador Sea, found that scaling EPRs to female body N slightly increased the $r^2$ value for the Ivlev fit for EPR vs. Intchl ($r^2 = 0.48$ vs. 0.47), while scaling to body C reduced it ($r^2 = 0.38$). These curves tended towards maximum EPR values of 8.5% body C $d^{-1}$ and 7.2% body N $d^{-1}$, very similar to the values on GB.

For a comparison of total $C.\text{finmarchicus}$ egg production across regions, it should be noted that, despite variability in estimates of individual female EPRs, total population egg production rates (eggs $m^{-2} d^{-1}$) are strongly influenced by the abundance of females, and that the contributions of the regions to the North Atlantic as a whole depend on their geographical areas. Thus, the gyres of the northeast (NNWS, SNWS) and the northwest (LS, IRM) Atlantic, with their high average female abundances and vast areas, account for >80% of the total North Atlantic egg production of $C.\text{finmarchicus}$ on a daily basis in spring (Table 7). On the other hand, the duration of the spawning season is probably shorter for the gyres than in coastal or more southerly regions (see dormancy duration Fig. 10) and mortality rates for the egg–CI transition are also relatively high (see following section).

**Mortality and survival of Calanus finmarchicus**

There were significant differences in stage specific daily mortality rates among offshore and shelf habitats in the northeast and northwest Atlantic (Fig. 17a). Most notably, mortality from egg to CI was lower on the shelf than in the offshore in the northwest Atlantic (Kruskal–Wallis test, $p < 0.0001$), whereas CIV–CV mortality was significantly greater in shelf habitats than in both oceanic basins (Mann–Whitney test, $p < 0.05$). Mortality estimates for stages CV–CVI also showed important variability, but negative values, likely due to recruitment to and/or advection of adult stages from the overwintering CV stock on the shelf in the northeast Atlantic and offshore in the northwest Atlantic, precluded a more detailed analysis. No significant differences among habitats and regions (eastern vs. western North Atlantic) were detected for the stage pairs CI–CII and CIII–CIV ($p > 0.05$). Daily mortality rates for the egg–CI transition and the stage pairs CIV–CV and CV–CVI were positively related to temperature but with relatively low coefficients of dependence, the highest being for the egg–CI transition.
No significant relationship between mortality and temperature was detected in the other stage pairs (Table 8). Because the proportion surviving through each stage pair represents the integration of daily mortality over stages, variations in survival among habitats and oceanic basins were somewhat different from variations depicted for daily mortality rates (Fig. 17b). Survival from egg to Cl was much greater for shelf than for offshore habitats on both sides of the Atlantic (habitats; M–W, p < 0.0001). Overall, differences in survival were significant until the CIII–CIV stage pair, but with a much lower significance level (Fig. 17b).

Average stage-specific recruitment rate (number m$^{-2}$ d$^{-1}$) was calculated using the population birth rate (PopEPR) and the proportion surviving through each stage pair for the offshore and shelf habitats in the northwest and northeast Atlantic (Fig. 18). Region-specific survival trajectories of the developing cohort were normalised using the same PopEPR (50,000 eggs m$^{-2}$ d$^{-1}$) for all regions. Survival trajectories were similar, with the notable exception of recruitment to CI offshore in the northwest Atlantic (low survival) and a low survival from CII to CIV in the offshore habitat in the northeast Atlantic.

Daily mortality rates for the egg–CI transition were generally higher in habitats colder than 6°C where there was a greater likelihood for C. finmarchicus to co-occur with high abundances of its congeners C. hyperboreus and C. glacialis in the surface layer (Mann–Whitney test, p < 0.0001) (Fig. 19). These latter species are thought to feed on C. finmarchicus eggs and nauplii, since both reproduce before the spring bloom, so that their offspring are abundant and feeding during the bloom when C. finmarchicus are spawning. Our observations are consistent with this idea, since,
**Discussion**

**Abundance, distribution and life history characteristics of Calanus finmarchicus across its North Atlantic habitat**

The data we have compiled here represent considerable multinational effort spanning several decades. Much progress has been made in understanding *C. finmarchicus* life histories and the underlying processes needed to model its population dynamics in the context of developing climate change scenarios for the North Atlantic. The ocean circulation system and its associated water mass characteristics exert important influences on the distribution of *C. finmarchicus*, but distribution patterns are also influenced by regional differences in physiology, life history and ecological characteristics. Our analysis and synthesis of the assembled datasets focuses on regional similarities and differences between the northwest and northeast Atlantic with respect to processes determining the distributions and abundances of shelf and basin *C. finmarchicus* populations and life history responses to environmental variables.

The mean annual distribution of *C. finmarchicus* in the near surface layer, based on CPR measurements alone, is mainly restricted to the northern and western North Atlantic within an area delimited between the 5 °C and 10 °C annually-averaged sea surface isotherms (Fig. 5), in agreement with previous reports of mean annual maximal abundances at SSTs of between 5 and 10 °C, and critical SST boundaries of 9 and 12 °C (Beaugrand et al., 2008; Helaouët and Beaugrand, 2009). Overall, CPR data show that *C. finmarchicus* is more abundant in the northwest Atlantic, which is cooler and where the average chlorophyll standing stock is greater, than in the northeast Atlantic (see also Longhurst, 1998; Helaouët and Beaugrand, 2009; Helaouët et al., 2011). However, the results
Based on net data that includes the population epicentres within the subpolar-gyres of the Norwegian and Labrador Seas (Heath et al., 2000a, 2004, 2008; Head et al., 2003; Melle et al., 2004) indicate that the highest *C. finmarchicus* abundances are found north of the CPR routes. This supports the idea that maximum *C. finmarchicus* abundances are found in the deep basins of these seas (Fig. 6) or close to them. In the warm northeast Atlantic particularly, this changes our view of *C. finmarchicus* distribution compared to the perspective from CPR data alone. For this reason, since 2008, the spatial coverage of CPR monitoring has been expanded to cover the core areas of *C. finmarchicus* distribution in the Norwegian Sea. We analysed temperature measurements from the vertical domain of *C. finmarchicus* during the productive season and calculated mean maximum temperatures for the sampling sites (Fig. 8). Net data show that maximum abundances of *C. finmarchicus* in the core area of its distribution occur at sites with maximum temperatures between 11 °C and 13 °C. This is slightly higher than previously reported values (Beaugrand et al., 2008; Helaouët and Beaugrand, 2009). To define the temperature ranges that are presently occupied and those that are critical (i.e. beyond which *C. finmarchicus* is absent), further analysis that includes net collected data across the species distributional range is needed. Thus we conclude that habitat and population dynamics modeling in the future should include data sets obtained from CPR and net hauls, which complement each other in terms of sampling coverage.

The major overwintering areas for *C. finmarchicus* in the North Atlantic are the southern Norwegian Sea and the Irminger/Labrador Sea Sub-polar Gyre (Heath et al., 2004). The 24 net sampling sites included here in the analyses of demography and phenology (Table 1, Fig. 1b). Proximity to an overwintering centre has been suggested to be the main prerequisite for high abundance of *C. finmarchicus* (e.g. Heath et al., 2000a, 2008; Speirs et al., 2004; Torgersen and Huse, 2005; Head et al., 2013b) and to a large extent our observations are consistent with this.
notion, as the seven sites with highest abundances are located within or close to the two major overwintering basins (Fig. 6). Station Mike and the Svinøy section Atlantic and Arctic water regions are situated within the gyre of the southern Norwegian Sea. The Svinøy coastal region is located on the Norwegian Shelf, on the eastern rim of the southern Norwegian Sea deep basin, and coupled life-history/circulation models have demonstrated that *C. finmarchicus* can be recruited to the shelf population from the gyre population to the west (Speirs et al. 2004; Samuelson et al. 2009). Similarly, the Westmannaey site on the southern Icelandic shelf and the West Greenland shelf site on the southwestern Greenland shelf are situated close to the Irminger/Labrador Seas Gyre, while the Eastern Labrador Sea site is within the gyre. The overwintering female population at the central Labrador Sea site, also located within this gyre, is very abundant prior to spawning but here the number of first generation copepodites is very low, indicating high mortality during development and low local recruitment (Head et al., 2013a).

Total maximum abundance of *C. finmarchicus* populations at the study sites increased with increasing maximum water temperature within the range of about 3–13 °C, although some locations particularly in the North Sea, seem to deviate from this trend. Apart from being more distant from the overwintering epicentres these locations may also be less favourably positioned with respect to advection of animals from the population centres. The earliest recruitment to the young copepodite stages occurred at sites with high maximum temperatures, except at some coastal sites (Figs. 8 and 9 upper panel), and maximum abundance of the young stages occurred during or just after the phytoplankton bloom maximum (Fig. 9 lower panel). From these three relationships it is reasonable to infer that if recruitment can match an early phytoplankton bloom, production of *C. finmarchicus* populations will be improved. By contrast, *C. finmarchicus* in cold Arctic regions of the Norwegian Sea and in the northwest Atlantic tend to recruit to young stages long after the bloom and abundances of the species are lower there than in Atlantic water (Broms et al., 2009; Plourde et al. 2009b).
duration) were used. Regions are as in Table 2. For the WGBB region results from all experiments (24–48 h duration) were used. Regions are as in Table 2.

Table 5

<table>
<thead>
<tr>
<th>Region</th>
<th>(a)</th>
<th>(b)</th>
<th>(r^2)</th>
<th>Intchl (95%) (mg m(^{-2}))</th>
<th>Avg. Intchl in spring (mg m(^{-2}))</th>
<th>No. of stns. &gt;Intchl 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>60.4</td>
<td>0.029</td>
<td>0.47</td>
<td>103.3</td>
<td>79.6</td>
<td>25</td>
</tr>
<tr>
<td>SS</td>
<td>36.8</td>
<td>0.056</td>
<td>0.15</td>
<td>53.3</td>
<td>80.5</td>
<td>63</td>
</tr>
<tr>
<td>RIM</td>
<td>50.3</td>
<td>0.032</td>
<td>0.26</td>
<td>91.6</td>
<td>97.5</td>
<td>33</td>
</tr>
<tr>
<td>LS</td>
<td>58.1</td>
<td>0.042</td>
<td>0.19</td>
<td>71.9</td>
<td>80.2</td>
<td>39</td>
</tr>
<tr>
<td>WGBB</td>
<td>10.9</td>
<td>0.035</td>
<td>0.07</td>
<td>85.5</td>
<td>275.1</td>
<td>76</td>
</tr>
<tr>
<td>IRM</td>
<td>35.0</td>
<td>0.033</td>
<td>0.08</td>
<td>90.8</td>
<td>36.4</td>
<td>8</td>
</tr>
<tr>
<td>ICE(N)</td>
<td>60.1</td>
<td>0.011</td>
<td>0.18</td>
<td>282.6</td>
<td>136.7</td>
<td>11</td>
</tr>
<tr>
<td>ICE(S)</td>
<td>30.1</td>
<td>0.062</td>
<td>0.13</td>
<td>48.6</td>
<td>55.1</td>
<td>39</td>
</tr>
<tr>
<td>BIS</td>
<td>19.0</td>
<td>0.215</td>
<td>0.05</td>
<td>13.9</td>
<td>42.6</td>
<td>63</td>
</tr>
<tr>
<td>SNWS</td>
<td>25.6</td>
<td>0.052</td>
<td>0.23</td>
<td>57.4</td>
<td>32.9</td>
<td>14</td>
</tr>
<tr>
<td>NNWS</td>
<td>18.9</td>
<td>0.174</td>
<td>0.08</td>
<td>17.2</td>
<td>84.2</td>
<td>85</td>
</tr>
<tr>
<td>NS</td>
<td>24.4</td>
<td>0.078</td>
<td>0.24</td>
<td>38.2</td>
<td>53.2</td>
<td>49</td>
</tr>
</tbody>
</table>

Neither high temperatures nor recruitment during early phytoplankton blooms are enough to guarantee an abundant population, since some sites are characterised by high temperature and agreement between recruitment and bloom time but yet have scarce populations. One explanation that we have not explored by data analysis here is unevenly distributed predation pressure among the sites. In the Norwegian Sea a range of different predators have been identified and both direct and circumstantial evidence of predation have been found. Predation from herring on copepods which were mainly \(C. finmarchicus\), was estimated to be similar to the annual production of the prey (Dommasnes et al., 2004), Skjoldal et al. (2004) estimated pelagic fish predation on \(Calanus\) to be ~30% of annual production, Utne et al. (2012) using ecosystem model simulations estimated predation from pelagic fish stocks at 35 mill tonnes, or 18% of the annual \(C. finmarchicus\) production (Hjollo et al., 2012). It has also been found that \(C. finmarchicus\) stock size is negatively correlated to total pelagic fish stock size the previous year in the Norwegian Sea (Olsen et al., 2007; Huse et al., 2012), suggesting top down controls at a large scale. Additionally, predation from macroplankton predators and mesopelagic fishes may greatly exceed predation from the pelagic fish stock (Skjoldal et al., 2004). In fact, when summing assumed consumption of \(C. finmarchicus\) by all the predators the total predation loss tends to be much larger than the \(C. finmarchicus\) production in the Norwegian Sea, strongly suggesting that predation is the terminal cause of mortality there and that new estimates on production and consumption are needed. We do not have similar information on \(C. finmarchicus\) predators in the other deep basins, but the presence of large pelagic fish stocks in the Norwegian Sea is one clear difference in the predatory communities between the two major overwintering deep basins in the Norwegian Sea and the Labrador/Irminger Seas. However, even though \(C. finmarchicus\) may be more heavily grazed in the Norwegian Sea, this is also the basin with the highest \(C. finmarchicus\) abundance. Therefore, we hypothesise that the Labrador and Irminger Sea possess predatory stocks made up of macrozooplankton and mesopelagic fishes that inflict considerable predation pressure on \(C. finmarchicus\).

Predation on the overwintering population is another source of mortality that needs further investigation, although data from the two major overwintering basins, the southern Norwegian Sea and the Labrador Sea, indicate that mortality during overwintering is low and less variable than during the active phase (Head et al., 2013a; Melle et al., in prep). Still, losses of almost the entire population from the Norwegian shelf during winter indicate that predatory or advective losses during winter may be substantial in shallower regions (Slagstad and Tande, 1996; Melle et al., 2004).

Predation may shape the population distribution in the regions of marginal \(C. finmarchicus\) productivity such as the sites with low temperature or with a mismatch to the bloom. Our mortality rate calculations suggest high predation pressure on eggs and nauplii, which we suspect is by the suspension feeders, \(C. hyperboreus\) and \(C. glacialis\) (in addition to cannibalism by \(C. finmarchicus\) CVI), This occurs because \(C. hyperboreus\) and \(C. glacialis\) have multi-year life cycles and therefore are present as copepodite stages early in the spring bloom, when \(C. finmarchicus\) reproduction is starting (Conover, 1988). Thus, during the late spring-early summer period, recruitment of \(C. finmarchicus\) is suppressed and there is a delay in the timing of maximum CI-CII abundance until well after the bloom (section ‘Mortality and survival of Calanus finmarchicus’, Figs. 19 and 20). This interaction with Arctic congeners should be more prominent at sites where CI-CII recruits peak several weeks after the bloom, such as at the Anticosti Gyre, Gaspé Current, Station 27 and Labrador Shelf sites. One exception is the lower St. Lawrence estuary (RIM) where the bloom is delayed relative to the adjacent Anticosti Gyre due to freshwater runoff, so that it co-occurs with the relatively late CI–III peak (Fig. 9). Surface layer temperatures in cold (3 °C mean) and warmer habitats (10 °C mean) during the population growth period should result in development times from egg to N6 of 30 and 15 days respectively.
representing only a two week difference (Campbell et al., 2001). Therefore, differences in temperature alone cannot explain the long delays (up to 3.5 months) observed between the timing of maximum in CI–CIII abundance and the bloom at the cold water sites, which is consistent with our suggestion of predation by the arctic Calanus species.

The demographic pattern observed in the central Labrador Sea is similar to the spatial demography observed within the central Irminger Basin, for which sources of overwintering copepodites are hypothesised to be recruitment along the eastern and northern margins and subsurface horizontal transport from the east Greenland slope and Labrador Sea (Heath et al., 2008). Recruitment failure in the central Irminger Basin, likely due to high predation mortality in the early life stages and/or starvation of the first feeding nauplii at persistently low food conditions, is hypothesised to preclude direct descent as a major source of overwintering stage CV (Heath et al., 2008). In the central Labrador Sea, food (i.e. phytoplankton) concentrations and egg production rates are higher (e.g. Fig. 15) than in the Irminger Basin, and early life stage mortality due to cannibalism by adult C. finmarchicus and predation by C. hyperboreus and other as yet unrecognised predators (Head et al., 2003, 2013a) may be more important sources of recruitment failure.

The deep basin populations appear to be the main sources of supply of C. finmarchicus overwintering stages to the central and

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**Table 8**

<table>
<thead>
<tr>
<th>Stage pair</th>
<th>r²</th>
<th>p-value</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egg–CI</td>
<td>0.227</td>
<td>&lt;0.0001</td>
<td>0.101</td>
<td>0.094</td>
</tr>
<tr>
<td>CI–CII</td>
<td>–</td>
<td>&gt;0.05</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CII–CIII</td>
<td>–</td>
<td>&gt;0.05</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CIII–CIV</td>
<td>–</td>
<td>&gt;0.05</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>CIV–CV</td>
<td>0.041</td>
<td>&lt;0.0001</td>
<td>0.034</td>
<td>0.090</td>
</tr>
<tr>
<td>CV–CVI</td>
<td>0.048</td>
<td>&lt;0.0001</td>
<td>0.044</td>
<td>0.098</td>
</tr>
</tbody>
</table>

**Fig. 17.** (A) Stage-specific daily mortality rates and (B) proportion surviving through each stage pairs during population growth period of C. finmarchicus in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean ± standard error.

**Fig. 18.** Stage-specific daily recruitment rate during population growth period of C. finmarchicus in offshore and shelf habitats in the northeast (NE) and northwest (NW) Atlantic. See text for definition of different habitats. Values represent the mean ± standard error.
northeastern North Atlantic shelf populations. On-shelf transport from the Norwegian Basin of overwintered adults prior to midsummer and early life stages later in the year is the primary source of *C. finmarchicus* to the relatively narrow Norwegian shelf (Samuelson et al., 2009). Field and modelling studies (e.g. Heath et al., 1999; Harms et al., 2000) support the hypothesis that the population of *C. finmarchicus* in the North Sea is sustained by annual spring advection of late-stage individuals originating from high concentrations of stage CVs overwintering in the deep Atlantic and Norwegian Sea, particularly the Faroe-Shetland Channel (Heath et al., 1999). In the North Sea, the maximum abundance of *C. finmarchicus* is low (on the order of $5 \times 10^3$ ind. m$^{-2}$: Heath et al., 2000a; Jónasdóttir and Koski, 2011), despite relatively high egg production rates (Jónasdóttir and Koski, 2011; Fig. 16). The primary factor controlling abundance in the North Sea appears to be predation mortality during the early life stages (Jónasdóttir and Koski, 2011), which probably also holds for the older stages, which cannot migrate vertically far enough to avoid predation, because of the relatively shallow bathymetry.

Other time series sites are farther from the deep basin epicentres or have lesser degrees of direct advective connection, which limits repopulation from the deep ocean overwintering sites by members of the overwintering or first generations. The Arendal and the two northern Icelandic sites have long transport routes from their nearest overwintering areas, the Norwegian Sea and the deep basins south of Iceland (Gislason and Astthorsson, 1998; Heath et al., 2000b; Astthorsson and Gislason, 2003; See Appendix and Fig. 1b), and the Faroese Shelf site is located behind a strong tidal front, within an anticyclonic shelf gyre that results in a short retention time and increased dispersal of shelf plankton and reduced advection of oceanic plankton onto the shelf (Debes and Eliassen, 2006). Recruitment of G0/G1 on the Labrador/Newfoundland shelves that are adjacent to a deep overwintering area does not seem to be as effective as the recruitment to the southern Icelandic and western Norwegian shelves (Westmannaeyj and Sviney Coast sites). This may be because the Labrador/Newfoundland shelves are broad relative to the Icelandic/Norwegian shelves and are not deep enough to sustain overwintering populations, and also because there are relatively high concentrations of *C. hyperboreus* and *C. glacialis* present in spring, which can consume *C. finmarchicus* eggs and nauplii (see sections ‘Mortality and survival of *Calanus finmarchicus*’ and ‘Mortality’).

In contrast to the northeast Atlantic, the marginal seas of the northwest Atlantic (the Gulf of St. Lawrence and the Gulf of Maine) harbour local overwintering stocks, and local production is as important as advective supply from the slope water in sustaining local *C. finmarchicus* populations. Overwintering stage CVs reside at 150–175 m in the deep (300–400 m) Laurentian Channel of the Gulf of St. Lawrence and the deep basins (250–400 m) of the Gulf of Maine (Plourde et al., 2001; Johnson et al., 2008) at abundances (20–40 $\times 10^3$ ind. m$^{-2}$) of the same order of magnitude as *C. finmarchicus* stocks in the deep basins (e.g. Heath et al., 2000b; Halvorsen et al., 2003). As well, a modeling investigation has indicated that the Gulf of St. Lawrence population is self-sustaining (Zakardjian et al., 2003). The roles of local production versus advective supply from the Scotian Shelf, Labrador and Atlantic slope water in maintaining the Gulf of Maine basin populations are still not determined, although there is evidence that coastal Gulf of Maine production is a significant local source (Maps et al., 2012). Nevertheless, the relatively warm overwintering temperatures in the deep Gulf of Maine reduce dormancy duration, and supply from the colder northern sources in the Gulf of St. Lawrence and
distant Labrador Sea may become increasingly important to maintain the population of *C. finmarchicus* in the Gulf of Maine region under climate forcing.

When considering impacts of climate warming on *C. finmarchicus* distribution in the northern North Atlantic, the differences in the interplay between bathymetry, advective supply and local birth and mortality rates all need to be taken into account. Increasing surface layer temperature will certainly be a factor at the southern geographical edge of the species range. Surprisingly, the upper temperature threshold at which growth and development rates start to be constrained is not well known, but is likely to be between 16 and 19 °C (Moller et al., 2012; Runge and Preziosi, unpubl. observations). Overwintering water temperature is also a factor for southern populations; for example, the warm deep water temperatures in the Gulf of Maine currently appear to force *C. finmarchicus* to emerge from diapause considerably earlier than it does in more northern regions (Saumweber and Durbin, 2006; Johnson et al., 2008; Maps et al., 2010, 2012), an effect that is likely to be exacerbated as water temperatures warm in the future. At the moment the southern limit of the distribution of *C. finmarchicus* in the northwest Atlantic (the Gulf of Maine/Georges Bank) is maintained by the stocks overwintering in the basins in the Gulf of Maine (Miller et al., 1998) and along the shelf-slope region of the Scotian Shelf (Head et al., 1999; Head and Pepin, 2008), in combination with advective input from upstream sources, including the surface layers of the Scotian Shelf and the Gulf of St. Lawrence (Head et al., 1999) and the Labrador Sea, via the Labrador Shelf and Slope water currents (Greene and Pershing, 2007; Head and Pepin, 2010). In the northeast Atlantic, however, the mean residual flow is from south to north, resulting in warmer water incursions at higher latitudes. Maintenance of *C. finmarchicus* on the northeast shelves will therefore depend on continuing advective supply from the deep Norwegian Sea. For the North Sea, the southern edge of the northeast Atlantic shelf distribution, advective supply is a function of the deep transport of *C. finmarchicus* from the Norwegian Sea to the Faroe-Shetland Channel, together with local and regional wind fields transporting individuals into the North Sea in the surface layers. The distribution of *C. finmarchicus* at its northern boundary and its ability to colonise the Arctic may be constrained by the effects of less light and colder temperatures, which lead to both a shorter phytoplankton growth season length and slower *C. finmarchicus* development rates (Broms and Melle, 2007; Broms et al., 2009; Ji et al., 2012). As well there is the potential for predation on *C. finmarchicus* early life stages by its Arctic congeners, *C. glacialis* and *C. hyperboreus*. Climate change scenarios can be investigated in coupled physical-life history models for shelf and offshore regions of both the northeast and northwest Atlantic, although accurate prediction of future distributions will also require information on the distributions of potential predators and how they respond to climate change.

### Life history responses to environmental variables

Understanding the spatial population dynamics of *C. finmarchicus*, or any animal population in the sea, requires the capability to quantitatively characterise birth and mortality rates, as well as immigration and emigration rates. The representation of copepod life histories, including population demographics, by life history models has been discussed elsewhere (e.g. Runge et al., 2005; Ji et al., 2010; Neumheimer et al., 2010; see also section below). Essential to this quantitative analysis is the parameterization of vital rates, including development, growth, egg production and mortality. While models of *C. finmarchicus* life cycles have already shown insight into factors controlling populations at both regional (e.g. Speirs et al., 2004; Samuelson et al., 2009; Maps et al., 2012) and basin scales (e.g. Speirs et al., 2006; Hjollo et al., 2012), the choice of parameter values in many cases is still open to considerable uncertainty (e.g. Maps et al., 2012) due to the need for more comprehensive datasets. For example, the parameterization of growth rates as functions of food availability and temperature is based almost exclusively on the now classic work by Campbell et al. (2001) using *C. finmarchicus* collected from the Gulf of Maine in the northwest Atlantic. The extent to which the physiological responses of *C. finmarchicus* captured from the northwest Atlantic are representative of those of individuals in the northeast Atlantic is still an open question in light of the finding of genetic differentiation of two and perhaps as many as four populations across the species’ range (Unal and Bucklin 2010). Here we interpret the available data on diapause timing, egg production and mortality rates in relation to habitat variables in order to assess the state of our understanding of parameterization of these variables across the entire basin.

#### Diapause duration and timing

Our analysis of the pan-Atlantic demographic data (Figs. A1–A6) provides evidence for a longer active period and shorter dormancy...
duration in the northwest Atlantic than in the northeast, although not necessarily for a greater number of distinct “generations”. An interpretation consistent with the finding of higher chlorophyll concentrations and lower surface temperatures in the northwest Atlantic is that the more favourable food conditions contribute to more sustained egg laying, leading to a prolonged growth season, but combined with slower development this does not necessarily result in more generations. For example, at the Gulf of St. Lawrence Rimouski station, prolonged summer production results in a broad period of recruitment lasting several months. Seasonally late egg production in the northwest Atlantic may, however, also yield an active population of early copepodites constituting a “lost generation”, i.e., individuals that do not enter dormancy with the bulk of the population and consequently delay the metric indicating start of diapause. The presence of a fraction of the population that continues to develop while most of the population enters dormancy has been observed in many locations (e.g., Meise and O’Reilly, 1996), although the offspring of these individuals may not survive to reproduce. Higher overwintering temperatures in the northwest Atlantic, where overwintering C. finmarchicus experience temperatures ranging from about 1 to 10 °C, with highest values in Emerald Basin on the Scotian Shelf (Head and Pepin, 2008) and in the Gulf of Maine (Maps et al., 2012), likely also contribute to differences in dormancy timing and duration.

There is variability in the number of identifiable generations among sampling sites, but without any distinct west–east pattern (Fig. A1–A6). In the coastal Gulf of Maine stage CV emerges from dormancy in late December, possibly earlier (Durbin et al., 1997; Maps et al., 2012), and 2–3 generations are produced over the course of a season. In contrast, upstream of the Gulf of Maine on the Scotian Shelf, emergence occurs in February–March and 1–2 generations are produced (Sameoto and Herman, 1990; Herman et al., 1991; McLaren et al., 2001), although production may extend into the fall in some areas and some years (Head and Pepin, 2008). In the adjacent slope water, emergence from dormancy also occurs in February–March, but yields only one generation (Miller et al., 1991). In the Gulf of St. Lawrence and on the Newfoundland Shelf, C. finmarchicus generally emerges from diapause in late March–early April and produces one large summer generation followed by a smaller one in autumn (Plourde et al., 2001; Johnson et al., 2008; Pepin et al., 2011). In the Iceland Basin, stage CVs emerge in March–April, while in the Irminger Basin, emergence begins in February (Gislason and Astthorsson, 2000). In the Irminger Basin, C. finmarchicus mainly produces one generation before entering diapause in late July or early August, but a small percentage molt to adulthood and continue active development (Heath et al., 2008). On the shelf south of Iceland, 2–3 generations are produced, with the main population peaks in May/June and June/July (Gislason et al., 2000). In the Norwegian Sea, C. finmarchicus start to emerge from dormancy in January and February (Melle et al., 2004; Edvardsen et al., 2006), and there are typically one or two generations annually (Petersen et al., 2000; Melle et al., 2004; Bros and Melle, 2007; Bros et al., 2009; Bagoeien et al., 2012).

A qualitative assessment finds the demographic data consistent with a lipid dependent mechanism (Ingrioen, 2004; Johnson et al., 2008; Maps et al., 2010, 2012) to explain spatial and temporal variability in dormancy timing and duration. Under this hypothesis, the food and temperature conditions determine the accumulation of storage lipid in individual copepodites. Only when lipid accumulates above a nominal threshold level is the signal (likely hormonal, see Tarrant et al., 2008) given for that individual to prepare for diapause in stage CV. During lipid accumulation, C. finmarchicus has been shown to regulate the composition of the storage lipids, biochemically altering the saturation state (Clark et al., 2012). If the threshold is not attained and hence the signal not received, the individual remains active and molts to adulthood. According to this hypothesis, duration of dormancy is determined by the rate of storage lipid utilisation, which is regulated by storage lipid composition (Clark et al., 2012) and is temperature dependent (Saumweber and Durbin, 2006; Pierson et al., 2013). Thus, the within-region and cross Atlantic differences in dormancy timing and duration could reflect the environmental conditions experienced by individuals within each local population. The warm overwintering temperatures in some areas of the northwest Atlantic may promote early emergence from dormancy, for example in the Gulf of Maine (Durbin et al., 1997), where the exceedingly warm (for this species) overwintering temperatures may force exit from dormancy in late summer and entry into dormancy later in the fall by subsequent cohorts (Maps et al., 2012). Short dormancy duration in these warm areas, and late entry in fall, may contribute to the explanation of the relatively short period in late winter (days 20–60: Fig. 10) over which stage CVs emerge from dormancy throughout the North Atlantic. The alternative (although not necessarily mutually exclusive) hypothesis of photo-awakening (Speirs et al., 2004), in which photoperiodic cues are invoked to explain synchronicity of arousal from dormancy, cannot be ruled out, however.

Future advances in understanding of dormancy timing and duration and the mechanisms to explain it will require continued collection of time series data and quantitative application of the lipid accumulation/metabolism hypothesis across data sets. Many of the data sets compiled here do not have sufficient frequency of sample collection or length of time series to allow accurate determination of dormancy timing and duration. There are fewer long-term offshore time series in the northwest Atlantic than in the northeast Atlantic, and none in the middle of the basin. Further insight into dormancy control will require time series observations at strategically selected stations at relatively high frequency (semi-monthly to monthly) over several years (Ji et al., 2010), including biochemical and perhaps genetic measurement of dormancy state in order to accurately characterise regional and individual differences in timing and duration of dormancy.

**Reproductive rates**

Egg production rates (EPRs) are clearly strongly related to food availability throughout the North Atlantic, but the goal of precisely predicting EPRs for C. finmarchicus from simple environmental variables, such as chlorophyll concentration and temperature, and female size remains elusive, in light of the high degree of variability reported here (e.g. Figs. 15 and 16). This variability is not surprising, since many other factors can also influence individual EPRs. For example, EPRs are affected by food type (Marshall and Orr, 1972; Niehoff et al., 1999; Jónasdóttir et al., 2002; Niehoff, 2004) and although diatoms are generally dominant during spring, in some regions blooms of other phytoplankton taxa, which may be inferior foods, such as the colonial prymnesiophyte Phaeocystis spp., are common (Soreide et al., 2008). Young females that have recently molted may take several days to attain reproductive maturity and until then are not reproductively active, effective lowering estimated per capita EPR (Plourde and Runge, 1993; Niehoff et al., 1999, 2002). As well, during the later stages of the spring bloom old females may be less fecund (Diel and Tande, 1992; Hirche et al., 1997; Head et al., 2013a, b) and may start to accumulate fat (Head et al., 2013a). At stations where chlorophyll concentrations are very low, particularly in post-bloom conditions, females are known to feed omnivorously (Ohman and Runge, 1994; Runge and de Lafontaine, 1996; Ohman and Hirche, 2001; Levinsen et al., 2000), in which case chlorophyll concentration may not be an appropriate measure of “food” concentration. Moreover, the extent to which contemporaneous estimates of chlorophyll a represent female feeding history will also be a factor; in some instances (e.g. patchy, advective environments such as the
RIM station), chlorophyll concentrations may change substantially from day to day.

Temperature undoubtedly influences EPR in laboratory studies (Hirche et al., 1997; Rey et al., 1999), but the effects of changes in temperature in situ are not broadly predictable. For example, after the effect of food had been accounted for, temperature had a positive correlation with EPRs in 3 study regions (RIM, LS, ICE(N)), a negative correlation in one (IRM) and no relationship in the other 8 (Table 6). On the other hand, EPRmax for females from the WGBB region during spring, where temperatures are close to 0 °C, were four times lower than for those from the SS, where average temperatures are only ~2 °C higher (cf. Figs. 4 and 15). Also, EPRs in the WGBB in spring were substantially lower than those measured for females that were collected at in situ temperatures of ~9 °C and switched to 0 °C (Hirche et al., 1997; Kjellerup et al., 2012) and females collected from the WGBB during the spring bloom took several days to increase their EPRs when fed and incubated at higher temperatures in the laboratory, implying that temperature effects may be relatively persistent. The inability of C. finmarchicus females to produce eggs at high rates at these low temperatures may be one factor limiting the species northern distribution at this time, since the periods of the year over which high food concentrations co-occur with acceptably high temperatures decrease in duration with increasing latitude, so that the effective reproductive and growth seasons are shorter. Indeed, it may be that C. finmarchicus populations are not currently self-sustaining in the WGBB. This region is, however, downstream of an important production area in the eastern Labrador Sea, which may serve as a source of overwintering females on an annual basis.

Temperature during the spring period was negatively or positively related to female size in 7 study regions, and female size was positively related to egg production residuals in 3 regions (GB, RIM, LS). In some regions the changes in temperature were probably associated with differences in water masses among stations, and thus in the source populations for females (e.g. IRM, NNWS) of varying sizes. In others, however, increasing temperatures may reflect the warming of the surface layers over the spring period, and the entry of larger females, possibly from the G1 generation, into the egg-laying population (e.g. GB). In addition, in stratified waters in particular, the selection of which temperature accurately represents the temperature of vertically mobile females is in itself problematic.

Given the observed variability in the relationship between egg production rate and chlorophyll a standing stock across regions, it is not possible at this time to identify any general parameterization of egg production response to measures of food availability and temperature across the North Atlantic. In some regions there is a useful fit (e.g. $r^2 > 0.2$) to an Ivlev-type relationship in spring (GB and RIM; arguably also SS, LS and ICE(N)); in others (IRM, ICE(S), BIS, NNWS), there appears to be no relationship with chlorophyll standing stock. It may be that each region has its own particular relationship (or lack thereof), reflecting regional differences in dynamics and species composition of primary producers, as well as possible physiological differences in resident C. finmarchicus. There is evidence (Figs. 15 and 16; Table 5) for broad regional differences in maximum egg production rate (35–60 eggs female$^{-1}$ d$^{-1}$ in the northwest Atlantic compared to 20–30 eggs female$^{-1}$ d$^{-1}$ in the northeast Atlantic) and in critical concentrations, which range from 53–94 mg chl a m$^{-2}$ in the upper 30 m (1.8 and 3.1 mg m$^{-3}$) in the northwest Atlantic, compared to 17–57 mg chl a m$^{-2}$ (0.6–1.9 mg m$^{-3}$) in the northeast Atlantic (with the exception of a very different relationship at ICE(N)). This factor of two difference may reflect the generally smaller female size in the northeast Atlantic, although the average prosome length of experimental females from GB was about the same as the one for experimental females from the Norwegian Sea, where maximum egg production rates were lower by nearly a factor of three. Alternatively, these broad regional differences in egg production characteristics may reflect physiological and perhaps genetically differentiated responses to the food, light and temperature regimes on the two sides of the North Atlantic. Consistent with this hypothesis is the apparent divergence in conclusions with respect to the use of internal lipid stores to produce eggs prior to the spring bloom; evidence for this process has been found in the northeast Atlantic (e.g. Niehoff et al., 1999; Richardson et al., 1999) but not in the northwest Atlantic (e.g. Plourde and Runge, 1993; Durbin et al., 2003). Production of eggs prior to the spring bloom may reflect the fact that females in the northeast Atlantic are adapted to the lower food conditions (as represented by chlorophyll standing stock) that are generally found there. Differences in number of eggs could to some extent be compensated by egg size, which we have not measured and would reflect genetic difference between the western and eastern C. finmarchicus populations. To our knowledge egg size has not been compared among sites on a basin scale. Analysis of prosome length-dry mass measurements for female C. finmarchicus also suggests differences between northwest and northeast Atlantic populations. Prosome length-dry mass relationships were determined for females on Georges Bank (Runge et al., 2006) and in the sea around Iceland (Gislason, 2005). Based on these relationships, a 2.6 mm female should have a dry mass of 289 μg on Georges Bank and 165 μg off Iceland, a difference of about 40%. The C and N contents of a 2.6 mm female on Georges Bank are predicted to be 135 μg and 29 μg, respectively and a similar relationship was found for females collected in the Labrador Sea (Head et al., 2013a). At Sm OWs Mike (SNWS), Irgoien et al. (1998) reported a carbon content of 50 μg and nitrogen content of 12 μg for females with an average PL of 2.6 mm (Niehoff et al., 1999) collected between April and June. From these measurements, and using the spring EPRmax for the SNWS from Table 5 and literature egg C and N contents (Runge and Plourde, 1996), C and N specific EPRmax values of 11.8% body C d$^{-1}$ and 9.4% body N d$^{-1}$ can be estimated, somewhat higher than those reported for Georges Bank or the Labrador Sea (8.5% and 7.2% for C and N specific rates, respectively). Similar calculations were made for the SS and WGBB regions, using EPRmax values from Table 5 and female C and N contents of 168 and 33 μg for the SS (R. Campbell, unpubl. data) and 109 and 21 μg for the WGBB (Kjellerup et al., 2012). For these regions the C and N specific EPRmax values were 5.1% body C d$^{-1}$ and 4.9% body N d$^{-1}$ (SS) and 2.5% body C d$^{-1}$ and 2.3% body N d$^{-1}$ (WGBB). In situ temperatures were 5–9 °C for GB, 3–8 °C for the LS, between −1 to +6 °C on the SS, and between −1.58 and +2 °C in the WGBB region. Thus, over four regions in the NW Atlantic, C and N specific EPRmax values appear to increase with increasing temperature. In the NE Atlantic (SNWS), average spring temperature was similar (~7 °C) to those on GB and in the LS, but C and N specific EPRmax values were higher. Head et al. (2013a) estimated a maximum C specific EPR of 5.8% body C d$^{-1}$ and a maximum N specific rate of 5.9% d$^{-1}$ for females from a northern Norwegian fjord, using maximum observed EPRs (Diel and Tande, 1992) and average female C and N contents (Tande, 1982). Here, the average temperature was ~5 °C, so that both the maximum EPR and temperature were lower than in the SNWS. From these few datasets the extent to which C and N specific EPRmax values are the same at similar temperatures among regions, or have similar relationships with temperature, is unclear. More observations of EPRs in concert with measurements of female body C and N are needed to explore this and the question of physiological differences among regions and populations remains open.

Mortality

We have extended the VLT approach applied by Plourde et al. (2009b) to a broader dataset based on several national monitoring
programs in the northeast and northwest Atlantic. Results for the population active growth period show a hyperbolic decrease in mortality rate from the early to late life stages, with values that are generally consistent in magnitude with those determined by Ohman et al. (2002). In most cases regional variations were relatively small, which is surprising given the likelihood of different predator fields among regions. Mortality rates of older copepodite stages (CV–V) active in the surface layer are highest on the shelves and positively correlated with temperature, suggesting there may be higher predation mortality by visually guided predators in shelf ecosystems than in the deep ocean. When integrated with stage-specific development times to construct development trajectories and to estimate daily recruitment, there were relatively small differences (no more than a factor of two, Fig. 18) in copepodite stage-specific daily mortalities and very similar survival trajectories from CI to CV across the different regions (Figs. 18 and 20). In contrast to the copepodite stages, differences in daily mortality rates in egg–CI, probably mostly caused by mortality in the egg and early naupliar stages (i.e., Ohman et al., 2004; Plourde et al., 2009a), appear to translate into markedly different survival trajectories, particularly in cold habitats (<6 °C). Here, small differences in daily mortality rates of egg–CI resulted in 5–6 times lower survival rates in regions where they were likely to be co-occurring with large the Arctic congeners C. hyperboreus and C. glacialis (Fig. 20). Our analysis identifies these species as potentially significant sources of mortality for the early stages of C. finmarchicus in cold regions that are influenced by Arctic water, e.g., the Labrador and Newfoundland shelves. Indeed, predation by these arctic species may represent a significant constraint on expansion of the species’ range northward in response to warming surface waters. As evidenced by the observations of seasonal demography, predation by these Arctic copepodes on C. finmarchicus eggs and nauplii appears to have the effect of displacing the recruitment window for the latter to a period either late in or after the bloom, resulting in a mismatch with optimal food conditions and thus lower productivity relative to warmer regions (Figs. 8 and 9). A similar ‘intraguild predation’ interaction has been hypothesised to control copepod species succession at Station India, a C. finmarchicus dominated system where the abundance of several small copepod species was inversely proportional to C. finmarchicus abundance, which, it has been suggested, leads to their optimal recruitment window being displaced outside the period when C. finmarchicus were active in the surface layer (Irgoien and Harris, 2006).

We did not investigate mortality and survival of C. finmarchicus during the overwintering period on a basin-wide scale because existing data sets were inadequate for such a study. Elsewhere, however, estimates of mortality rates for dormant C. finmarchicus are generally very low ranging from 0.004 to 0.027 d⁻¹, so that overwintering mortality does not appear to be very important compared to mortality at other times of the year. On the other hand, predation on overwintering Calanus may be important in certain locations. For example Norwegian fjords, with mesopelagic fish present had mortality rates up to three times higher (0.011–0.027 d⁻¹) than one that had only invertebrate predators (0.008–0.009 d⁻¹; Bagoeien et al., 2001). Few estimates of overwintering mortality have been made for deep oceanic regions although there is one that has suggested that mortality of overwintering C. finmarchicus is substantially lower in Framinger Sea and Iceland Basin (0.004 d⁻¹) relative to shelf locations, a difference mainly attributed to a reduced vertical overlap between the overwintering stock and mesopelagic fishes such as myctophids in the deeper regions (Bagoeien et al., 2001; McLaren et al., 2001; Gislason et al., 2007; Pepin, 2013). This limited degree of vertical overlap in the centres of distribution of C. finmarchicus, could represent the expression of long-term evolutionary processes resulting in an optimal life-cycle strategy that minimizes mortality for the species as a whole (Gislason et al., 2007).

Modeling mesozooplankton distribution and abundance in the North Atlantic in the context of climate change: statistical and spatial dynamics modeling approaches

The compilation of information reported here represents a step toward modeling the population distribution and dynamics of C. finmarchicus, and in turn, their responses to climate change drivers over the North Atlantic. In the recent years, two main modeling approaches, statistical (niche-based) and dynamic (mechanistic or process-based), have been employed to improve our understanding of distribution patterns in Calanus spp. in the northern North Atlantic.

Statistical-based modeling is based upon the ecological niche theory relating species occurrence (or abundance) to environmental variables and food as predictors. This approach has been termed habitat suitability (Hirzel et al., 2002), species distribution (Elith and Leathwick, 2009) or habitat distribution (Guisan and Zimmermann, 2000) modelling. Although initially habitat models were applied to terrestrial species (especially vascular plants, Elith and Leathwick, 2009), more recently they have also been applied to a wide variety of marine species including zooplankton to provide projections of future climate-driven shifts in species distributions (Beaugrand et al., 2002, 2008; Helaouët and Beaugrand, 2007, 2009; Reyngondeau and Beaugrand, 2011; Helaouët et al., 2011). Most of the zooplankton studies use distance measures, in contrast to the more capable generalised additive (Chust et al., 2013b) and Maximum Entropy models (Provan et al., 2009). Model validation and variable selection are critical steps in order to extrapolate habitat models to conditions outside of those used to generate the model, for instance for future climate scenarios or other areas (e.g. Valle et al., 2011). This is especially problematic for modeling consequences of future climate change. Most of the habitat modeling software (BIOLIM (Nix, 1986), Maxent (Elith et al., 2011), dismo R package (Hijmans and Elith, 2013), Ecological Niche Factor Analysis (ENFA, Hirzel et al., 2002), BIOMOD (Thuiller et al., 2009), openModeller (Muñoz et al., 2009)) were conceived to be applied for species with low spatial variation throughout the seasonal cycle, such as sessile organisms, from a set of spatial layers of environmental variables. Species with high seasonality such as zooplankton need to be modeled taking into account the temporal domain explicitly (Chust et al., 2013b).

The coupled physical-life history modeling approach is mechanistic and mainly based upon factors affecting spatial population dynamics (reproduction, mortality and migration rate). There are two distinct methods for simulating the spatial dynamics of plankton, namely the Lagrangian (Individual Based Models IBMs) and Eulerian approaches (reviewed in Runge et al., 2005). Several models have been developed to simulate the spatial and population dynamics of C. finmarchicus both using IBMs (e.g. Carlotti and Nival, 1992; Carlotti and Wolf, 1998; Miller et al., 1998; Hjollo et al., 2012; Ji et al., 2012; Maps et al., 2012; Huse et al. (submitted for publication); Pepin et al., 2013), and Eulerian (e.g.: Bryant et al., 1997; Lynch et al., 1998; Tittensor et al., 2003; Zakardjian et al., 2003; Speirs et al., 2004, 2006; Slagstad and Tande, 2007; Maps et al., 2012) models. Eulerian models are numerically more efficient than IBMs. On the other hand, the mechanistic process formulation of IBMs permits a more detailed biological description of individuals (Grimm and Railsback, 2005; Maps et al., 2012). A 3-D IBM for C. finmarchicus in the Norwegian Sea has been developed that takes into account growth, mortality, movement and reproduction of C. finmarchicus as well as adaptive traits, which control its interaction with the environment (Hjollo et al., 2012). This model addresses the entire life cycle of C. finmarchicus; the main life history features and vertical movement are emergent properties resulting from many evolved generations using a genetic algorithm. A genetic algorithm procedure (Record
et al., 2010) has also been used in a Calanus IBM model to determine values for “soft parameters”, for which available knowledge only allows a range of values to be specified (Maps et al., 2012). Uses of coupled physical–biological models in the context of understanding C. finmarchicus distribution and abundance include identification of advective and life history factors determining biogeographical boundaries (Ji et al., 2012), assessment of advection vs. local production in maintaining regional abundance (Zakardjian et al., 2003; Speirs et al., 2006), investigation of sources of supply (Pepin et al., 2013) and role of life history in scenarios of climate forcing (Maps et al., 2012). Variations of these models will undoubtedly see application in future assessments of C. finmarchicus population abundance in relation to ecosystem based management of fishery resources.

Compared with habitat suitability models, spatial dynamical models require extensive computational resources, and can only be applied when demographical, physiological, and life traits of species are well known. On the other hand, habitat modeling studies have often neglected dispersal limitation and advection, even though they can play an important role in driving plankton spatial distributions (Irigoien et al., 2011; Chust et al., 2013a,b). In line with taking a balanced view between the importance of the role of dispersal limitation and of niche partitioning on zooplankton spatial distributions (Irigoien et al., 2011, and Chust et al., 2013b), research efforts should focus on integrating the two mechanisms in the modelling approach for zooplankton species, in the same way as has already been done for fish and invertebrates (e.g. Cheung et al., 2009). Thus, a detailed dynamic approach to understanding species distribution in relation to habitat can only be undertaken for species like C. finmarchicus that are clearly of fundamental functional importance for the ecosystem, such that resources can be devoted to acquiring the necessary data. As a direction of future research, a synthesis of the two approaches, focusing on C. finmarchicus, might provide insight into the likely effects of climate forcing on abundance and distribution of species in the North Atlantic. In order to obtain a synoptic view of the zooplankton species community, coupling of simplified life history models to the physical circulation and application of statistical habitat models is suggested.

Summary, research needs and directions

The great advancement in habitat suitability and life history and coupled physical–biological modeling of C. finmarchicus populations over the past 10 years puts new demands for abundance and environmental data and accurate and comprehensive parameterization of life history processes. Our analysis of the combined distributional, demographic and physiological datasets has shown that the best approach to model the distribution of C. finmarchicus requires a combination of different approaches to monitoring data. While CPR data show the basin scale surface distribution of the species, CPR coverage does not include the population centres in the Norwegian Sea or the Labrador Sea; net sampling provides more targeted information on these important areas as well as on the vertical distributions of C. finmarchicus populations. Vertical distribution data can be crucial in identifying ambient temperatures for modelling purposes and for defining critical temperature ranges within which the species may thrive or fail to survive. A more thorough analysis using net and CPR data is recommended to explore this issue. We observed the highest population densities were within the deep basins of the Labrador and Norwegian Seas and that locations not closely connected to these deep basins by advection, had lower population densities (such as many North Sea sites). High winter mortality in shallow water regions may be why these sites need replenishment from the deep basins.

Phenology associated with the C. finmarchicus life cycle was variable across the North Atlantic. There was a 3.5 month difference in timing of the occurrence of the first generation, with the western sites showing later occurrences relative to the spring phytoplankton bloom than the eastern sites. We found that temperatures at which peak abundance occurred varied between 3 and 15°C, with highest population densities at about 13°C. It is currently unclear whether the process models are able to reflect these differences in timing and if they do not, we need to improve model parameterization.

Our analyses also yielded seasonal and spatial differences in stage specific mortality. Mortality rates of young stages were particularly high in cold water areas, leading us to suggest significant predation by the larger congeners, C. hyperboreus and C. glacialis, which are abundant in these areas in spring. This hypothesis warrants a proper field investigation. In the population centres of C. finmarchicus the major predators are other invertebrates (e.g. chaetognaths, euphausiids, etc.). mesopelagic and pelagic fish, and possibly adult females, the latter via cannibalistic feeding on their own eggs and nauplii. We have cited several investigations where predation impact has been quantified and related to the annual production of C. finmarchicus. Precise quantification of the impact of predation on C. finmarchicus populations cannot be accomplished, however, until the population sizes of the predators and prey are more accurately characterised. Due to short life spans and rapid and spatially variable developmental rates of both prey and some of the predators, this cannot be solved by more observations alone, but must involve the application of population dynamic models, preferably with data assimilation capabilities. Representative sampling of predator stomachs and verification of predation by other methods on a population scale is another largely neglected but challenging task, given the complexity and costs involved. Studies on mortality during the overwintering period are also needed in order to describe and understand the relative role of the physical environmental conditions and different predator guilds (fishes, invertebrates) in controlling the survival success during this portion of the life cycle in regions across the entire C. finmarchicus distribution range. Estimating winter mortality in shelf areas is important in order to understand the drivers of population dynamics of C. finmarchicus in these habitats and the importance of these overwintering populations to potential predators that reside on the shelves and stay active during the winter.

There remain questions about the generality of parameterization of growth, reproduction and diapause timing across the North Atlantic. Further detailed investigations of egg production rate responses across regions are needed in order to resolve possible methodological sources for differences between results obtained using females from either the northwest or the northeast Atlantic. The hypothesis that apparent cross-basin differences in egg production and female body size are the consequence of genetically differentiated physiological responses to habitat differences in food conditions, temperature and light can be tested against the alternative: namely, that the observations presented here are the consequences of differences in food and body size alone. Cross basin experiments investigating growth, development and reproductive responses of C. finmarchicus collected from both northwest and northeast Atlantic sites under identical experimental conditions would provide insight, as would a careful cross-basin comparison of body size dry mass, carbon and nitrogen relationships. Our quantitative understanding of timing of diapause entry and exit is still rudimentary. Improved, long term and high frequency (i.e., semi-monthly to monthly) time series sampling at a few selected sentinel sites for demographic analysis combined with biochemical (i.e., body mass, lipid content, RNA/DNA ratios: Wagner et al., 1998) and perhaps genetic indicators of diapause/active state would be useful for further testing of dormancy hypotheses.
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Appendix A. Calanus finmarchicus demographic patterns

Descriptions of the data sets used to characterise demographic patterns across the North Atlantic are summarized in Table 1. Here we provide detailed figures of seasonal patterns of abundance by stage in relation to temperature and chlorophyll concentration at the sampling sites across the North Atlantic analysed in the demographic, dormancy and mortality sections above (Fig. A1–A6). Details on sampling depth of chlorophyll and temperature can be read from the axes labels.
Fig. A2. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).
Fig. A3. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).
Fig. A4. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).
Fig. A5. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).
Fig. A6. Abundance of *Calanus finmarchicus* copepodite stages 1 to 5 and adult males and females (colored histograms). Temperature (solid line) and chlorophyll (dashed line).
References


