Resting eggs in free living marine and estuarine copepods

Holm, Mark Wejlemann; Kiørboe, Thomas; Brun, Philipp Georg; Licandro, P.; Almeda, Rodrigo; Winding Hansen, Benny

Published in:
Journal of Plankton Research

Link to article, DOI:
10.1093/plankt/fbx062

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Resting eggs in free living marine and estuarine copepods

MARK WEJLEMANN HOLM1,2, THOMAS KIØRBOE2, PHILIPP BRUN2, PRISCILLA LICANDRO3,4, RODRIGO ALMEDA2 AND BENNI WINDING HANSEN1*

1DEPARTMENT OF SCIENCE AND ENVIRONMENT, UNIVERSITETSVEJ 1, BUILDING 11.2, ROSKILDE UNIVERSITY, 4000 ROSKILDE, DENMARK, 2CENTRE FOR OCEAN LITE, TECHNICAL UNIVERSITY OF DENMARK, KEMITORVET, BUILDING 202, 2800 KGS. LYNGBY, DENMARK, 3SIR ALISTER HARDY FOUNDATION FOR OCEAN SCIENCE (SAHFOS), THE LABORATORY, CITADEL HILL, PLYMOUTH PL1 2PB, UK AND 4PLYMOUTH MARINE LABORATORY, PROSPECT PLACE, THE HOE, PLYMOUTH, PL1 3DH, UK

*CORRESPONDING AUTHOR: bhansen@ruc.dk

Received March 30, 2017; editorial decision October 23, 2017; accepted October 24, 2017

Corresponding editor: Roger Harris

Marine free living copepods can survive harsh periods and cope with seasonal fluctuations in environmental conditions using resting eggs (embryonic dormancy). Laboratory experiments show that temperature is the common driver for resting egg production. Hence, we hypothesize (i) that seasonal temperature variation, rather than variation in food abundance is the main driver for the occurrence of the resting eggs strategy in marine and estuarine copepod species; and (ii) that the thermal boundaries of the distribution determine where resting eggs are produced and whether they are produced to cope with warm or cold periods. We compile literature information on the occurrence of resting egg production and relate this to spatio-temporal patterns in sea surface temperature and chlorophyll a concentration obtained from satellite observations. We find that the production of resting eggs has been reported for 42 species of marine free living copepods. Resting eggs are reported in areas with high seasonal variation in sea surface temperature (median range 11°C). Temporal variation in chlorophyll a concentrations, however, seems of less importance. Resting eggs are commonly produced to cope with both warm and cold periods and, depending on the species, they are produced at the upper or lower thermal boundaries of a species’ distribution.

KEYWORDS: embryonic dormancy; seasonality; thermal boundaries; chlorophyll; aestivation; overwintering

INTRODUCTION

Organisms living in unstable environments are exposed to adverse conditions of varying length (e.g. unfavourable temperature and food availability) and traits have therefore developed to allow species to cope with this adversity. It is known that marine calanoid copepods can survive adverse environmental conditions as resting eggs (dormant embryos), and can therefore disappear periodically from the plankton (Dahms, 1995; Marcus, 1996). There is general consensus that there are two
types of resting eggs; quiescent and diapause eggs. Quiescent resting eggs are embryos responding to adverse conditions by going into dormancy. These resting eggs are not related to seasonality, but related to fast and unpredictable changes in living conditions such as oxygen deficiency, abrupt salinity changes and crowding (Ban and Minoda, 1994; Holmstrup et al., 2006; Høggaard et al., 2008). In contrast, the production of diapause eggs is predetermined by the females (Grice and Marcus, 1981; Uye, 1985; Dahms, 1995). These eggs can survive in the sediment for a time that by far exceeds the time scale of the seasonal adverse conditions. Viable diapause eggs from marine copepods have been estimated to be up to 70 years old (Marcus et al., 1994; Madhupratap et al., 1996; Sichlau et al., 2011), and in freshwater even up to several hundred years old (Hairston et al., 1995; Jiang et al., 2012). Compared with a monthly time span for quiescent eggs viability (Drillet et al., 2006), it is therefore expected that the older eggs found in sediment samples are predominantly diapause eggs.

The trigger for the production of resting eggs can be driven by token stimuli (i.e. non-lethal environmental conditions) and is therefore not the underlying reason for their production. If their production is predetermined, however, the characteristics of the environment in which they are found might explain why they are produced. Resting eggs represent a strong link between the pelagic and benthic environments, as the abundance of resting eggs in the sediment is significant, ranging from $10^4$ to $10^7$ m$^{-2}$ (Marcus, 1989; Nass, 1991; Hairston, 1996; Jiang et al., 2004; Gioppa et al., 2011). There is a large variation in the production of resting eggs as some individuals in a population produce varying fractions of eggs as resting eggs, while others do not produce resting eggs at all (Marcus, 1984b; Avery, 2005b; Drillet et al., 2011). Drillet et al. (2015) showed that 5–9% of the egg production by a >30 years old laboratory population of Acartia tonsa at all times were resting eggs, despite consistently favourable conditions. Avery (2005a) examined the influence of temperature and photoperiod on the production of resting eggs in Acartia hudsonica and found temperature to be the primary environmental driver for the production of resting eggs. However, a large variation in the fraction of resting eggs that were produced (42–83%) was ascribed to differences between individuals. Within the same treatments individual production of resting eggs varied from nearly 0 to 100% of the eggs produced. Furthermore, geographically separated populations can differ in their ability to produce resting eggs (Marcus, 1984b; Avery, 2005a; Drillet et al., 2011). Production of resting eggs is clearly influenced by individual variation and population differences, and thus seems a very flexible trait.

For resting eggs to successfully cope with seasonal changes in the environment, the use of cues that signal future changes in environmental conditions may be important. During the winter period, copepods are expected to be exposed to low food availability and low temperature. These two factors are the most characteristic factors that change seasonally. Many copepod species, have been shown to increase the production of resting eggs as a function of temperature and/or photoperiod (Arndt and Schnese, 1986; Dahms, 1995; Chinnery and Williams, 2003; Drillet et al., 2006; Holst and Peck, 2006; Wu et al., 2006; Hansen et al., 2010; Yoshida et al., 2012; Berasategui et al., 2013; Gioppa et al., 2013; Peck et al., 2015). However, other abiotic and biotic factors also elicit the production of resting eggs, such as food availability (Drillet et al., 2011), abrupt salinity changes (Høggaard et al., 2008) and crowding (Ban and Minoda, 1994). For instance, it has been observed that reduced food availability can decrease the fraction of resting eggs in the freshwater copepod Onychodiaptomus biega (Walton, 1985). However, the most common cue in marine copepods for inducing the production of resting eggs or breaking their dormancy is temperature (Drillet et al., 2006; Berasategui et al., 2013). Interestingly, resting eggs produced by some copepod species require periods of either warm or cold conditions in order to allow (Sullivan and McManus, 1986) or increase hatching (Uye et al., 1979; Uye, 1985; Ness, 1996; Chen and Marcus, 1997) and some species produce resting eggs primarily at either high or low temperatures (Johnson, 1980; Arndt and Schnese, 1986; Peck et al., 2015). This suggests that these resting eggs are produced to cope with either winter or summer conditions and therefore a strategy related to seasonality. Based on evidence from laboratory studies we hypothesize that (i) seasonal variation in temperature, rather than variation in food availability, is the main driver for the occurrence of resting eggs in marine and estuarine copepod species; (ii) the thermal regime supporting the production of resting eggs, on a species level, depends on the thermal distribution of the species, where resting eggs are produced towards the boundaries of their thermal distribution. We test the hypothesis by comparing reported spatio-temporal occurrences of resting eggs with the seasonal variation in sea surface temperature and chlorophyll a concentrations.

METHOD

We used Web of Knowledge, based on predefined search criteria (resting eggs, dormant eggs and embryonic dormancy in combinations with copepods or...
species names), to identify studies on resting egg production in marine copepods. Species names are based on the nomenclature of the World Register of Marine Species (WoRMS Editorial Board, 2016). To examine the global distribution of the “resting egg production trait”, we used three different approaches.

First, we compiled all reports of the occurrence of resting eggs in marine sediments where the species had been determined. We also included studies where field collected copepods were shown to produce resting eggs in laboratory incubation immediately following the collection. The location where the copepods originate from was used as the location for the production of resting eggs. If coordinates were not provided for the location where samples of resting eggs or adults had been collected, then published maps and written descriptions were used to determine the spatial reference. We did not distinguish between different types of resting eggs (i.e. diapause or quiescent eggs) but the eggs were categorized according to whether they were produced to cope with warm or cold periods. If the purpose of the production was not explicitly stated in the original articles, they were put into these categories according to how temperature affected hatching patterns and the production of resting eggs and how season affected occurrence and hatching patterns of resting eggs in situ.

Secondly, we mapped the global distribution of species that are known to be able to produce resting eggs using presences data from Ocean Biogeography Information System (OBIS, 2016), covering the period from 1902 to 2013. Spatial data for all species producing resting eggs were not available, and therefore Acartia teclae and Sulcaneus conflictus are not included in this analysis.

Finally, we used data from the Continuous Plankton Recorder (CPR) (Richardson et al., 2006) to investigate the relative contribution of the weight fraction of taxa producing resting eggs in copepod assemblages and their spatial distribution in the North Atlantic. We used roughly 49 000 abundance-class observations for 67 copepod taxa in the North Atlantic and adjacent seas that were made in the period 1998–2008 (Johns, 2014). Distributions of weight fractions were estimated following a two-step approach. Firstly, we determined the weight fraction of resting egg producing taxa for each observed assemblage by weighting their relative abundances with their cubed body length, assuming isomorphism for all copepod taxa (body length data taken from Brum et al. (2017)). Secondly, we produced spatial interpolations of the weight fractions across the sampled area using the Integrated Nested Laplace Approximation approach (Rue et al., 2009). Distributions of weight fractions were assumed to be isotropic Gaussian Fields (Blangiardo and Cameletti, 2015) with beta-binomial error distributions. The interpolation was made using the Stochastic Partial Differential Equation approach and a discrete mesh to approximate the spatial relationships (Appendix 1).

To compare the distribution of species producing resting eggs with the seasonality of the environment, we used data on monthly differences in sea surface temperature ($T_{\text{max}} - T_{\text{min}}$) and chlorophyll $a$ concentration ($\text{Chl}_{\text{max}} - \text{Chl}_{\text{min}}$). Data on temperature were extracted from the Hadley Centre (Rayner et al., 2003). We used monthly averages of the HadISST1 product for the period 1981–2010. We estimated seasonal variation in temperature simply by calculating the difference between the annual maximum and minimum temperatures, computed in a $1^\circ$ latitude-longitude grid. Seasonality in chlorophyll $a$ concentration was calculated similarly based on average monthly concentrations (mg m$^{-3}$) based on merged data extracted from GlobeColour (http://www.globcolour.info/) covering the period from 1997 to 2010. Mean values for seasonal variation in temperature and chlorophyll $a$ concentrations were calculated within equally sized circles ($\Theta = 111$ km) around the points where resting eggs had been registered.

Analyses of the relationship between where resting eggs are produced as a response to low and high temperatures and how this relates to the thermal distribution of the species were conducted on eight selected copepod species. These were exemplified by low temperatures: Acartia tonsa, Eurytemora affinis and Labidocera aestiva; high temperatures: Acartia hudsonica, Centropages abdominalis, and Anomalocera patersoni; high and low temperatures: Acartia bifilosa and Centropages hamatus. The species were selected based on several criteria: (i) difference in their distribution (global vs. regional); (ii) availability of distribution data; (iii) availability of data for several locations with resting eggs. We used species distribution modelling to estimate the thermal niche of each of these species from their observed distributions. For the period 1960–2013, we matched presence locations and times with corresponding temperature information. From these data, we then estimated habitat suitability in relation to temperature using the MaxEnt species distribution modelling technique (Phillips et al., 2006). For the MaxEnt algorithm we used background temperatures based on approximately 10 000 randomly sampled points that were uniformly distributed in space and time, and disabled threshold features to keep the model fits at a reasonable complexity. Analyses were performed with the MaxEnt software 3.3.3e (http://www.cs.princeton.edu/~schapire/magent/). Similarly, we matched locations where resting eggs have been found in the sediment with temperature data. For species that
produce resting eggs to cope with cold periods, we considered the coldest month, and for species producing resting eggs for warm periods, we considered the warmest month. Sometimes temperature data was not available for the exact location where resting eggs were found, in particular when observations were made very close to the coast. In these cases we assumed temperature to be equal to the temperature of the closest grid cell with information.

STATISTICAL METHODS
All data failed the Shapiro–Wilks test for normality, and a non-parametric Kolmogorov–Smirnov test was therefore applied to test the difference in global seasonal variation in sea surface temperature and chlorophyll a concentrations with data from areas where resting eggs were found. All statistical analysis were conducted using GraphPad software version 7.02 (GraphPad Software, La Jolla California USA) with α = 0.05. Mean values are reported ±1 SD.

RESULTS
We found that 42 copepod species belonging to six families (Acartiidae, Centropagidae, Pontellidae, Sulcanidae, Temoridae and Tortaniidae) have been reported to produce resting eggs (Table 1). Out of these, 21 species produce resting eggs solely to cope with cold periods, 6 to cope with warm periods and 7 produce resting eggs to overcome both periods with warm and cold conditions. For the last 8 species it has not been possible to determine whether they are produced to cope with cold or warm conditions.

 Locations where resting eggs have been found are in temperate areas and mainly on the northern hemisphere between 20 and 70°N, with few additional observations on the southern hemisphere (the Bahia Blanca estuary in Argentina (39°S) and Warrnambool in Australia (38°S)) (Fig. 1). This coincides with the distribution of species that are known to be capable of producing resting eggs, as they are distributed primarily in the temperate regions of the North Atlantic, North Indian Ocean and North Pacific Ocean (Fig. 1). Resting eggs were not only found in areas where there are many observations of species that produce resting eggs but also where there are only few records of species producing resting eggs (Fig. 1). Based on the analysis of the importance of species producing resting eggs in the North Atlantic, it shows that these species form the largest fraction of the copepod assemblages in shelf areas and offshore throughout the mid-Atlantic (Fig. 2).

The average global seasonal variation in chlorophyll a was estimated to be 0.6 ± 1.6 mg m⁻³. Resting eggs were found in areas where the average seasonal variation in chlorophyll a was 3.57 ± 4.06 mg m⁻³, hence in regions where the seasonality in chlorophyll a was significantly higher than the global chlorophyll a range (P = 0.0025) (Fig. 3A and B). Similarly, resting eggs were produced in areas where the average seasonal variation in temperature was significantly higher (11.0 ± 3.3°C) than the global variation (3.8 ± 2.8°C) (P < 0.0001) (Fig. 4A and B). However, more interestingly, 50% of all records of resting eggs are from areas with a seasonal variation in temperature of >10°C, which accounts for only 5% of the global data set. The presence of resting eggs therefore appears to depend on seasonality of temperature, which is also consistent with the temperate distribution of species producing resting eggs (Fig. 1).

Resting eggs produced to cope with either cold or warm periods have a similar spatial distribution (Fig. 5A and B). However, north of 54°N resting eggs are only produced to cope with cold conditions (Fig. 5A). The seasonal variation in temperature in areas where resting eggs are produced to cope with low temperatures is 10.4 ± 3.4°C, and for resting eggs produced to cope with high temperatures it is 9.9 ± 4.0°C. Hence, the seasonal variation in temperature that induces both of these two strategies appears to be similar.

The eight copepod species selected for detailed analyses differ in their global distributions: some are present regionally (A. biflosa, A. hudsonica, A. patersoni, E. affinis and L. aestiva) and others are more cosmopolitan (A. tonsa, C. abdominalis and C. hamatus). The analysis showed that resting eggs are found primarily towards the thermal limits of the species’ distribution (Fig. 6). Resting eggs to cope with cold conditions are found toward the lower thermal limit and resting eggs used for coping with warm conditions are found towards the upper limit of the species thermal distribution, which is often seen as a latitudinal adaptation. There is, however, one exception: A. tonsa, which produces resting eggs throughout its thermal distribution (Fig. 6).

DISCUSSION
Main findings
We show that resting eggs are found in areas with a high seasonal variation in temperature, and it appears that seasonal fluctuations in chlorophyll a concentration are of less importance. Resting eggs to cope with cold or
Table I: Copepod species producing resting eggs divided into categories depending on whether the eggs are produced to cope with warm or cold periods

<table>
<thead>
<tr>
<th>Category</th>
<th>Species</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting eggs in response to...</td>
<td>Acartia (Acanthacartia) californiensis</td>
<td>Johnson (1980)*</td>
</tr>
<tr>
<td>low temperatures</td>
<td>Acartia (Acanthacartia) italica</td>
<td>Belmonte (1997)*</td>
</tr>
<tr>
<td></td>
<td>Acartia (Acartiura) teclae</td>
<td>Niess (1996)*</td>
</tr>
<tr>
<td></td>
<td>Acartia (Hypoacartiura) adriatica</td>
<td>Belmonte (1997)*</td>
</tr>
<tr>
<td></td>
<td>Acartia (Odontacartia) erythroae</td>
<td>Kasahara et al. (1975)<em>, Uye et al. (1979)</em></td>
</tr>
<tr>
<td></td>
<td>Calanopia thompsoni</td>
<td>Kasahara et al. (1975)<em>, Uye et al. (1979)</em></td>
</tr>
<tr>
<td></td>
<td>Eurytemora pacifica</td>
<td>Solokhina (1992)*</td>
</tr>
<tr>
<td></td>
<td>Labidocera aestiva</td>
<td>Grice and Gibson (1975)<em>, Grice and Lawson (1976)</em>, Marcus (1979)<em>, Marcus (1984a,b)</em></td>
</tr>
<tr>
<td></td>
<td>Labidocera rotunda</td>
<td>Uye et al. (1979)<em>, Itoh and Aoki (2010)</em></td>
</tr>
<tr>
<td></td>
<td>Paracartia latistota</td>
<td>Belmonte (1992), Siokou-Frangou et al. (2005), Belmonte and Pati (2007)*</td>
</tr>
<tr>
<td></td>
<td>Pontella meadi</td>
<td>Grice and Gibson (1977)*, Chen and Marcus (1997)</td>
</tr>
<tr>
<td></td>
<td>Pteriacartia josephinae</td>
<td>Belonte and Puce (1994)*</td>
</tr>
<tr>
<td></td>
<td>Tortanus (Boreotortanus) discaudatus</td>
<td>Marcus (1990, 1995)*</td>
</tr>
<tr>
<td></td>
<td>Tortanus (Tortanus) forcipatus</td>
<td>Kasahara et al. (1975)*, Chen and Li (1991), Dahms et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Sulcanus conflict</td>
<td>Newton and Mitchell (1999)*</td>
</tr>
<tr>
<td>No spatial reference</td>
<td>Centropages ponticus</td>
<td>Sazhina (1968)</td>
</tr>
<tr>
<td>high temperatures</td>
<td>Acartia (Acartiura) omorii</td>
<td>Itoh and Aoki (2010)**</td>
</tr>
<tr>
<td></td>
<td>Anomalocera patersoni</td>
<td>Lanona and Santella (1991)**</td>
</tr>
<tr>
<td></td>
<td>Centropages abdominalis</td>
<td>Kasahara et al. (1975)<strong>, Uye et al. (1979)</strong>, Itoh and Aoki (2010)**</td>
</tr>
<tr>
<td></td>
<td>Eurytemora americana</td>
<td>Marcus (1984b), Berasategui et al. (2012)**</td>
</tr>
<tr>
<td></td>
<td>Sinocalanus tenellus</td>
<td>Hada et al. (1986)**</td>
</tr>
<tr>
<td></td>
<td>Centropages tenguiremis</td>
<td>Kasahara et al. (1975)<strong>, Uye et al. (1979)</strong>, Wang et al. (2005a)<strong>, Wu et al. (2006)</strong>, Itoh and Aoki (2010)*, Xu et al. (2011)</td>
</tr>
<tr>
<td>Unknown</td>
<td>Acartia (Acartiura) discaudata</td>
<td>Lindeque et al. (2013)</td>
</tr>
<tr>
<td></td>
<td>Anomalocera ornata</td>
<td>Chen and Marcus (1997)</td>
</tr>
<tr>
<td></td>
<td>Centropages velificatus</td>
<td>Chen and Marcus (1997)</td>
</tr>
<tr>
<td></td>
<td>Epiplabidocera amphitrites</td>
<td>Johnson (1980), Marcus (1990, 1995)</td>
</tr>
<tr>
<td></td>
<td>Labidocera mirabilis</td>
<td>Chen and Marcus (1997)</td>
</tr>
<tr>
<td></td>
<td>Labidocera scotti</td>
<td>Chen and Marcus (1997)</td>
</tr>
<tr>
<td>No spatial reference</td>
<td>Eurytemora velox</td>
<td>Gaudy and Pagano (1987)</td>
</tr>
<tr>
<td></td>
<td>Tortanus (Eutortanus) derugini</td>
<td>Chen and Li (1992)</td>
</tr>
</tbody>
</table>

Asterisks after the references denotes whether the reference was used for categorizing the species to produce resting eggs to cope with low (*) or high (**) temperatures, if nothing is noted, it has not been possible using these studies to categorize the resting eggs. The species names are based on the nomenclature of World Register of Marine Species (WoRMS Editorial Board, 2016).
warm periods are found in areas with similar seasonal range in temperature and their occurrence overlap, suggesting that their production does not relate to global distribution of the resting egg trait. For several species we find that resting eggs are produced primarily at the species upper and/or lower thermal boundaries of their distribution, suggesting that the signal in the distribution of resting eggs could be related to species’ thermal tolerance. Even though resting eggs are found primarily in the neritic environment, species known to produce resting eggs, have relatively high concentration in some offshore regions.

**Which species produce resting eggs?**

Here we revise the number of copepod species producing resting eggs previously assessed (Uye, 1985; Marcus, 1989; Mauchline, 1998). The more restricted number reported here is due to several practical and confounding factors: firstly only published original articles have been used in this study, therefore excluding species such as *Centropages furcatus*, Dana 1849 (Marcus, 1989), *Labidocera trispinosa* Esterly, 1905 (Uye, 1985), *Acartia (Acanthacartia) tsuensis* Ito, 1956 (Uye, 1985), *Calanopia americana* Dahl F., 1894 (Marcus, 1996), as they are only referred to in the literature as “unpublished data”. Secondly, some species...
have been reported twice due to changes to the species name, viz. *Labidocera rotunda* (synonym *Labidocera bipinnata*) and *Centropages tenuiremis* Thompson and Scott, 1903 (*Centropages yamadai*) (Uye, 1985). Furthermore, species such as *Centropages typicus*, *Acartia* (*Acartia*) *longiremis* Lilljeborg, 1853 and *Acartia* (*Acanthacartia*) *sinjensis* Mori, 1940, as opposed to previous indication by Mauchline (1998), have been considered as not producing resting eggs, following evidence reported by several authors (Uye, 1985; Smith and Lane, 1987; Marcus, 1990; Engel and Hirche, 2004; Durbin and Kane, 2007; Wesche et al., 2007).

**Resting eggs as a life history strategy**

The production of resting eggs provides a means to cope with unfavourable environmental periods (predictable and unpredictable), storing high productivity of good periods (egg bank), and to reduce genetic drift (Hairston and De Stasio, 1988). If seasonal changes in environmental conditions, affecting food uptake and survival, are predictable, then evolution would favour traits that enable organisms to cope with this seasonality (Hairston and Bohonak, 1998). However, there is significant individual variation in the production of resting eggs.
eggs (Avery, 2005b) and in the duration of the refractory period (i.e. period where the egg cannot hatch) (Chen and Marcus, 1997; Engel and Hirche, 2004). If the variations in environmental conditions are unpredictable then it is expected that a strategy such as bet-hedging will evolve (Slatkin, 1974). Resting eggs (primarily diapause eggs) can function as a bet-hedging strategy by having an extended period of hatching, thus reducing the temporal variance in fitness at the expense of the arithmetic mean (Olofsson et al., 2009). Hence, it might be an adaption to the unpredictable nature of the neritic habitat, which is where resting eggs are mostly found (Fig. 1). Other resting eggs (quiescent) are a direct response to adverse environmental conditions experienced by the embryo and therefore functions as an immediate escape from adverse conditions. Therefore, the different types of resting eggs represent different adaptations to predictable and unpredictable environmental variability, and hence function at different time scales.

Resting eggs produced on a global scale and across many copepod species may not all show a seasonal signal, as implicitly assumed in our analysis. For example, the production of resting eggs by *A. tonsa* was clearly not restricted to the thermal boundaries of its distribution, and thus the production of resting eggs is possibly also induced by non-seasonal signals. However, the overarching pattern is that resting eggs are more common in areas with a large seasonal variation in temperature (Fig. 4A and B) and, hence, mainly represent an adaptation to seasonality. We observe that resting eggs to cope with either cold or warm conditions are found towards...
Avery (2005a) found that the cold water species *Acartia hudsonica* produce resting eggs to cope with warm conditions in Rhode Island, USA, where summer temperatures seem to exceed the lethal limit, for this species. In this area *A. hudsonica* produce resting eggs, which need a period of warming before they hatch, and therefore clearly is an adaption to the seasonal variation in temperature. However, a northern population in Maine, USA, where summer temperature is lower or in the same range, but for a shorter period, the species shows activity all year. This observation supports the idea that resting eggs are produced towards the thermal boundaries of the species distribution, because of the thermal tolerance of the species.

**Resting eggs are not an overwintering strategy in the Arctic**

It is striking that there are no reports of resting eggs from marine free living copepod species at high latitudes. These regions have a low seasonal variation in temperature, but large seasonal fluctuations in availability of food, which is driven by a long winter and a short productive season (Figs 3 and 4). While this of course may be due to lack of sampling, it is consistent with observations for freshwater copepods, where egg density and the abundance of emerging nauplii from the sediment peaks at mid latitude (~54 °N) and declines towards higher latitudes (~64 °N) (Jones and Gilbert, 2016). Because of the short growth season and low temperature, resting eggs in the sediment may not be able to hatch, grow to maturation, and reproduce within one season. Thus, for marine copepods at high latitudes dormancy at later life stages may be more favourable. In fact, in the Arctic region overwintering as late copepodite stages and surviving the winter on accumulated lipids appears to be the main overwintering strategy (Conover and Huntley, 1991; Falk-Petersen et al., 2009; Maps et al., 2014), exemplified by the *Calanus* spp. sibling complex in the Arctic (Dahms, 1993; Hirche, 1996; Mauchline, 1998). This allows reproduction at the immediate onset of the productive period, growth and accumulation of lipids within the productive season, and supports a 1- or 2-year life cycle for *Calanus glacialis* and a 3–5-year life cycle for *Calanus hyperboreus* (Slagstad and Tande, 1990; Conover and Huntley, 1991; Hirche, 1997). Species producing resting eggs, on the other hand, typically have short lifespans and multiple generations per year (Katona, 1970; Fryel et al., 1991; Liang et al., 1996; Yoon et al., 1998; Kiørboe et al., 2015).

**Factors influencing resting eggs**

It remains controversial whether resting egg production is an adaptation to periods of low food, unfavourable temperatures, both, or something else. Laboratory experiments have demonstrated that resting egg production can be induced by both food and temperature, as well as by photoperiod, abrupt salinity changes, crowding and oxygen deficiency (Uye et al., 1979; Sullivan and McManus, 1986; Ban and Minoda, 1994; Chimney and Williams, 2003; Holmstrup et al., 2006; Holme and Peck, 2006; Drillet et al., 2011). It has also been suggested that the higher protein content of resting eggs from *A. tonsa* produced under starvation is an indication of resting eggs being an adaption to cope with low food availability (Acheampong et al., 2011). In the present study resting eggs are viewed as an adaption to seasonality, which is why seasonal range and not actual values of chlorophyll *a* concentrations or SST is related to their production. We find that resting eggs are most commonly found in areas where the seasonal differences in chlorophyll *a* concentrations are significantly higher that the global average. The seasonal range in chlorophyll *a* concentrations might be affected by the ability of

---

**Fig. 6.** Thermal niches and temperatures at resting egg locations for eight copepod species. Triangles and squares indicate the maximum and minimum monthly mean temperature at locations with cold and warm adaptive resting eggs, respectively. The intensity of the colour is an indication of the number of observations at locations with that temperature, n<sub>o</sub> is the number of observations of the copepod species and n<sub>r</sub> number of registrations of areas with resting eggs. (A) *Acartia (Acartapecten) tonsa*, n<sub>o</sub> = 2336, n<sub>r</sub> = 28; (B) *Eurytemora affinis*, n<sub>o</sub> = 4594, n<sub>r</sub> = 15; (C) *Labidocera aestiva*, n<sub>o</sub> = 852, n<sub>r</sub> = 12; (D) *Centropages hamatus*, n<sub>o</sub> = 34 719, n<sub>r</sub> = 51; (E) *Acartia bifilosa*, n<sub>o</sub> = 8156, n<sub>r</sub> = 10; (F) *Anomalocera patersoni*, n<sub>o</sub> = 2228, n<sub>r</sub> = 1; (G) *Acartia hudsonica*, n<sub>o</sub> = 456, n<sub>r</sub> = 8; (H) *Centropages abdominalis*, n<sub>o</sub> = 2266, n<sub>r</sub> = 3.
zooplankton to graze down a significant fraction of the production (Schmoker et al., 2013). This would dampen the seasonal difference in chlorophyll a concentrations, and hence the actual seasonality of the area, in terms of food availability, is not possible to detect. However, very few studies have shown food availability to be the driver of resting egg production and the global spatial distribution of the copepod strategy may not be inconsistent with one another. Relating the presence of resting eggs to seasonality of temperature is done to examine the driver, not the cues for their production.

CONCLUSION

There is no clear global pattern of where copepods produce resting eggs to cope with warm or cold periods, as areas where resting eggs are produced to cope with warm conditions overlap with the areas where they are produced to cope with cold conditions. However, for several of the studied species there is a pattern showing that resting eggs are produced at the lower and higher end of their thermal distribution, despite the multiple purposes (including non-seasonal) resting eggs can have. In spite of this potential driver for the production of resting eggs, they are generally found in areas with a large seasonal variation in temperature.

SUPPLEMENTARY DATA

Supplementary data are available at Journal of Plankton Research online.

ACKNOWLEDGEMENTS

We would like to thank D.G. Johns and the Sir Alister Hardy Foundation for Ocean Science for access to Continuous Plankton Recorder data and to those researchers that have contributed to the Continuous Plankton Recorder surveys. Furthermore, we are grateful for the data provided by the Ocean Biogeographic Information System platform. Lastly we would like to thank two anonymous reviewers for valuable comments on earlier versions of this contribution.

FUNDING

This work was funded through The Centre for Ocean Life which is a VKR Center of Excellence supported by the Villum Kann Rasmussen Foundation.

REFERENCES


Itoh, H. and Aoki, N. (2010) Temporal and spatial distribution of

Højgaard, J. K., Jepsen, P. M. and Hansen, B. W. (2008) Salinity-


Hairston, N. G. (1996) Zooplankton egg banks as biotic reservoirs in

dynamics: life-history theory, phylogenetic pattern and invasion of

Hairston, N. G. (1990) Calanoid copepod, cladoceran, and rotifer eggs


Marcus, N. H. (1989) On the population biology and nature of dia-

Marcus, N. H. (1979) On the population biology and nature of dia-

Marcus, N. H. (1978) Dormant eggs of calanoid copepods in sea-bed

Marcus, N. H. (1978) Dormant eggs of calanoid copepods in sea-bed

Marcus, N. H. (1975) Calanoid copepod eggs in sea-bottom muds. II. Seasonal cycles of abundance in the popula-


Katona, S. K. (1970) Growth characteristics of the copepods

Kasahara, S., Uye, S. and Onbi, T. (1975) Calanoid copepod eggs in


Katsanis, N. (1968) Life cycle of the copepod Calanus hyperborea in the


Holmstrøm, M., Overgaard, J., Sorensen, T. F., Drillet, G., Hansen, B.

and Sørensen, T. F. (2010) Temperature effects on copepod egg


Hirche, H. J. (1996) Diapause in the marine copepod, Calanus finmarchi-
cus—a review. Ophelia, 44, 129-143.

Hirche, H. J. (1997) Life cycle of the copepod Calanus hyperborea in the


Hoffmeyer, M. S., Berasategui, A. A., Beigt, D. D. and Piccolo, M. C.

(2009) Environmental regulation of the estuarine copepods Acartia

Holmstrøm, M., Overgaard, J., Sorensen, T. F., Drillet, G., Hansen, B.

W., Ramløv, H. and Engell-Sørensen, K. (2006) In

the

inland waters.

in the

innermost part of the bay, in the early 1990s.

Anomalocera patersoni

copepod

Acartia tonsa

induced quiescence in eggs of the calanoid copepod

Acartia tonsa

– (Copepoda; Calanoida) the importance of benthic-pelagic

coupling.

Acartia


on the population biology and nature of dia-


Lindley, J. A. (1986) Dormant eggs of calanoid copepods in sea-bed


zooplankton (Copepoda and Cladocera) from the Kiel Bay and


approach to dormancy in pelagic copepods helps explaining inter-


Marcus, N. H. (1979) On the population biology and nature of dia-
pause of Labidocera aestiva (Copepoda: Calanoida). Biol. Bull., 157,

297–305.

Marcus, N. H. (1984a) Recruitment of copepod nauplii into the plank-

Prog. Ser., 15, 47–54.

Marcus, N. H. (1984b) Variation in the diapause response of

Labidocera aestiva (Copepoda: Calanoida) from different latitudes

and its importance in the evolutionary process. Biol. Bull., 166,

127–139.


requirements of eggs of Centropages hamatus (Copepoda: Calanoida)

from the Alligator Harbor region, Florida. Biol. Bull., 176,

142-146.

Marcus, N. H. (1990) Calanoid copepod, cladoceran, and rotifer eggs

in sea-bottom sediments of northern Californiaan coastal waters:


Marcus, N. H. (1991) Planktonic copepods in a sub-tropical estuary:

seasonal patterns in the abundance of adults, copepodites, nauplii,


