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ICES COOPERATIVE RESEARCH REPORT  
*RAPPORT DES RECHERCHES COLLECTIVES*

NO. 307 SPECIAL ISSUE  
MAY 2011

**ICES Zooplankton Status Report**  
**2008/2009**





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## **ICES Zooplankton Status Report 2008/2009**

### **Editors**

Todd D. O'Brien, Peter H. Wiebe, and Steve Hay



**International Council for the Exploration of the Sea**  
***Conseil International pour l'Exploration de la Mer***

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***Above.***

Assorted zooplankton collected  
from the Subarctic regions of  
the North Atlantic.  
Photo by R. Hopcroft

***Cover image.***

Mixed zooplankton  
and copepods.  
Photo by M. G. Mazzocchi.



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Preparing to sample zooplankton at the Plymouth L4 Monitoring site in the English Channel (report site# 29).  
Photo by C. Halsband-Lenk.



# FOREWORD

Environmental time-series data are essential for observing changes in marine ecosystems over seasonal, interannual, and longer time frames. These changes may be continuous or they may occur as sudden shifts, requiring longer time-series for better detection of trends and statistical comparison. Every year of data added to a time-series makes the entire dataset more valuable than it was the year before. As more years are added to a time-series, the subset of questions that can be answered grows, and exciting new questions and discoveries often develop. Yet a majority of the funding vehicles available for this kind of research make it extremely difficult to fund sampling for more than three to five years from a given grant or funding source. For this reason, any long-running time-series is a true sign of the commitment of the scientists and institutions involved in keeping such an ongoing programme funded and staffed. With zooplankton time-series, the level of effort required is even greater because, unlike an automated buoy or conductivity–temperature–depth (CTD) cast, the datapoints often represent hours of laboratory and microscope work.

Looking beyond the growing evidence of warming and acidifying oceans, increases in the jellyfish component of the plankton, and biogeographic shifts in key food components of the plankton community, some of the trends in this report's data collection are less obvious, although equally concerning. For example, more than 30% of the featured time-series contain at least one 6-month gap in their sampling (and a number have more or even larger gaps). Three of the time-series in the collection have a multiyear backlog in sample

processing, whereas more than a handful of programmes have had to reduce their sampling frequency over time (i.e. from monthly to just a few times a year). Finally, although not apparent from any of the datasets, many of the taxonomic experts are approaching retirement age and there are no trained replacements available.

At a crucial time, when we are seeing substantial changes in marine ecosystems globally, the monitoring capability and human expertise needed to detect these changes is being reduced, which in turn reduces our ability to understand the full impact and implications of these changes. There is an immediate need to modify the short-term funding focus and policies of the various government science funding entities across North America, Europe, and the rest of the world in order to increase these crucial monitoring components so that their capacity to track the status and health of marine ecosystems is not only continued but also enhanced.

This report would not be possible without the hard work and contributions of the scientists, institutes, and agencies involved directly and indirectly in these ongoing monitoring efforts.

Todd D. O'Brien  
Peter H. Wiebe  
Steve Hay

# 1. INTRODUCTION

*Todd D. O'Brien, Peter H. Wiebe, and Steve Hay*

In its *Strategic Plan*, ICES recognizes its role in making scientific information accessible to the public and to fishery and environmental assessment groups. During the ICES Annual Science Conference 1999, ICES requested that the Oceanography Committee working groups develop data products and summaries that could be provided routinely to the ICES community. The Working Group on Zooplankton Ecology (WGZE) has prioritized the production of a summary report on zooplankton activities in the ICES Area, based on the time-series obtained from national monitoring programmes.

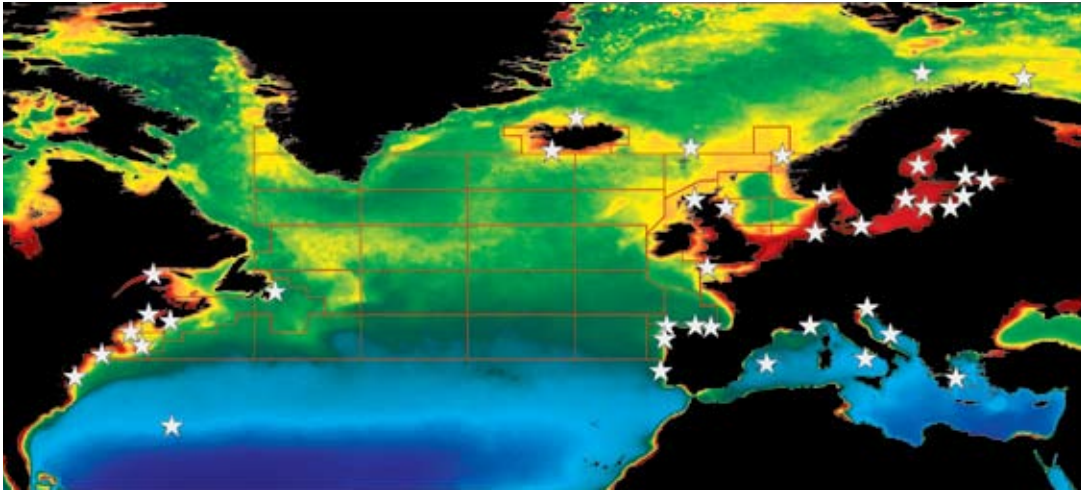
This is the eighth summary report of zooplankton monitoring in the ICES Area. This year's report includes seven new survey sites: one in the western North Atlantic (Site 9, Bermuda Atlantic Time-series Study, or BATS), two in the Baltic Sea (Site 19, Gulf of Finland; Site 23, the Baltic Proper), one adjacent to the North Sea (Site 28, Loch Ewe), and three along the west Iberian peninsula (Site 31, Gijón; Site 33, Vigo; Site 34, Cascais). The total site count has only increased from 37 to 40 from the last report because four transect-based sites from the previous 2008 report were combined into a single site and summary section (e.g. Svinøy East and Svinøy West are now summarized under Svinøy transect, Site 13). This report summarizes the North Atlantic Basin and its major subregions using these 40 zooplankton monitoring sites (Figure 1.1) as well as the 40 Continuous Plankton Recorder (CPR) standard areas (Figure 1.2).

Although this report follows previous reports in its general structure and analysis, new standardized data components and graphical visualizations have been added. For example, each site report now begins with a standard figure series demonstrating the seasonal cycles of zooplankton, chlorophyll, and temperature at that site. Multivariate figures then provide a quick overview of zooplankton interactions and/or synchrony with other co-sampled biological and hydrographic variables available for the site. Finally, a long-term assessment of each monitoring area is made using a 100-year record of sea surface temperature data and up to 60 years of CPR zooplankton data (when available near that site). The methods and data sources used for this report are summarized in Section 2.

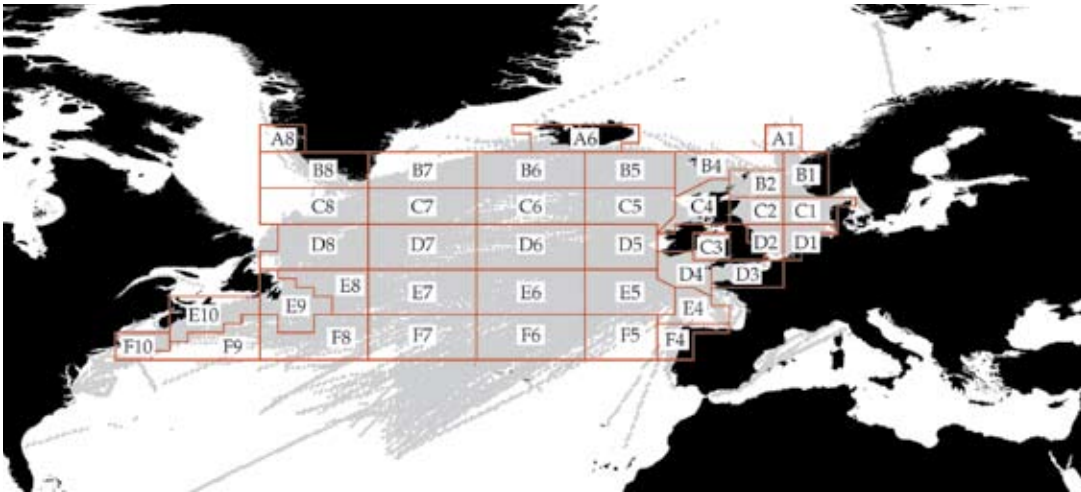
The monitoring sites in this report represent a broad range of hydrographic environments, ranging from the temperate latitudes south of Portugal to the colder regions north of Norway, Iceland, and Canada (Figure 1.3), and from the lower salinity waters of the Baltic to the higher salinity waters of the Mediterranean. Across this broad range of physical conditions, the diversity, abundance, and biomass of zooplankton vary between sites and years, with clear seasonal and cyclical patterns, ranging from a few years to decades in duration, apparent at all sites. Temperature greatly influences the community structure and productivity of zooplankton, causing large seasonal, annual, and decadal changes in population size and in species composition and distribution.

This summary report does not attempt extensive synthesis or cross-site comparison of the sites in this report. Given the evidence of ocean climate changes and regime shifts, as well as the potential effects of acidification and pressures on marine ecosystems from fishing, aquaculture, and offshore energy developments, it is hoped that, in future, time and expertise can be harnessed and funded to provide a more comprehensive and detailed analysis and synthesis. Increasingly, these data are incorporated into models and syntheses of ecosystems at local to basin scales, providing insights, evidence, and ecosystem perspectives, and relating the impacts of climate and other factors on marine communities. The detailed examination of individual species is beyond the scope of this report. However, changes in ocean climate are likely to affect some species more than others, particularly those at the boundaries of their geographic ranges, where they may be most susceptible to changes in seasonal temperature, food supply, competitors, or predators. Such species may prove to be the best indicators of changes in their environment. The need for continuous monitoring of marine plankton at local, regional, and global scales is becoming increasingly central to our understanding of marine ecosystems and to our advice on the sustainable management of marine services and resources.

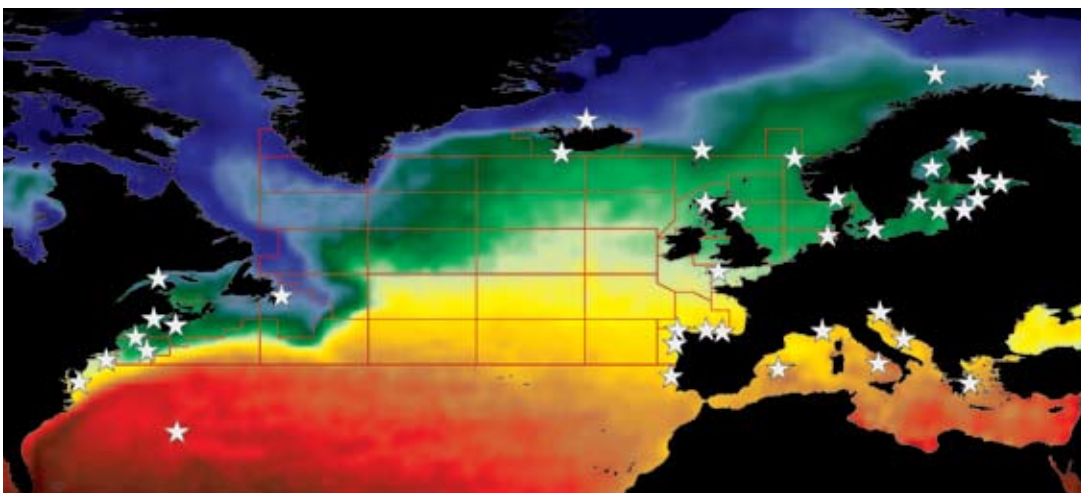




**Figure 1.1**  
Zooplankton monitoring sites within the ICES Area plotted on a map of average chlorophyll concentration. Only programmes summarized in this report are indicated on this map (white stars). The red boxes outline CPR standard areas (see Figure 1.2 and Section 9).



**Figure 1.2**  
Map of CPR standard areas in the North Atlantic (see Section 9 for details). Grey dots and lines indicate CPR sampling tracks.



**Figure 1.3**  
Zooplankton monitoring sites within the ICES Area plotted on a map of average sea surface temperature. Only programmes summarized in this report are indicated on this map (white stars). The red boxes outline CPR standard areas (see Figure 1.2 and Section 9).



## 2. TIME-SERIES DATA ANALYSIS AND VISUALIZATION

*Todd D. O'Brien*

The Coastal and Oceanic Plankton Ecology, Production & Observation Database (COPEPOD; <http://www.COPEPOD.org>) is a global database of plankton cruise data, time-series, and advanced data products hosted by the National Marine Fisheries Service (NMFS) of the National Oceanic and Atmospheric Administration (NOAA). Through its scientific collaboration and data-processing support with groups such as the ICES Working Group on Zooplankton Ecology (WGZE) and the Scientific Committee on Ocean Research (SCOR) Working Group on Global Comparisons of Zooplankton Time-Series (WG125), COPEPOD has developed a collection of plankton-tailored, time-series analysis and visualization tools, many of which have been used in the creation of this and previous WGZE reports (Figure 2.1).

This section describes the time-series data-analysis methods (Section 2.1), the standard data-visualization figures used throughout this report (Section 2.2), and the supplemental data sources (e.g. sea surface temperature, salinity, and chlorophyll) included in the standard analyses of each monitoring site (Section 2.3).

### 2.1 Time-series data analysis

The WGZE time-series analysis compares zooplankton and other hydrographic variables from a number of different variable types, measurement units, and sampling frequencies (e.g. “milligrams of total zooplankton biomass per cubic metre sampled three times a year” vs. “number of copepods per square metre sampled monthly”). The WGZE analysis method uses a unitless ratio (or “anomaly”) to look at changes in data values over time relative to the long-term average (or “climatology”) of those data.

Each zooplankton time-series  $Z(t)$  is represented as a series of log-scale anomalies  $z'(t)$  relative to the long-term average  $\bar{Z}$  of those data:

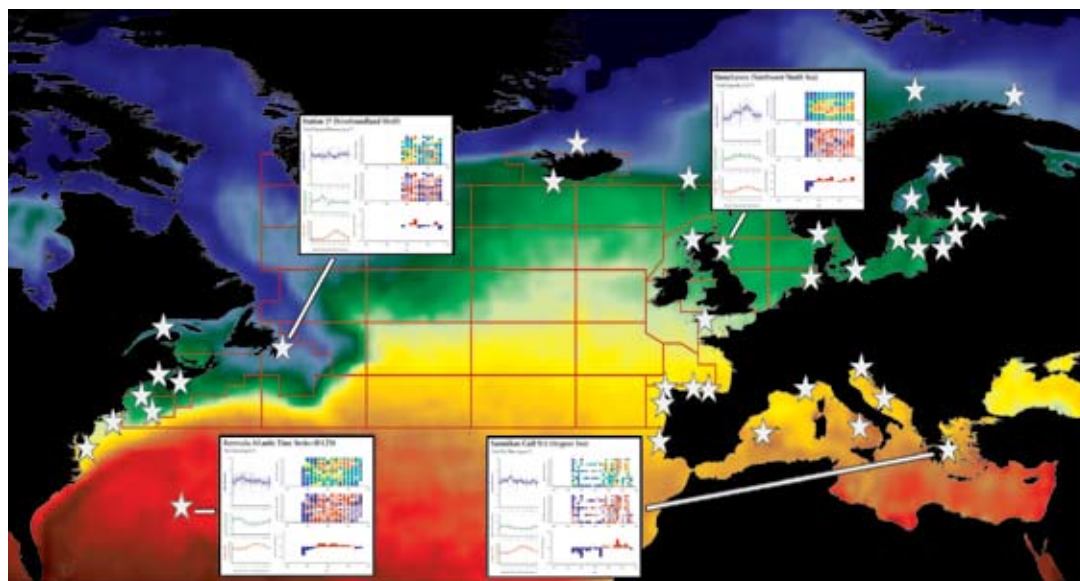
$$z'(t) = \log_{10}[Z(t)] - \log_{10}[\bar{Z}] = \log_{10}[Z(t)/\bar{Z}]$$

If a dataserie at a given site is collected consistently and uniformly for the duration of a monitoring programme, the sampling bias  $b$  is represented in the equation as follows:

$$z'(t) = \log_{10}[b \times Z(t)] - \log_{10}[b \times \bar{Z}] = \log_{10}[bZ(t)/b\bar{Z}]$$

As the sampling bias ( $b$ ) is present in both the numerator and denominator of the equation, it is cancelled out during the calculation. Likewise, the measurement units of the values are also cancelled out, creating a unitless ratio (the anomaly):

$$z'(t) = \log_{10}[b \times Z(t)] - \log_{10}[b \times \bar{Z}] = \log_{10}[bZ(t)/b\bar{Z}] = \log_{10}[Z(t)/\bar{Z}]$$



**Figure 2.1**  
Illustration of the interactive mapping and visualization tools used for the creation of this report and as available online at: <http://WGZE.net>.

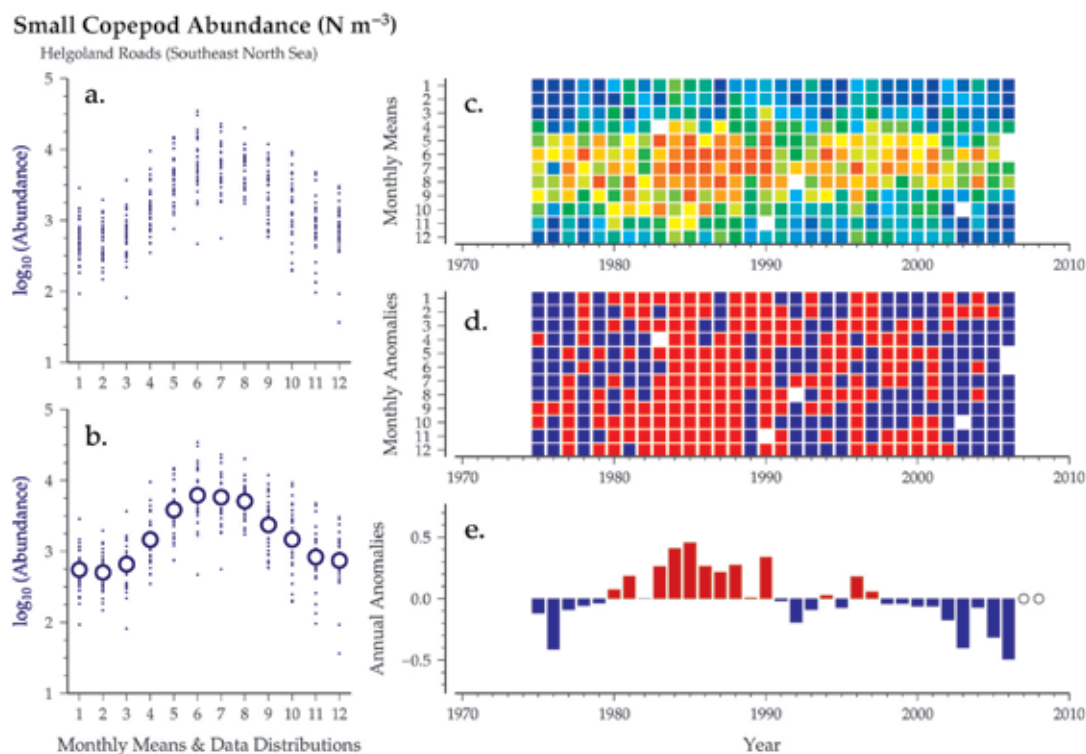
By using unitless anomalies, WGZE can make cross-site comparisons in the form “at Site A, copepod abundance doubled during the same time interval that total zooplankton biomass increased by half at Site B”.

The WGZE analysis examines interannual variability and long-term trends by looking at average annual values throughout a time-series. In most regions of the North Atlantic, zooplankton has a strong seasonal cycle, with periods of high (usually in summer) and low (usually in winter) abundance and/or biomass. As a result of this strong seasonal cycle, calculation of a simple annual average of zooplankton from low-frequency or irregular sampling (e.g. once per season, once per year) can be greatly influenced

by when the sampling occurs (e.g. during, before, or after the summer peak). This problem is further compounded by missing months or gaps between sampling years. The WGZE analysis addresses this problem by using the method of Mackas *et al.* (2001), in which the annual value (actually the interannual anomaly) is calculated from the average of individual monthly anomalies within each given year. As this effectively removes the seasonal signal from annual calculations, this method reduces the majority of issues caused by using low-frequency and/or irregular monthly sampling to calculate annual means and anomalies.

**Figure 2.2**

Figure series illustrating the steps used in the WGZE analysis for creating annual anomalies of small copepod abundance from the Helgoland Roads time-series (Site 26).



The WGZE analysis involves a series of calculation steps (Figure 2.2).

1. The incoming data (i.e. total copepod abundance) are binned by month over the entire time-series. During this step, the plankton and nutrient values (but not temperature and salinity) are  $\log_{10}$  transformed. The average values for each month of each year of the time-series are plotted as small blue dots (Figure 2.2.a). The same monthly data are shown over the duration of the time-series by month and by year in Figure 2.2.c.
2. The long-term average for each month, also known as its climatology, is then calculated (the large open circles in Figure 2.2b).
3. Each month's climatology value (Figure 2.2b) is then subtracted from each month-by-month-by-year value (e.g. Figure 2.2c) in order to calculate the month-by-month-by-year monthly anomaly values for the time-series (Figure 2.2d). In this figure, any month with an anomaly value greater than that of its climatology is shown in red, indicating a positive monthly anomaly. Likewise, any month with an anomaly value less than that of its climatology is shown in blue, indicating a negative monthly anomaly.

4. Annual anomalies for all of the years in the time-series (Figure 2.2e) are then calculated as the average of all of the monthly anomalies (Figure 2.2d) within each year. Any years in the time-series with no monthly data are indicated with an open circle (e.g. 2007 and 2008 in Figure 2.2e). Months with no data are left as a blank white area (see Figure 2.2c and d).

The highest positive annual anomaly of small copepod abundance (Figure 2.2e) was in 1985, and the lowest negative anomaly was in 2006. As these anomalies represent  $\log_{10}$  values, the annual average small copepod abundance in 1985 was approximately threefold higher than the long-term average abundance, i.e.  $\log_{10}(3.2) \approx 0.5$ , and approximately one-third of the long-term average in 2006. Over the extended period from 1985 to 2006, small copepod abundance decreased tenfold.



## 2.2 Time-series data visualization: standard figures

With more than 250 different time-series variables in the WGZE collection (e.g. wet and dry mass; taxonomic group counts and individual genus or species counts; surface, at-depth, or integrated temperature, salinity, and nutrients), drawn from zooplankton monitoring sites across the North Atlantic, one of the biggest challenges in creating this report was to find a way of quickly representing these data in a standard visual format. From a zooplankton perspective, these figures need to quickly report the seasonal variability, interannual changes, and the presence (or absence) of any long-term trends. In this year's report, this was done using three types of figure: the seasonal summary plot (Section 2.2.1), the multiple-variable comparison plot (Section 2.2.2), and the long-term comparison plot (Section 2.2.3).

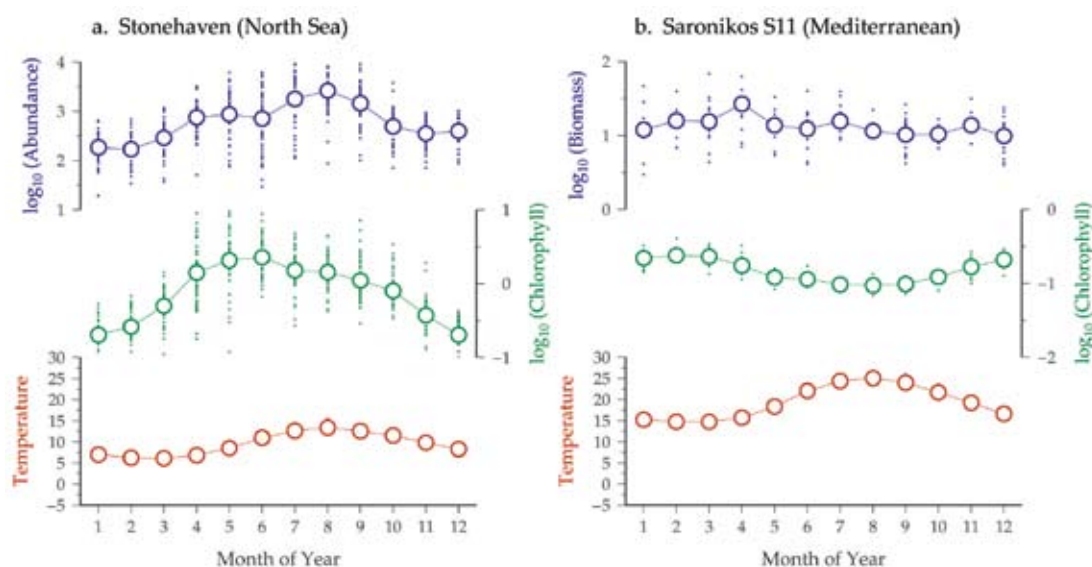
### 2.2.1 Seasonal summary plot

The seasonal summary plot (see example in Figure 2.3) shows the seasonal cycle of the key variables (average monthly values of zooplankton, chlorophyll, and surface temperature) at a given monitoring site. For the zooplankton subplot, the primary biomass or abundance variable from the monitoring site is plotted (typically "total biomass" or "total copepod abundance"). For the chlorophyll subplot, at-site collected data (if available) or the corresponding GlobColour dataset (see Section

2.3.2) is plotted. For the surface temperature subplot, the corresponding HadISST dataset (see Section 2.3.1) is plotted.

In each subplot, the small solid dots (not always visible in the surface temperature subplots) show the spread of individual datapoints within that month, and the large open circles indicate the monthly average of those points. The  $y$ -axis value ranges for the zooplankton and chlorophyll subplots are data-dependent and vary from plot to plot. This is necessary for better visualization of the seasonal minima and maxima within each site. In contrast, all of the surface temperature subplots have a fixed  $y$ -axis range of  $-5$  to  $30^{\circ}\text{C}$  in order to illustrate both seasonal cycle and average year-round conditions.

The seasonal summary plots in Figure 2.3 allow quick comparison of two monitoring sites: one in the North Sea (Figure 2.3a) and one in the Mediterranean (Figure 2.3b). Both sites exhibit a seasonal surface temperature maximum in August and a minimum in February–March, with surface temperatures consistently around  $10^{\circ}\text{C}$  cooler in the North Sea than in the Mediterranean. Zooplankton demonstrates a late-summer maximum at the North Sea site and a spring maximum at the Mediterranean site. Chlorophyll follows a similar pattern, with the seasonal chlorophyll maximum preceding the zooplankton maximum at both sites. Note that the zooplankton subplots are not always quantitatively comparable; in Figure 2.3, for example, the North Sea data refers to (copepod) abundance, whereas the Mediterranean data refers to biomass (total sample dry weights).



**Figure 2.3**  
Two seasonal summary plots showing average month-to-month zooplankton, chlorophyll, and surface temperature values in the North Sea (Stonehaven, Site 27) and the eastern Mediterranean (Saronikos S11, Site 40).

## 2.2.2 Multiple-variable comparison plot

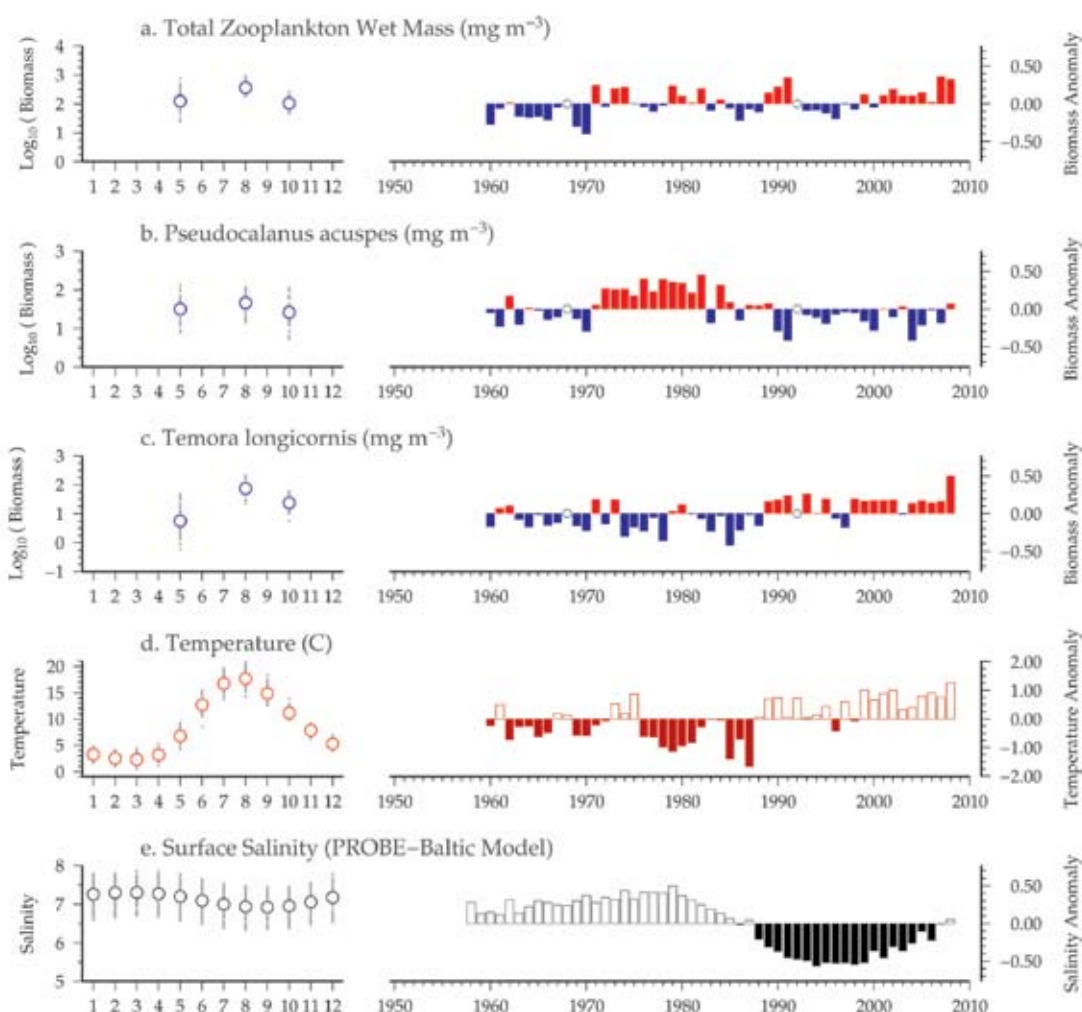
The multiple-variable comparison plot (see example in Figure 2.4) provides a seasonal and interannual comparison of co-sampled variables within each of the monitoring sites, some of which have more than 30 variables. An interactive figure showing all available variables is accessible online via the interactive ICES WGZE time-series explorer at <http://www.WGZE.net>. For this printed publication, however, only a select number of variables are shown in this figure because of space limitations.

The subplots on the right-hand side of Figure 2.4 summarize the interannual patterns within the time-series, using annual anomaly values (see Section 2.1 for method of calculation). Positive annual anomalies, indicating years with an average value greater than the long-term average of the entire time-series, are represented by a red bar. Negative annual anomalies, indicating years with an average value below the long-term average of the entire time-series, are represented by a blue bar. Within a time-series, any entire year in which data are not available is indicated with an open circle in this plot.

In this example, a clear shift in plankton and hydrographic conditions in the central Baltic Sea is quickly apparent. The figure illustrates a major abundance reversal between two copepod species, linked to a major shift in surface salinity that can be attributed to an increase in temperature and an increase in freshwater input into the region. (This is discussed in greater detail in the summary for the eastern Gotland Basin, Site 22.) The online interactive version of this figure (at <http://www.WGZE.net>) includes additional zooplankton taxa and hydrographic variables.

At a small subset of monitoring sites, zooplankton is only sampled in one month of each year, typically during its local peak biomass period in late spring–early summer. As this would show up as only a single point in the left-hand “seasonal” subplot and would not provide any seasonal information for that site, only the right-hand (“interannual comparison”) portion of the multiple-variable comparison figure is provided in these cases.

**Figure 2.4**  
Seasonal and interannual comparison of *Pseudocalanus acuspes* and *Temora longicornis* biomass with surface temperature and salinity in the eastern Gotland Basin of the Baltic Sea (Site 22).



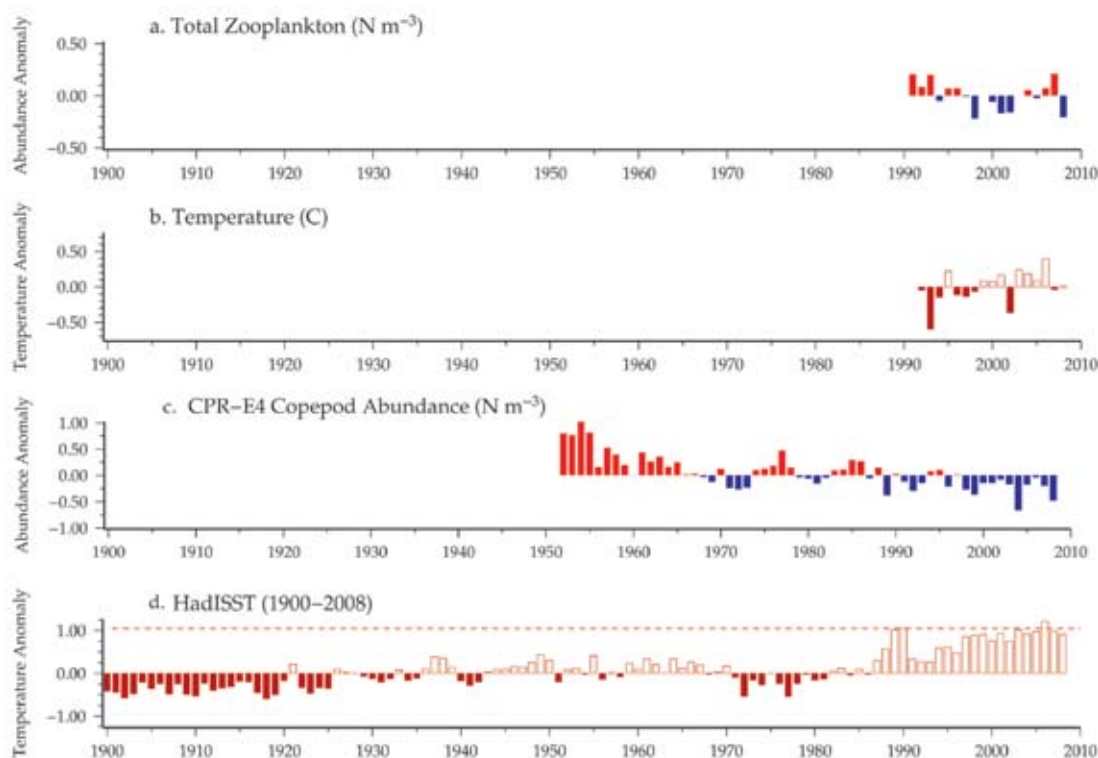
### 2.2.3 Long-term comparison plot

The long-term comparison plot (see example in Figure 2.5) displays a given zooplankton time-series on a common axis with its corresponding 100-year HadISST temperature time-series and, when available, Continuous Plankton Recorder (CPR) copepod abundance data from the nearest CPR standard area. By showing these longer time-series data, this plot can often illustrate how recent (shorter term) water temperature or zooplankton conditions relate to the longer time-record for a region. For example, using the available *in situ* data from a 20-year time-series of zooplankton (copepod) abundance (Figure 2.5a) and surface temperature (Figure 2.5b), a plot of annual anomalies demonstrates large interannual variation in copepod abundance with a slight hint of increasing temperature over the sampling period.

The addition of the 100-year HadISST temperature time-series (see Section 2.3.1) for this region (Figure 2.5d) makes clearer the warming trend over the period of the zooplankton time-series. Further, it is evident that water temperature in this region has been generally warming over the past 100 years and

is currently at or above the warmest temperature seen in the past 100 years (Figure 2.5d, red dashed line). Looking at the longer-term zooplankton record for this region, copepod abundance from CPR standard area E4 (see Section 9) appears to be at the bottom of an almost 50-year decrease in abundance (Figure 2.5c).

Comparisons with adjacent CPR standard areas, however, must be made with caution, because the CPR data generally represent a larger spatial area of deeper, open-ocean waters. This is in contrast to WGZE monitoring stations, which are typically smaller spatial areas, often located nearshore or on shelf waters that may experience local currents, upwelling events, or shelf-water mixing. The CPR and local zooplankton data may not always demonstrate synchronous behaviour, but the long-term trends of the CPR data may still be useful in characterizing how the broader zooplankton populations are faring in the areas surrounding a sampling site.



**Figure 2.5**  
Long-term comparison plot of zooplankton abundance with CPR copepod abundance and HadISST sea surface temperatures at the Santander (Site 30) monitoring site. Sections 9 and 2.3.1, respectively, discuss the CPR and HadISST time-series data. The red dashed line in (d) marks the maximum temperature anomaly seen from 1900 to 2008.



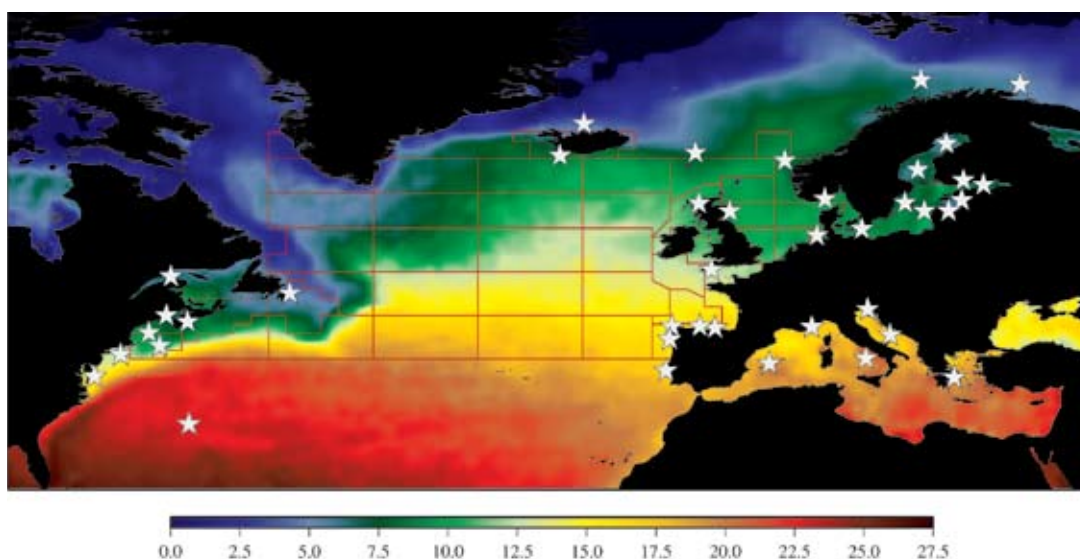
## 2.3 Time-series supplemental data

Water temperature is an excellent indicator of the physical environment in which zooplankton is living because it affects zooplankton both directly (i.e. through physiology and growth rates) and indirectly (i.e. through water column stratification and related nutrient availability). Similarly, chlorophyll concentration is an excellent indicator of the availability of zooplankton food (i.e. phytoplankton). Unfortunately, co-sampled

temperature and chlorophyll data are not available at every site, and the limited data that exist frequently differ in the depth and method of sampling (e.g. “surface temperature” vs. “temperature at 50 m” vs. “integrated temperature from 0 to bottom”). In order to provide a collection-wide set of standard-method temperature and chlorophyll data, WGZE includes supplemental time-series data (in addition to any available *in situ* data) with each site. These datasets are summarized below.

**Figure 2.6**

Map of HadISST sea surface temperatures overlaid with zooplankton time-series site locations (white stars) and CPR standard areas (red boxes).

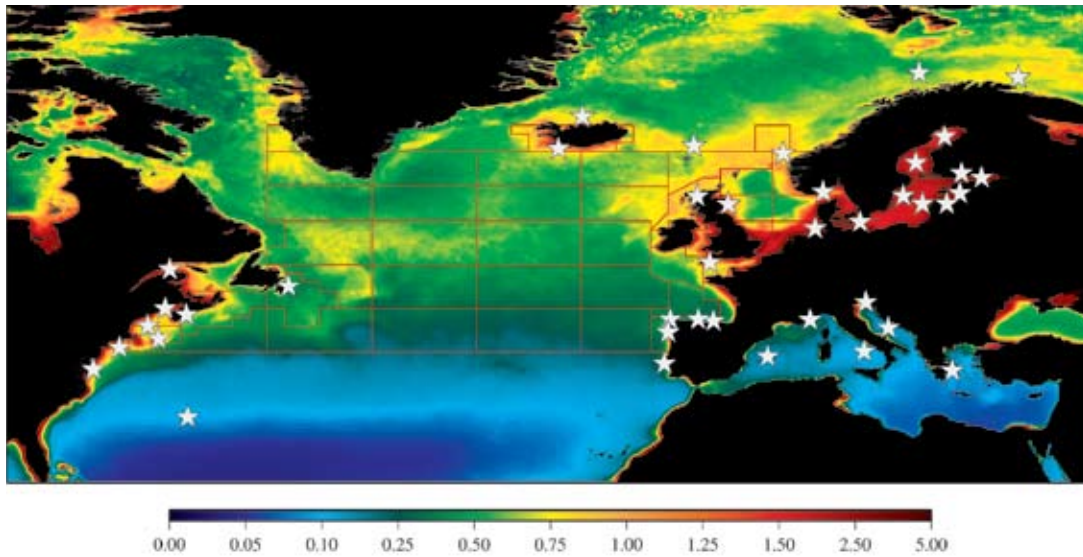


### 2.3.1 Sea surface temperature data: HadISST

In order to provide a common, long-term dataset of water temperatures for every site in the North Atlantic study area, the Hadley Centre Global Sea Ice Coverage and Sea Surface Temperature (HadISST, version 1.1) dataset, produced by the UK Met Office, was used to add standard temperature data to each site (Figure 2.6). The HadISST is a global dataset of monthly SST values from 1870 to present. This product combines historical *in situ* ship and buoy SST data with more recent bias-adjusted satellite SST and statistical reconstruction (in data-sparse periods and/or regions) to create a continuous global time-series at one-degree spatial resolution (roughly 100 km × 100 km). The HadISST data are not intended to represent the exact temperatures in which zooplankton were sampled, but they do provide a >100-year average of the general water temperatures in and around the sampling area.

For each zooplankton time-series, the immediately overlaying HadISST one-degree grid cell was selected. For single-point zooplankton sampling sites (e.g. Stonehaven, Plymouth L4), this one-degree cell included a ~100 km × 100 km area in and around the sampling site. For transects and region-based surveys (e.g. Iceland, Norway, Gulf of Maine), the centre point of a transect or region was used to select a single one-degree cell to represent the general conditions of the entire sampling area. (Comparisons with multicell averages revealed no substantial differences.) Once a one-degree cell was selected, all HadISST temperature data were extracted from that cell for the period 1900–2008 and used to calculate annual anomalies.

The HadISST v. 1.1 dataset is available online at <http://badc.nerc.ac.uk/data/hadisst/>.



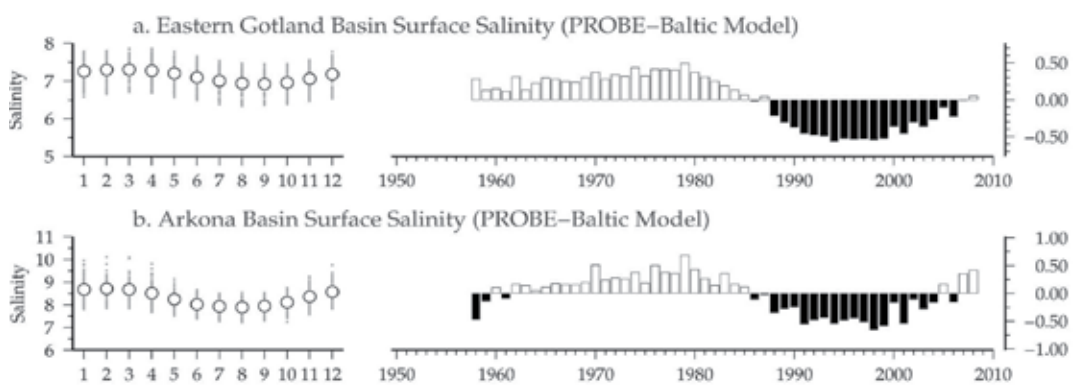
**Figure 2.7**  
Map of GlobColour chlorophyll concentrations overlaid with zooplankton time-series site locations (white stars) and CPR standard areas (red boxes).

### 2.3.2 Sea surface chlorophyll data: GlobColour

In order to provide a common, long-term dataset of chlorophyll for every site in the North Atlantic study area, the GlobColour Project chlorophyll merged level-3 ocean colour data product (GlobColour) was used to add standard chlorophyll data to each site (Figure 2.7). This product is a global dataset of monthly satellite chlorophyll data from 1998 to the present. Although the original product is available

at a resolution of 4.63 km, it was binned into a one-degree spatial resolution (roughly 100 km × 100 km) in order to be compatible with the HadISST dataset. The GlobColour dataserries were assigned to corresponding one-degree boxes using the same method outlined for the HadISST dataserries (see Section 2.3.1).

The GlobColour Project chlorophyll concentration merged level-3 dataset (GlobColour) is available online at <http://www.globcolour.info/>.



**Figure 2.8**  
Seasonal and interannual variability of PROBE-Baltic model surface salinity data from (a) eastern Gotland Basin and (b) Arkona Basin.

### 2.3.3 Baltic surface salinity data: PROBE–Baltic model

Zooplankton composition and biomass in the Baltic Sea are governed heavily by salinity, which, in turn, is driven by freshwater input from land and precipitation in the region, and from occasional influxes of seawater from the North Sea (see Section 5 for a full discussion and site-specific examples). Despite salinity playing such a large role in the zooplankton community, *in situ* co-sampled salinity time-series data were not readily available for any of the Baltic Sea zooplankton time-series sites at the time of this report. Therefore, the WGZE study used a time-series of surface salinity generated by the PROgram for Boundary layers in the Environment (PROBE)–Baltic model (Omstedt and Axell, 2003), which uses a database of *in situ* data for initialization and validation of the model parameters.

The PROBE–Baltic salinity data consist of monthly mean salinity values from 1958 to 2008 (Figure 2.8). Unlike the gridded one-degree spatial fields of the HadISST and GlobColour datasets, the PROBE–Baltic data are spatially divided into the major basins of the Baltic Sea (e.g. Bothnian Bay, Bothnian Sea, Gulf of Finland, Gulf of Riga, eastern Gotland Basin, northwestern Gotland Basin). PROBE–Baltic salinity from the corresponding basin was added to each of the Baltic Sea zooplankton time-series sites in Section 5.

Additional information on the PROBE–Baltic model and data products is available online at <http://www.oceanclimate.se/>.

**Right.** Gathering freshly caught plankton from the Plymouth L4 monitoring site in the English Channel (report site #29). Photo by C. Halsband-Lenk.





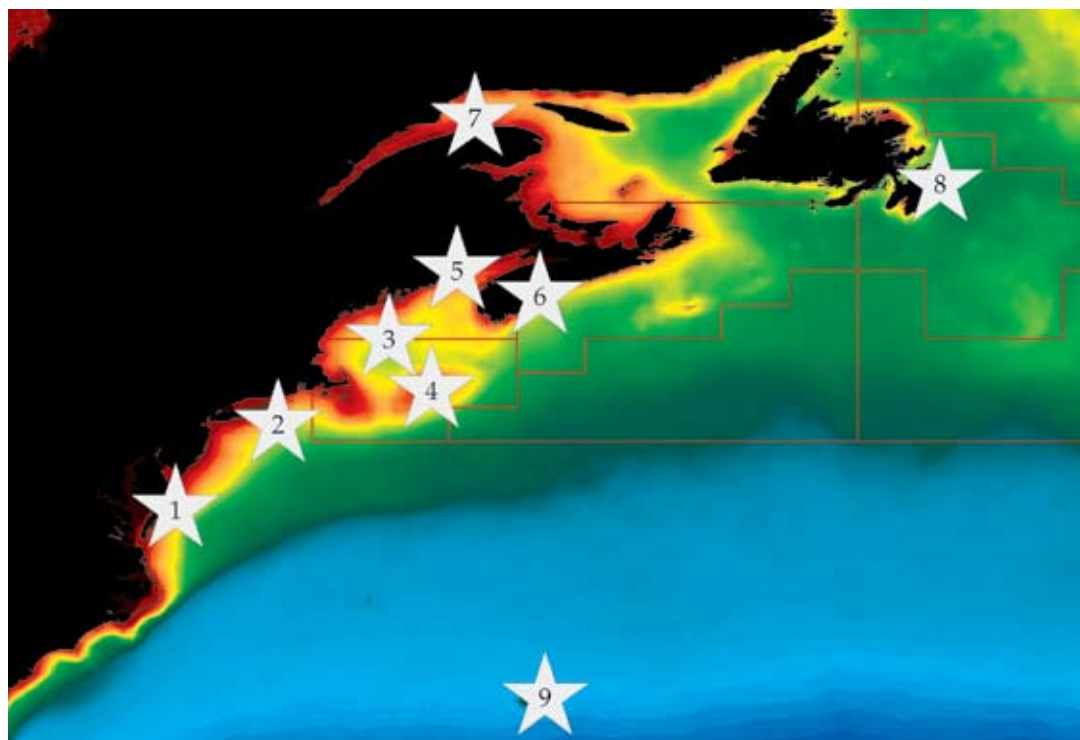
### 3. ZOOPLANKTON OF THE WESTERN NORTH ATLANTIC

*Peter Wiebe, Erica Head, Jon Hare, Jack Jossi, Michel Harvey, Pierre Pepin, Debbie Steinberg, Jack Jossi, Joe Kane, Ann Bucklin, Cabel Davis, Jeffrey Runge, and Jamie Pierson*

The Northwest Atlantic shelf regions, where these zooplankton time-series samples are collected (Figure 3.1), are influenced by water flowing towards the equator from the Arctic via the Labrador Sea/ Shelf (Loder *et al.*, 1998). Sea ice is present on the Labrador and Newfoundland shelves and in the Gulf of St Lawrence from late winter to early spring (December–March). Since the early 1990s, as temperatures have risen, the duration and extent of sea ice have decreased (ICES, 2008): in winter 2008/2009, there was virtually no ice in the Gulf of St Lawrence (E. Head, pers. comm.). On the shelf, cold, relatively fresh water flows southwards from the Labrador Shelf to the Newfoundland Shelf, around the southern tip of Newfoundland, and into the Gulf of St Lawrence through the Strait of Belle Isle. From the Gulf of St Lawrence, water flows out through Cabot Strait and southwestwards along the coast of Nova Scotia, where it mixes with flow from the offshore slope water in the central region. This mixture flows westwards to the Gulf of Maine, where it is joined by inflow from the slope waters via the Northeast Channel. From the Gulf of Maine, water flows around Georges Bank and along the Mid-Atlantic Bight to Cape Hatteras.

The changing composition of the water along the shelf is reflected in changes in the zooplankton species composition, with boreal species most abundant in the north and temperate species more important in the south (Head and Sameoto, 2007). The Gulf of Maine–Georges Bank region represents a southern boundary for many boreal species and a northern limit for some temperate and subtropical coastal species, although this is changing with the warming trend that is becoming evident in the area. In the Gulf of Maine, broadscale surveys have revealed that zooplankton abundance and biomass are higher in coastal regions and on Georges Bank than in central deep-water areas, reflecting differences in phytoplankton biomass and production.

An increased influx of Arctic freshwater during the early 1990s was accompanied by increased abundance of Arctic zooplankton species (*Calanus glacialis*, *Calanus hyperboreus*), first on the Newfoundland Shelf in the 1990s and then on the Scotian Shelf in the 2000s (Head and Sameoto, 2007). This increase in freshwater input also led to increased stratification on the Northwest Atlantic continental shelf and in the Gulf of Maine, which, in turn, led to earlier starting times for spring blooms (Ji *et al.*, 2008). In the 2000s, salinities increased on the Newfoundland and Scotian shelves, as did sea



**Figure 3.1**  
Locations of the western North Atlantic survey areas (Sites 1–9) plotted on a map of average chlorophyll concentration (see Section 2.3.2).

surface temperatures (SSTs), the net effect being a slight decrease in stratification. On the Scotian Shelf and in the Gulf of Maine, the increases in phytoplankton biomass in the 1990s were associated with increases in the abundance of small copepods and with changes in the abundance of larger forms (e.g. *Calanus finmarchicus*; Pershing *et al.*, 2005; Head and Sameoto, 2007). Most of these changes reversed in the 2000s, although phytoplankton levels did not decline much.

The spring bloom on the Newfoundland Shelf generally starts earlier in warm years when the ice retreat is early (Head *et al.*, In press). On the Scotian Shelf, the bloom started particularly early in 1999 and was associated with early reproduction in *C. finmarchicus* and a high level of haddock (*Melanogrammus aeglefinus*) recruitment (Platt *et al.*, 2003; Head *et al.*, 2005). Bloom intensities on the Newfoundland (Station 27) and Scotian (HL2) shelves were unusually high in 2007, but returned to average values in 2008 (Harrison *et al.*, 2009). Diatoms dominate during the spring bloom on the Newfoundland and Scotian shelves, and on the Scotian Shelf in autumn; in the Bay of Fundy, they are dominant year-round.

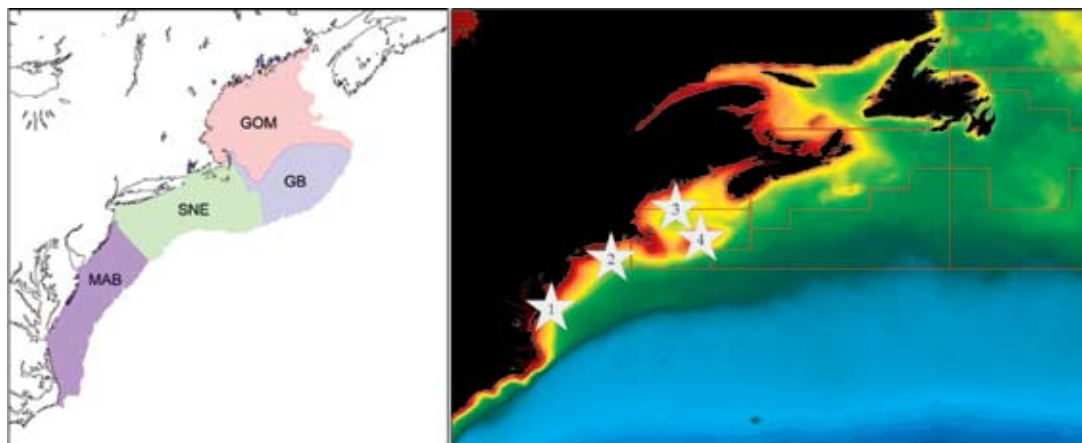
In the Gulf of Maine, conditions in the past few years have returned to those seen in the 1980s, with a relatively high North Atlantic Oscillation (NAO) index, lower surface salinities, and higher *C. finmarchicus* abundance (A.J. Pershing, pers. comm.). However, the NAO index in winter 2009/2010 has taken a dramatic negative trend, which may portend major changes in the hydrography and plankton dynamics in the Gulf of Maine and Georges Bank, with a 1- to 2-year time-lag similar to changes experienced in the Gulf of Maine after the 1996 negative NAO index (Greene and Pershing, 2003).

## Sites 1–4: NMFS Ecosystem Monitoring (northeast US continental shelf)

*Jon Hare, Jack Jossi, and Joe Kane*

**Figure 3.2**

Location of the NMFS Ecosystem Monitoring regions (Sites 1–4) plotted on a map of average chlorophyll concentration. Regions are determined by biophysical properties: MAB = Mid-Atlantic Bight, SNE = Southern New England, GOM = Gulf of Maine, and GB = Georges Bank.



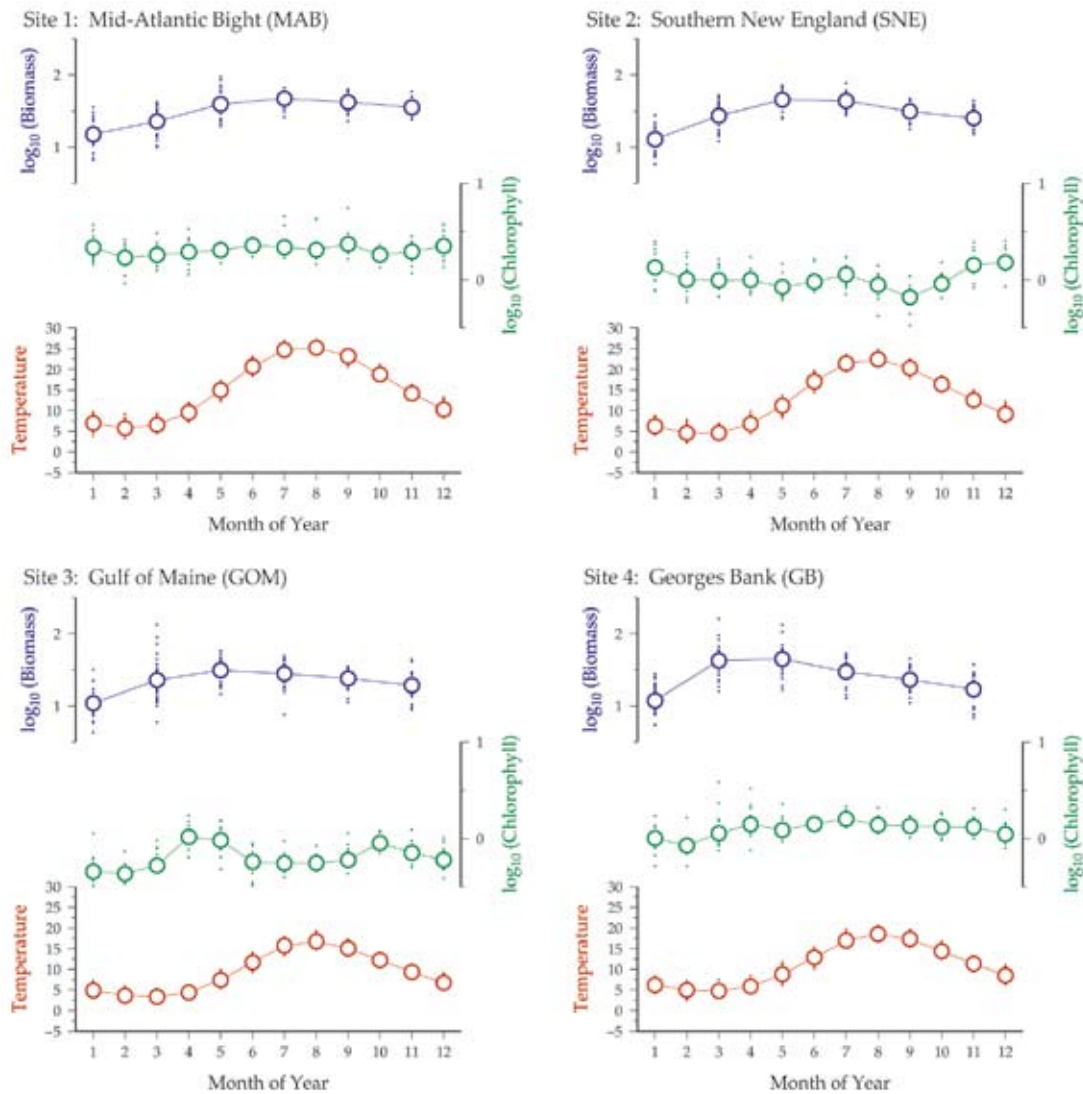
The Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service (NMFS) has a long-standing Ecosystem Monitoring programme covering most of the northeast US continental shelf. The NEFSC sampling protocol divides the continental shelf into four regions (Figure 3.2), based on their different physical and biological characteristics, and collects hydrographic and tow data using a randomized spatial sampling technique that samples approximately 30 stations per region per 2-month period. During these surveys, zooplankton is collected using a bongo net (60 cm diameter, 333  $\mu$ m mesh) towed obliquely from 200 m (or near the bottom) to the surface. The zooplankton time-series started in 1977 and continues to the present.

Along the northeast US continental shelf, primary production is highest near the shore. The distribution of zooplankton biomass is similar to that of primary production, with high levels also found during summer (Figure 3.3). Changes in the northeast US continental shelf zooplankton community have been observed in all regions, with a generally increasing trend in total annual zooplankton biomass since the early 1980s (Figure 3.4).

Changes in species composition over this period have been observed in the adjacent Georges Bank region (Kane, 2007), with smaller-bodied taxa increasing in abundance in the 1990s (Figure 3.5). There is also some evidence of a shift in seasonality for some zooplankton species (e.g. *Temora longicornis*), with the peak abundance period beginning earlier in the season and lasting longer. These changes probably occurred in the Mid-Atlantic region as well.

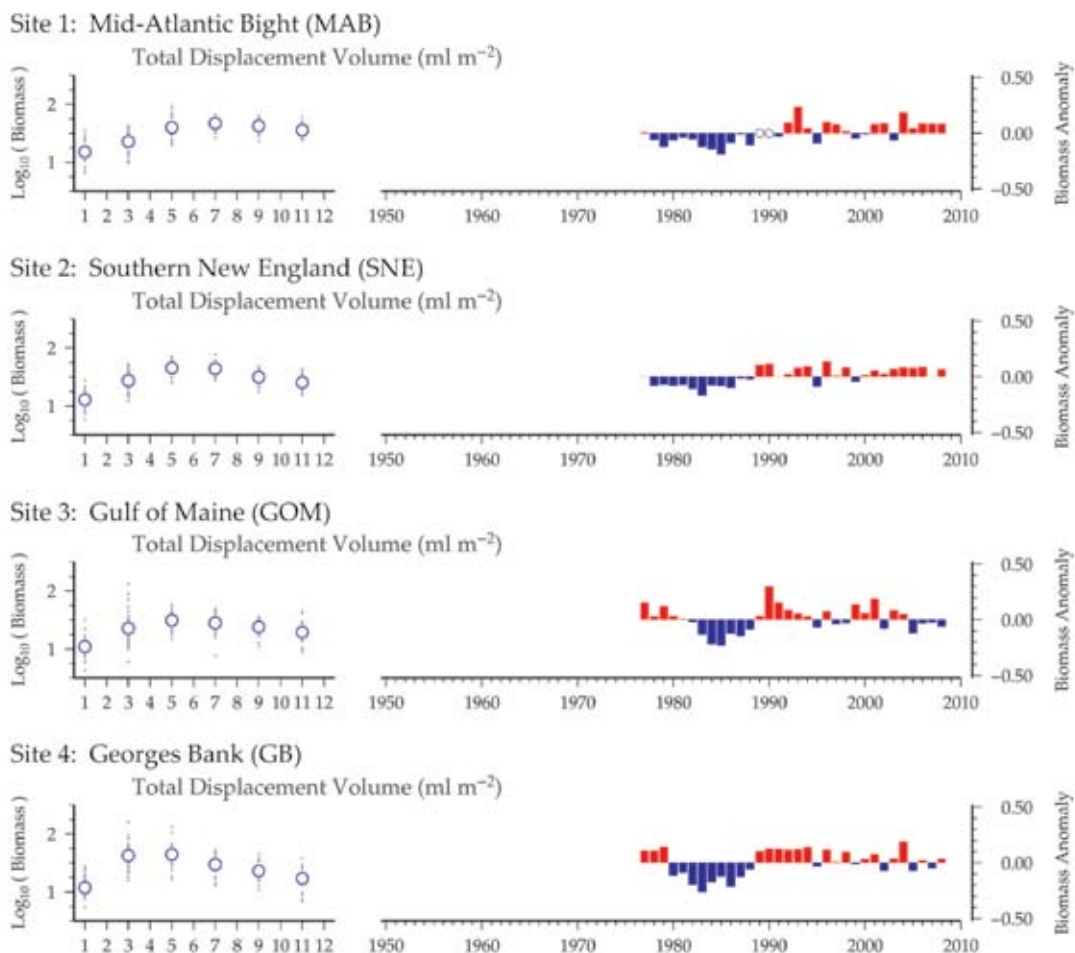
Long-term SST trends within each of the regions (Figure 3.6) demonstrate that temperatures are currently at or above the 100-year average, but lower than the 100-year maximum seen in the 1950s. Since 1960, water temperatures in the Mid-Atlantic Bight have remained cooler than the 1950 maximum, but have been slowly increasing towards this maximum in all of the regions (Ecosystem Assessment Program, 2009). Water temperatures are influenced by the influx of cooler, fresher water from the north, and the occurrence of low-salinity events has also increased since the early 1990s (Mountain, 2004).

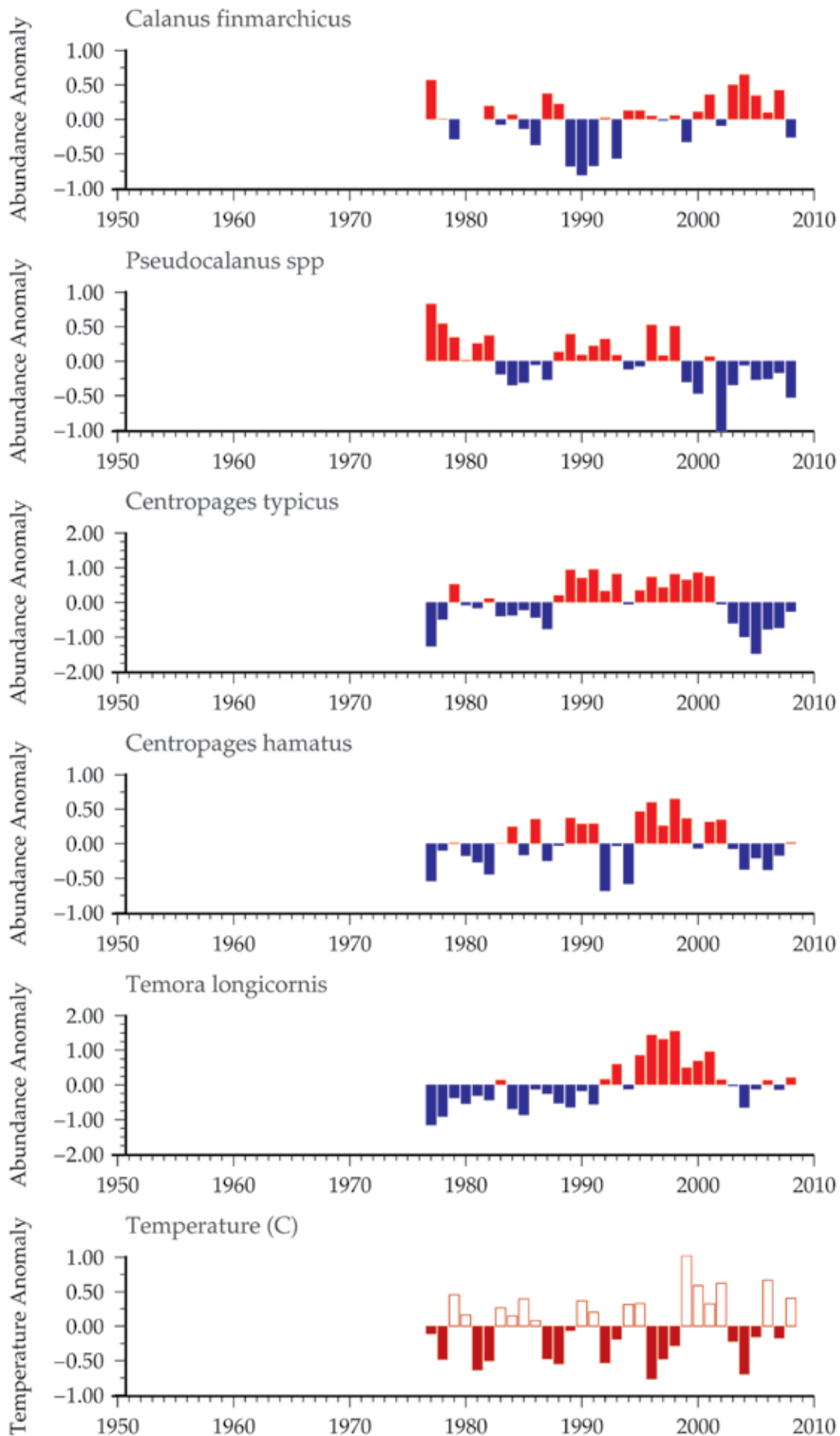




**Figure 3.3**  
Seasonal summary plots for zooplankton, chlorophyll, and surface temperature in each of the NMFS Ecosystem Monitoring regions (see Section 2.2.1 for an explanation of this figure).

**Figure 3.4**  
Seasonal and interannual comparison of select co-sampled variables across the NMFS Ecosystem Monitoring regions (see Section 2.2.2 for an explanation of this figure).

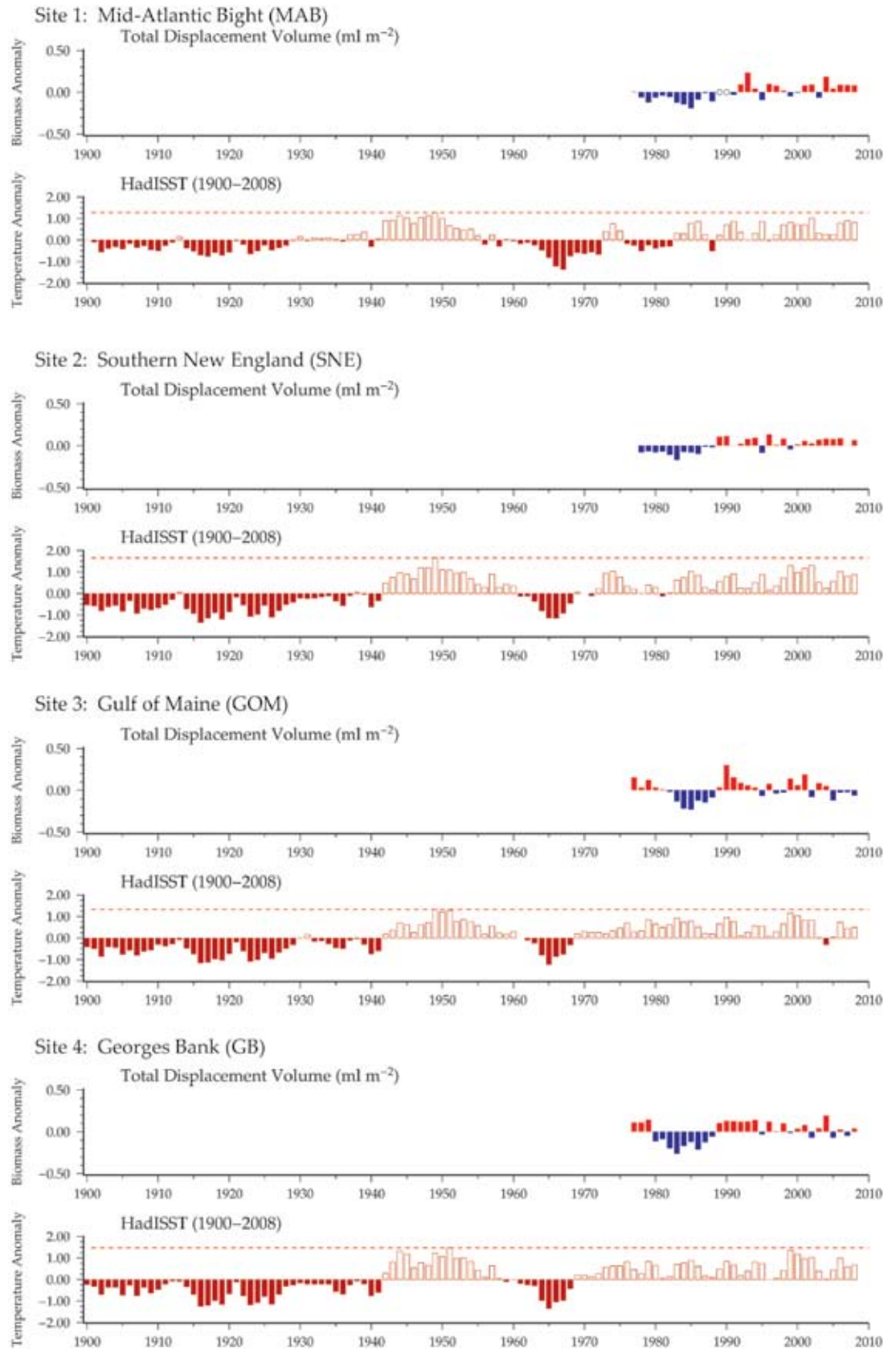




**Figure 3.5**  
Interannual comparison of five dominant copepod species and water temperatures sampled at Georges Bank.

**Figure 3.6**

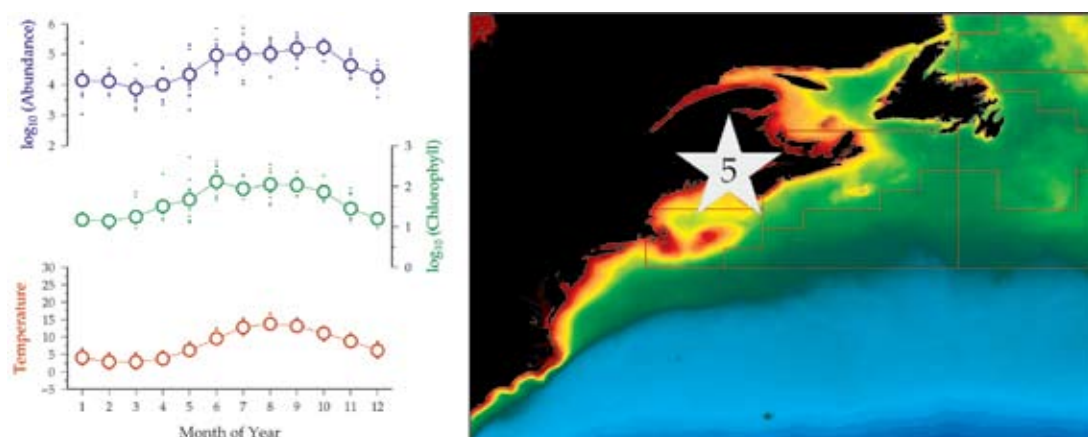
Long-term comparison of NMFS Ecosystem Monitoring regions zooplankton (total displacement volume) with HadISST sea surface temperatures for each region (see Section 2.2.3 for an explanation of this figure).





## Site 5: Prince 5 (Bay of Fundy)

Erica Head



**Figure 3.7**  
Location of the Prince 5 (Site 5) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

Zooplankton are sampled every 2–4 weeks at Prince 5, which is 100 m deep and located just off Campobello Island in the northwestern Bay of Fundy, approximately 6 km offshore from St Andrews, New Brunswick (Figure 3.7). Vertical tows are made from near-bottom to surface using a ringnet (75 cm diameter, 200  $\mu$ m mesh). A small vessel is used as the sampling platform. Conductivity–temperature–depth (CTD) profiles are recorded, and water samples are collected with Niskin bottles for measuring phytoplankton, nutrients, and extracted chlorophyll. Zooplankton samples are split: one half is used for wet–dry weight determination and the other half is subsampled for taxonomic identification and enumeration. Biomass of the dominant groups is also calculated using dry weights and abundance data for the dominant species groups (*Calanus*, *Oithona*, *Pseudocalanus*, and *Metridia*).

The data are entered into the “BioChem” database at the Canadian Department of Fisheries and Oceans (DFO). A Scientific Advisory Report (previously an Ecosystem Status Report) on the state of phytoplankton and zooplankton in Canadian Atlantic waters is prepared every year by the Canadian Science Advisory Secretariat. This report is available online at [http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex\\_e.asp](http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex_e.asp).

Monthly average abundance of total copepods is variable, but values are lowest during winter (January–April) and highest in late summer/autumn

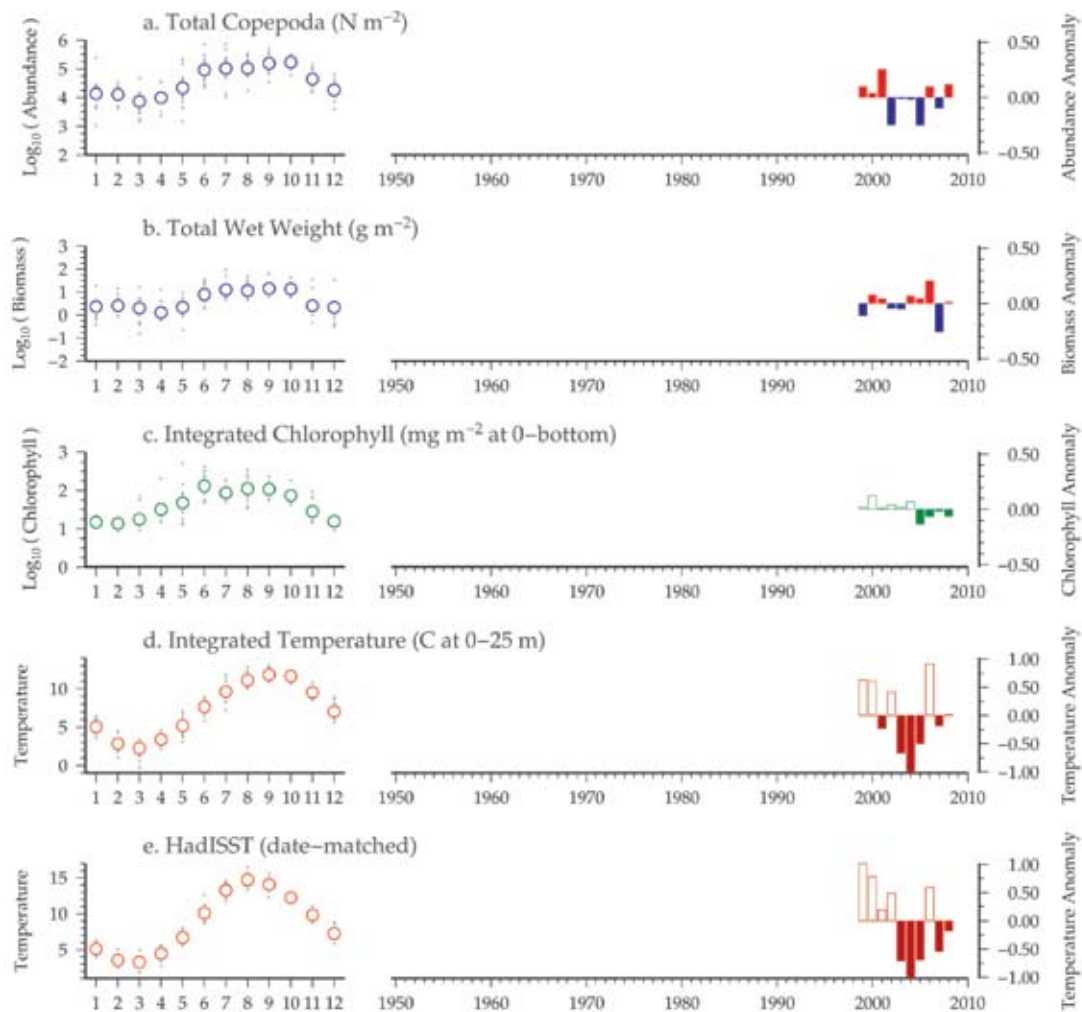
(August–October). Annual average copepod abundance anomalies were highest in 2001 and 2006 and lowest in 2002 and 2005 (Figure 3.8a). In years of low abundance (i.e. years with negative annual abundance anomalies), the summer/autumn period of high abundance was often weaker and/or of shorter duration.

In addition to copepod abundance, co-sampled time-series of total zooplankton wet weight, integrated chlorophyll, and integrated temperature data are available for the site (Figure 3.8b–d). Although the seasonal cycles of copepod abundance and total wet weight are similar, the annual anomalies of total wet weight differ slightly because of the influence of phytoplankton blooms on the measurement. Chlorophyll concentrations demonstrate a seasonal cycle similar to that of the copepods, but preceding it by one month, and the annual chlorophyll concentrations have demonstrated a slight downward trend over time. Integrated temperature sampled at this site and HadISST temperatures demonstrate similar interannual increases and decreases (Figure 3.8d and e), but differ slightly in their seasonal cycles, most probably because of the larger spatial area represented by the HadISST data.

The SST values are at the high end of an approximately 50-year multidecadal trend (Figure 3.9). Within this region, water temperatures are often correlated with the state of the NAO. At this time, any relationship between water temperature and zooplankton abundance is inconclusive.

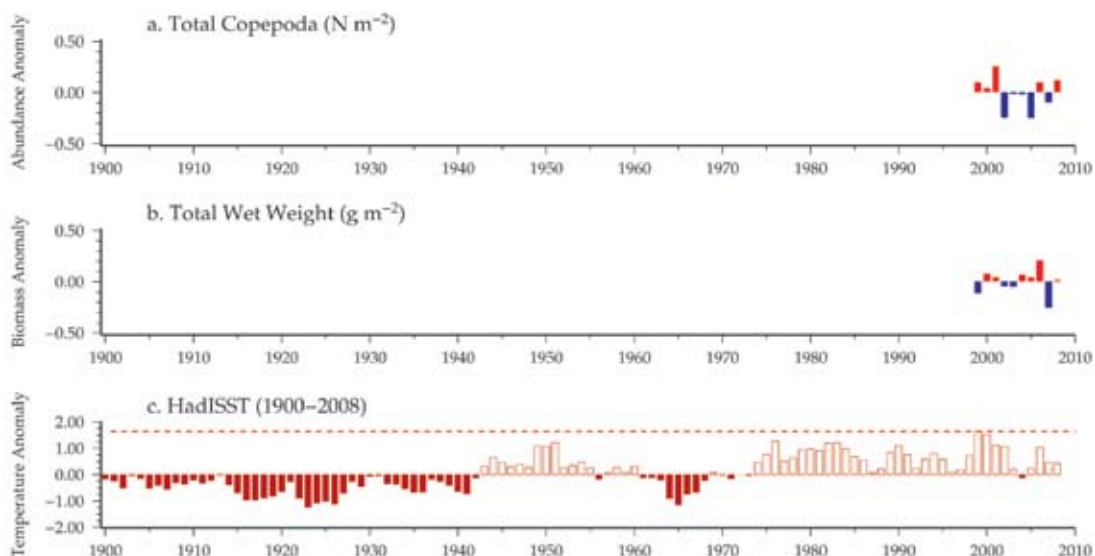
**Figure 3.8**

Seasonal and interannual comparison of select co-sampled variables at Prince 5 (see Section 2.2.2 for an explanation of this figure).



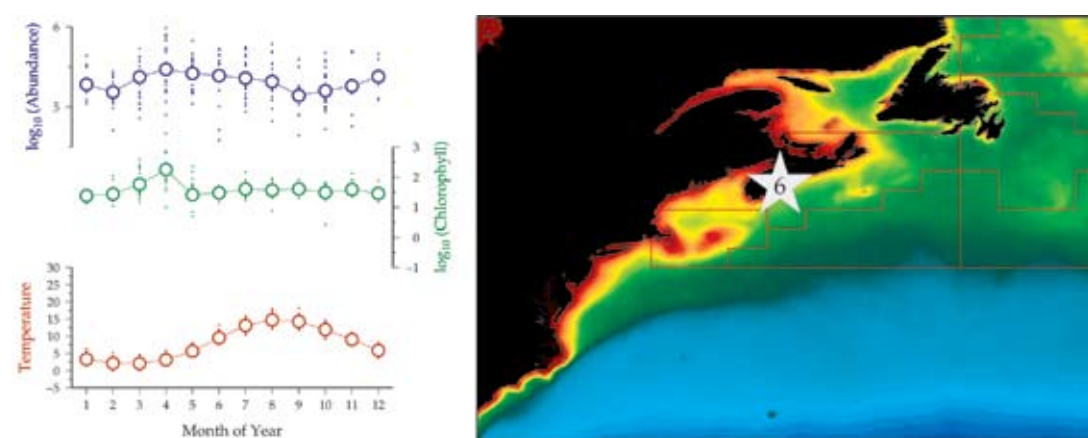
**Figure 3.9**

Long-term comparison of Prince 5 copepod abundance, total wet weight, and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



## Site 6: Halifax Line 2 (Scotian Shelf)

Erica Head



**Figure 3.10**

Location of the Halifax Line 2 (Site 6) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

Zooplankton are sampled every 2–4 weeks at Station 2 of the Halifax Line (HL2), which is 150 m deep and located approximately 12 km offshore from Halifax, on the inshore edge of Emerald Basin (Figure 3.10). Vertical tows are made from near-bottom to surface using a ringnet (75 cm diameter, 200  $\mu$ m mesh). Research ships, trawlers, and small vessels are used as sampling platforms. CTD profiles are recorded, and water samples are collected with Niskin bottles for the measurement of phytoplankton, nutrients, and extracted chlorophyll. Chlorophyll and nutrient concentrations are measured for individual depths, whereas subsamples from each depth are combined to give an integrated sample for phytoplankton cell counting. Zooplankton samples are split: one-half is used for wet–dry weight determination and the other half is subsampled for taxonomic identification and enumeration. Biomass of the dominant groups is calculated using dry weights and abundance data for various groupings.

The data are entered into the “BioChem” database at the DFO. A Scientific Advisory Report (previously an Ecosystem Status Report) on the state of phytoplankton and zooplankton in Canadian Atlantic waters is prepared every year by the Canadian Science Advisory Secretariat. This report is available online at [http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex\\_e.asp](http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex_e.asp).

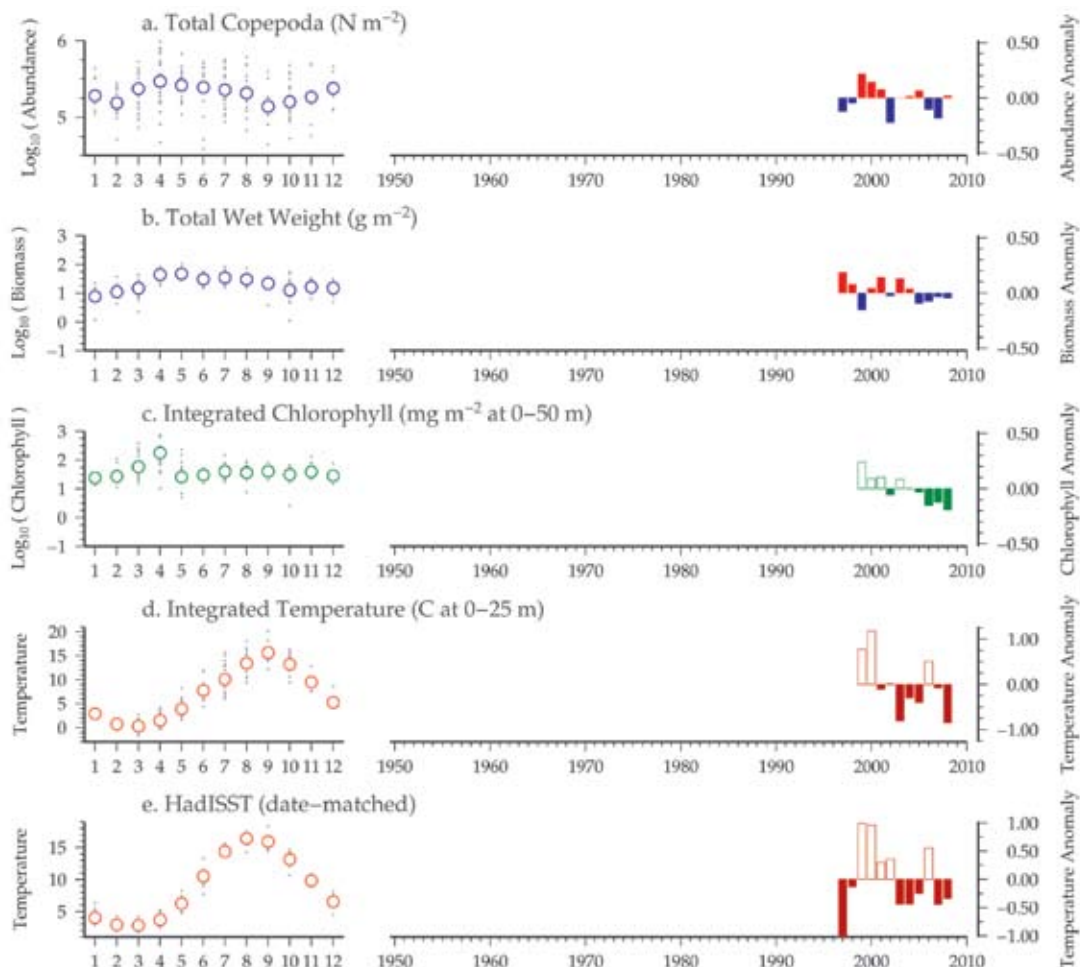
Monthly average abundance of total copepods is variable at HL2, but demonstrates minima in February and September. Annual average abundance anomalies were highest in 1999 and

2000 and lowest in 2002 and 2007 (Figure 3.11a), suggesting an overall downward trend. In addition to copepod abundance, co-sampled time-series of total zooplankton wet weight, integrated chlorophyll, and integrated temperature data were available for the site (Figure 3.11b–d). Although the seasonal cycles of copepod abundance and total wet weight are similar, the annual anomalies of total wet weight differ slightly because of the influence of phytoplankton blooms on the measurement. Chlorophyll concentrations demonstrate a seasonal cycle similar to that of the copepods. Like Prince 5, the annual chlorophyll concentrations demonstrate a slight downward trend over time, thought to be caused by a decline in diatom abundance (Li *et al.*, 2006). Integrated temperature sampled at the site and HadISST temperatures demonstrate similar interannual increases and decreases (Figure 3.11d and e), but differ slightly in their seasonal cycles, most probably attributable to the larger spatial area represented by the HadISST data.

The CPR standard area closest to HL2 is E10 (Figure 1.2). Copepod abundance from the CPR corresponds neatly with the HL2 copepod abundance (Figure 3.12), whereas differences between CPR copepod abundance and HL2 wet weight are probably caused by contamination with phytoplankton in the wet-mass measurement. The SST values are at the high end of an approximately 50-year, multidecadal trend (Figure 3.12). In general, water temperature is often correlated with the state of the NAO. At this time, any relationship between water temperature and zooplankton abundance is inconclusive.

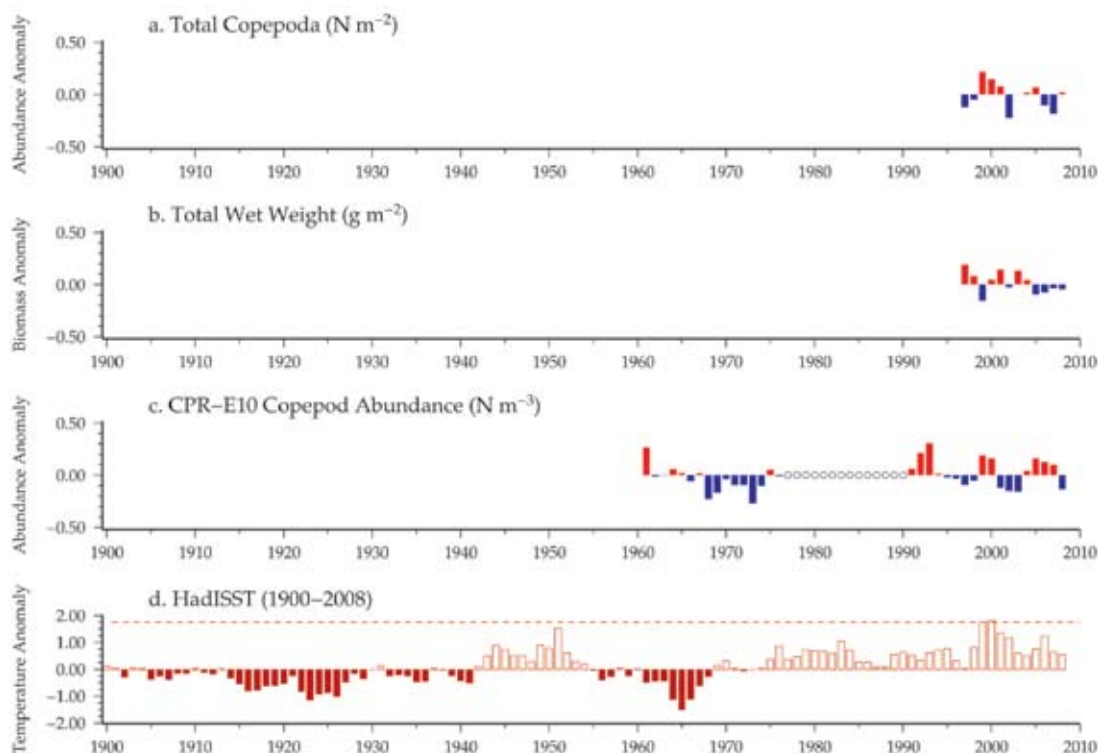
**Figure 3.11**

Seasonal and interannual comparison of select co-sampled variables at Halifax Line 2 (see Section 2.2.2 for an explanation of this figure).



**Figure 3.12**

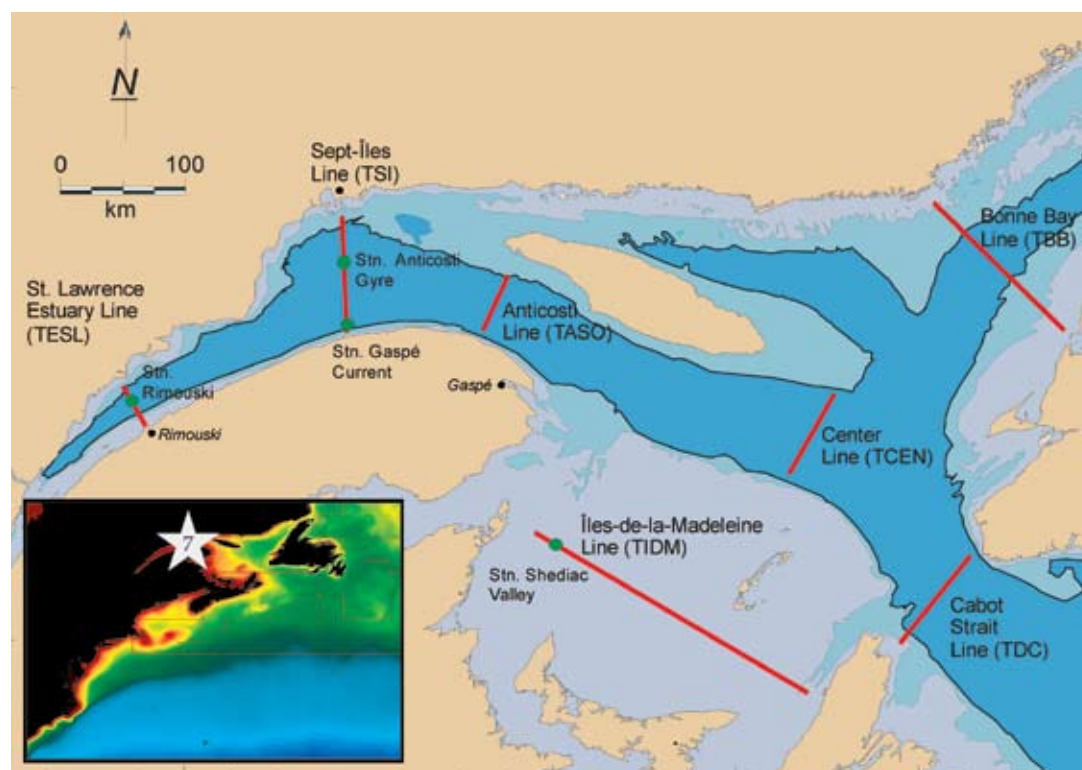
Long-term comparison of Halifax Line 2 copepod abundance and wet weight with copepod abundance in CPR standard area E10 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).





## Site 7: Anticosti Gyre and Gaspé Current (Gulf of St Lawrence)

Michel Harvey



**Figure 3.13**  
Location of the Anticosti Gyre and Gaspé Current (Site 7) survey areas plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).

The Atlantic Zone Monitoring Programme (AZMP) was implemented in 1998 to collect and analyse the biological, chemical, and physical field data necessary to (i) characterize and understand the causes of oceanic variability at the seasonal, interannual, and decadal scales; (ii) provide multidisciplinary datasets that can be used to establish relationships among the biological, chemical, and physical variables; and (iii) provide adequate data to support the sound development of ocean activities. The key element of AZMP sampling strategy is oceanographic sampling at fixed stations and along sections. Fixed stations are occupied approximately every 2 weeks, conditions permitting, and sections are sampled in June and November. Zooplankton is sampled from the bottom to the surface with a ringnet (75 cm diameter, 200 µm mesh). CTD profiles are recorded, and samples for phytoplankton, nutrients, and extracted chlorophyll are collected using Niskin bottles at fixed depths. Samples are combined to give an integrated sample.

An ecosystem status report on the state of phytoplankton and zooplankton is prepared every year.

This report is available online at [http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex\\_e.asp](http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex_e.asp).

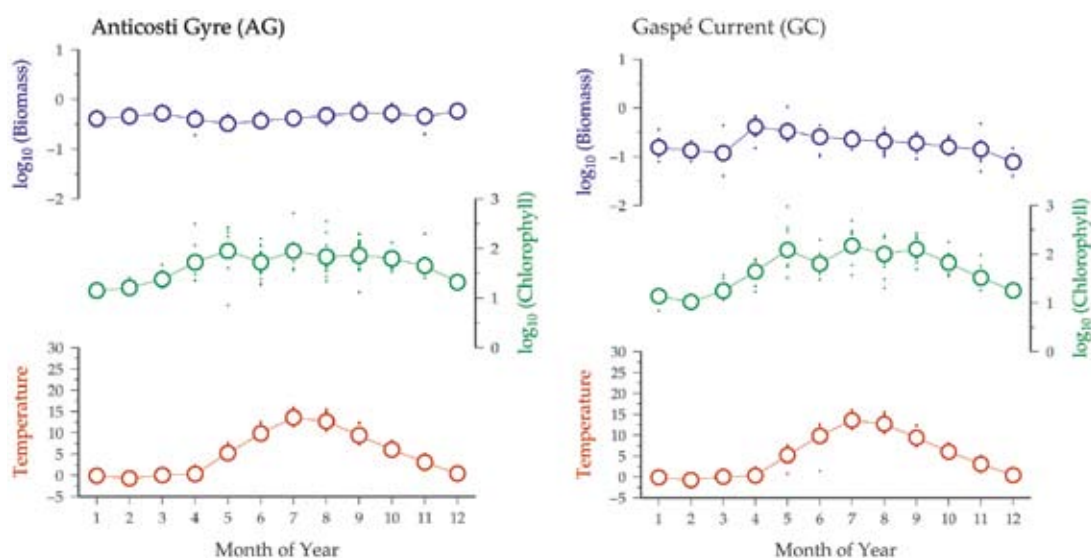
Data presented in this report are from two sampling stations in the northwest Gulf of St Lawrence (GSL): the Anticosti Gyre (AG) and the Gaspé Current (GC), which together comprise Site 7 (Figure 3.13). The GSL is a coastal marine environment with a particularly high zooplankton biomass, relative to other coastal areas, which is dominated by *Calanus* species (de Lafontaine *et al.*, 1991). Annual anomalies of zooplankton biomass and abundance indicate that, in 2007–2008, biomass was slightly below normal at AG (Figure 13.15a and b) and lower than normal at GC (Figure 3.15e and f), whereas abundance at both sites was normal in 2007 and much higher than normal in 2008. Hierarchical community analysis revealed that, numerically, copepods continued to dominate the zooplankton year-round at both fixed stations in 2007–2008, except for a pulse of larvaceans that was observed during summer 2007 at AG and GC. There was no apparent change in copepod community structure in 2007–2008 at either station (Harvey and Devine, 2009).

Zooplankton abundance and biomass do not follow the same seasonal cycle or interannual patterns as chlorophyll (Figures 3.14 and 3.15). For example, the zooplankton minimum observed at AG in 2001 corresponded to a chlorophyll *a* peak (Figure 3.15b and c), whereas the zooplankton peak at GC in 2003 corresponded to a chlorophyll *a* minimum (Figure 3.15f and g). This absence of correlation between zooplankton and algal biomass has been observed in the GSL (de Lafontaine *et al.*, 1991; Roy *et al.*, 2000) and was attributed to the complex estuarine circulation pattern observed at GC and AG.

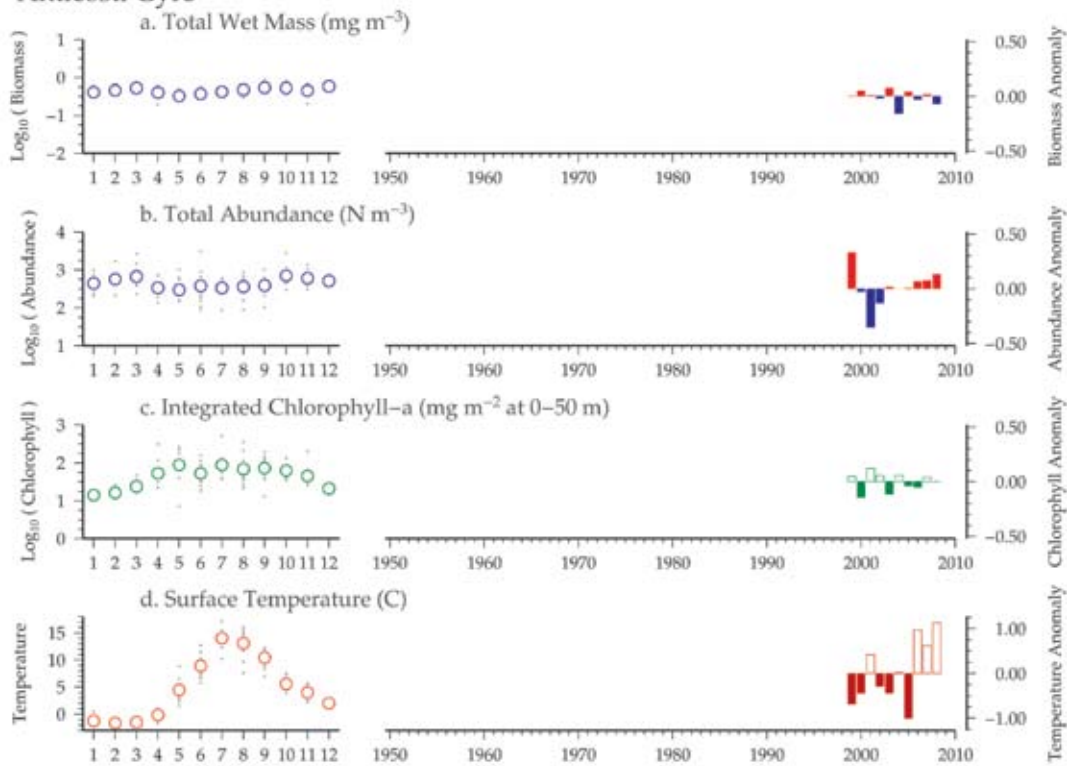
Annual cycles of sea surface temperature at both sites are similar, with values below 0°C in winter and peaks above 14°C during summer (Figure 3.15d and h). Long-term temperatures in the region reveal that temperatures are currently at the high end of an approximately 50-year multidecadal trend. Temperature has been near, or even above, the 100-year maximum (Figure 3.16c and f, red dashed line) since 1998. The exact effects of these high temperatures are not fully understood, although total zooplankton abundance at both regions (Figure 3.16b and e) is currently increasing with increasing temperature at AG and GC.

**Figure 3.14**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature at the Anticosti Gyre and Gaspé Current sites (see Section 2.2.1 for an explanation of this figure).



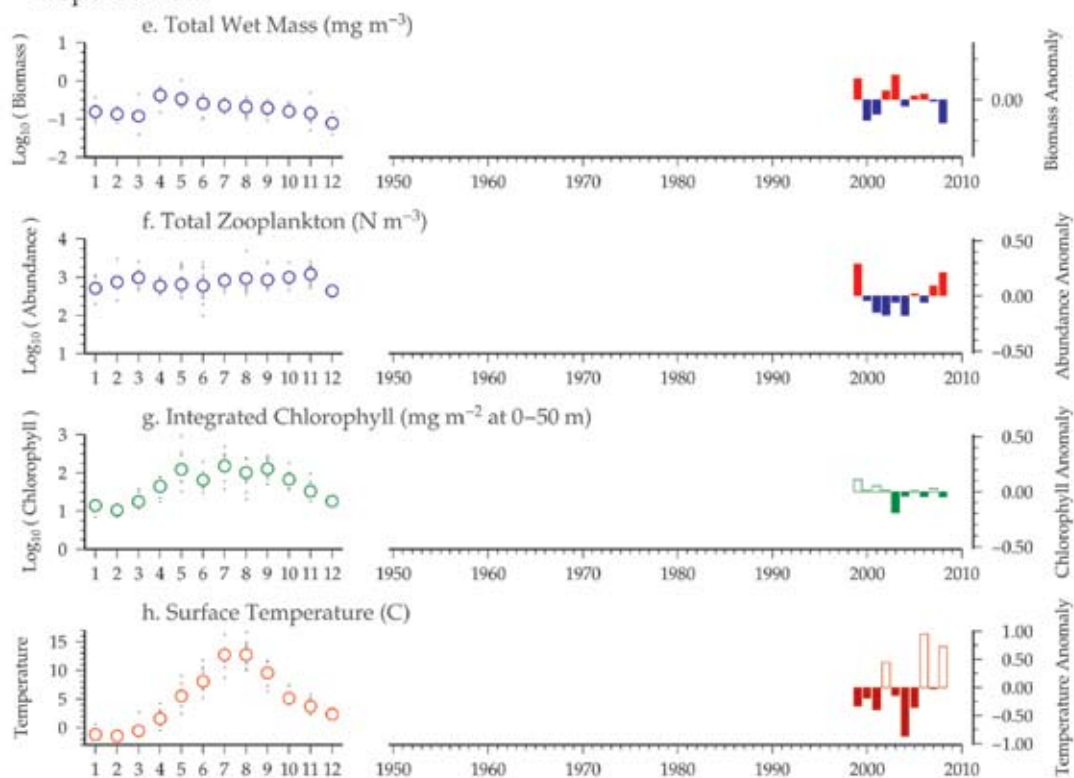
## Anticosti Gyre



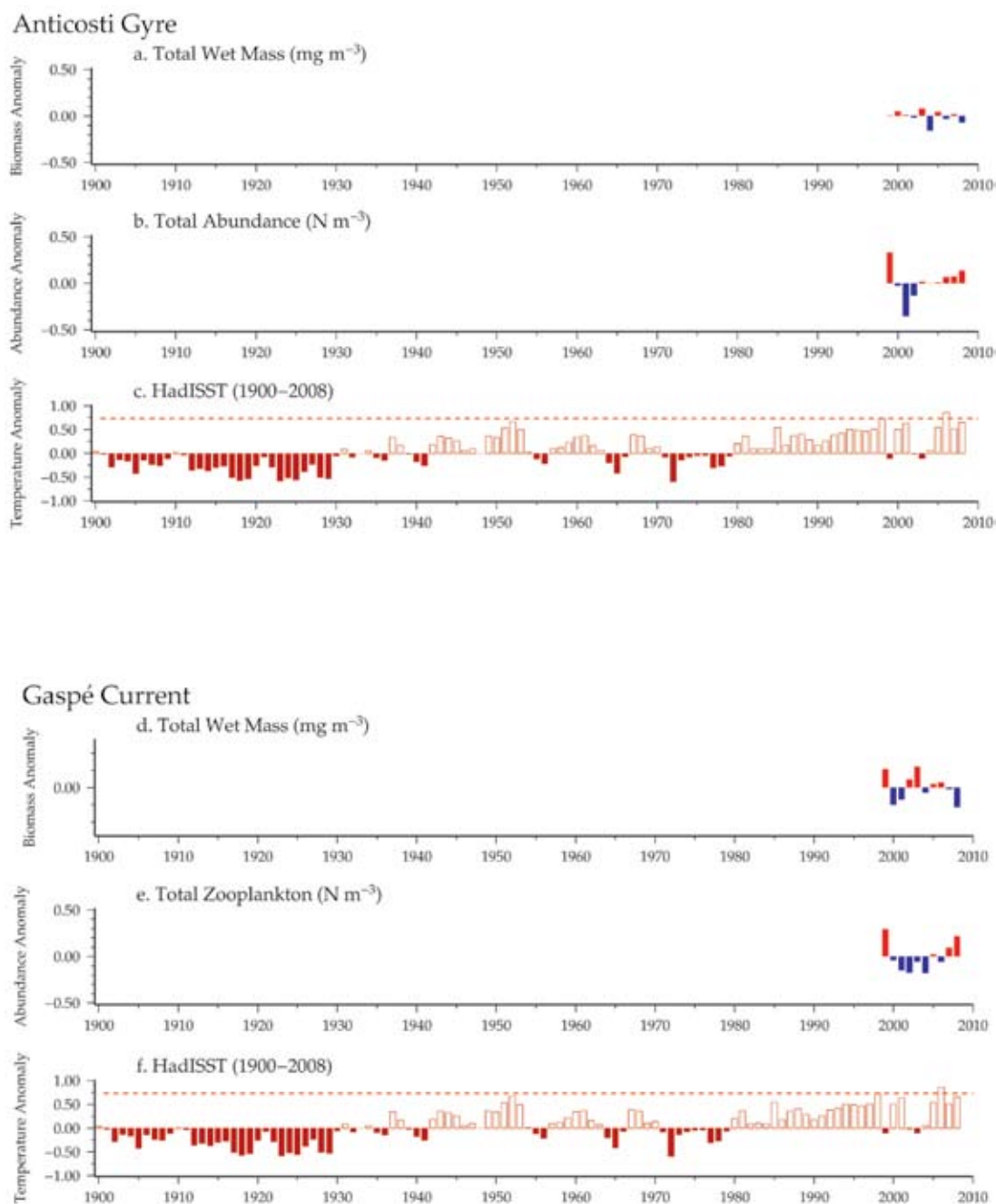
**Figure 3.15**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature at the Anticosti Gyre and Gaspé Current sites (see Section 2.2.1 for an explanation of this figure).

## Gaspé Current



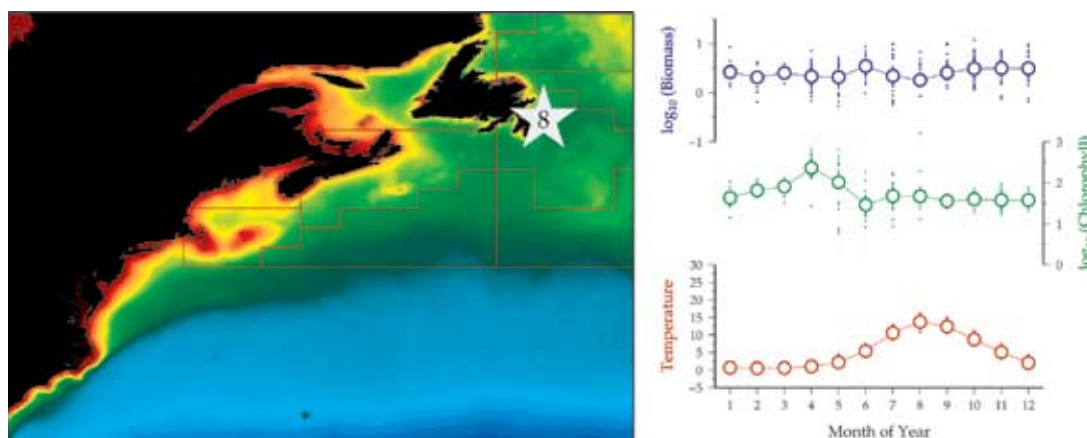
**Figure 3.16**  
Long-term comparison of Anticosti Gyre and Gaspé Current zooplankton wet mass and abundance with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).





## Site 8: Station 27 (Newfoundland Shelf)

Pierre Pepin



**Figure 3.17**  
Location of Station 27 (Site 8) and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

Zooplankton is sampled every 2–4 weeks (if possible) from research vessels, using a ringnet (75 cm diameter, 200  $\mu$ m mesh) from a fixed site (Station 27), and seasonally from a number of stations on a series of transects running perpendicular to the coast of Newfoundland across the Newfoundland and Labrador shelves and the Grand Banks. The most frequently sampled station, Station 27, is located 5 nautical miles east of St John's harbour, on the northwestern edge of the Grand Banks, at a depth of 170 m (Figure 3.17). CTD profiles are recorded, and samples for phytoplankton, nutrients, and extracted chlorophyll are collected using Niskin bottles at fixed depths. Subsamples are combined to give an integrated sample.

Zooplankton samples are split: one half is used for wet–dry weight determination, and the other half is subsampled to give at least 200 organisms, which are identified to genus or species and counted. Another subsample is taken containing at least 100 *Calanus* spp., which are identified to species and stage and then counted. Biomasses of the dominant groups are calculated using average dry weights of various groupings (*Calanus*, *Oithona*, *Pseudocalanus*, and *Metridia*) and abundance data.

Total copepod biomass is limited in seasonal variability (Figure 3.18a) but, overall, tends to be higher in autumn than in winter or spring. Interannual variations in total copepod biomass tend to mirror that of large copepods (Figure 3.18b), which dominate the community in weight, but not in numbers. Large copepods are most abundant following a spring phytoplankton bloom, reflecting the production cycle of nauplii and copepodites of the dominant *Calanus* species, whereas the biomass

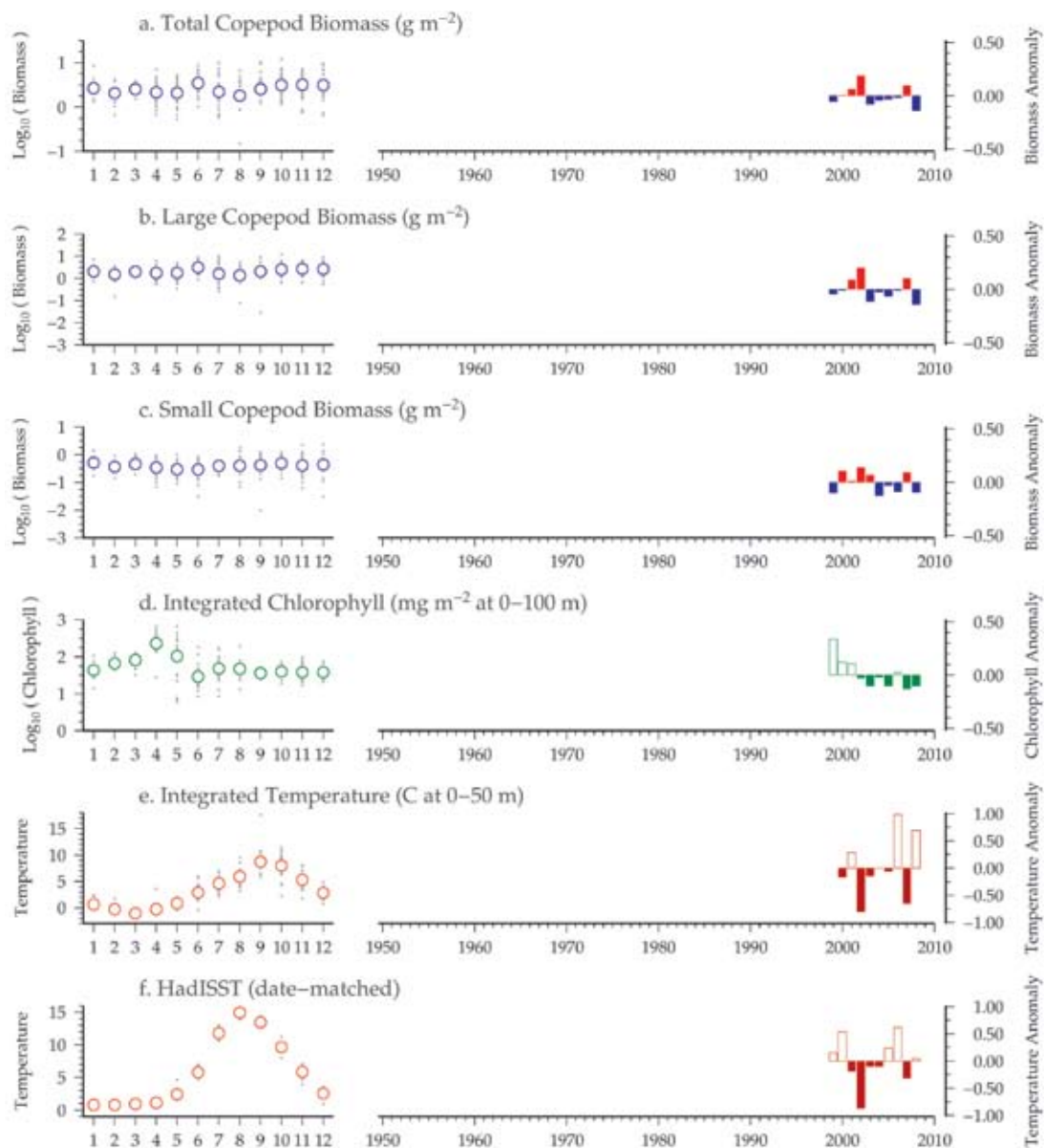
of small copepods peaks in late autumn (Figure 3.18c) as a result of large numbers of *Oithona* spp. Overall, there are greater interannual variations in the biomass of large copepods relative to smaller species.

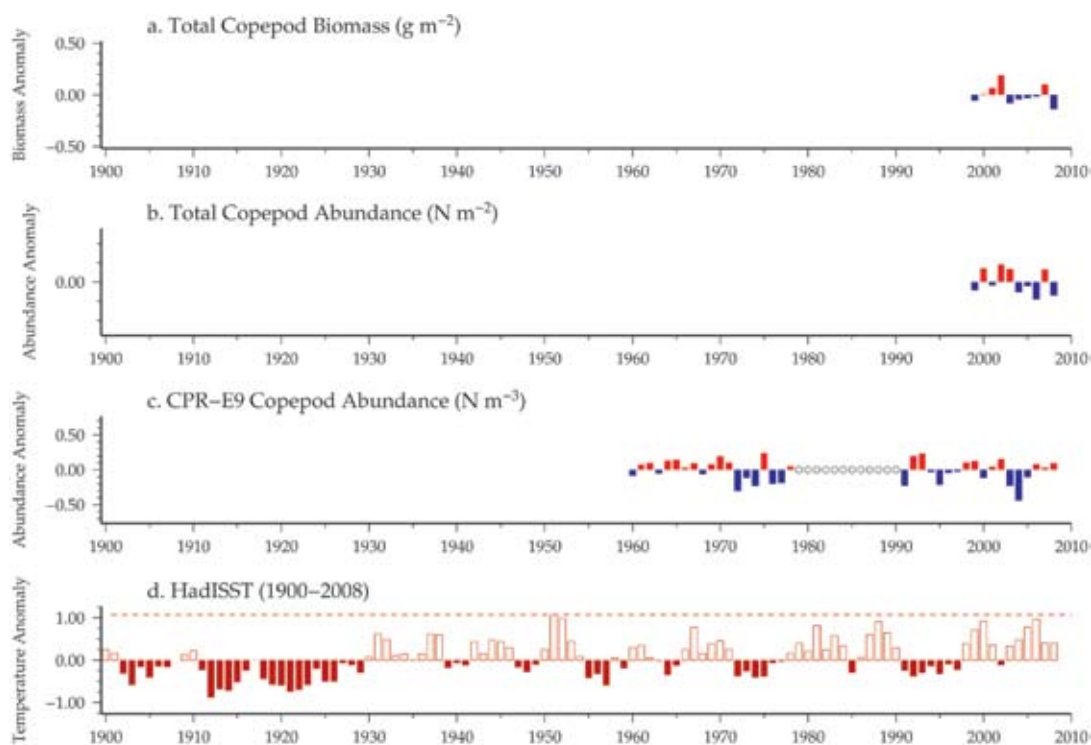
The seasonal cycle in local temperatures differs markedly from the HadISST temperatures, although the general pattern in interannual variability is similar (Figure 3.18e and f). The differences reflect the wide area of the continental shelf represented in the HadISST estimates relative to the more local measurements taken at Station 27, which is located in the inshore arm of the Labrador Current. Similarities in interannual variations are the result of large decorrelation scales for SST anomalies in the region (Ouellet *et al.*, 2003).

Interannual variations in the abundance and biomass of copepods correspond well with the nearest CPR standard area (E9), but the long-term pattern in variation demonstrates no clear relationship with temperature anomalies in the region (Figure 3.19). Overall, the abundance of copepods at Station 27 increased in 2007, following 3–4 years with low abundance indices, but returned to low levels in 2008.

A more detailed report on the ecosystem status of chemical and biological oceanographic conditions in the Newfoundland and Labrador region (Canadian Atlantic waters) is prepared every year as a Science Advisory Report by the Canadian Science Advisory Secretariat (CSAS). This report is available online at [http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex\\_e.asp](http://www.meds-sdmm.dfo-mpo.gc.ca/csas/applications/Publications/publicationIndex_e.asp).

**Figure 3.18**  
Seasonal and interannual comparison of select co-sampled variables at Station 27 (see Section 2.2.2 for an explanation of this figure).





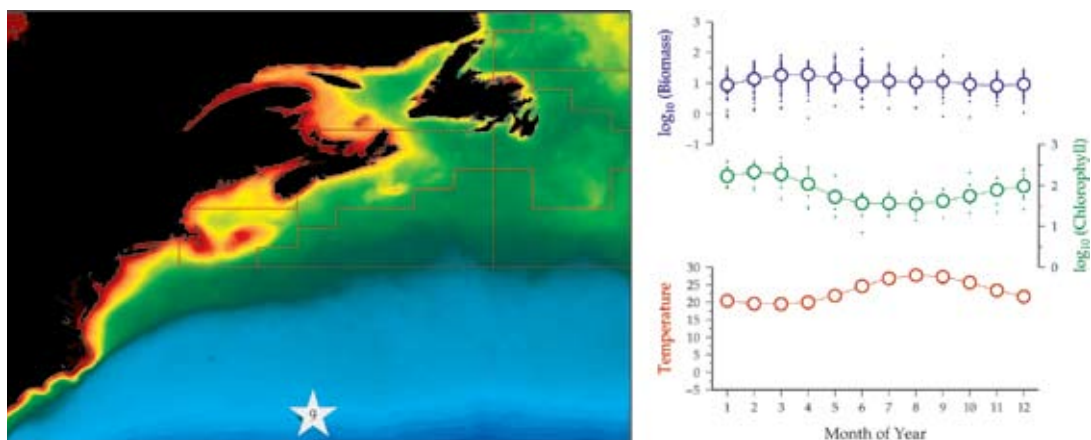
**Figure 3.19**  
Long-term comparison of Station 27 copepod biomass and abundance with copepod abundance in CPR standard area E9 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## Site 9: BATS (Sargasso Sea)

Debbie Steinberg

**Figure 3.20**

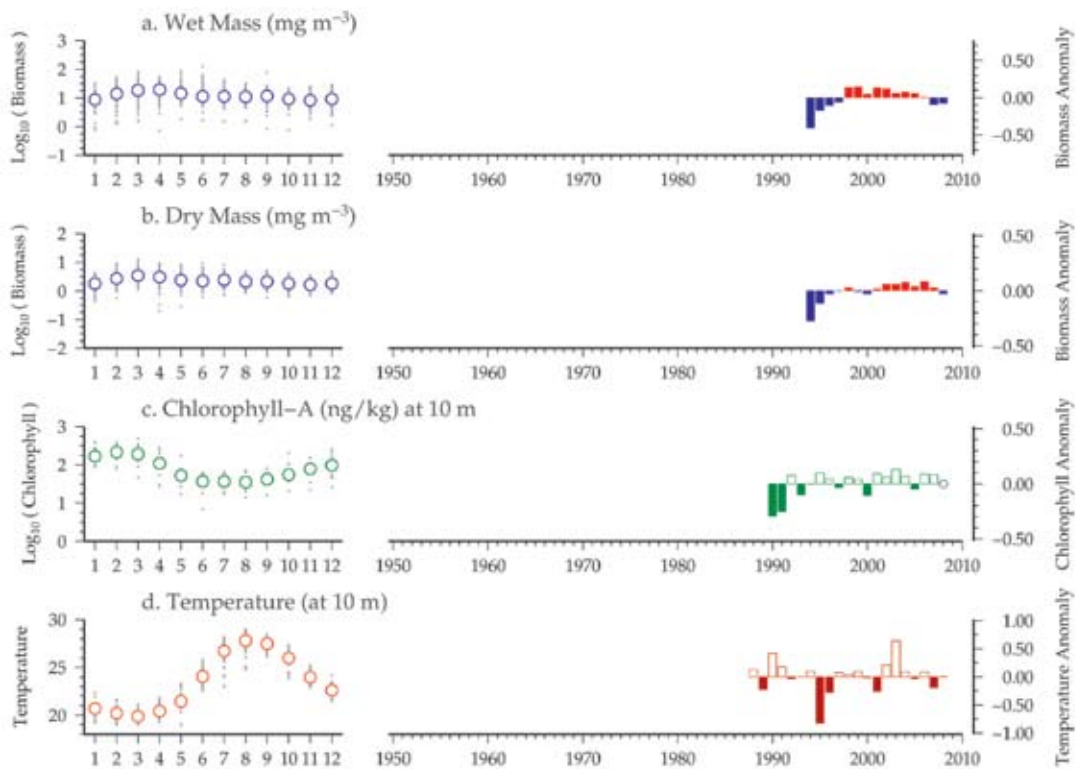
Location of the BATS (Site 9) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



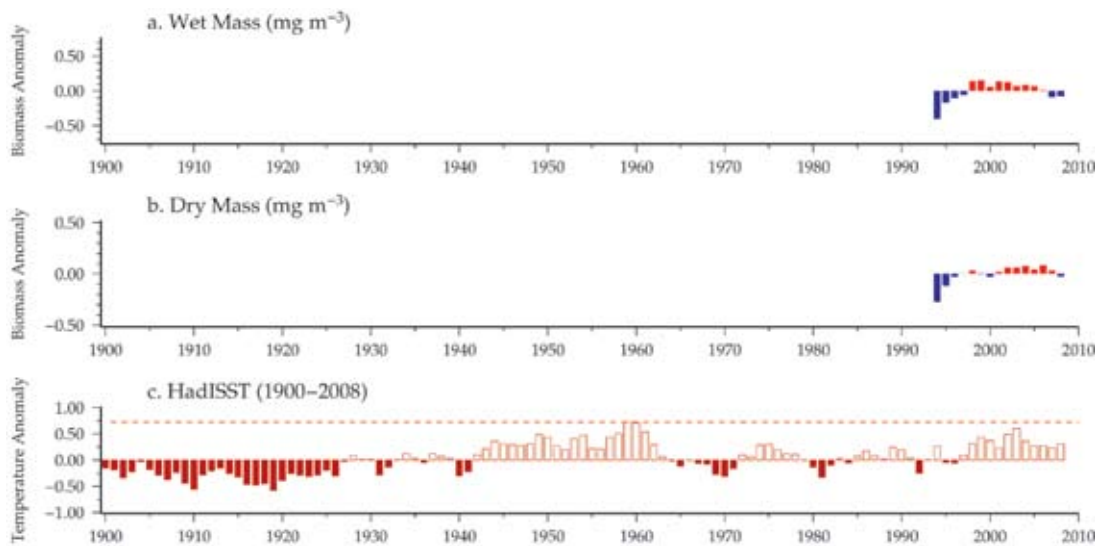
The Bermuda Atlantic Time-series Study (BATS) site is located in the Sargasso Sea at 31°50'N 64°10'W (Figure 3.20) and is monitored by the Bermuda Institute of Ocean Sciences (BIOS). Zooplankton is collected at least once a month with a ringnet (100 cm diameter, 202  $\mu\text{m}$  mesh). Two replicate oblique tows are made during the day (between 09:00 and 15:00) and night (between 20:00 and 02:00) to a depth of approximately 200 m. Night-time biomass values on average are 1.7–3.4-fold higher than daytime biomass, indicating the importance of diel migrators at the site (Madin *et al.*, 2001). *Pleuromamma* spp. copepods and the euphausiid *Thysanopoda aequalis* accounted for up to 70% of the night-only biomass (Steinberg *et al.*, 2000).

There is a limited seasonal variability within the BATS zooplankton biomass (Figure 3.21a and b), with a relatively small March–April maximum that follows the spring chlorophyll maximum (Figure 3.21c). On an annual basis, zooplankton biomass increased from the mid-1990s to the mid-2000s and may now be decreasing in what appears to be a decadal cycle. Long-term temperatures in the region are currently at the high end of an approximately 50-year multidecadal trend (Figure 3.22). Any relationship between zooplankton biomass and long-term temperature is inconclusive at this time.





**Figure 3.21**  
Seasonal and interannual comparison of select co-sampled variables at BATS (see Section 2.2.2 for an explanation of this figure).



**Figure 3.22**  
Long-term comparison of BATS zooplankton biomass with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

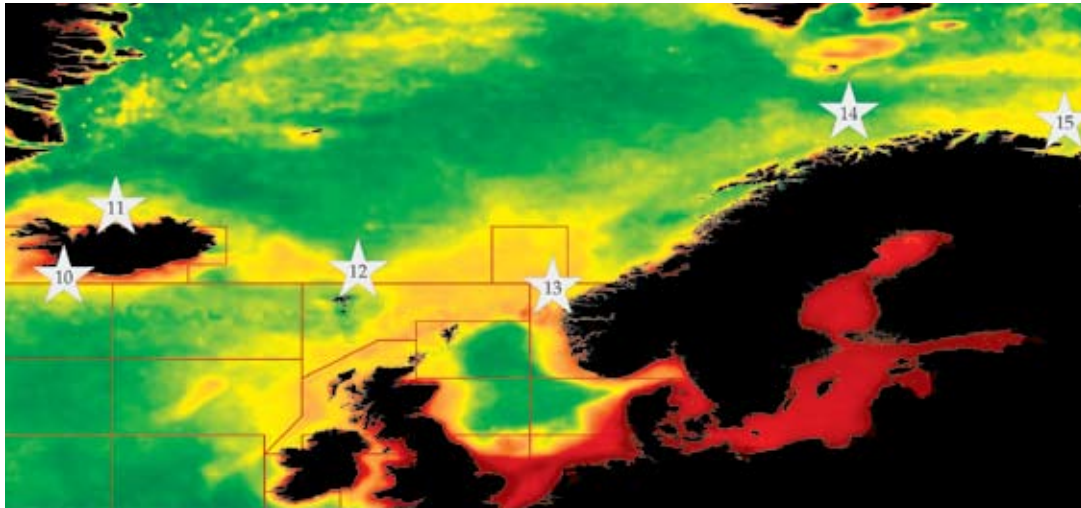
## 4. ZOOPLANKTON OF THE NORDIC AND BARENTS SEAS

*Astthor Gislason, Webjørn Melle, Cecilie Broms, Sigrún Jónasdóttir, and Hogni Debes*

The Nordic and Barents seas (Figure 4.1) are influenced by warm saline Atlantic water entering from the south as the North Atlantic Current. One branch flows west along the south coast of Iceland, north along the west coast, then splits into two components at the Greenland–Iceland Ridge. The larger component turns west into the Irminger Sea, whereas the smaller one continues north of Iceland. Atlantic water also enters the Norwegian Sea on both sides of the Faroe Islands. This water flows north along the Norwegian coast as the Norwegian Atlantic Current, past the Svalbard islands, and into the Arctic Ocean. Between Bear Island (south of Svalbard) and the north coast of Norway, a branch of the Atlantic Current flows into the Barents Sea.

Cold, lower salinity water enters the Nordic and Barents seas from the Arctic Ocean. In the Greenland Sea, Arctic water flows south into the Iceland Sea as the East Greenland Current. North of Iceland, part of this current turns east, mixes with Atlantic water, and enters the Norwegian Sea as the East Icelandic Current. Arctic water enters the Barents Sea in the northeast and flows west north of the Polar front. Fresh, lower salinity coastal water flows along the Norwegian coast. The deep ocean basins adjoining the coastal areas are subject to intensive winter cooling and deep convection. Deep return currents carry the convected water back into the deep basins of the North Atlantic.

The populations of zooplankton are dominated by arctic–boreal species, and there is a typical seasonal cycle of primary and secondary production, beginning with a spring bloom that is triggered by increasing light and water-column stabilization through stratification. In some places, a secondary autumn peak in production accompanies the onset of the breakdown in summer stratification and increasing inorganic nutrients.



**Figure 4.1**  
Locations of Nordic and Barents seas survey areas (Sites 10–15) plotted on a map of average chlorophyll concentration (see Section 2.3.2).

Four species of *Calanus* are among the dominant mesozooplankton species of the region. *C. finmarchicus* is an Atlantic species, overwintering in the deep basins, ascending in late winter and spring, and advected onto the shelf areas. *C. finmarchicus* has a 1-year life cycle, and its main spawning is linked to the phytoplankton bloom. The main habitat of *C. hyperboreus* is the Arctic water of the deep Greenland Sea, and it has a life cycle of two years or longer. It reproduces in deep water during winter, and juvenile stages ascend to the surface

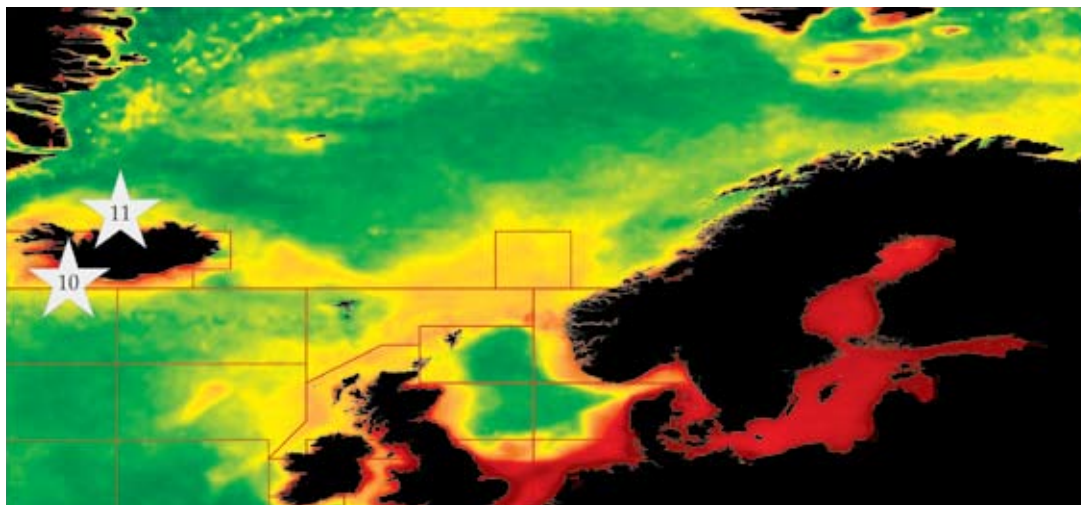
layer during spring. *C. glacialis* is regarded as an Arctic shelf species, has a 2-year life cycle and reproduces during the phytoplankton bloom. *C. helgolandicus* has the southernmost distribution of the four species. It is mainly a shelf species found in the southern parts of the Norwegian Sea. It has a 1-year life cycle, reproduces in autumn, and does not seem to have a typical dormant period.

## Sites 10–11: Selvogsbanki and Siglunes transects (Iceland)

*Astthor Gislason*

**Figure 4.2**

Location of the Selvogsbanki (Site 10) and Siglunes (Site 11) transects plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).



The Icelandic monitoring programme for zooplankton consists of a series of transects perpendicular to the coastline. Sampling at stations along the transects to the north and east of Iceland was started in the 1960s. Additional section lines to the south and west were added in the 1970s. Currently, there are approximately 90 stations. Zooplankton investigations are carried out at these stations every year in May and June. In this summary, long-term changes in zooplankton biomass are examined at the Selvogsbanki (Figure 4.2, Site 10) and Siglunes transects (Figure 4.2, Site 11). Values for Selvogsbanki are calculated from an average of five stations, whereas values for Siglunes are from an average of eight stations.

At Selvogsbanki, zooplankton biomass exhibited a low during the late 1980s, whereas a maximum was observed during the mid-1990s (Figure 4.4a). The period between zooplankton peaks at Selvogsbanki is 5–10 years. In the waters off northern Iceland (Siglunes transect), the high values of zooplankton at the beginning of the time-series dropped drastically with the onset of the Great Salinity Anomaly (GSA) of the 1960s (Figure 4.4c and d). Since then, zooplankton biomass has varied, with highs at intervals of approximately 7–10 years.

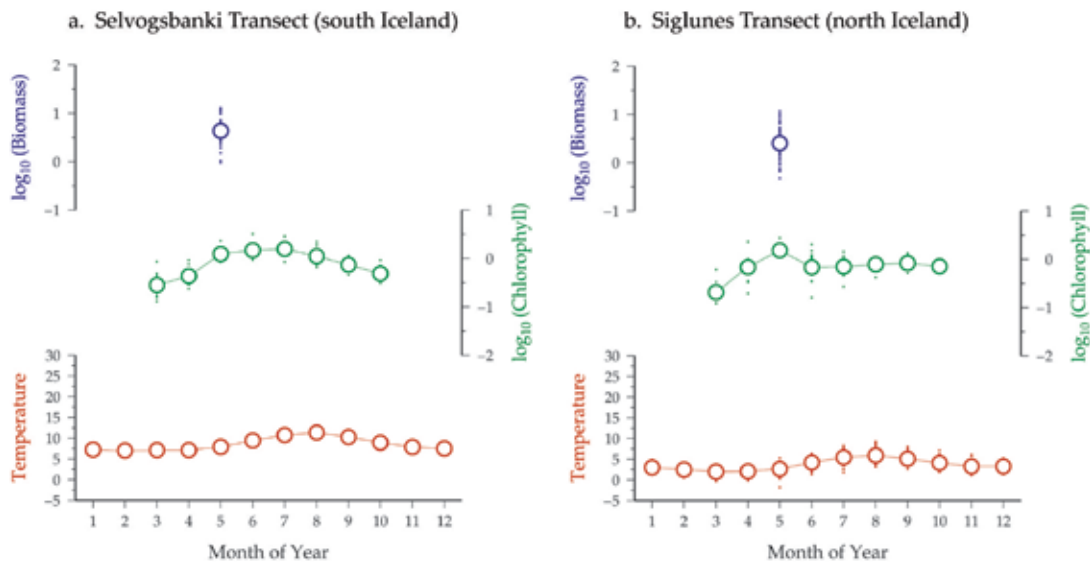
Copepods (mainly *Calanus finmarchicus* and *Oithona* spp.) generally dominate the zooplankton, comprising >60–70% of the plankton in most years (Gislason *et al.*, 2009). Among the copepods, *C. finmarchicus* tends to be more abundant south of Iceland (~20–70%) than in the north (~10–60%). Temperature and salinity are the most important environmental variables in terms of explaining the differences in species composition north and south of Iceland, with species and groups such as *Podon leuckarti* and cirripede larvae being relatively abundant south and *Calanus hyperboreus* abundant north of Iceland. A significant year-to-year variability in community structure is observed both south and north of Iceland, with salinity and the collapse in nitrate (an index of phytoplankton production) dictating the variability in the south whereas temperature is the main factor in the north (Gislason *et al.*, 2009).



Zooplankton biomass north of Iceland is influenced by the inflow of warm Atlantic water (AW). Thus, in warm years, when the flow of higher salinity AW onto the northern shelf is high, the zooplankton biomass can be almost twice as high as in cold years, when this inflow is not as evident (Astthorsson and Gislason, 1998; Astthorsson and Vilhjalmsen, 2002). This trend is visible in the annual anomalies (Figure 4.4c–e). The reasons for this may include (i) better feeding conditions for zooplankton, resulting from increased primary production in warm years; (ii) advection of zooplankton with AW from the south; and (iii) more rapid, temperature-dependent growth of zooplankton in warm years. During both 2000 and 2001, when the biomass of zooplankton north of Iceland was particularly high, the inflow

of warm AW onto the northern shelf was also high. South of Iceland, the links between climate and zooplankton biomass are not as evident as those north of Iceland. Most probably, the variability off the south and west coasts is related to the timing and magnitude of the primary productivity on the banks, which, in turn, are influenced by freshwater from rivers and by wind force and direction, influencing the mixing regime and nutrient supply.

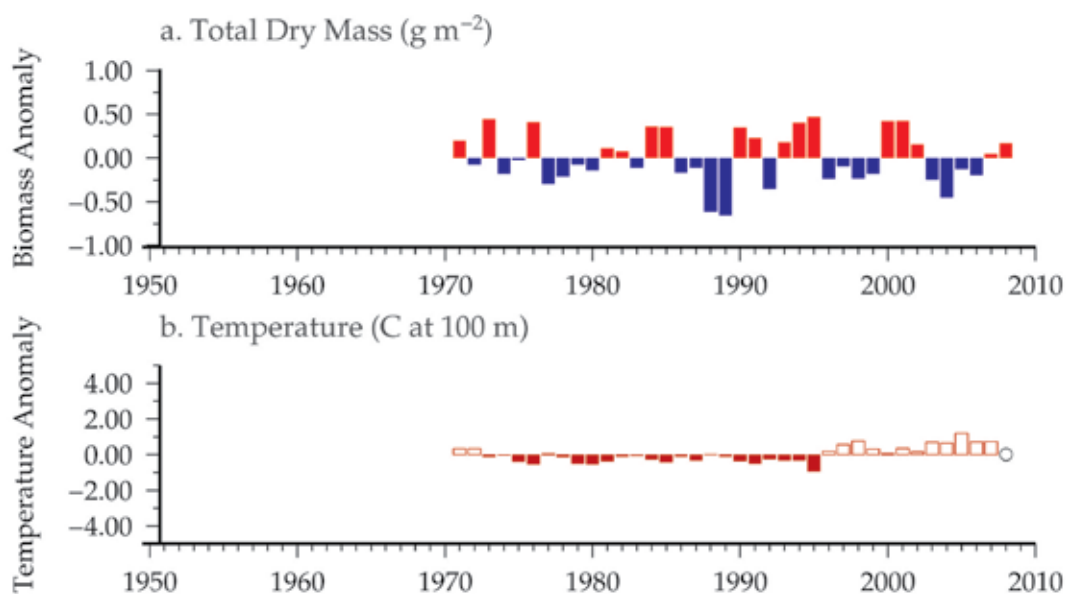
Currently, sea surface temperature values at both Siglunes and Selvogsbanki are higher than the 100-year averages for each region (Figure 4.5b and d), but remain below the 100-year maximum. The temperatures in both regions appear to follow a 50–60 year cycle.



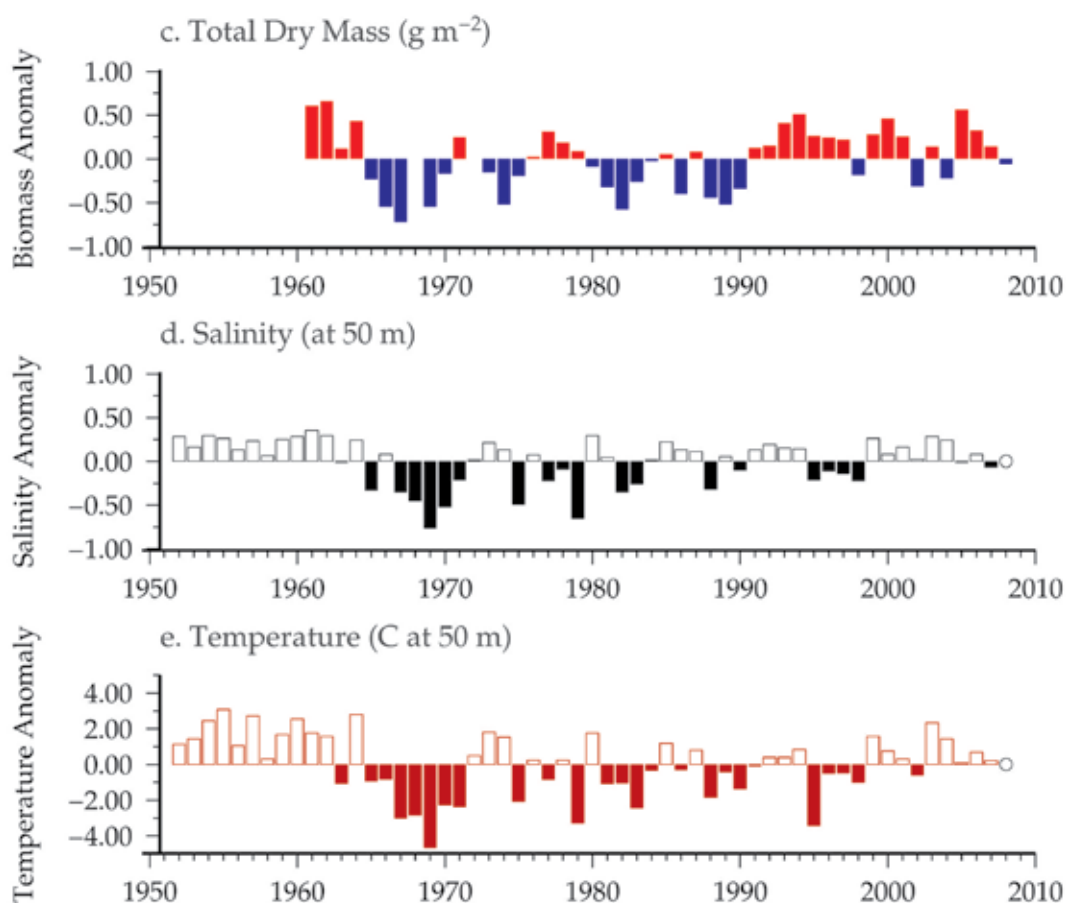
**Figure 4.3**  
Seasonal summary plots for zooplankton, chlorophyll, and surface temperature at the Selvogsbanki and Siglunes transects (see Section 2.2.1 for an explanation of this figure). Zooplankton was only sampled in May, during the peak biomass.

**Figure 4.4**  
Interannual comparison of select co-sampled variables at Selvogsbanki and Siglunes transects (see Section 2.2.2 for an explanation of this figure).

### Selvogsbanki Transect (south Iceland)

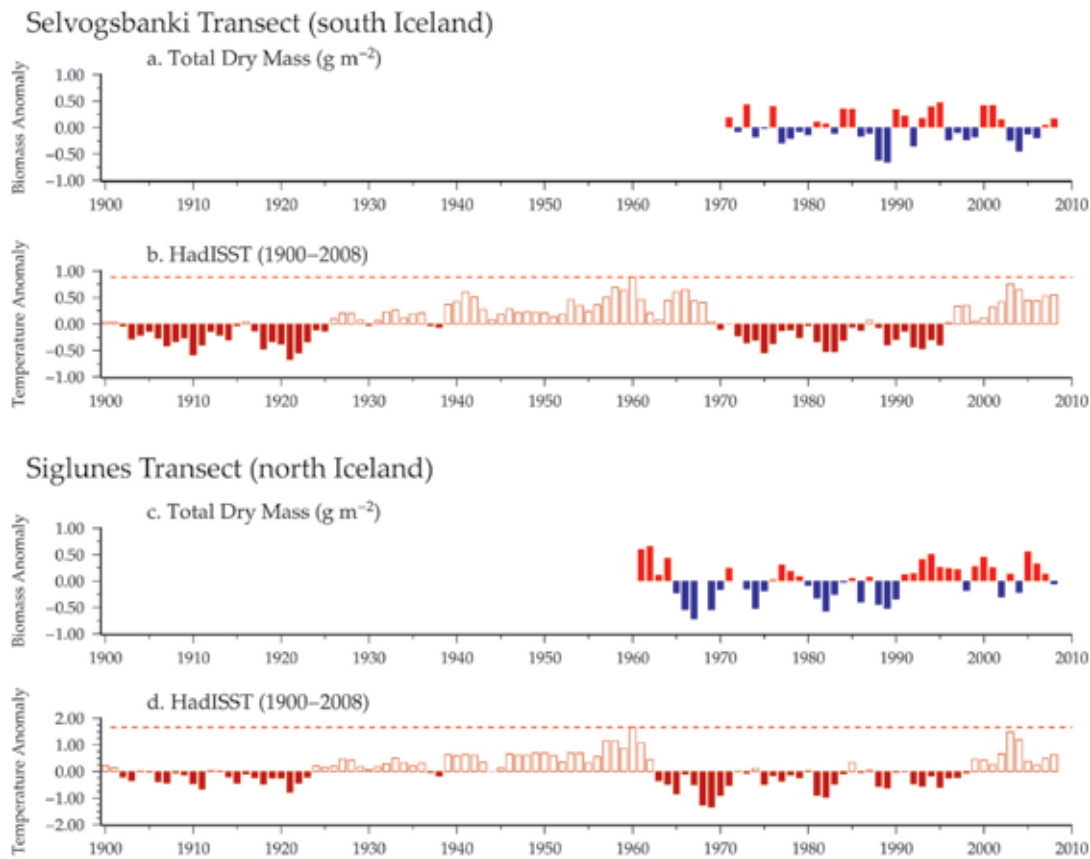


### Siglunes Transect (north Iceland)



**Figure 4.5**

Long-term comparison of Selvogsbanki and Siglunes transect zooplankton (total dry mass) with HadISST sea surface temperatures for the regions (see Section 2.2.3 for an explanation of this figure).

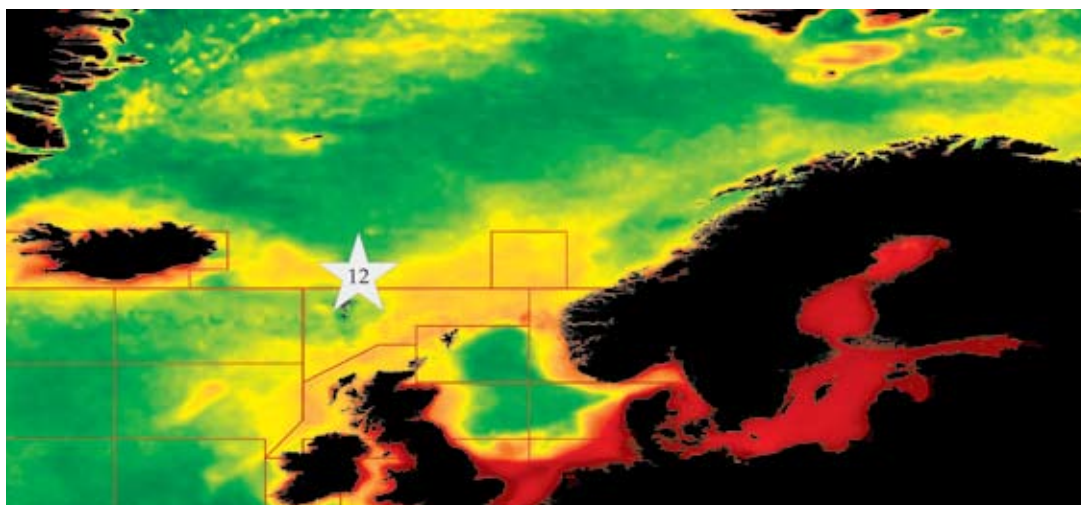


## Site 12: Faroe Islands (southern Norwegian Sea and Faroe Shelf)

*Eilif Gaard and Hogni Debes*

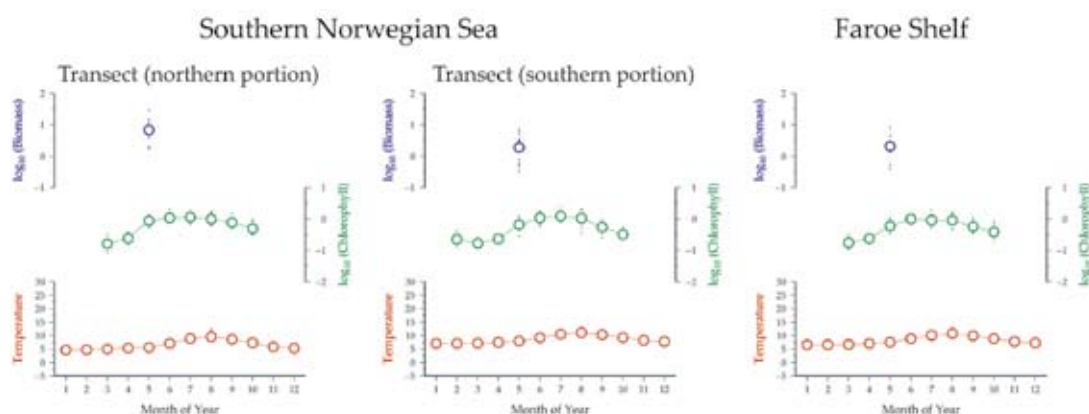
**Figure 4.6**

Location of the Faroe Islands (Site 12) survey area plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).



**Figure 4.7**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature along the southern Norwegian Sea transect (north and south) and the Faroe Shelf (see Section 2.2.1 for an explanation of this figure).



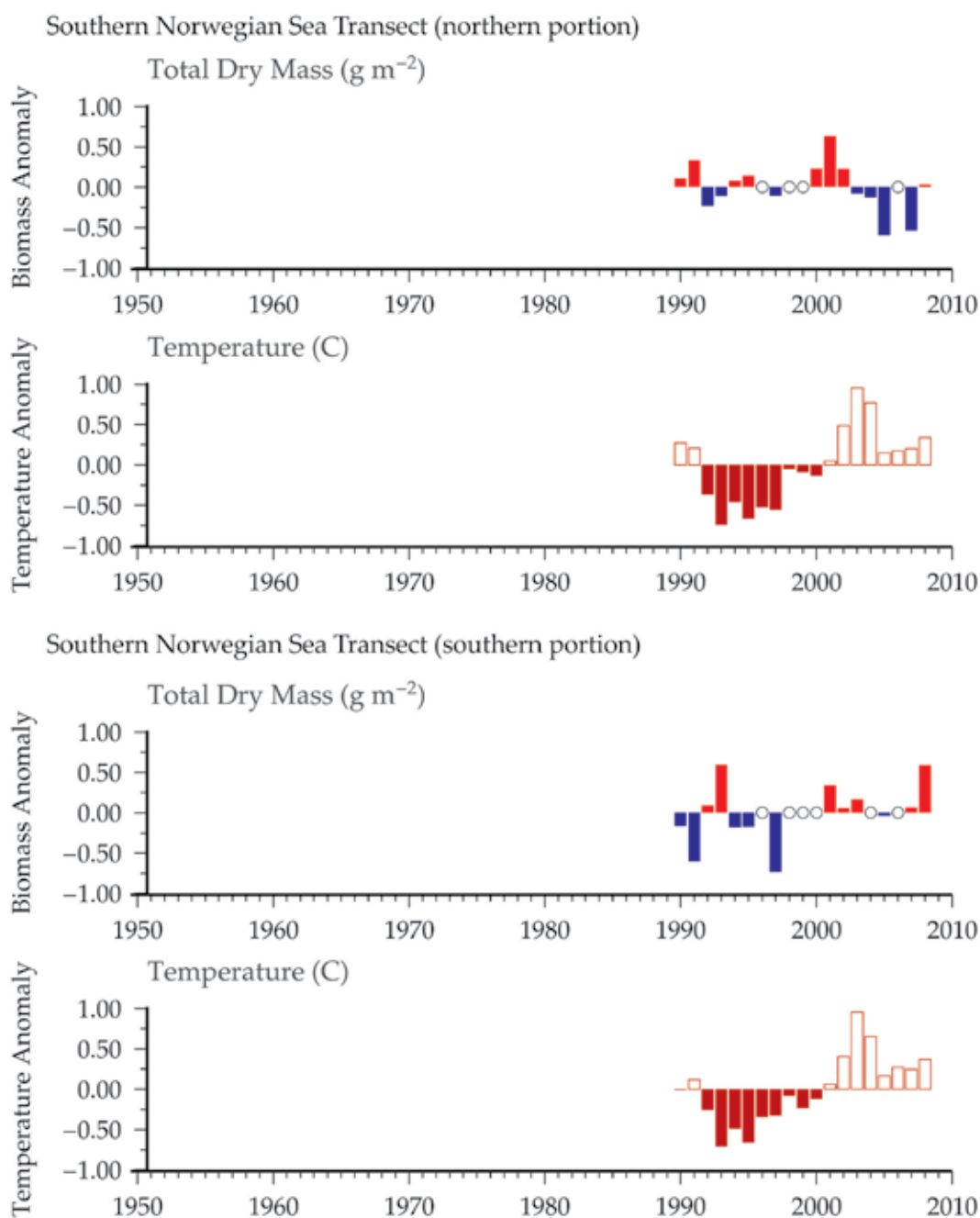
The Faroe Marine Research Institute (FMRI) operates four standard transects radiating north, west, east, and south of the Faroe Islands (Figure 4.6). This section summarizes zooplankton monitoring along the northern and southern portions of the southern Norwegian Sea transect and the Faroe Shelf region.



## Southern Norwegian Sea

Zooplankton is collected annually (in May), using a WP-2 net (56 cm diameter, 200  $\mu\text{m}$  mesh) and vertical hauls from a depth of 50 m to the surface. The northern portion of the transect contains 14 stations, 10 nautical miles apart, crossing between two major water bodies. The southern portion of the transect is located in warm Atlantic water (AW), flowing from the west-southwest, whereas the northern portion is located in cold East Icelandic water (EIW) flowing from the northwest.

In most years, the average zooplankton biomass in the upper 50 m of both the northern and southern portions in May 1990–2008 (Figure 4.8) is close to the phytoplankton spring bloom. *Calanus finmarchicus* is the dominant species in both water masses. In earlier years, the biomass was clearly higher in the cold-water mass in the northern portion than in the warmer southern portion. However, in recent years, the biomass in the EIW (the northern portion of the transect) has decreased significantly and is no longer higher than that in the AW (the southern portion of the transect).



**Figure 4.8**  
Interannual comparison of select co-sampled variables in the southern Norwegian Sea transect (see Section 2.2.2 for an explanation of this figure).

The reason for the usually higher biomass in the northern portion in previous years was a higher abundance of overwintering *C. finmarchicus* (CV and adults) in the northern portion (Figure 4.9a and b), combined with the presence of *Calanus hyperboreus*. In the AW, fewer large individuals, but larger numbers of small stages, were present in May. As the copepod's reproduction in earlier years started earlier in the southern portion, the total numbers of *C. finmarchicus* were, on average, usually higher in the AW than in the EIW, despite the lower biomass.

However, since 2003, the abundance of young *C. finmarchicus* copepodite stages in May in the northern portion of the transect has increased significantly and now no clear differences are evident in the *C. finmarchicus* stage composition in these two water masses (Figure 4.9a and b). This indicates an earlier reproduction in the EIW in recent years than in previous years. Thus, in May 1990–2002, the fraction of *C. finmarchicus* recruits in this water mass was only ~10%; in 2003, it increased to ~45% and, since 2004, it has been 75–80%. Another change in the last few years is that, since 2003, practically no *C. hyperboreus* have been found in the northern

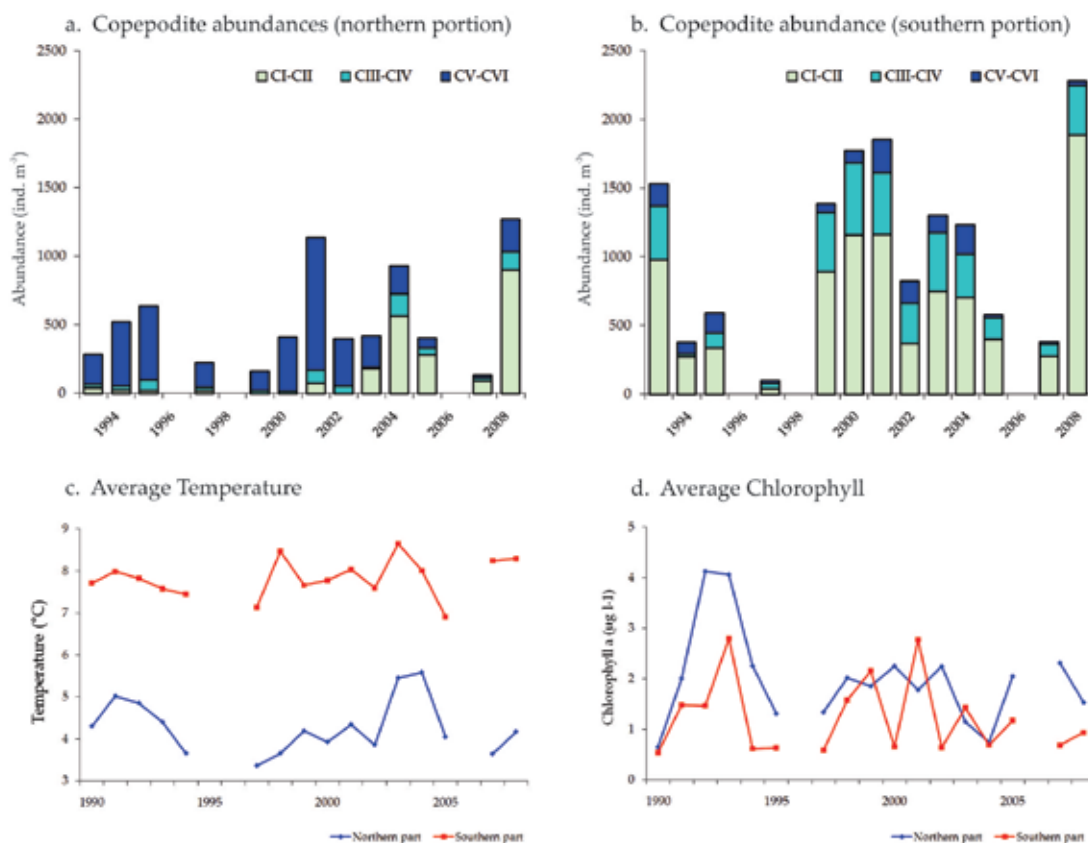
portion of the transect. These large copepods were quite plentiful in the first years of the time-series and had a substantial effect on the biomass.

Lower temperatures in the northern portion of the transect (Figure 4.9c) may explain the generally later *C. finmarchicus* reproduction, compared with the southern portion, in previous years. The difference does not seem to be explained by phytoplankton abundance because the chlorophyll *a* concentrations in most years were higher in the cold EIW than in the warmer AW (Figure 4.9d).

For the time being, it is difficult to identify a cause for the apparently early reproduction of *C. finmarchicus* and for the disappearance of *C. hyperboreus* in the EIW in 2003–2008, compared with previous years in the time-series. Potential weakening of the East Icelandic Current or temperature changes of the EIW (or a combination of both) might explain this change.

**Figure 4.9**

Mean abundance of *Calanus finmarchicus* copepodite stages in East Icelandic waters (northern portion of the transect) and in Atlantic waters (southern portion of the transect). Corresponding average temperature and chlorophyll values are plotted in the lower panels.



## The Faroe Shelf

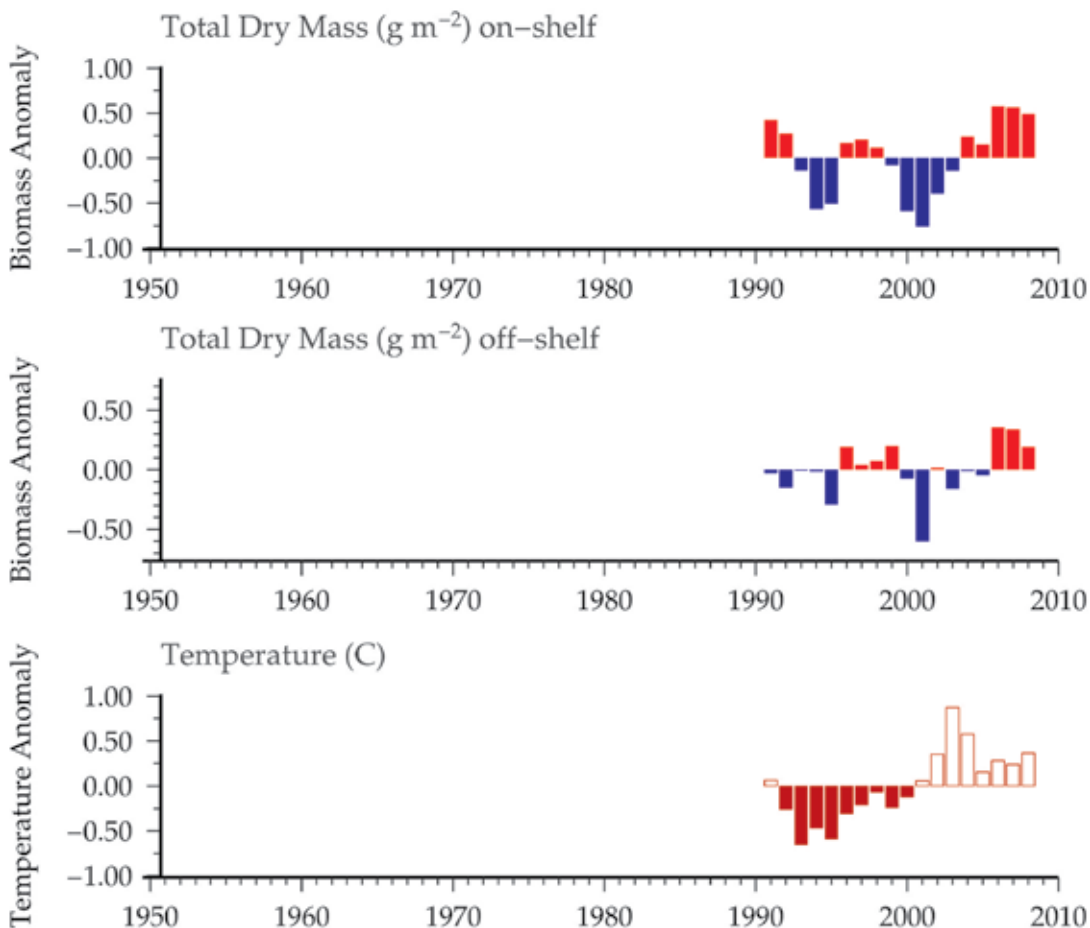
On the Faroe Shelf, strong tidal currents mix the shelf water very efficiently and result in a homogeneous water mass in the shallow shelf areas. The well-mixed shelf water is separated relatively well from the offshore water by a persistent shelf front that circles the islands at a depth of ca. 100–130 m. In addition, residual currents have a persistent clockwise circulation around the islands. The shelf front provides a reasonable, although variable, degree of isolation between the “on-shelf” and “off-shelf” areas. This allows the on-shelf areas to support a relatively uniform shelf ecosystem that, in many ways, is distinct from off-shelf waters.

Although the zooplankton community outside the shelf front (“off-shelf”) is dominated by the copepod *C. finmarchicus*, the on-shelf zooplankton community is basically neritic, with variable abundance of *C. finmarchicus*. During spring and summer, the zooplankton in the shelf water is usually dominated by *Temora longicornis* and *Acartia longiremis*. *C. finmarchicus* is advected from the surrounding oceanic environment and occurs in the shelf water in interannually variable abundance, which is usually highest in spring and early

summer. Meroplanktonic larvae (mainly cirripede larvae) may also be abundant, and decapod larvae and fish larvae and juveniles are common on the shelf during spring and summer.

In most years, the zooplankton summer biomass on the Faroe Shelf is low, and is clearly lower than in the surrounding oceanic environment. This is explained by the higher abundance of off-shelf *C. finmarchicus*. This species is much larger than the neritic species and therefore strongly affects the total zooplankton biomass (Figure 4.10). Owing to the interannually variable abundance of on-shelf *C. finmarchicus*, the biomass of the shelf is also more variable than that in the surrounding oceanic environment; this is probably the result of the variable amounts of advection onto the shelf.

In 2006–2008, the zooplankton biomass on the shelf and in the surrounding off-shelf oceanic water was higher than in previous years. This seems to be mainly the result of a higher abundance of *C. finmarchicus* in late copepodite stages (CIV and CV) in both water masses, compared with the dominance of younger stages in the previous years, indicating phenological variability or changes.



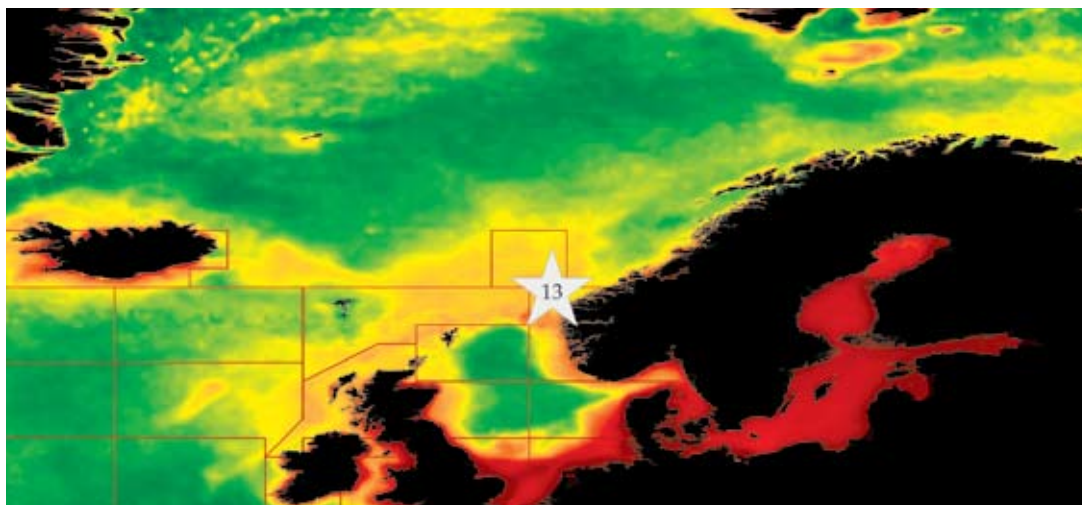
**Figure 4.10**  
Interannual comparison of select co-sampled variables on and off the Faroe Shelf (see Section 2.2.2 for an explanation of this figure).

## Site 13: Svinøy transect (Norwegian Sea)

*Webjørn Melle and Cecilie Broms*

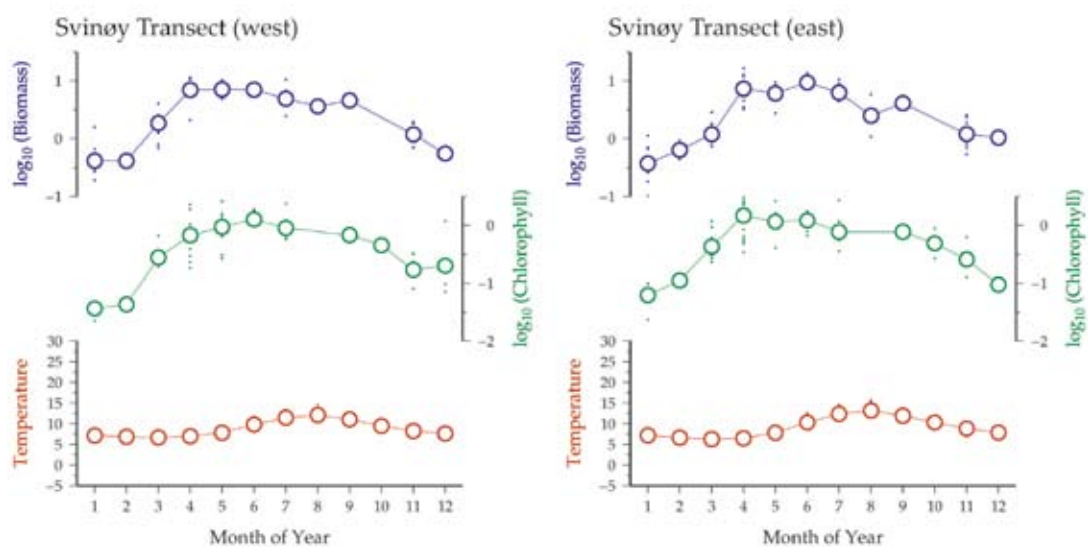
**Figure 4.11**

Location of the Svinøy transect (Site 13) plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).



**Figure 4.12**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature along the Svinøy transect (western and eastern sections; see Section 2.2.1 for an explanation of this figure).





The Norwegian Institute of Marine Research (IMR) Monitoring Programme samples two fixed transects in the Norwegian Sea: the Svinøy transect (Figure 4.11, this site) and the Gimsøy transect (not shown). In addition, the Norwegian Sea is surveyed in May and July–August, both surveys covering approximately 50–100 zooplankton sampling stations. Data are held within local databases at the IMR, and annual reports are made to the Ministry of Fisheries and in the IMR Annual Report on Marine Ecosystems.

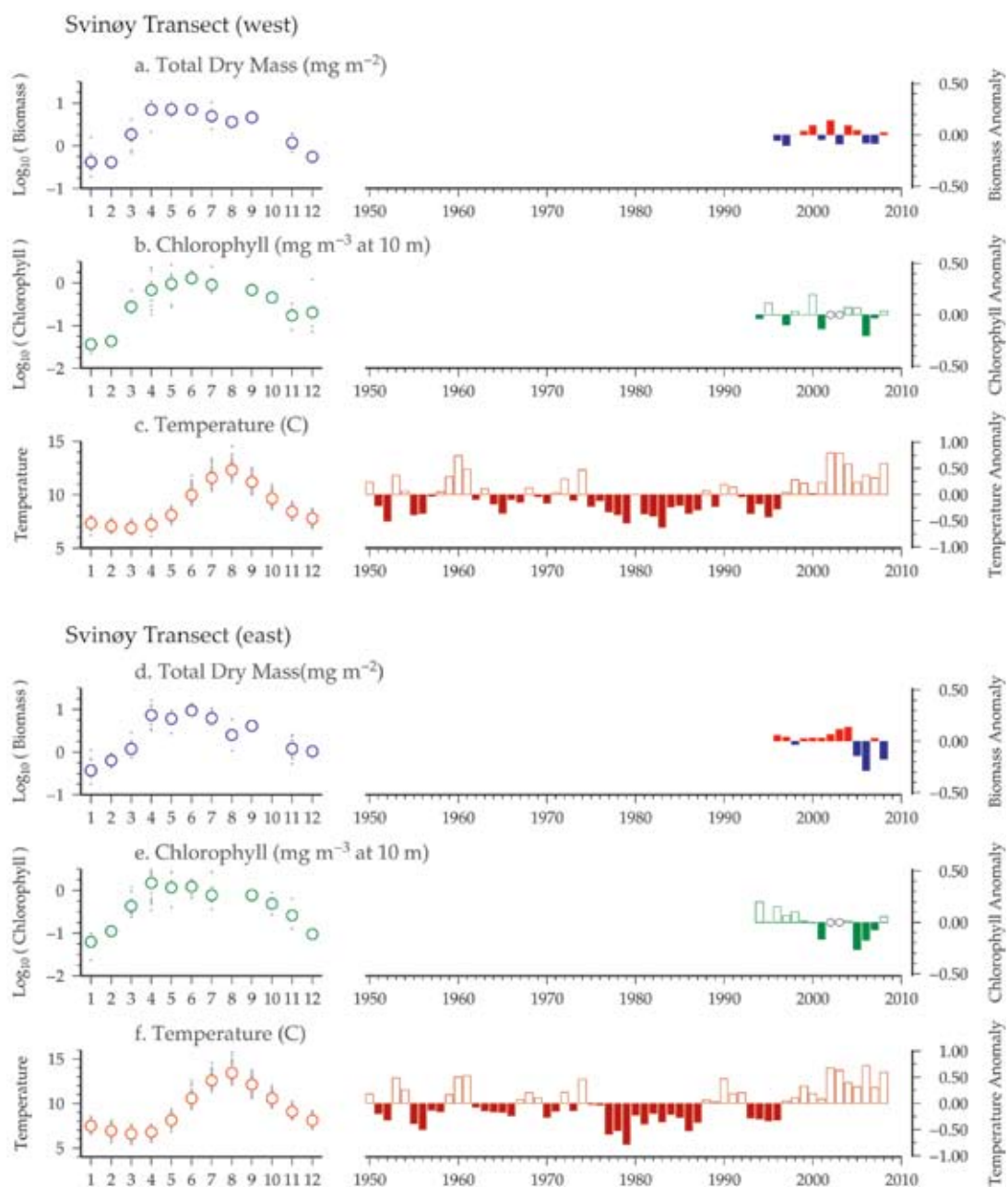
The Svinøy transect is split into two sections: west and east. Each section is sampled 4–10 times each year with a WP-2 net (56 cm diameter, 180 µm mesh) from 200 m depth (or the bottom) to the surface. The zooplankton catch of the net hauls is divided into two, using a Folsom Splitter. One half is fixed in buffered 4% formaldehyde for subsequent taxonomic analyses, and the other half is dried and weighed for dry weight determination. In addition, temperature, salinity, nutrients, and chlorophyll are measured at all sampling stations.

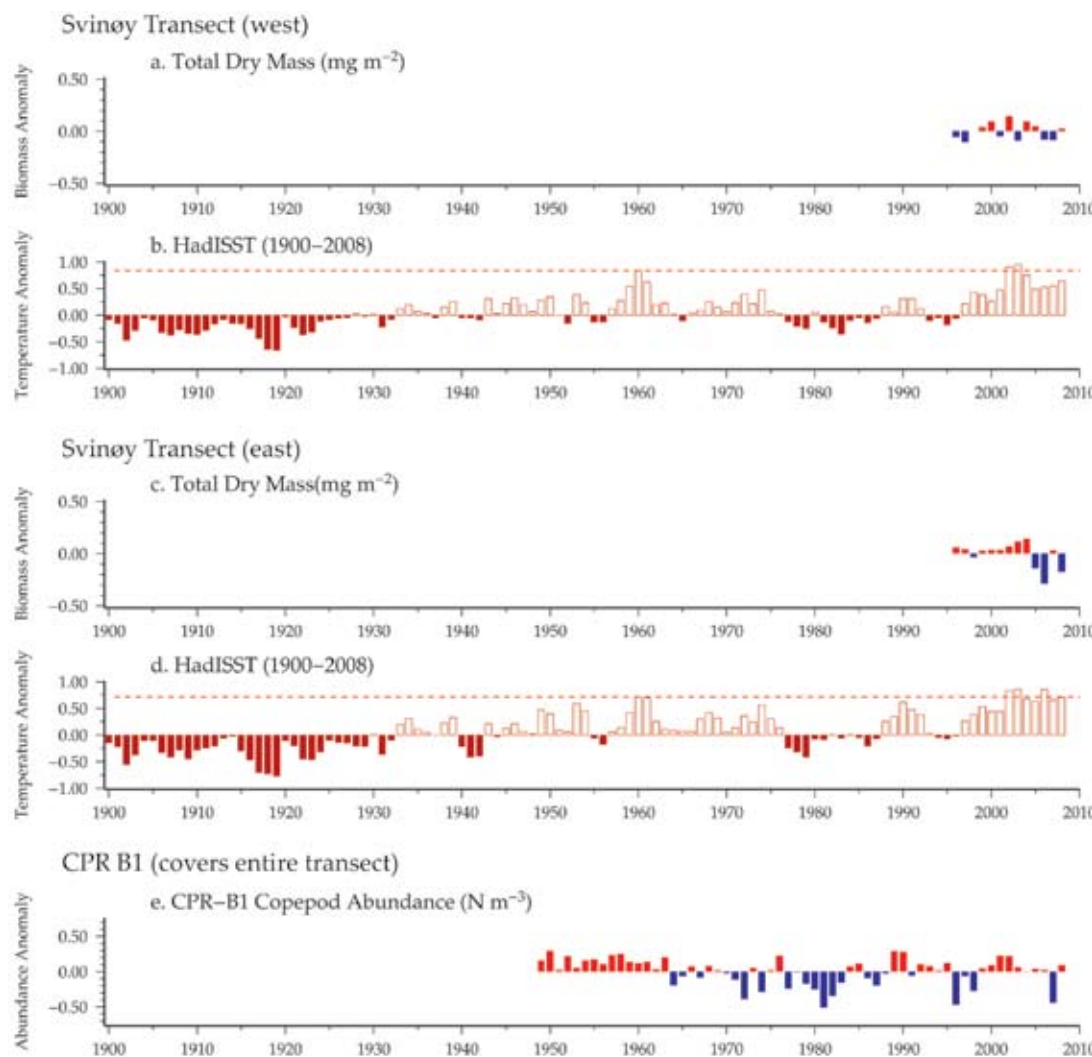
Along the Svinøy transect, zooplankton biomass begins to increase in March in the western section (Figure 4.13a) and slightly earlier, in February, in the eastern section (Figure 4.13d). The development (timing) of zooplankton biomass in spring at the Svinøy transect does not otherwise indicate any shifts in seasonality over the sampling period 1997–2007. Both eastern and western sections are currently in a period of average or lower-than-average biomass, a trend coherent with other zooplankton biomass data from the Norwegian Sea.

Water temperatures along both sections of the Svinøy transect range from 5 to 15°C, with the seasonal high in August and the seasonal low in March (Figure 4.13c and f). Chlorophyll concentrations indicate that phytoplankton growth starts in March in the western section, with a peak in May, and in February in the eastern section, with a peak in April (Figure 4.13b and e). Along the transect, a protracted post-bloom period persists throughout summer and early autumn, which is typical of the southern Norwegian Sea. For the duration of the time-series, chlorophyll concentrations in the eastern section of the transect demonstrate a downward trend, whereas water temperatures have been increasing. Chlorophyll in the western section is more variable over the years. Zooplankton biomass appears to be positively correlated with chlorophyll and negatively correlated with temperature during this period.

The nearest CPR standard area is B1. Interannual trends within CPR copepod abundance (Figure 4.14e) correspond fairly well with zooplankton biomass in both the western (Figure 4.14a) and eastern (Figure 4.14c) sections of the Svinøy transect. Long-term SST values along the transect are above the 100-year average for this region. In the eastern section of the transect, temperatures have been at or above the 100-year maximum (Figure 4.14d, red dashed line) since 2002. In the western section, temperatures briefly reached the 100-year maximum in 2002 and then decreased after 2004 (Figure 4.14b).

**Figure 4.13**  
Seasonal and interannual comparison of select co-sampled variables from the Svinøy transect (see Section 2.2.2 for an explanation of this figure).





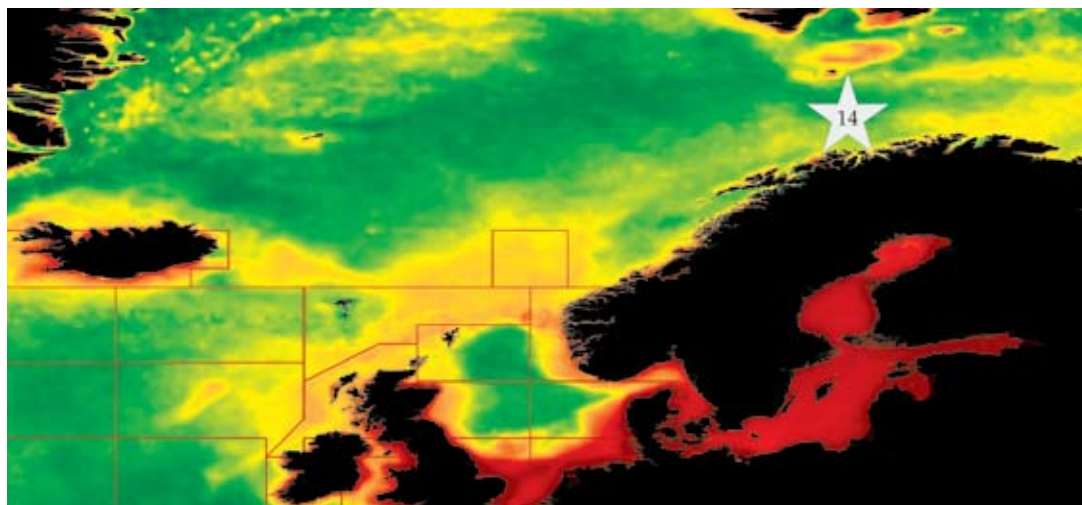
**Figure 4.14**  
Long-term comparison of Svinøy transect zooplankton (dry mass) and HadISST sea surface temperatures for the region with copepod abundance in CPR standard area B1 (see Section 2.2.3 for an explanation of this figure).

## Site 14: Fugløya–Bjørnøya transect (western Barents Sea)

*Webjørn Melle and Cecilie Broms*

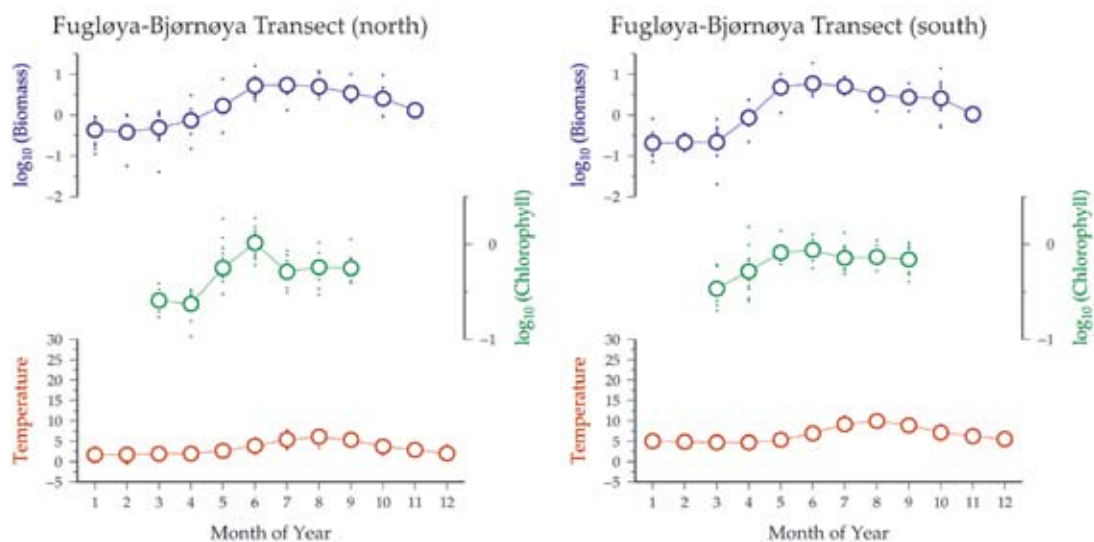
**Figure 4.15**

Location of the Fugløya–Bjørnøya transect (Site 14) plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).



**Figure 4.16**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature along the Fugløya–Bjørnøya transect (west and east; see Section 2.2.1 for an explanation of this figure).





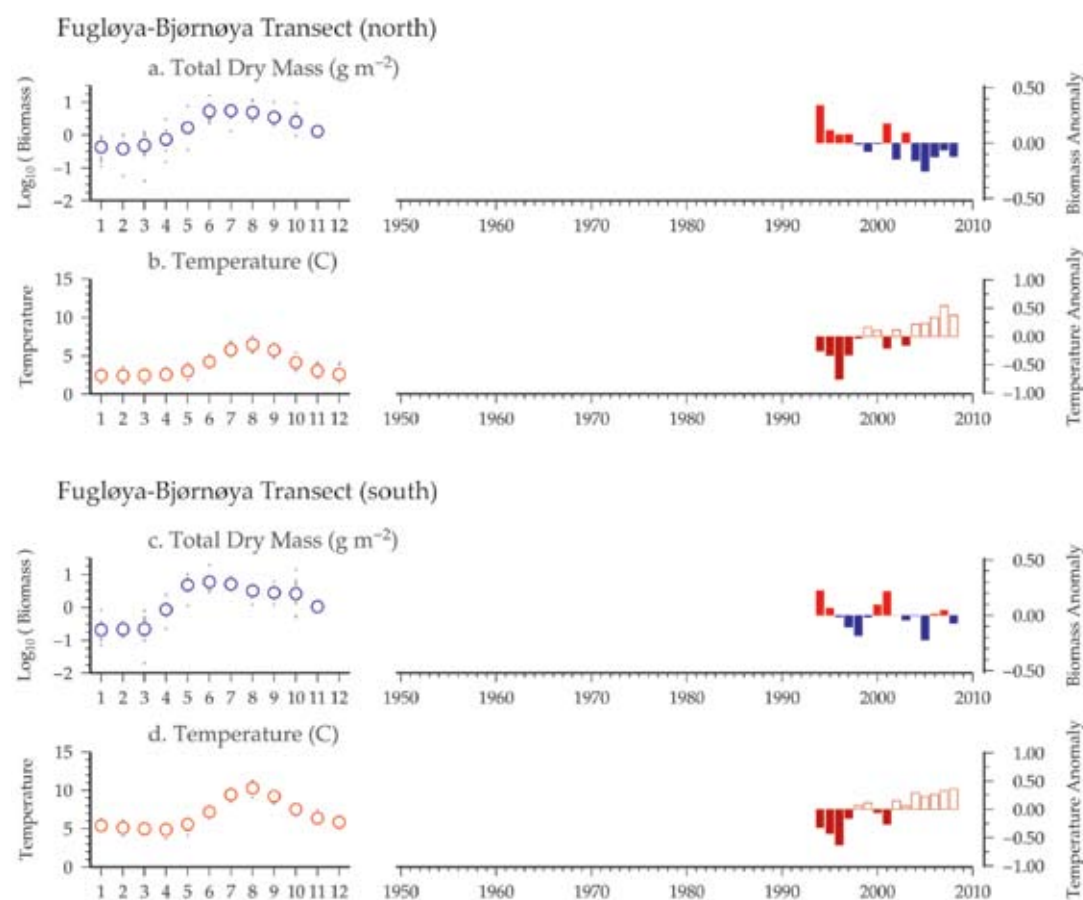
The Norwegian Institute of Marine Research (IMR) Monitoring Programme samples two standard transects in the Barents Sea: the Fugløya–Bjørnøya transect (Figure 4.15; this site) and the Vardø–Nord transect (see Site 15). In addition, the Barents Sea is surveyed in August–September on a basin scale. Data are held within local databases at the IMR and annual reports are made to the Ministry of Fisheries, in the IMR Annual Report on Marine Ecosystems, and in joint Norwegian/Russian reports.

The Fugløya–Bjørnøya transect is split into two sections, north and south, which are each sampled 3–6 times a year with WP-2 nets (56 cm diameter, 180  $\mu\text{m}$  mesh) from 100 m and/or from the bottom to the surface, in two separate net hauls. The data in this report are from the bottom-to-surface hauls. The zooplankton catch of the net hauls is divided into two using a Folsom Splitter. One half is fixed in buffered 4% formaldehyde for subsequent taxonomical analyses, and the other half is dried and weighed for dry weight determination. In addition,

temperature, salinity, nutrients, and chlorophyll are measured at all sampling stations.

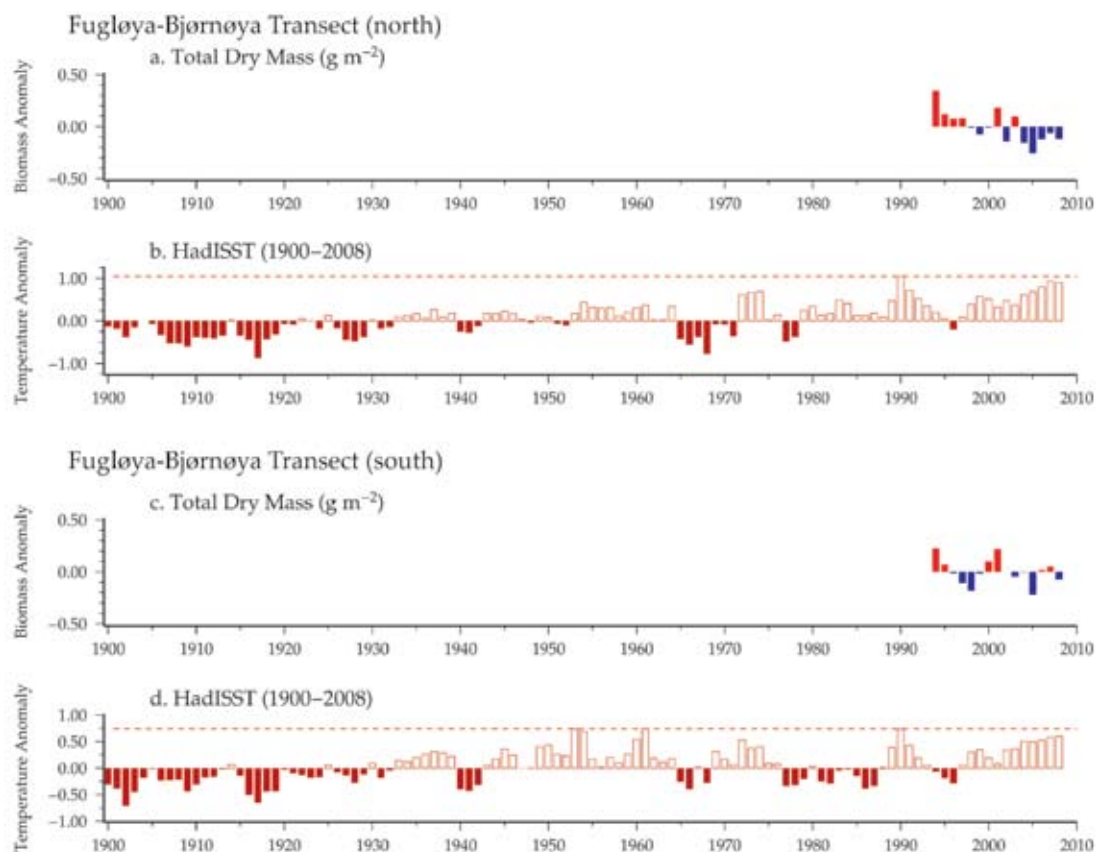
Zooplankton biomass begins to increase in March in the northern section (Figure 4.17a) and in April in the southern section (Figure 4.17c). Peak zooplankton biomass is reached in June–August in the northern section and in May–July in the southern section. Zooplankton biomass has been steadily decreasing over the duration of the time-series, most noticeably in the northern section (Figure 4.17a).

Water temperatures in both sections of the Fugløya–Bjørnøya transect range from 2 to 9°C, with a seasonal high in August and a seasonal low in April, and they have been increasing since the start of sampling (Figure 4.17b and d). Long-term water temperatures along the transect reveal that these temperatures are slightly below the 100-year maximum (Figure 4.18b and d, red dashed line).



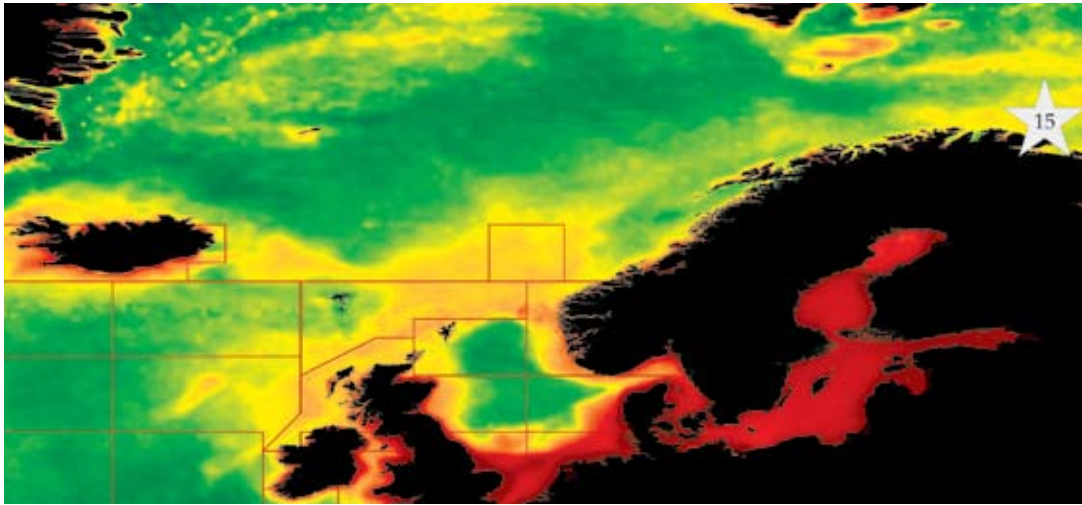
**Figure 4.17**  
Seasonal and interannual comparison of select co-sampled variables from the Fugløya–Bjørnøya transect (see Section 2.2.2 for an explanation of this figure).

**Figure 4.18**  
Long-term comparison of Fugløya-Bjørnøya transect zooplankton (dry mass) and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

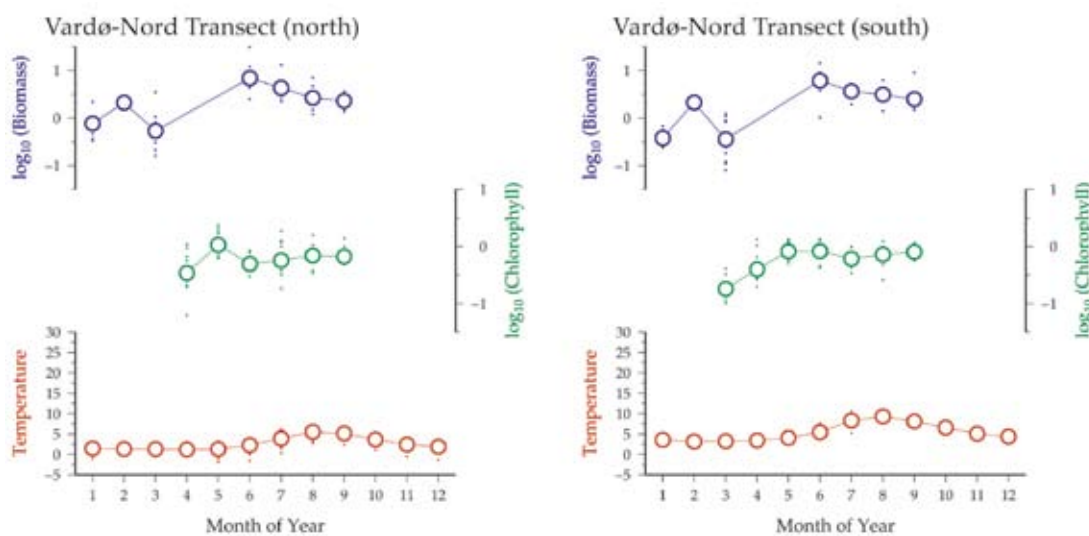


## Site 15: Vardø-Nord Transect (eastern Barents Sea)

*Webjørn Melle and Cecilie Broms*



**Figure 4.19**  
Location of the Vardø-Nord transect (Site 15) plotted on a map of average chlorophyll concentration (see Section 2.2.1 for an explanation of this figure).



**Figure 4.20**  
Seasonal summary plots for zooplankton, chlorophyll, and surface temperature along the Vardø-Nord transect (west and east; see Section 2.2.1 for an explanation of this figure).

The Norwegian Institute of Marine Research (IMR) Monitoring Programme samples two standard transects in the Barents Sea: the Fugløya-Bjørnøya transect (see Site 14) and the Vardø-Nord transect (eight zooplankton stations; Figure 4.19; this site). In addition, the Barents Sea is surveyed in August–September on a basin scale. Data are held within local databases at the IMR, and annual reports are made to the Ministry of Fisheries, in the IMR Annual Report on Marine Ecosystems, and in joint Norwegian/Russian reports.

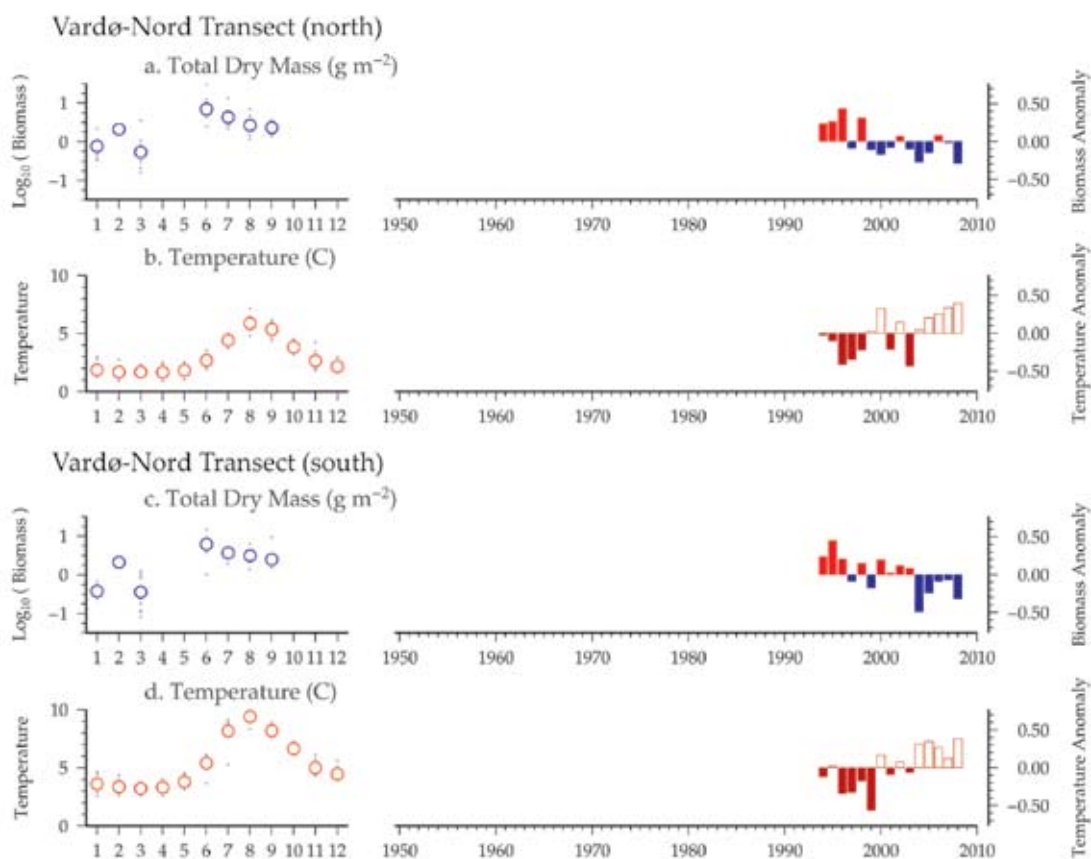
The Vardø-Nord transect is split into two sections, north and south, which are each sampled 3–6 times a year with a WP-2 net (56 cm diameter, 180 µm mesh) from 100 m or the bottom to the surface and from the bottom to the surface in two separate net hauls. The data in this report are from the bottom-to-surface hauls. The zooplankton catch of the net hauls is divided into two using a Folsom Splitter. One half is fixed in buffered 4% formaldehyde for subsequent taxonomical analyses, and the other half is dried and weighed for dry weight determination. In addition, temperature, salinity, nutrients, and chlorophyll are measured at all sampling stations.

The zooplankton biomass along the Vardø–Nord transect begins to increase at sometime between April and June and peaks in June (Figure 4.21a and c). Zooplankton biomass has been steadily decreasing over the duration of the time-series, most noticeably in the southern section. Lower biomass (during the past four years of sampling) and an overall decreasing trend are common among all sampling sites in the Norwegian and Barents seas.

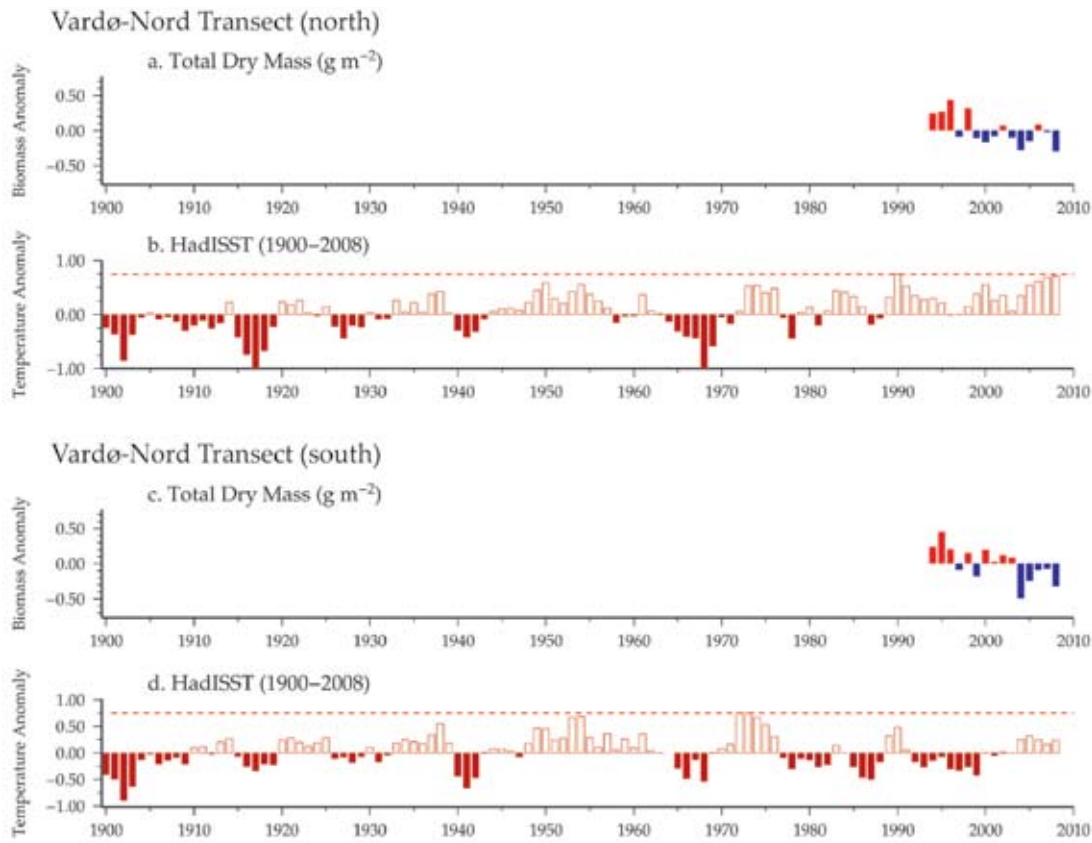
Water temperatures along the Vardø–Nord transect range from 2 to 9°C, with a seasonal high in August in both sections, and a seasonal low in March in

the southern section and in April in the northern section (Figure 4.21b and d). Water temperatures are increasing in both sections and correspond to a decrease in chlorophyll (not shown) and zooplankton biomass (Figure 4.22a and c). Although temperatures in the northern section are currently at or near the 100-year maximum for this region (Figure 4.22b, red dashed line), they are significantly lower than the 100-year maximum for the southern section (Figure 4.22d, red dashed line).

**Figure 4.21**  
Seasonal and interannual comparison of select co-sampled variables from the Vardø–Nord transect (see Section 2.2.2 for an explanation of this figure).







**Figure 4.22**  
Long-term comparison of Vardø–Nord transect zooplankton (dry mass) and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## 5. ZOOPLANKTON OF THE BALTIC SEA

*Lutz Postel, Piotr Margonski, Maiju Lehtiniemi, Juha Flinkman, Arno Põllumäe, Maria Põllupüü, Mart Simm, Anda Ikauniece, Solvita Strake, Georgs Kornilovs, Norbert Wasmund, and Gunta Rubene*

The Baltic Sea is a brackish inland sea bounded by the Scandinavian peninsula, mainland Europe, and the Danish islands (Figure 5.1). Average salinity in the Baltic Sea is much lower than that in the North Atlantic and adjacent North Sea because of freshwater rivers and run-off from the surrounding land. There is an estuarine circulation, with an outflow of low-salinity water above the halocline and irregular reverse inflows of higher salinity deep water from the North Sea. This produces a permanent halocline at ca. 60–80 m depth, which restricts vertical exchange. Owing to seasonality, there is an additional thermocline from late spring until autumn. This strong stratification in the water column, combined with eutrophication and pollution, leads to low oxygen levels and brief anoxic periods in the Baltic Sea deep water. Climate change and decadal-scale variability of these parameters further affect the Baltic Sea's hydrographic characteristics (Feistel *et al.*, 2008).

The zooplankton of the Baltic Sea ranges from freshwater–brackish species to North Sea neritic and occasional oceanic species, depending mainly on the distance from the Baltic Sea–North Sea interface. Profound changes in zooplankton species composition have been attributed to changes in the deep-water salinity (e.g. a decline in *Pseudocalanus* spp. since the late 1980s; Möllmann *et al.*, 2000,

2003), changes in temperature (e.g. an increase in *Temora longicornis* and *Acartia* spp. during the 1990s; Möllmann *et al.*, 2000, 2003), and predation pressure (Casini *et al.*, 2008). Changes in the northern and the southern Baltic Sea copepod communities, recently described by Flinkman and Postel (2009), are attributed to changes in temperature, salinity, and degree of eutrophication.

In the eastern Gotland Basin, five years after the last medium-sized, deep-water renewal and saltwater influx of 2003, the waters below the halocline became almost abiotic. Abundance of the marine species *Oithona similis*, an indicator of higher salinity water, declined to nearly zero, as a result of a narrowing of its habitat layer (oxygenated water with suitable salinity) from 160 m to 30 m. The general decline in total mesozooplankton abundance across the Baltic since the 1990s continues, largely because of a decrease in the maximum abundance of rotifers. As rotifers are generally an indicator taxon for eutrophication, this decrease indicates an improvement in water quality in the open Baltic Sea.



**Figure 5.1**  
Locations of the Baltic Sea survey areas (Sites 16–24) plotted on a map of average chlorophyll concentration (see Section 2.3.2).

During 2000, 2004, 2005, and 2007, concentrations of *Bosmina* spp. remained below 100 000 individuals  $\text{m}^{-3}$ . These relatively low concentrations were related to suboptimal water temperatures. Concentrations were found to be higher at temperatures above 18°C, with mass occurrences observed between 18 and 22°C. Concentrations remained lower by an order of magnitude in years when the carnivorous water flea, *Cercopagis pengoi*, an invasive species to the Baltic in 1992, occurred in the open Baltic Sea. *C. pengoi* feeds on *Bosmina* spp. and other small crustaceans, thus competing with herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) for food. It is also eaten by herring and sprat, but because it is on a higher trophic level, there is less food for the fish. Effects on ecosystem productivity first became evident in 1999, seven years after the invasion of this alien carnivorous species into the Gulf of Riga.

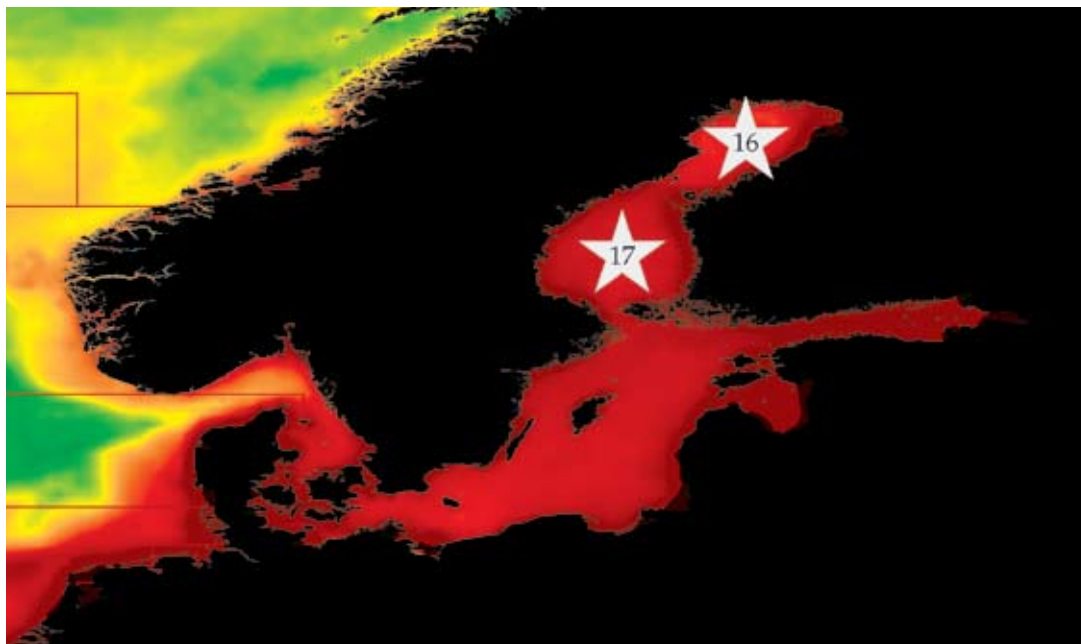
In addition to *C. pengoi*, *Mnemiopsis leidyi*, an invasive comb jellyfish, was recorded for the first time in the Baltic Sea in 2006. This ctenophore is the fifth invasive species of zooplankton observed in the region and was not previously known in the Baltic Sea ecosystem. In future, the invasion of *Penilia avirostris*, a herbivorous water flea of subtropical origin, could become important in the western Baltic Sea. It is now dominating the summer plankton of the southern North Sea and is currently observed in the Belt Sea and the Sound.

## Sites 16–17: Bothnian Bay and Bothnian Sea (northern Baltic Sea)

*Maiju Lehtiniemi and Juha Flinkman*

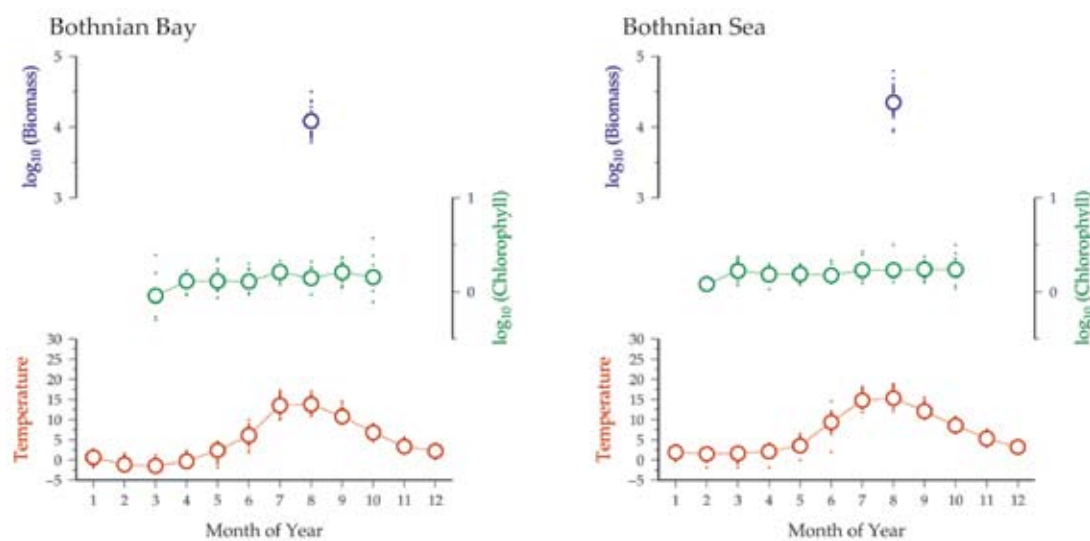
**Figure 5.2**

Location of the Bothnian Bay (Site 16) and Bothnian Sea (Site 17) survey areas plotted on a map of average chlorophyll concentration (see Section 2.3.2).



**Figure 5.3**

Seasonal summary plots for zooplankton, chlorophyll, and surface temperature at the Bothnian Bay and Bothnian Sea sites (see Section 2.2.1 for an explanation of this figure).





Zooplankton monitoring by the Finnish Institute of Marine Research (FIMR; now the Finnish Environment Institute) began in 1979 after the Helsinki Commission (HELCOM) initiated cooperative environmental monitoring of the Baltic Sea. Monitoring was divided into four subareas, based on differing hydrographic environments: Bothnian Bay and Bothnian Sea (these sites, Figure 5.2), Gulf of Finland (see Site 19), and the Baltic Proper (see Site 23).

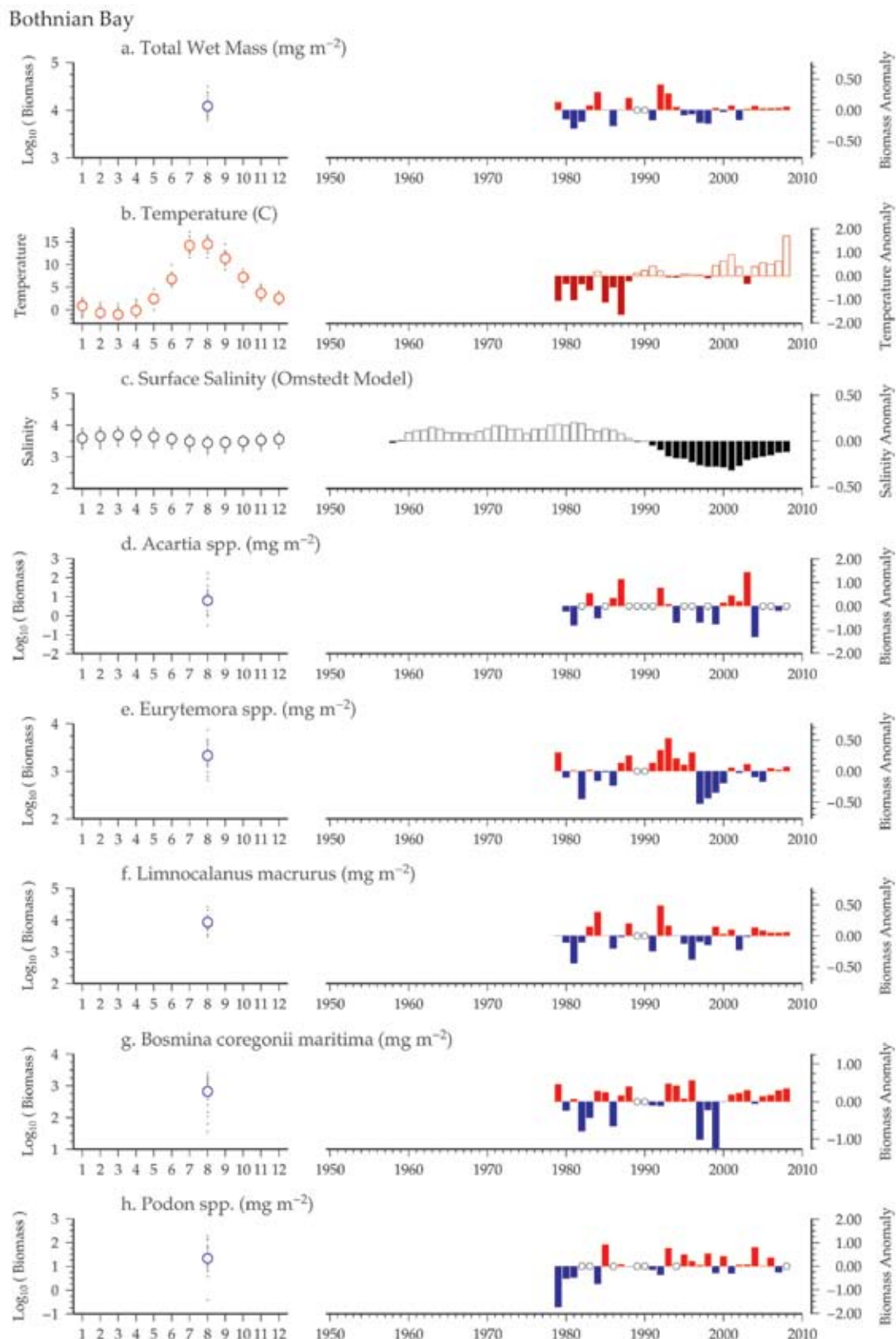
Zooplankton samples were collected in August, the peak abundance period, using a WP-2 net (56 cm diameter, 100 µm mesh). The zooplankton data for Bothnian Bay are an average of two stations, whereas data from the Bothnian Sea are an average of three stations. Water temperatures in Bothnian Bay are generally 1–2°C colder than those in the Bothnian Sea (Figures 5.4b and 5.5b). At both sites, water temperatures are lowest in February–March and warmest in August.

Both regions have relatively low salinities, ranging from 2 to 4 psu in Bothnian Bay (Figure 5.4c; Leppäranta and Myrberg, 2009) and from 4 to 6 psu in the Bothnian Sea (Figure 5.5c). These differences in salinity influence the zooplankton community structure in each region, with taxa that prefer higher salinity (e.g. *Acartia* spp.) being nearly absent in Bothnian Bay (Figure 5.4d, ~5 mg m<sup>-2</sup>) but fairly abundant in the Bothnian Sea (Figure 5.5d, ~5000 mg m<sup>-2</sup>). This is changing, however, as surface salinity in both areas has been decreasing since the 1960s (Figures 5.4c and 5.5c).

In the late 1970s, the Bothnian Sea zooplankton biomass was dominated by *Eurytemora* spp. and *Acartia* spp. (Flinkman *et al.*, 2007). Since 1990, the biomass of *Acartia* spp. has been steadily decreasing, whereas the biomass of the brackish-water species *Eurytemora* spp. and *Limnocalanus macrurus* and the total biomass in the region have been increasing since the beginning of the monitoring programme (Figure 5.5d–f). This increase in *L. macrurus* and in the total biomass can also be seen in Bothnian Bay during the past ten years (Figure 5.4f and a). The biomass of a cladoceran species, *Bosmina coregoni maritima*, has been increasing over the past ten years in both sub-basins, as has *Podon* spp. biomass since the 1990s.

The general Baltic-wide decrease in salinity is the result of warmer temperatures and increased precipitation, run-off, and river outputs in the Baltic. Long-term sea surface temperature values in both regions have been near or above the 100-year maximum since 2000 (Figure 5.6b and d, red dashed line).

**Figure 5.4**  
Seasonal and interannual comparison of select co-sampled variables in Bothnian Bay (see Section 2.2.2 for an explanation of this figure).



## Bothnian Sea

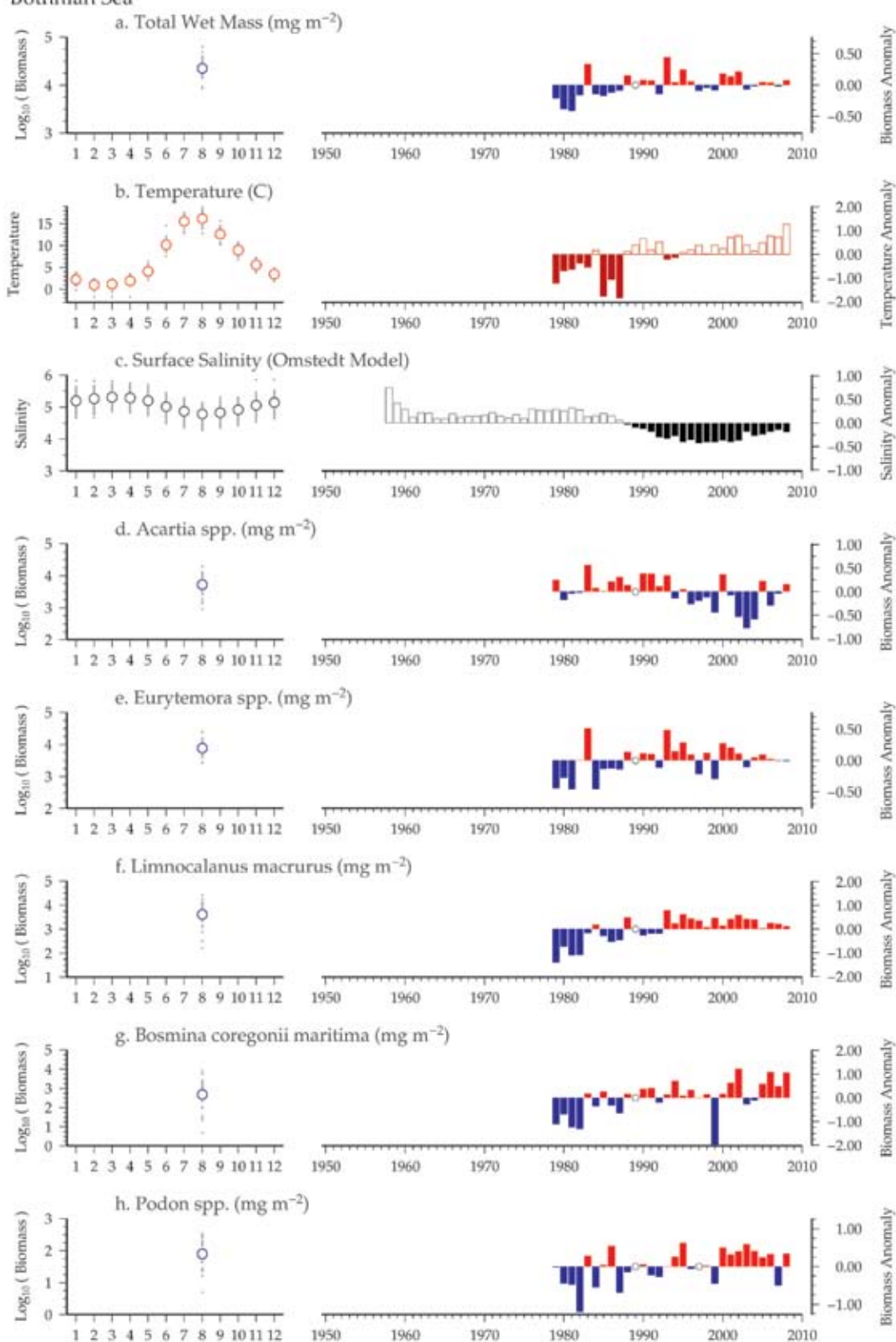
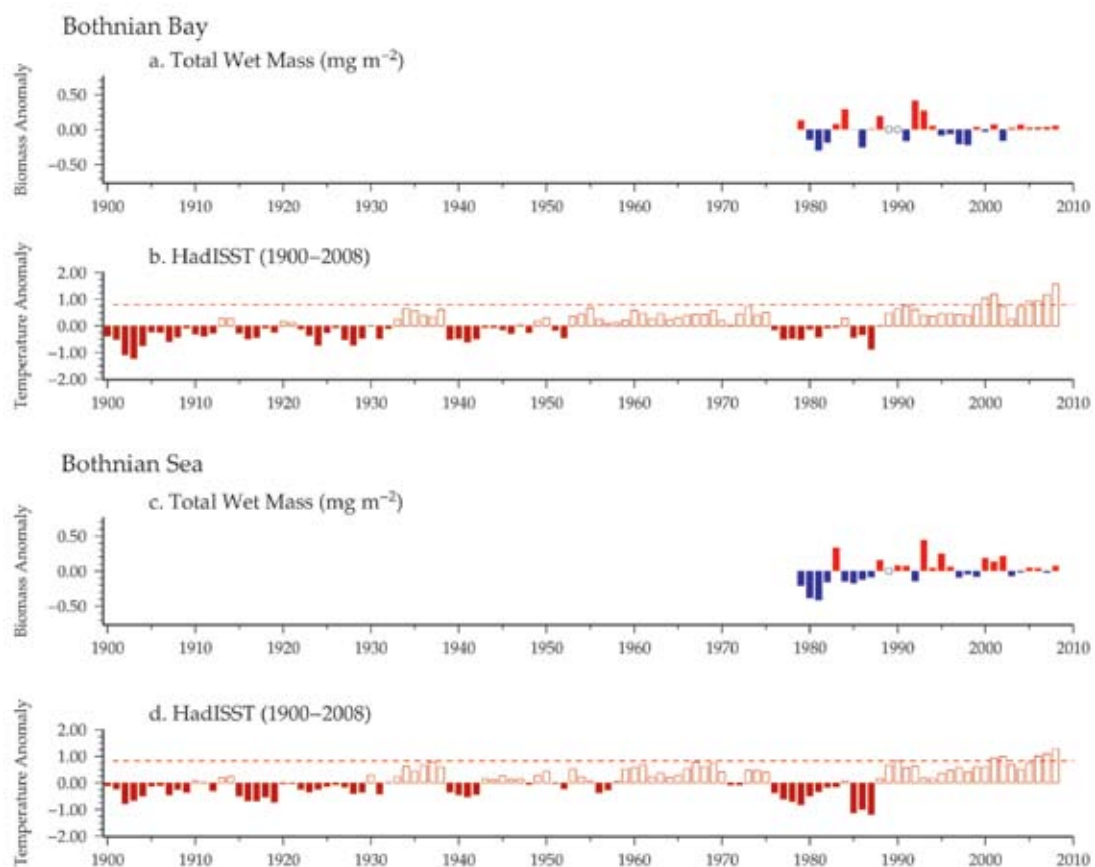


Figure 5.5

Seasonal and interannual comparison of select co-sampled variables in the Bothnian Sea (see Section 2.2.2 for an explanation of this figure).

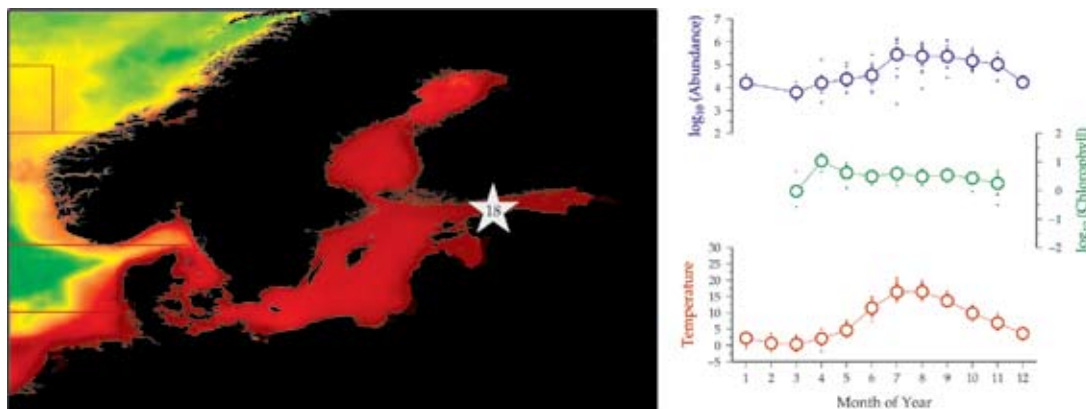
**Figure 5.6**  
Long-term comparison of Bothnian Bay and Bothnian Sea zooplankton biomass with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).





## Site 18: Tallinn Bay (Gulf of Finland)

Arno Põllumäe



**Figure 5.7**  
Location of the Tallinn Bay (Site 18) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Gulf of Finland is represented by one HELCOM sampling station located in the middle of Tallinn Bay at 59°32.2'N 24°41.3'E (Figure 5.7). Tallinn Bay is relatively exposed, and the water exchange between it and the open gulf is good. The maximum depth of the bay is ca. 100 m, whereas the depth of the sampling station is 45 m. Seasonal fluctuations in water temperature occur above 30 m depth, mainly from May to November. During winter, the bay is usually covered with ice, whereas in summer, surface water temperatures as high as 24°C can be observed in July. In the deeper parts of the bay, the temperature is stable throughout the year at 2–5°C. The average salinity at the station is 6 psu, whereas the maximum salinity near the bottom has reached 9.25 psu. These averages are slightly higher than the Omstedt model data (Figure 5.8c), which is averaged over a larger spatial area of the gulf. The large urban area of Tallinn affects the nutrient status of Tallinn Bay.

Zooplankton has been collected since 1993, using vertical hauls of a Juday plankton net (38 cm diameter, 90 µm mesh) up to 12 times a year. Mesozooplankton sample analyses were performed according to guidelines outlined by HELCOM (1988). Phytoplankton, macrozoobenthos, and water chemistry samples are also sampled at the same station with the same frequency.

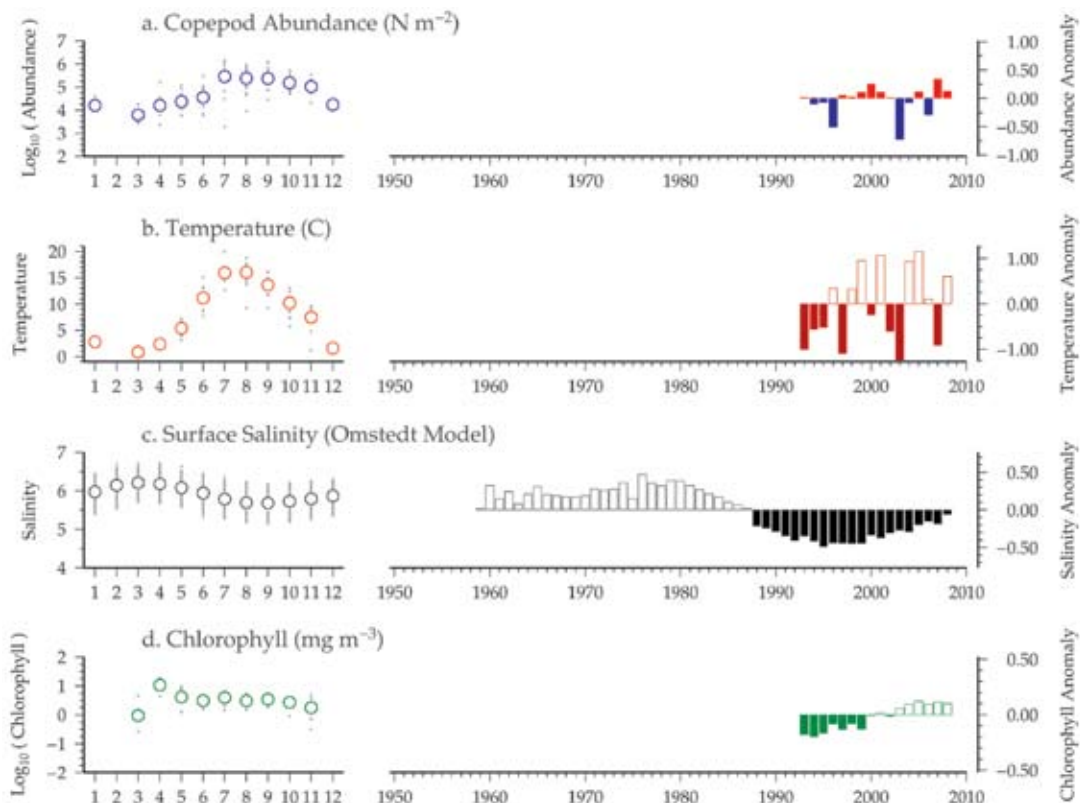
Zooplankton in the Baltic Sea is typically smaller than in the North Atlantic. The dominant copepod species in Estonian waters are *Eurytemora affinis* and *Acartia bifilosa*, the most abundant cladoceran is *Bosmina coregoni*, and rotifers also constitute a large proportion of the total zooplankton abundance.

Maximum copepod abundance is usually observed in late summer, corresponding to the warmest water temperatures (Figure 5.8a and b). In years with warmer winters, high abundance may be observed in spring, when a shorter period of ice cover causes more mixing and phosphorus release from the bottom, resulting in higher chlorophyll concentrations in spring and summer. This mechanism may also explain the corresponding increase in chlorophyll with temperature over time and the slight increase in copepod abundance during the same period (Figure 5.8a, b, and d). The phytoplankton spring bloom usually occurs in April, but the exact timing depends on ice cover.

The abundance of copepods in Tallinn Bay is positively correlated with HadISST temperature (1900–2008;  $r^2 = 0.4$   $p < 0.01$ ), with higher abundance present through all months during the warmer years. Temperatures in the bay have been above the 100-year average since the 1990s (Figure 5.9b). Recent studies at species level demonstrate that climatic conditions at some spatial scales play an important role for most mesozooplankton species in the Gulf of Finland. The effect of nutrient loads at local and regional scales is also important (Põllumäe *et al.*, 2009). The dynamics of some local mesozooplankton species (e.g. *Bosmina coregoni*) may also be affected by the recent predatory invader *Cercopagis pengoi* (Põllumäe and Kotta, 2007).

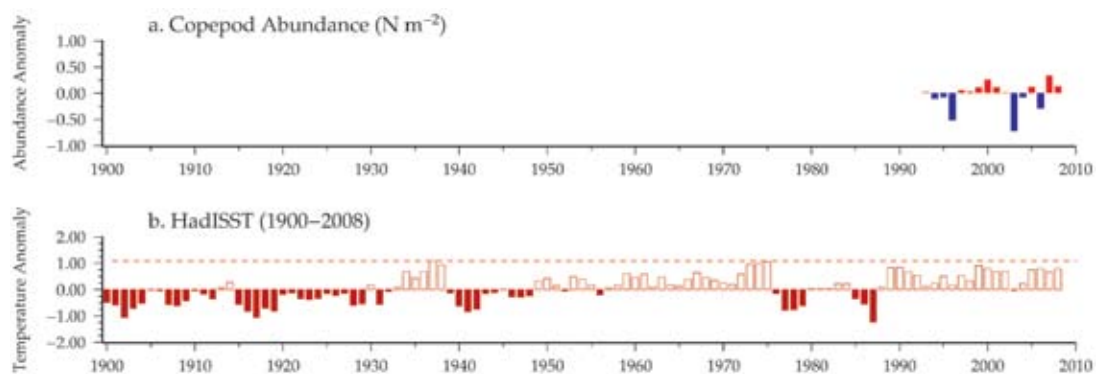
**Figure 5.8**

Seasonal and interannual comparison of select co-sampled variables in Tallinn Bay (see Section 2.2.2 for an explanation of this figure).



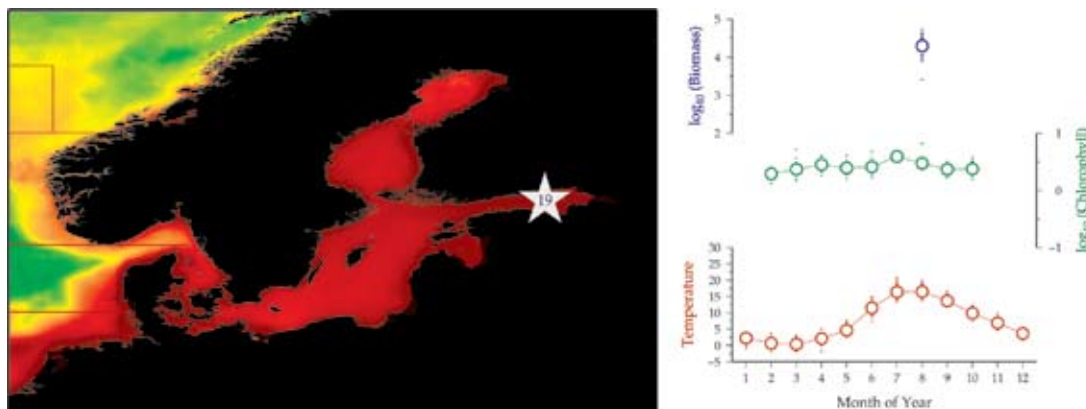
**Figure 5.9**

Long-term comparison of Tallinn Bay copepod abundance with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



## Site 19: Gulf of Finland (eastern Baltic Sea)

Maiju Lehtiniemi and Juha Flinkman



**Figure 5.10**

Location of the Gulf of Finland (Site 19) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

Zooplankton monitoring by the Finnish Institute of Marine Research (FIMR, now the Finnish Environment Institute) began in 1979 after the Helsinki Commission (HELCOM) initiated cooperative environmental monitoring of the Baltic Sea. Monitoring was divided into four subareas based on differing hydrographic environments: Bothnian Bay and Bothnian Sea (see Sites 16–17), Gulf of Finland (this site, Figure 5.10), and the Baltic Proper (see Site 23).

Zooplankton is collected in August, the peak abundance period for this region, using a WP-2 net (56 cm diameter, 100  $\mu$ m mesh). Zooplankton data for the Gulf of Finland are an average of three stations.

The hydrography of the Gulf of Finland is similar to the Baltic Proper owing to a direct connection between these basins. Water temperatures are lowest in February–March and warmest in July–August (Figure 5.11b).

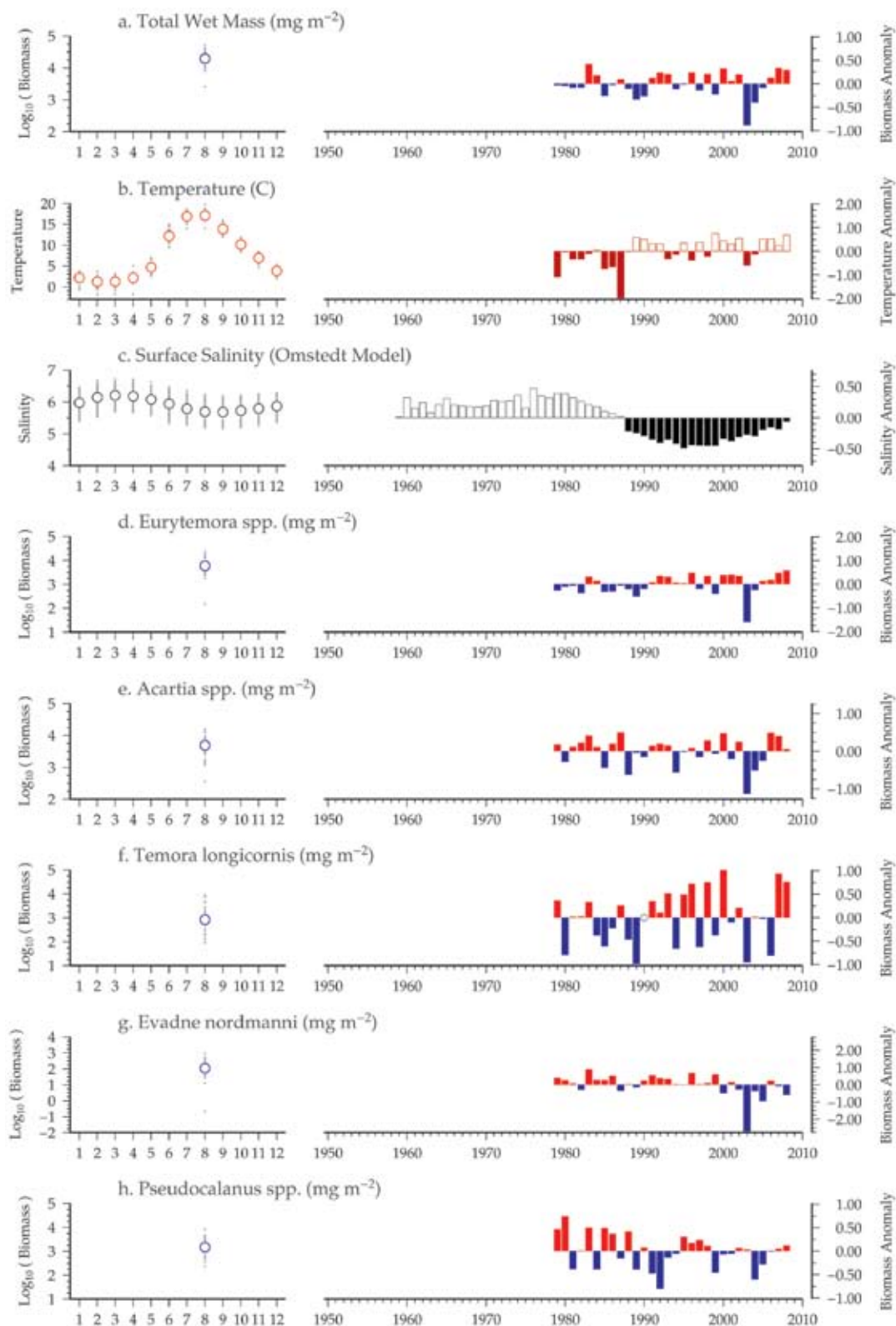
The general Baltic-wide decrease in salinity is also present in the Gulf of Finland (Figure 5.11c), because of warmer temperatures and increased precipitation and river run-off in the Baltic. The surface salinity varies from almost freshwater in the eastern parts of the Gulf, owing to freshwater discharge from the River Neva, to >6 psu in the west. A halocline is formed at 60–80 m depth, preventing mixing of the deeper saltier (5–9 psu) waters with surface layers (Leppäranta and Myrberg, 2009).

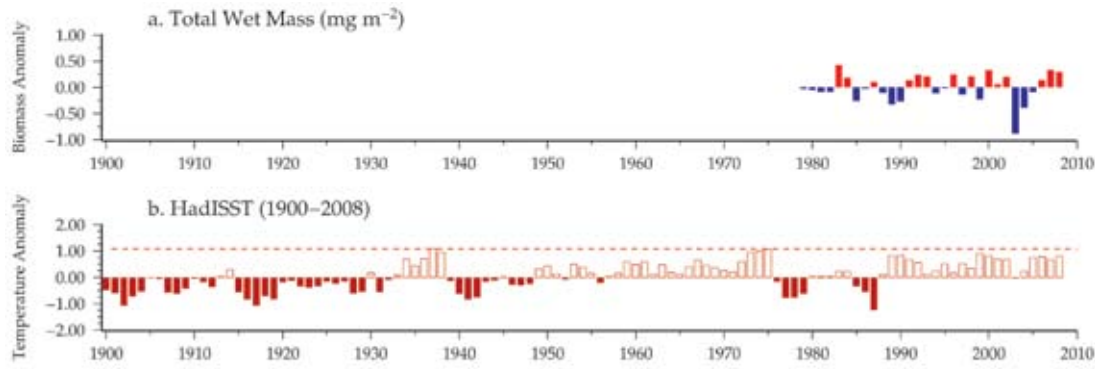
The zooplankton community is a mixture of freshwater, brackish, and marine species (Figure 5.11a). The dominant species are copepods from the group *Eurytemora* spp. (Figure 5.11d), followed by *Acartia* spp., *Temora longicornis*, and the cladoceran *Evdne nordmanni* (Figure 5.11e, f, and g).

Although the presence of any long-term trends in total zooplankton biomass are not very obvious (Figure 5.12a), increasing or decreasing trends are apparent when looking at a single species or genera. For example, Flinkman *et al.* (2007) note a decrease in *Pseudocalanus elongatus* biomass over the monitoring period (Figure 5.11h), whereas other species may be slightly increasing. Comb jellies, recently identified as the Arctic ctenophore *Mertensia ovum* (Gorokhova *et al.*, 2009), have become abundant during the last few years.

The SST values in the Gulf of Finland (Figure 5.12b) have been above the 100-year average since the 1990s, with the exception of one cooler year in 2003.

**Figure 5.11**  
Seasonal and interannual comparison of select co-sampled variables in the Gulf of Finland (see Section 2.2.2 for an explanation of this figure).





**Figure 5.12**  
Seasonal and interannual comparison of select co-sampled variables in the Gulf of Finland (see Section 2.2.2 for an explanation of this figure).

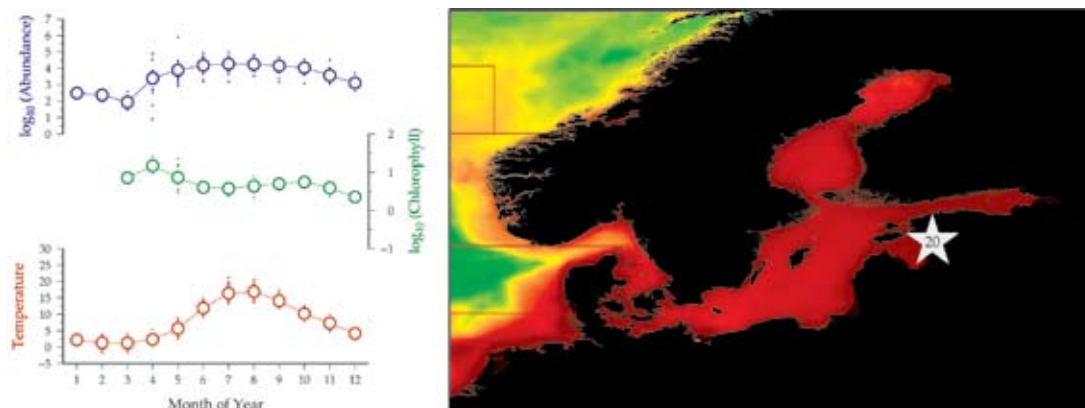


## Site 20: Pärnu Bay (northeast Gulf of Riga)

Maria Põllupüü and Mart Simm

**Figure 5.13**

Location of the Pärnu Bay (Site 20) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



Pärnu Bay is a shallow, semi-enclosed brackish-water basin located in the northeastern part of the Gulf of Riga and covering approximately 700 km<sup>2</sup>, with a volume of 2 km<sup>3</sup> (Figure 5.13). Its maximum depth gradually increases from 7.5 m in the inner part to 23 m in the southwestern part. In most years, Pärnu Bay is covered with ice in winter.

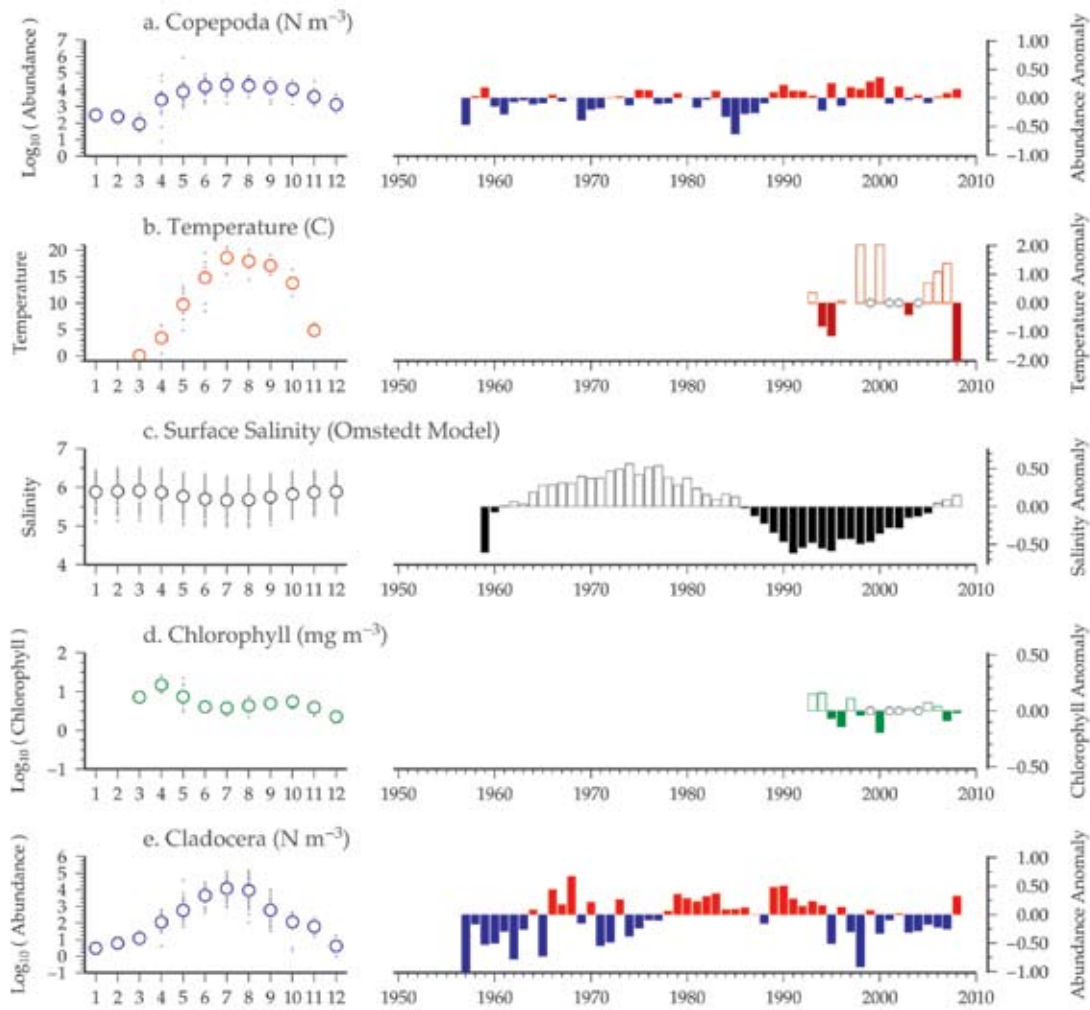
The hydrographic conditions of Pärnu Bay are formed under the complex influence of winter ice conditions, freshwater inputs from the Pärnu River, and water exchange with the open part of the Gulf of Riga. The bay suffers from extensive human pressures (recreation, eutrophication, fishing; Kotta *et al.*, 2008). In summer, surface water temperatures may reach 23°C during July–August. Long-term water temperatures have been warmer than the 100-year average since 1989 (Figure 5.15b).

Zooplankton sampling has been carried out since the late 1950s at a monitoring station (10 m depth) located in the middle part of the bay. From 1957 to 1975, sampling started in April–May and was generally performed weekly until the end of October. From 1976 onwards, the sampling period was extended to include all ice-free months. Sampling was performed vertically using a Juday plankton net (0.1 m<sup>2</sup> mouth opening, 90–100 µm mesh) integrating over the whole water column. Mesozooplankton sample analyses are performed according to guidelines outlined by HELCOM (1988).

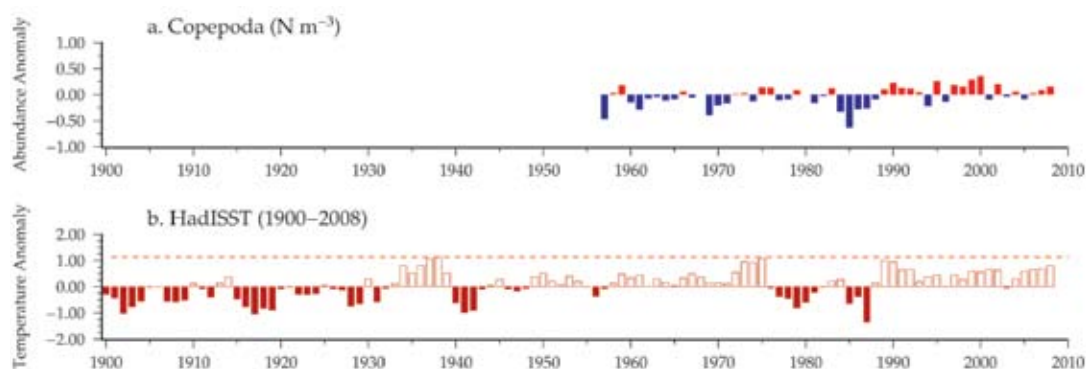
The zooplankton taxa are represented by brackish-water, eurythermal, oligothermal, and polythermal species. Rotifers, copepods, cladocerans, and

meroplankton dominate the zooplankton communities (Kotta *et al.*, 2009). The diversity of zooplankton in Pärnu Bay is low; two species, *Eurytemora affinis* and *Acartia bifilosa*, constitute 99% of the total copepod abundance, and *Bosmina coregoni maritima* is the prevailing cladoceran. Peak copepod abundance occurs in the warmer summer months (June–July), after the spring chlorophyll peak and just before the summer temperature maximum (Figure 5.14a, b, and d).

Different trends in the long-term abundances of the copepods and cladocerans were observed (Figure 5.14a and e). In Pärnu Bay, during the period from the late 1950s to the late 1980s, total copepod abundance was generally lower than the long-term average. This period was followed by a rise in both copepod abundance and water temperature from below-average to above-average levels. In contrast to the copepods, cladoceran abundance went from an increasing to a decreasing trend at the beginning of the 1990s. After decreasing rapidly for a few years, it then stabilized at levels considerably lower than the earlier period in the middle of the time-series. Over the last few decades, invasions of two additional cladoceran species (*Cercopagis pengoi* and *Evadne anonyx*) of Ponto–Caspian origin have been recorded (Ojaveer and Lumberg, 1995; Põllupüü *et al.*, 2008). The decrease in native cladoceran abundance coincides with the invasion of the predatory cladoceran *C. pengoi*, which now occurs in large numbers in Pärnu Bay during periods of warm water (Ojaveer *et al.*, 2004; Kotta *et al.*, 2004, 2009).



**Figure 5.14**  
Seasonal and interannual comparison of select co-sampled variables in Pärnu Bay (see Section 2.2.2 for an explanation of this figure).



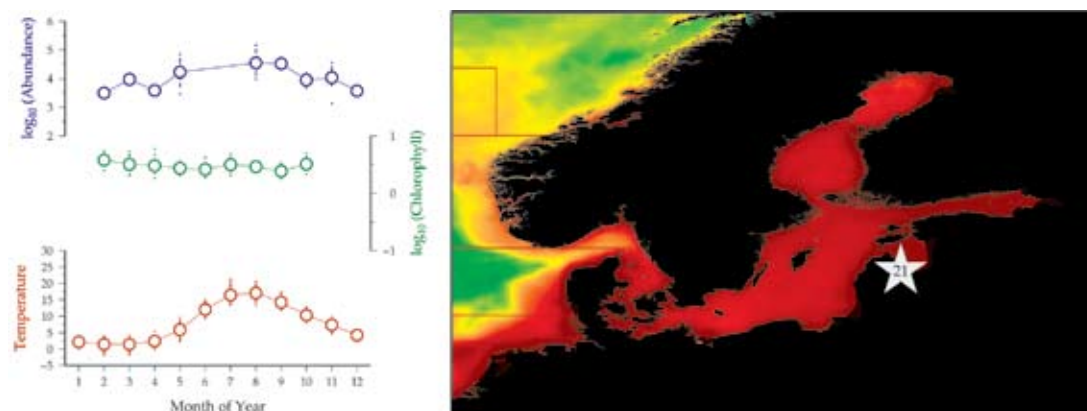
**Figure 5.15**  
Long-term comparison of Pärnu Bay zooplankton with HadISST sea surface temperatures from the region (see Section 2.2.3 for an explanation of this figure).

## Site 21: Central Gulf of Riga (Station 121)

*Anda Ikauniece*

**Figure 5.16**

Location of the Station 121 (Site 21) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



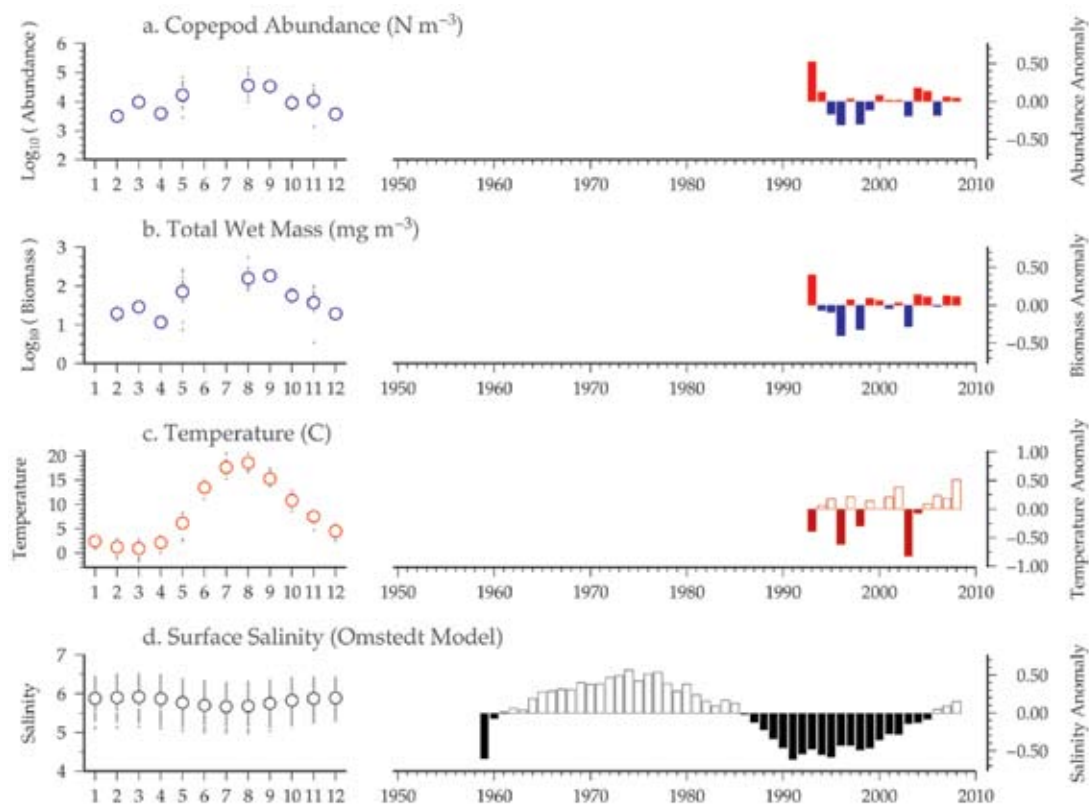
In the context of the National Monitoring Programme of Latvia, mesozooplankton has been sampled since 1993 as a parameter of aquatic environment status. Sampling Station 121 is located in the central part of the Gulf of Riga, approximately 50 km from the coast and at a depth of 55 m (Figure 5.16). A network of monitoring stations was constructed across the gulf to study the impact of various factors, such as freshwater discharge and general currents. Station 121 represents the central part of the gulf, the deepest of the monitoring stations, which is minimally affected by freshwater and nutrients. Plankton productivity indicators in this area are lower than those of the coastal zones, but species composition does not differ substantially because the whole Gulf is a brackish-water basin, with dominant salinity values of ca. 5 psu.

Zooplankton was sampled with a WP-2 net (56 cm diameter, 100 µm mesh), using vertical hauls from 50 m depth to the surface. Sampling was carried out at least three times a year, representing the most productive seasons: spring (May), summer (August), and autumn (October–November).

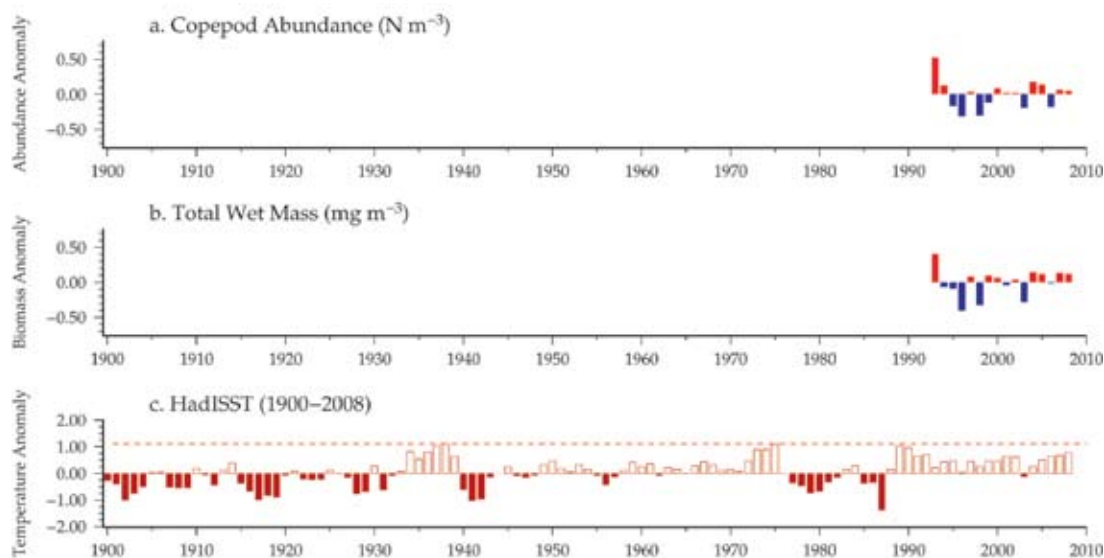
Species diversity in the gulf is low. The total number of zooplankton species does not exceed 40, and there are seldom more than 15 species in a sample. The zooplankton follows a strong seasonal pattern that is determined by temperature during the first half of the year and by the combined effect of predation and temperature during the second half. Interannual values of zooplankton abundance and biomass are extremely variable (Figure 5.17a and b), but the seasonal pattern has remained constant throughout the observation period. Copepod abundance and

total sample wet mass are lowest from December through April, corresponding to the period of coldest water temperatures. Relatively few species of copepods occur within the monitoring area: *Acartia bifilosa*, *Eurytemora affinis*, and *Limnocalanus macrurus* (the latter mostly naupliar stages). A steep temperature rise starts in May, causing mass development of rotifers (*Synchaeta* spp.) and copepods. With further temperature increases in June, more species of rotifers (*Keratella* spp.) and cladocerans (*Evadne nordmanni*, *Pleopsis* spp., and *Bosmina longispina*) appear in the zooplankton community. The highest annual abundance and biomass levels are reached in July or early August, with up to 50% of the total biomass comprising cladocerans, mostly *B. longispina*. Starting in mid-August, predation by herring, mysids, and the invasive cladoceran *Cercopagis pengoi* affects the total abundance of the zooplankton community. Herring and mysids generally target the copepods, whereas *C. pengoi* preys on the local cladoceran *Bosmina*. Gradual temperature decreases in autumn lead to a reduction in the number of species and abundance values of the community. The autumn species composition resembles that of spring, with the addition of meroplankton, the pelagic larvae of benthic fauna.

Long-term SSTs in the region are fairly variable (Figure 5.18c), but have been warmer than the 100-year average since 1990. There is no clear relationship between temperature and zooplankton within the site, although temperature and salinity changes have been shown to influence zooplankton at other sites within the Baltic.



**Figure 5.17**  
Seasonal and interannual comparison of select co-sampled variables at Station 121 (see Section 2.2.2 for an explanation of this figure).



**Figure 5.18**  
Long-term comparison of Station 121 zooplankton with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

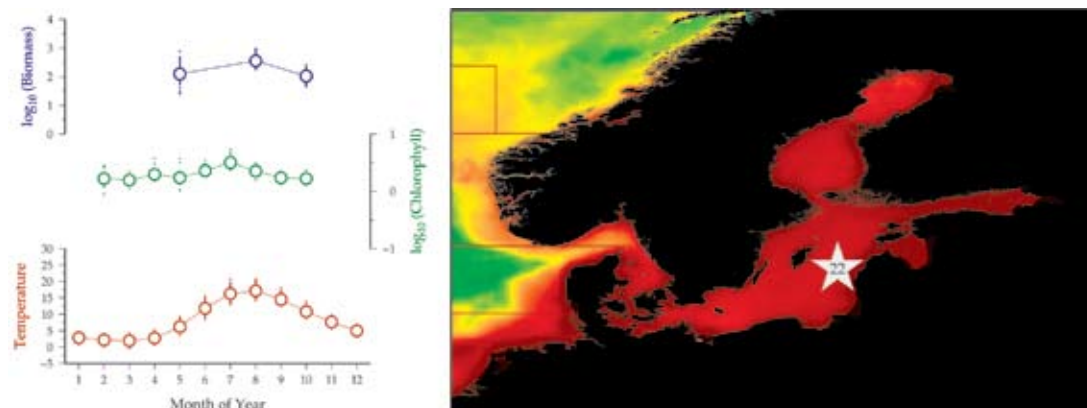


## Site 22: Eastern Gotland Basin (central Baltic Sea)

*Solvita Strake, Georgs Kornilovs, and Gunta Rubene*

**Figure 5.19**

Location of the eastern Gotland Basin (Site 22) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



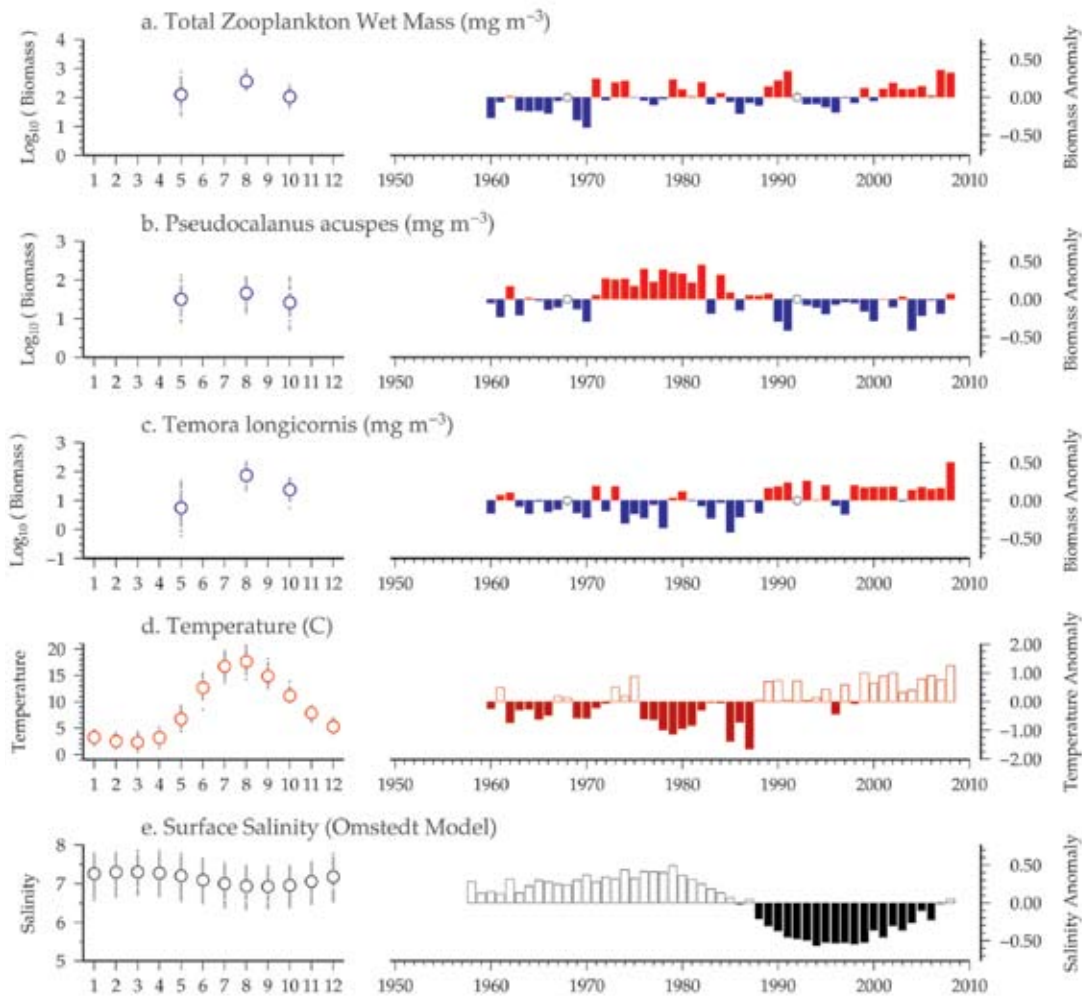
The eastern Gotland Basin sampling site is located in the central Baltic Sea, ICES Subdivision 28 (Figure 5.19). Zooplankton biomass (wet weight) was sampled using a Juday net (36 cm diameter, 160  $\mu$ m mesh). Individual hauls were carried out in vertical steps, resulting in full coverage of the water column to a maximum depth of 100 m. Sampling has been conducted in spring (May), summer (August), and autumn (October–November) since 1959.

In the central Baltic Sea, the zooplankton biomass is highly seasonal. After an increase from low values at the beginning of the year, peak biomass of all copepod species was regularly found in August–September. Cladocerans appear in considerable numbers from spring onwards, with a maximum biomass in August. In terms of biomass, the most important copepod species in the central Baltic Sea was *Pseudocalanus acuspes*, followed by *Temora longicornis*, *Acartia* spp., and *Centropages hamatus*. The biomass of *P. acuspes* drastically declined after 1990, but has increased again in recent years (Figure 5.20b). At the same time, an opposite trend was observed for *T. longicornis*, which had a low biomass until 1990, followed by high values at the end of the time-series (Figure 5.20c). Similarly, *Acartia* spp., which had a low abundance during the 1980s, increased stepwise during the 1990s (not shown). Increasing water temperatures (Figure 5.20d) and decreasing salinity (Figure 5.20e) are thought to be the reason for the shift in zooplankton species composition from *P. acuspes* to *T. longicornis* and *Acartia* spp. (Möllmann *et al.*, 2005).

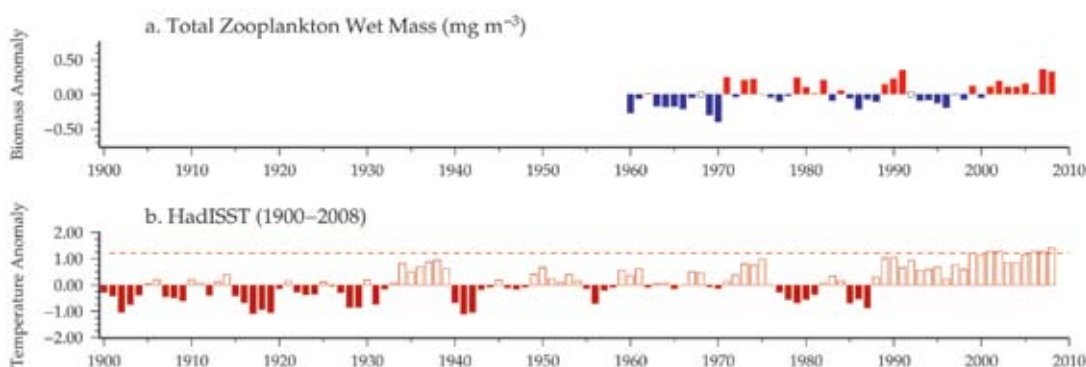
Although there are few published studies on the long-term trends of phytoplankton, changes in phytoplankton species composition were also observed in the central Baltic Sea. A downward trend was found for diatoms in spring and summer, whereas dinoflagellates generally increased in the Baltic Proper (Wasmund and Uhlig, 2003). Similarly, the species composition of the central Baltic fish community shifted from cod (*Gadus morhua*), which was very abundant during the 1980s, to sprat, which became dominant during the 1990s (Möllmann *et al.*, 2005).

Water temperatures in the survey area have been increasing since the 1900s, with some variability, and are currently warmer than any measured during the past century (Figure 5.21b). Increased precipitation and river run-off have accompanied the warmer temperatures. This directly affects the Baltic and its zooplankton communities by freshening surface waters (Matthäus and Schinke, 1999).




**Figure 5.20**

Seasonal and interannual comparison of select co-sampled variables in the eastern Gotland Basin (see Section 2.2.2 for an explanation of this figure).


**Figure 5.21**

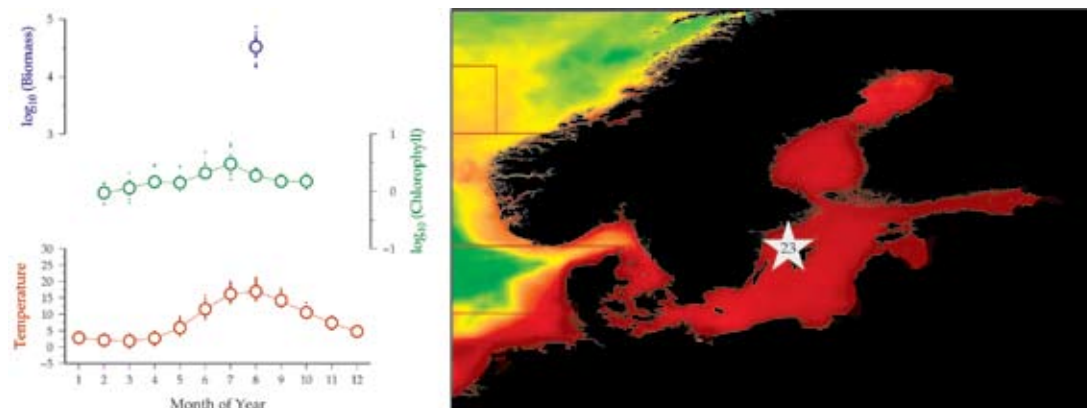
Long-term comparison of eastern Gotland Basin zooplankton with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## Site 23: The Baltic Proper (central Baltic Sea)

Maiju Lehtiniemi and Juha Flinkman

**Figure 5.22**

Location of the Baltic Proper (Site 23) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

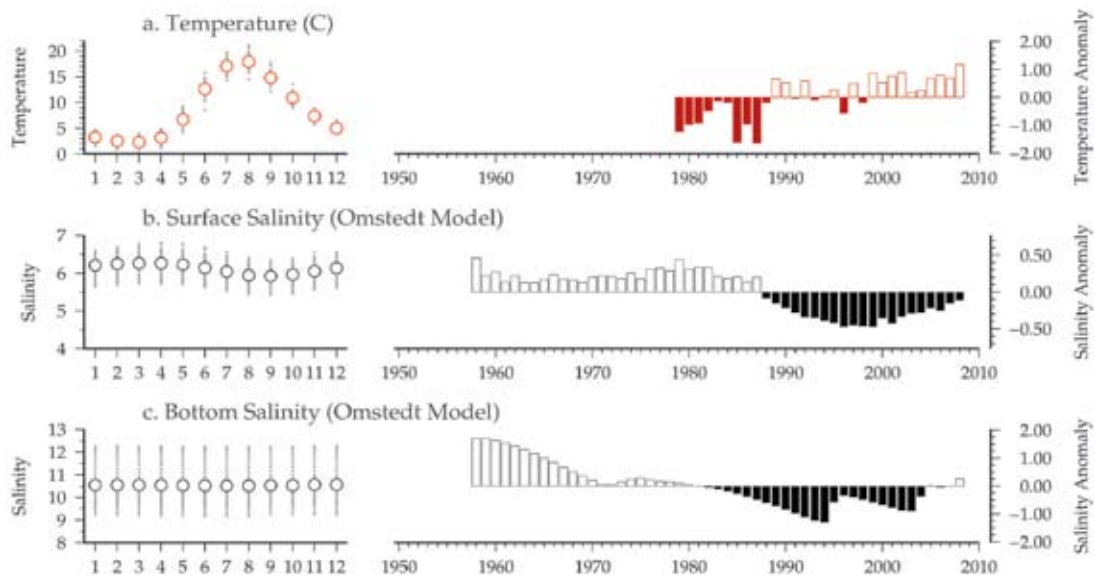


Zooplankton monitoring by the Finnish Institute of Marine Research (FIMR; now the Finnish Environment Institute) began in 1979 after the Helsinki Commission (HELCOM) initiated cooperative environmental monitoring of the Baltic Sea. Monitoring was divided into four subareas, based on differing hydrographic environments: Bothnian Bay and Bothnian Sea (see Sites 16–17), Gulf of Finland (see Site 19), and the Baltic Proper (this site; Figure 5.22).

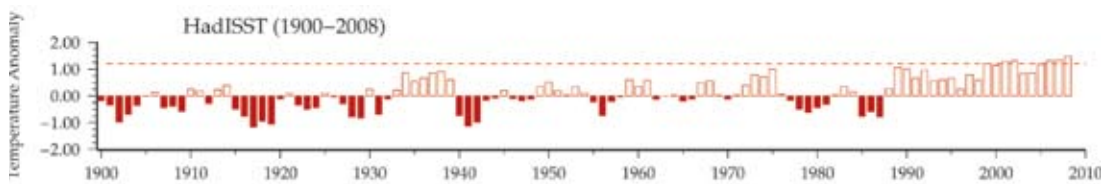
Zooplankton is collected in August, the peak abundance period, using a WP-2 net (56 cm diameter, 100  $\mu\text{m}$  mesh). Zooplankton data for the Baltic Proper are an average of four stations located within the eastern and northwestern Gotland Basin. The hydrography of the Baltic Proper is characterized by strong stratification, which prevents mixing of the water column. Water temperatures are lowest in February–March and warmest in August (Figure 5.23a). A stable halocline is formed at approximately 70 m depth. Water-column salinity varies from 6–8 psu at the surface to 9–13 psu in the deeper water (Figure 5.23b and c; Leppäranta and Myrberg, 2009). Pronounced salinity stratification often leads to oxygen depletion in bottom waters. Only irregular saltwater intrusions from the North Sea ventilate the deep bottom waters of the central Baltic Sea. The general Baltic-wide decrease in salinity is the result of warmer temperatures and

increased precipitation/river run-off in the Baltic. Long-term SSTs in the Baltic Proper have been above the 100-year average since the late 1980s and have repeatedly been at or above the 100-year maximum since 2000 (Figure 5.24, red dashed line).

The dominant zooplankton taxa are the copepods *Acartia* spp., *Temora longicornis*, and *Eurytemora* spp. (Figure 5.25b–d). The biomass of *T. longicornis* and *Eurytemora* spp., as well as that of another copepod species, *Centropages hamatus* (Figure 5.25e), has been steadily increasing from the start of the monitoring programme. At the same time, the biomass of the formerly dominant copepod species, *Pseudocalanus elongatus*, has been decreasing (Figure 5.25f; Flinkman *et al.*, 2007). During the past two years, the biomass of the largest copepod species, *Limnocalanus macrurus*, has also been decreasing (Figure 5.25g).



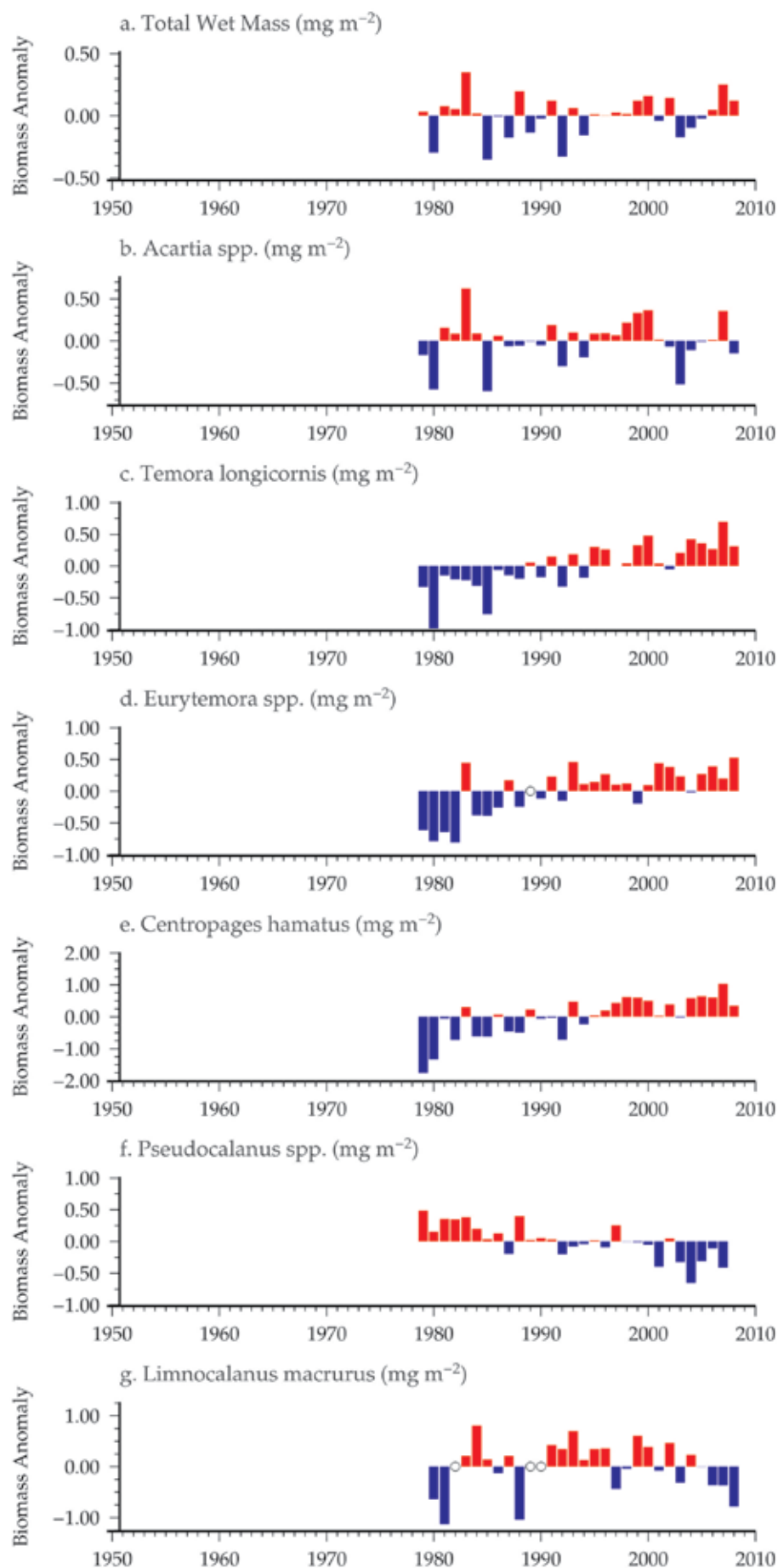
**Figure 5.23**  
Seasonal and interannual comparison of select hydrographic variables in the Baltic Proper (see Section 2.2.2 for an explanation of this figure).



**Figure 5.24**  
Long-term HadISST sea surface temperatures for the Baltic Proper study area (see Section 2.2.3 for an explanation of this figure).

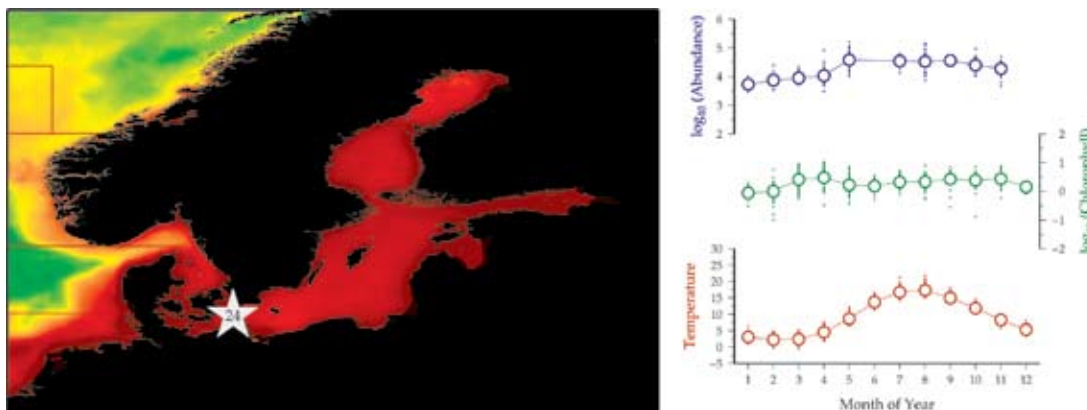
**Figure 5.25**

Seasonal and interannual comparison of select zooplankton wet mass and dominant taxa in the Baltic Proper (see Section 2.2.2 for an explanation of this figure).



## Site 24: Arkona Basin (southern Baltic Sea)

Lutz Postel and Norbert Wasmund



**Figure 5.26**

Location of the Arkona Basin (Site 24) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Arkona Basin site (54°55'N 13°03'E) is one of six German monitoring stations in the Baltic and extends from Kiel Bight to the eastern Gotland Basin (Figure 5.26). At this site, zooplankton is collected five times a year, using a WP-2 net (56 cm diameter, 100 µm mesh) and sampling from the surface to an average depth of 25 m. Although sampling began in 1979, some years have been poorly sampled or completely missed (e.g. 1990 and 1996). Chlorophyll is collected at standard depths and averaged for the 0–10 m layer at three locations surrounding the zooplankton sampling station.

Maximum zooplankton abundances occur in May–August (Figure 5.27a). The mesozooplankton community is dominated by *Acartia* spp. and *Pseudocalanus* spp. nauplii in early spring, followed by meroplanktonic larvae (polychaetes) in March. *Temora longicornis* nauplii and rotifers then dominate during early May, whereas the summer communities are dominated by bivalve larvae. Chlorophyll concentrations at the Arkona Basin site are usually high, with concentrations of more than 2 µg l<sup>-1</sup> during most of the year, reaching 6 µg l<sup>-1</sup> during the spring bloom (Figure 5.27b).

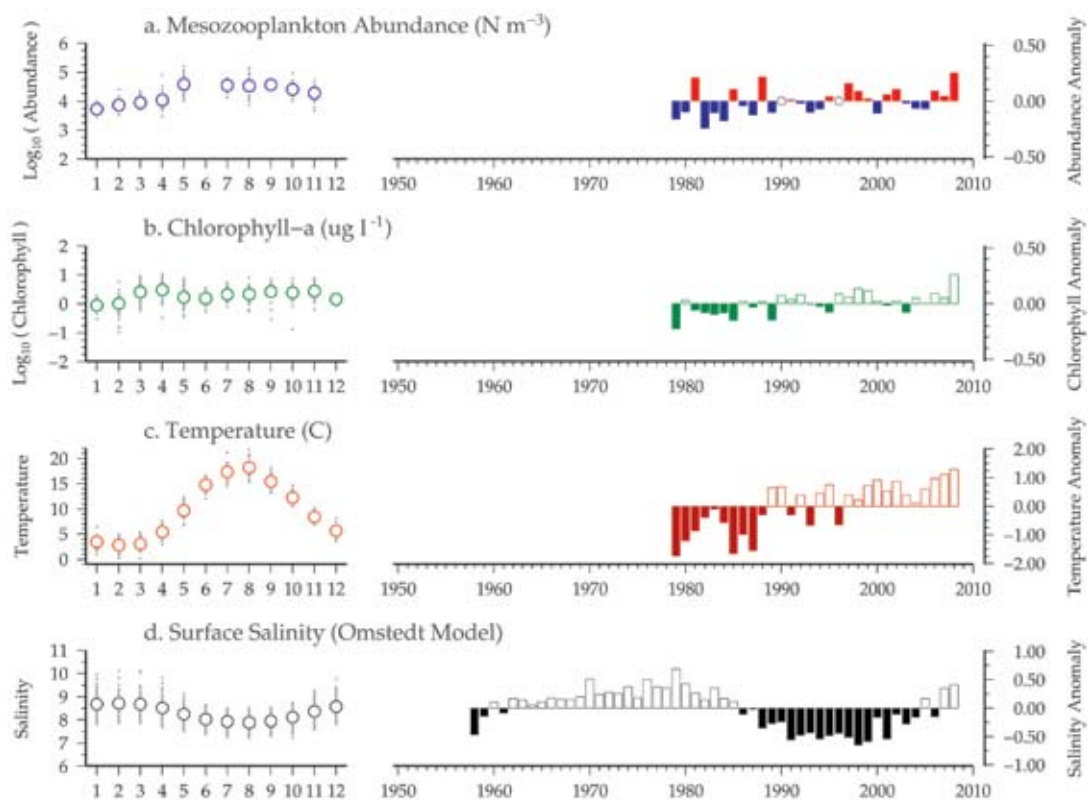
Mass development of rotifer populations in spring is responsible for the annual peaks of total zooplankton abundance seen in some years (e.g. 1981, 1988, 1997, and 2008), particularly in those springs following a mild winter. During summer, when water temperatures exceed 16°C (Figure 5.27c), the cladoceran *Bosmina coregoni* becomes the dominant species.

From a biogeographical point of view, the Arkona Basin zooplankton community reflects a transition between the dominating marine species assemblage in the western Baltic Sea and the euryhaline and brackish-water taxa in the Baltic Proper. Long-term variability is caused by salinity and temperature influences as well as by the trophic interactions and state of the Baltic Sea (Flinkman and Postel, 2009). Water temperature, zooplankton abundance, and chlorophyll have demonstrated a positive trend since the beginning of the time-series in 1979. The long-term record in regional SST values reveals that, since 1999, this region has experienced a particularly warm period, with temperatures frequently higher than the 100-year maximum observed prior to 2000 (Figure 5.28, red dashed line).



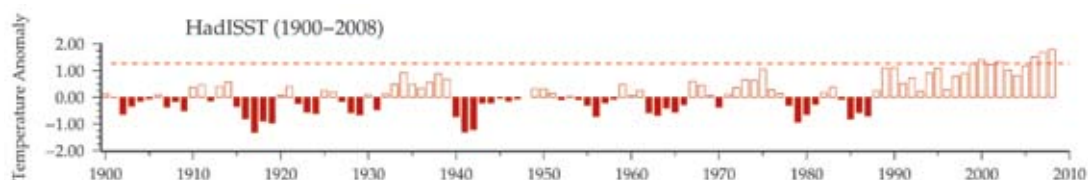
**Figure 5.27**

Seasonal and interannual comparison of select co-sampled variables in the Arkona Basin study area (see Section 2.2.2 for an explanation of this figure).



**Figure 5.28**

Long-term HadISST sea surface temperatures for the Arkona Basin study area (see Section 2.2.3 for an explanation of this figure).



**Right.** Assorted zooplankton from the western North Atlantic. Photo by N. Copley.





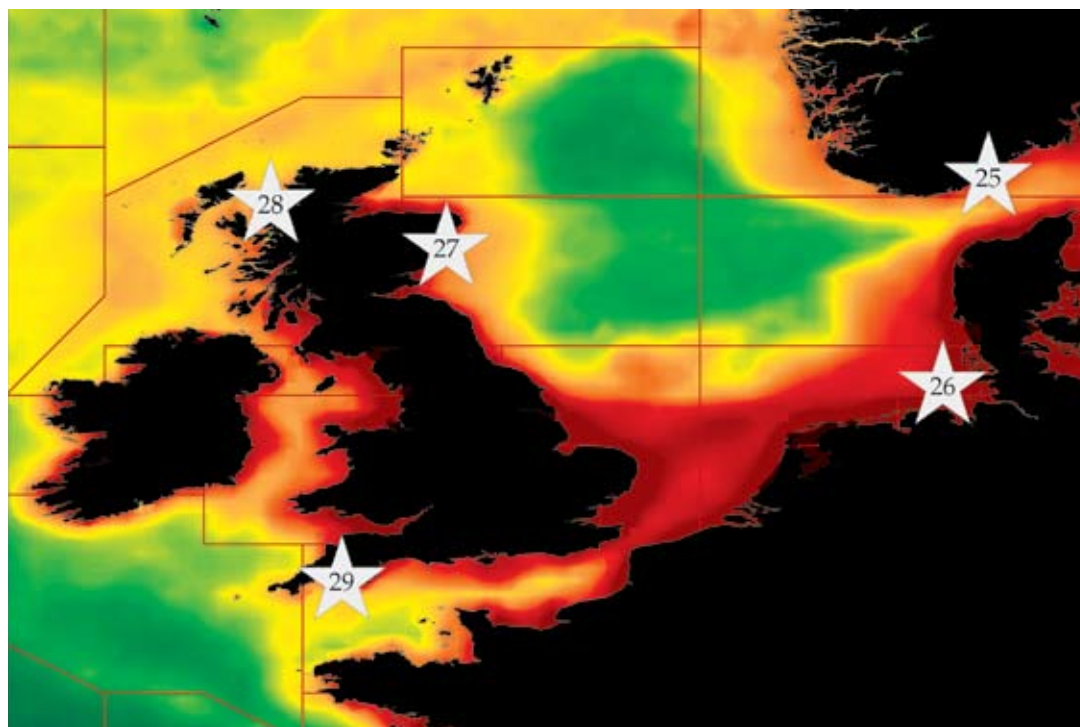
## 6. ZOOPLANKTON OF THE NORTH SEA AND ENGLISH CHANNEL

*Steve Hay, Tone Falkenhaug, Lena Omli, Maarten Boersma, Jasmin Renz, Claudia Halsband-Lenk, Tim Smyth, Roger Harris, Priscilla Licandro, and Martin Edwards*

The North Sea and English Channel (Figure 6.1) are classified by Longhurst (1998) as part of the Northeast Atlantic Shelf Province (NASP). This extends from northern Spain to Denmark and is separated from the Atlantic Subarctic Region by the Faroe–Shetland Channel and the Norwegian Trench. The NASP follows the classic seasonal pattern for temperate regions: well-mixed conditions in winter, when nutrients are replenished and light is limited; a strong spring bloom, becoming nutrient-limited as summer stratification sets in; and a more or less pronounced secondary bloom during autumn, as increased mixing breaks down the thermocline to release nutrient supplies. This general pattern is often broken up by locally strong tidal and shelf fronts (Pingree and Griffiths, 1978), where primary and secondary production is often enhanced, and may lead to subsurface blooms, at times extensive. The zooplankton in the shelf areas of the region is a characteristic mixture of neritic species, with strong seasonal components of benthic larvae (meroplankton; Beaugrand *et al.*, 2002a, 2002b; Vezzulli and Reid, 2003), and with occasional and temporary influxes of oceanic species. Several of the common neritic species overwinter as resting stages, whereas other holoplankton species remain more or less active all year. There are also substantial problems with harmful algal blooms, alien-species introductions, and local areas with evidence of

eutrophication, all influencing the zooplankton ecology in the region.

The north-flowing Continental Slope Current in the west, flowing off the Iberian peninsula, carries oceanic plankton communities (Lusitanian fauna) that become entrained to varying degrees into the coastal seas. Evidence suggests a strengthening of this influx in recent years. These mixed coastal and oceanic waters form influxes into the Bay of Biscay, the Celtic and Irish seas, and through the English Channel into the shallow southern North Sea, where the flow is eastward along the continental margin. These mixed waters and plankton are also carried into the Irish and Scottish western shelf seas and form major inflows into the deeper basin of the northern North Sea via the Fair Isle inflow and inflows east of the Shetland Isles. The northern North Sea is a fairly deep basin, which shelves in the west to the Scottish mainland and northern islands, with the deep Norwegian Trench in the east shelving into the fjordic coast of Norway. The deeper northern basin shallows distinctly into the central and southern North Sea, where prominent topographic features are Dogger Bank in the west, and the Skagerrak and entrance to the Baltic Sea in the east. The residual North Sea circulation is anticyclonic, with inputs from the surface outflow of the low-salinity Baltic Sea in the east and from



**Figure 6.1**  
Locations of North Sea and English Channel survey areas (Sites 25–29) plotted on a map of average chlorophyll concentration (see Section 2.3.2).

major rivers and coastal estuaries. The whole empties northwards along the Norwegian coast, following the Norwegian Trench northwards into the Norwegian Sea.

Surrounded by active and prosperous countries, this maritime region provides a wide range of ecosystem services (e.g. fish and shellfish harvests, energy production, transport, and tourism) and, historically, is perhaps the most studied marine area on earth. In addition to the venerable and comprehensive monthly series of Continuous Plankton Recorder (CPR) surveys (conducted since before 1948), there are significant coastal time-series of plankton collections and environmental data. The main time-series that sample zooplankton are: Helgoland Roads (German Bight; since 1975), Plymouth L4 (western English Channel; since 1988), Dove (western central North Sea; since the mid-1970s), Stonehaven (northwestern North Sea; since 1997), Arundel (eastern central North Sea; since 1994), and the new Loch Ewe station (northwest Scotland; since 2002).

In addition to direct output of important results from the time-series, there are many related surveys and studies. The time-series often provide sampling opportunities, essential context, background, and enhanced interpretation for short-term and

intensive research on physiological rates and processes in the plankton, benthic-pelagic coupling, fish recruitment, etc. Together with such studies, the time-series have explored and defined seasonal patterns of plankton species, population dynamics and phenology, productivity, climate effects and regime shifts, fishery recruitment, and many other issues. These and other regional time-series datasets also gather phytoplankton and environmental data; therefore, the combined time-series data continue to make substantial contributions to the development, parameterization, and validation of population dynamics and ecosystem models. Historical and recent studies, plus those in progress, continue to add to our knowledge and understanding of marine biology and ecology. The combined data and models provide for more holistic ecosystem perspectives and for assessment of status and trends in these productive and often stressed marine ecosystems.

Analysis of plankton, fisheries, oceanographic, and meteorological data in recent years, particularly data related to the CPR survey, demonstrates that the region has been subject to a series of regime shifts and changes associated with changes in the climate and global-ocean systems (Reid and Edwards, 2001a, 2001b; Edwards *et al.*, 2002; Beaugrand and Reid, 2003; Beaugrand *et al.*, 2003; Alheit *et al.*, 2005). These changes in water-mass fluxes and properties,

such as temperatures, mixing depths, and seasonal stratification, have seen corresponding shifts in diversity, niche ranges, and phenology of species and communities (Lindley and Batten, 2002; Lindley and Reid, 2002). Such changes have also been seen in fish, and, in general, they mirror the often less dramatic climate effects on terrestrial ecosystems and species. Increasingly, plankton is being studied and modelled on ocean-basin scales, for example, in relation to changes seen along the eastern seaboard of the US and Canada, around Iceland, Faroes, Norway, and into Subarctic and Arctic seas. Not only do ocean-climate changes affect the geographic ranges of plankton and the seasonal timing of their life cycles, but different species are affected differently and respond variously to change. Effects on plankton communities propagate through species interdependence in foodwebs, thus affecting patterns of growth, development, survival, and productivity.

The combination of climate change and overfishing in the North Sea has seen shifts in the patterns of foodweb fluxes and productivity in recent years. Changes in plankton production, biodiversity, species distribution, community composition, and phenology are related to effects on fish and other species. Most of these changes are correlated with shifts in climate indices, such as the North Atlantic Oscillation (NAO), particularly with northern hemisphere temperature, which has been increasing for >30 years and warming the European continental shelf surface waters. Many plankton and fish species have demonstrated northward shifts in distributions in the Northeast Atlantic region (some by >1000 km) over the past 50 years (Edwards *et al.*, 2001, 2002; Reid and Edwards, 2001a; Beaugrand, 2003; Beaugrand *et al.*, 2002b; Beaugrand and Reid, 2003; Brander *et al.*, 2003; Edwards and Richardson, 2004; Genner *et al.*, 2004; Richardson and Schoeman, 2004; Southward *et al.*, 2004; Alheit *et al.*, 2005; Brander, 2005; Heath, 2005; Leterme *et al.*, 2008).

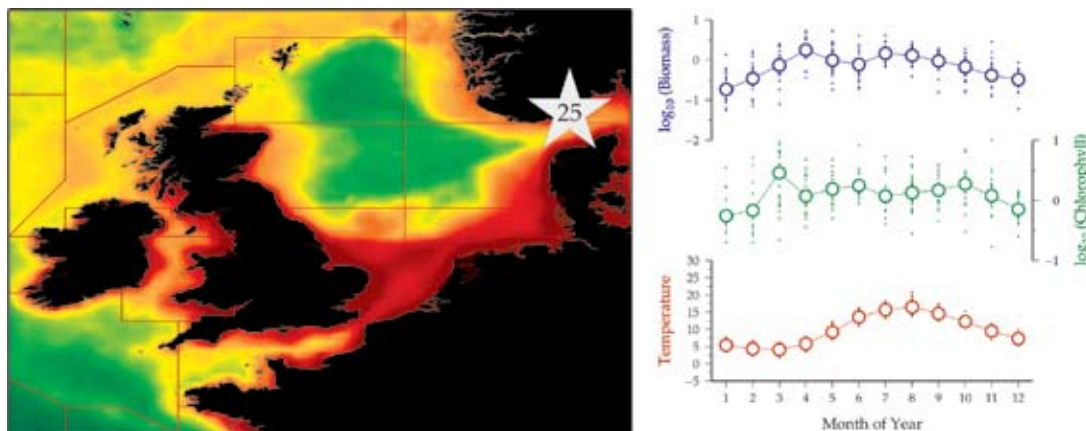
Some examples include 40 years of declining abundance and northward retreat of the northern boreal copepod *Calanus finmarchicus*, with simultaneous increase in its southern temperate congener *Calanus helgolandicus*. Since the 1960s, in the North Sea, the biomass of *C. finmarchicus*, previously a dominant, declined by 70%, as the 10°C isotherm moved northwards by more than 21 km year<sup>-1</sup> (Helaouët and Beaugrand, 2007). Seasonal and interannual changes in the relative abundance of meroplankton larvae of benthic invertebrates have been observed (Kirby and Lindley, 2005). There have been indications of increased jellyfish abundance (Lynam *et al.*, 2005; Attrill *et al.*, 2007), with notable increases and incursions of the oceanic scyphozoan *Pelagia noctiluca* into western shelf areas, causing mortalities in farmed salmon (Licandro *et al.*, 2010). Some species, such as the dinoflagellate *Ceratium*, have demonstrated dramatically reduced abundance in recent years (Edwards *et al.*, 2009). Appearances of “alien” species have been noted, such as the voracious ctenophore *Mnemiopsis leydyi* (Oliveira, 2007) and the cladoceran *Penilia avirostris* (Johns *et al.*, 2005) in the Baltic Sea and in northern European coastal waters, from Dutch waters to as far north as southern Norway.

Species declines, losses, shifts, introductions, and an increased presence of invertebrate predators are occurring in the North Sea. These changes influence recruitment, mortality, and resource supply to the benthos and to higher predators, such as pelagic and demersal fish, seabirds, and mammals (Lindley *et al.*, 2002; Heath, 2005; Frederiksen *et al.*, 2006). Changes affect and propagate through foodwebs, with potentially critical mismatches between predators and prey. Brander (2005) has demonstrated that declining cod populations, while affected by fishing pressure, may also be responding to changes in availability of zooplankton food for their larvae. Although these climate-related changes form a general pattern in the Northeast Atlantic, there are regional differences, with the southern North Sea warming faster than the deeper northern basin. There is variability among species in their sensitivities, adaptive capabilities, and responses. It is becoming increasingly evident that future changes in plankton populations will affect ecosystem services ranging from biogeochemical cycles to the survival and production of fish, birds, and mammals.



## Site 25: Arendal Station 2 (northern Skagerrak)

Tone Falkenhaug and Lena Omli



**Figure 6.2**  
Location of the Arendal Station 2 (Site 25) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Arendal sampling site (northern Skagerrak) is located at 58°23'N 8°49'E, approximately 1 nautical mile offshore from the Flødevigen Research Station (Norwegian Institute of Marine Research, IMR) off southern Norway (Figure 6.2). The water depth at the site is 105 m. Sampling for hydrographic parameters and abundance of phytoplankton and zooplankton (biomass and species) has been carried out twice a month since January 1994. Zooplankton is sampled fortnightly with a WP-2 net (56-cm diameter, 180 µm mesh) towed vertically from a depth of 50 m to the surface. Each sample is split in half, providing data on both species composition–abundance and biomass.

The Arendal sampling site is influenced by relatively fresh coastal waters (25–32 psu) in the upper 30 m and by saltier Skagerrak water (32–35 psu) in the greater depths. Water movement is generally westward and is caused by the coastal current bringing low-salinity water from the Baltic Sea and Kattegat. The site is also influenced by Atlantic water (>35 psu) advected from the Norwegian Sea into the Skagerrak Deep during winter. Together, these influxes create a relatively large seasonal cycle in salinity (Figure 6.3d). The seasonal minimum temperature in the surface layer (Figure 6.3c) generally occurs in February (2°C) and the maximum in August (>20°C). At 75 m, the variation is less pronounced (minimum 4°C in February–March to maximum 14°C in August–September). Although the water column is mixed throughout winter, increased freshwater run-off causes a strong halocline to appear from February/March to June (Figure 6.3d). A spring bloom usually occurs in

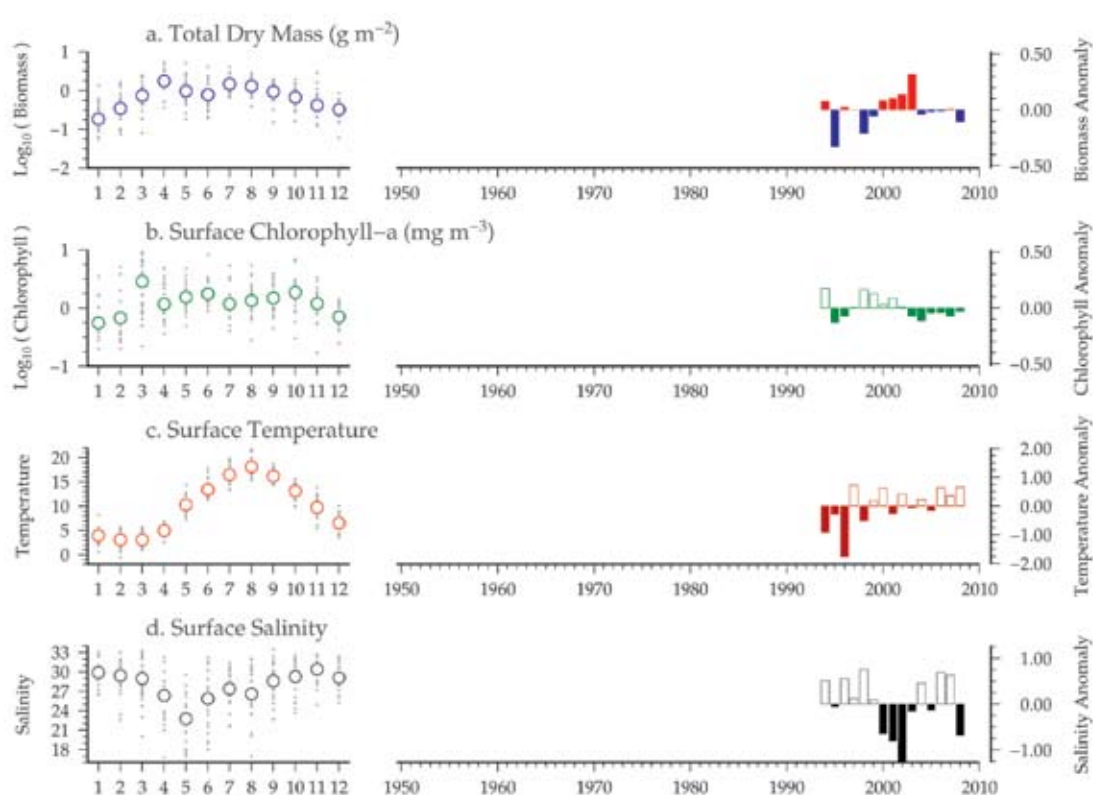
April–March, dominated by diatoms. Chlorophyll values (Figure 6.3b) are generally low during summer (May–August), followed by an autumn bloom of dinoflagellates in August–September. In summer, the water remains stratified because of surface heating. During the past 20 years, a trend towards higher temperatures has been observed in Skagerrak, both in surface and deeper layers. Since 2001, water temperatures in the region have been higher than those seen in the past 100 years (Figure 6.4).

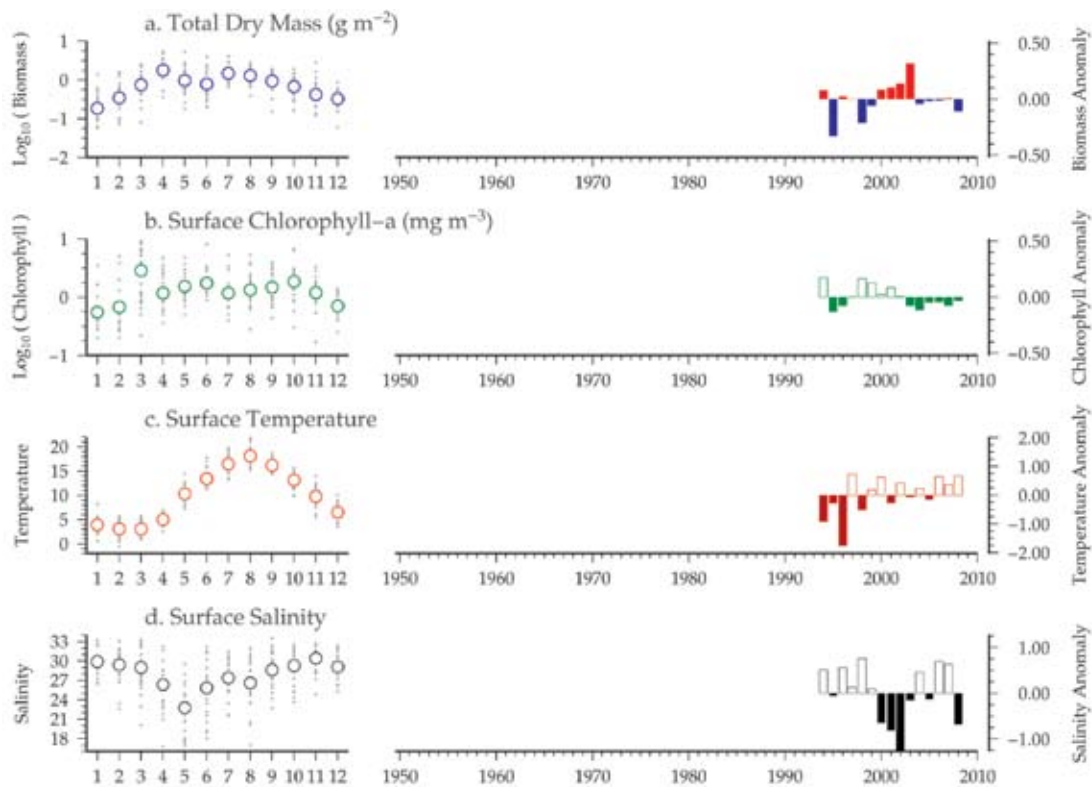
The seasonal maximum in zooplankton biomass generally occurs in April–May (Figure 6.3a), with a secondary, smaller peak occurring in July–August. Large interannual differences can be seen in the observed biomass of zooplankton, with maximum values in 2003 and minimum values in 1998. A general increase in biomass and abundance was observed from 1998 to 2003, but a lesser abundance overall was observed in 2004–2008 (Figure 6.3a). The observed lesser abundance in recent years is especially pronounced in the late summer peak (July–August). This is mainly caused by the reduced abundance of the copepods *Oithona* spp. and the *Para*- and *Pseudocalanus* spp. in the period 2004–2008 (Figure 6.5a). The seasonal maximum in zooplankton biomass (April–May) is dominated by *Calanus finmarchicus* (Figure 6.5b), whereas the secondary peak (July–August) is dominated by smaller copepods (*Para*- and *Pseudocalanus*, *Oithona*, *Acartia*, *Temora*). The important common copepod genus, *Calanus*, is represented by three species at the Arendal sampling site: *C. finmarchicus*, *C. helgolandicus*, and *C. hyperboreus*. *C.*

*finmarchicus* is the most abundant species during spring. This species overwinters in the Skagerrak Deep (Norwegian Trench, 20 nautical miles farther offshore from this station). Interannual variability in overwinter survival and advection is likely to affect the population dynamics. *C. helgolandicus* generally occurs in smaller numbers than *C. finmarchicus*, although the proportion of *C. helgolandicus* increases from spring (<10%) to autumn (>80%). *C. hyperboreus* is rarely observed in spring (March–April) and is associated with the influx of Atlantic water from the Norwegian Sea.

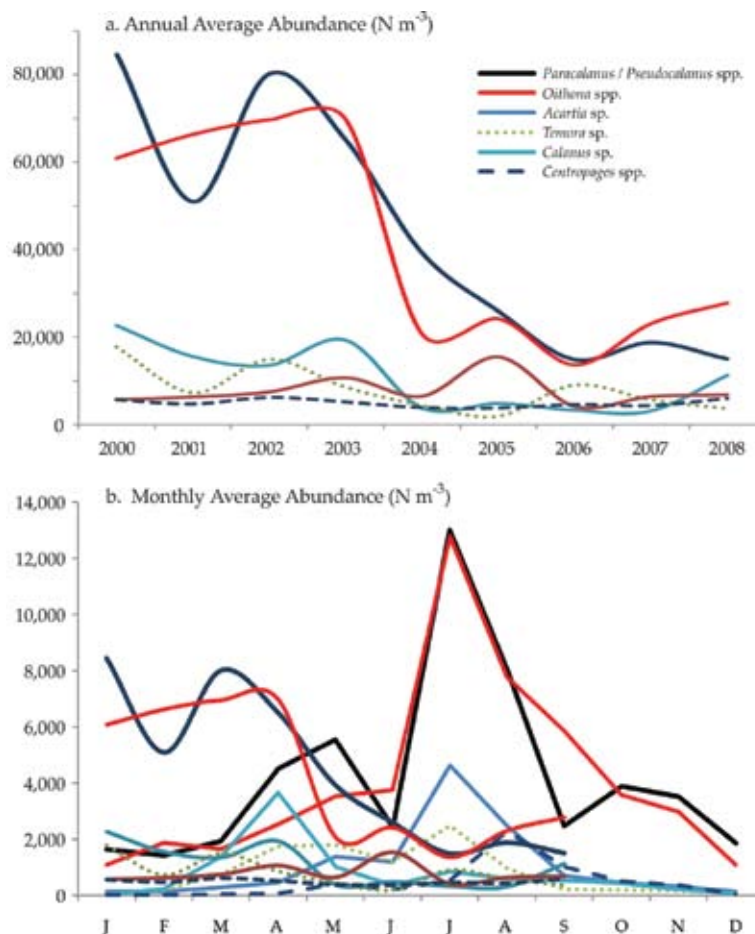
The invasive ctenophore species *Mnemiopsis leidyi* was observed in Skagerrak for the first time in 2006. Since then, this species has occurred in high densities at Arendal Station 2 in late summer–autumn each year. The seasonal peak of *M. leidyi* coincides with maximum temperatures in the surface water (>20°C), which occur after the seasonal maximum in zooplankton abundance.

**Figure 6.3**  
Seasonal and interannual comparison of select co-sampled variables at Arendal Station 2 (see Section 2.2.2 for an explanation of this figure).





**Figure 6.4**  
Long-term comparison of Arendal zooplankton (total dry mass) with copepod abundance in CPR standard area B1 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



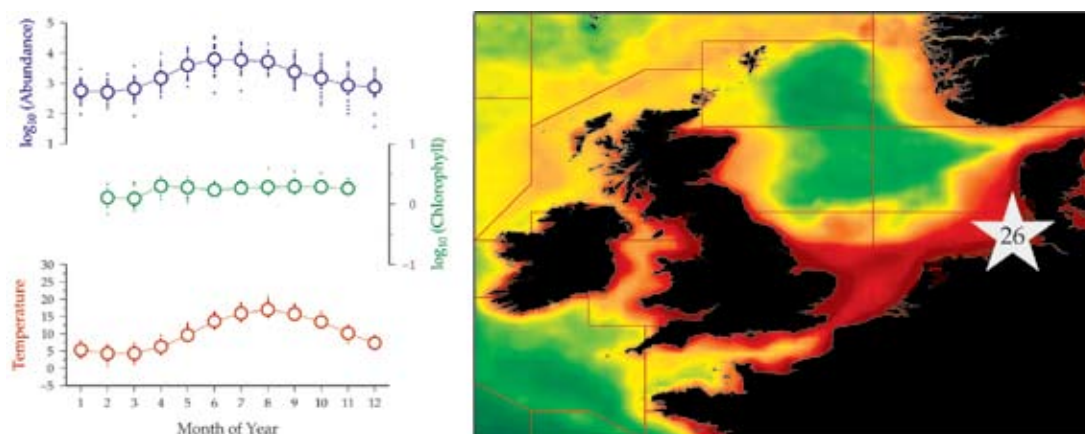
**Figure 6.5**  
Annual average abundance (a) and monthly average abundance (b) of six major copepod genera at Arendal Station 2.

## Site 26: Helgoland Roads (southeastern North Sea)

*Maarten Boersma and Jasmin Renz*

**Figure 6.6**

Location of the Helgoland Roads (Site 26) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



The Helgoland Roads time-series was started in 1975 by Wulf Greve, initially at the Biologische Anstalt Helgoland Institute and later continued in cooperation with the German Centre for Marine Biodiversity and the Federal Maritime and Hydrographic Agency. Every Monday, Wednesday, and Friday, two oblique plankton net samples (150  $\mu\text{m}$  and 500  $\mu\text{m}$  mesh) are collected from the monitoring site, which is located at 54°11'18"N 7°4'E (Figure 6.6). From each sample, almost 400 taxonomic entities of holoplankton and meroplankton (e.g. benthic and fish larvae) are identified and counted for abundance, making the Helgoland Roads time-series one of the finest WGZE sites in both taxonomic and sampling resolution.

The purpose of the Helgoland Roads programme is to monitor and document high-frequency plankton population dynamics for the recognition of variances and irregularities in distributions, such as changes in biodiversity caused by external factors. A wealth of publications and material available about the site cover the use of several analytical techniques, the types of information extracted from the data, and models on prognosis for zooplankton dynamics on several time-scales (Heyen *et al.*, 1998; Johannsen *et al.*, 1999; Greve *et al.*, 2001, 2004; Wiltshire *et al.*, 2008).

At the Helgoland Roads sampling site, small copepods, mostly *Acartia clausi*, *Temora longicornis*, and *Pseudocalanus* spp. (Figures 6.7b–d), represent a significant fraction of the total zooplankton population. Seasonal and interannual variations in

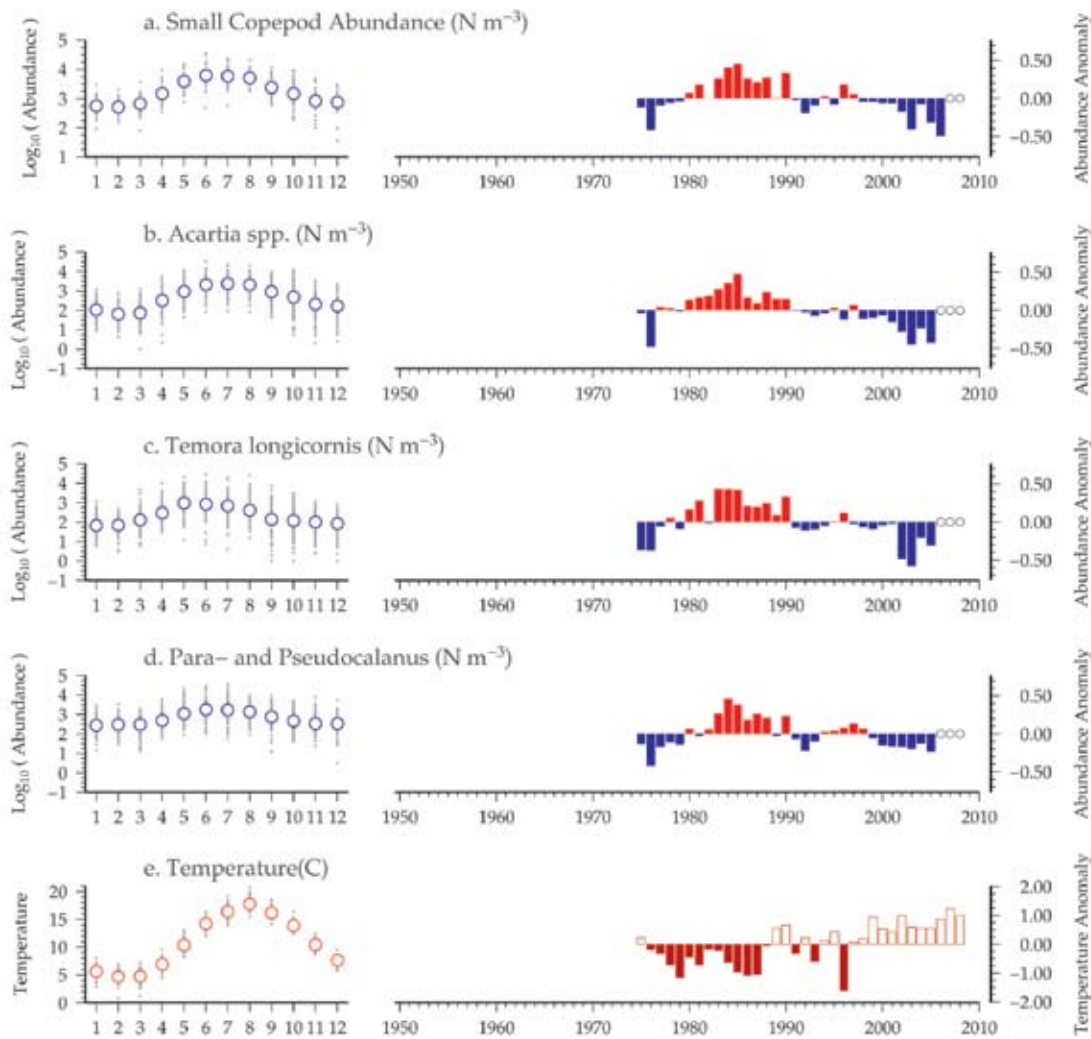
the numbers of small copepods are large, both in timing and magnitude. In most years, maximum density occurs in midsummer (Figure 6.7a, left), and the 30-year time-series reveals clear decadal variability (Figure 6.7a, right). Starting with a negative phase at the beginning of the time-series (1975), copepod abundance increased steadily and was consistently higher than average during much of the 1980s. After a period of transition (1990–1997), copepod density decreased and has remained in a negative phase, where abundance is consistently low. Values for the monthly mean copepod abundance by year (Figure 6.7a, right) reveal that years with a strong positive annual anomaly (e.g. 1983–1988) are characterized by an extended period of high maximum abundance in midsummer, whereas years with a strong negative annual anomaly (e.g. 2003–2006) have a shorter period of lesser maximum abundance during midsummer.

Average SST anomalies at Helgoland Roads over the past 100 years reveal that, since 2000, the average water temperatures at the site have been at or above the 100-year maximum (Figure 6.8c, red dashed line). Anomalies in SST values and small copepod abundance seem to be inversely related, with the lowest copepod abundance occurring during the past few years of highest water temperatures (Figure 6.7a and e). Further research is needed to determine whether this is the result of a direct causal relationship (i.e. biophysical factors within the copepod organisms), or the effect of temperature on food availability or predator pressure.



The CPR standard area nearest to Helgoland Roads is D1 (see Section 2.3.3). Like the Helgoland Roads data, the CPR data clearly demonstrate that copepod abundance has entered a phase of negative and decreasing annual anomalies since 1988 (Figure 6.8b). A comparison of the Helgoland Roads and CPR data suggests a time-lagged synchrony in copepod abundance, with the Helgoland Roads abundance anomalies being ahead of the CPR anomalies by 3–5 years. The relationship between

CPR copepod abundance and water temperature (Figure 6.8b and c) has been variable, switching from positive to negative throughout periods in the time-series. Increases in water temperature around the shallow Helgoland Roads site have been more dramatic than those in the North Sea as a whole, which may explain why the changes in the copepod population occur more rapidly than in those sampled in the larger water body within the CPR standard area.

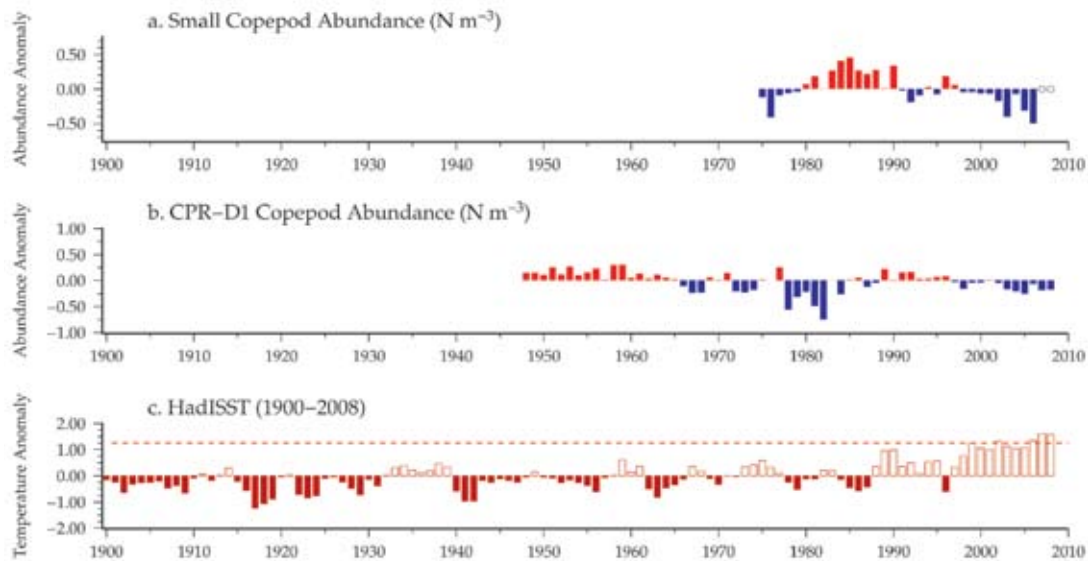


**Figure 6.7**  
Seasonal and interannual comparison of select co-sampled variables at Helgoland Roads (see Section 2.2.2 for an explanation of this figure).



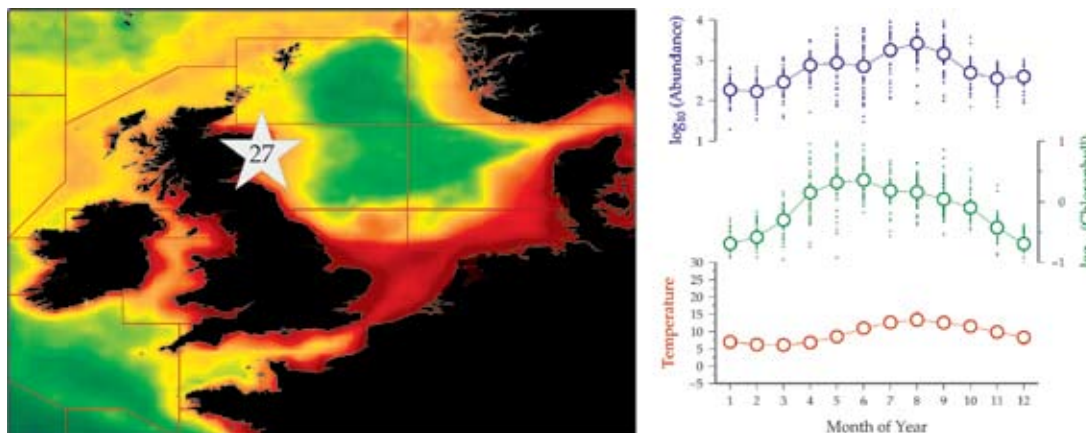
**Figure 6.8**

Long-term comparison of Helgoland Roads small copepod abundance with copepod abundance in CPR standard area D1 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



## Site 27: Stonehaven (northwestern North Sea)

Steve Hay



**Figure 6.9**  
Location of the Stonehaven (Site 27) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Stonehaven sampling site is located at 56°57.80'N 02°06.20'W (Figure 6.9), approximately 5 km offshore from Stonehaven, a small town 28 km south of Aberdeen, in a water depth of 50 m. Sampling is carried out by the Marine Scotland Science team from the MV “Temora”, a 10-m catamaran. Weekly samples have been taken since January 1997 for the determination of hydrographic parameters and concentrations of inorganic chemical nutrients (using water bottles and reversing digital thermometers) and for the abundance of phytoplankton and chlorophyll (using a Lund tube, integrating 0–10 m) and of zooplankton species.

Zooplankton are collected using a bongo net (40 cm diameter, 200 µm mesh) and flowmeter, and, since 1999, detailed taxonomic analysis has been carried out on the mesozooplankton and phytoplankton samples. The 40-cm bongo net samples are also collected with a fine mesh (95 µm from 1997 to April 2001, then 68 µm to the present). These fine-mesh samples are currently archived and not analysed because of the limited availability of trained staff. The site is also sampled for macroplankton, using a ringnet (100 cm diameter, 350 µm mesh) with a double oblique tow at 2 knots; these samples are also archived. A recent project is currently analysing these macroplankton samples using a ZooScan system and automated species-group recognition.

Other sampling at the site is done in support of a variety of time-limited research projects that study aspects of the coastal species or ecology in more detail. The Stonehaven time-series samples are collected consistently and at a relatively high frequency, affording insight into the seasonal dynamics and succession of plankton species

throughout the annual cycle. This time-series dataset provides excellent background and context both for experimental work and for more intensive or focused studies of individual species groups, ecosystem dynamics, rates, and processes. Strong support is provided for model development and validation, whereas comparisons with other monitoring sites assess and consider local variability relative to broader patterns of ocean-climate change.

The objective of the sampled time-series is to establish a monitoring base for assessing the status of the Scottish coastal ecosystem and to gauge responses to climate change. Comparison of the results with archived regional data on temperature, salinity, nutrients, and phytoplankton chlorophyll *a* indicates that the site provides a reliable index of the state of the coastal waters. The biological data illustrate the consistencies and variability in seasonal life cycles of plankton species and their abundance. There are significant seasonal and interannual differences (Figure 6.10). The water column at the sampling site remains well mixed throughout much of the year, with the exception of summer and early autumn, when surface heating and calm weather often cause temporary thermoclines to appear. Occasional haloclines are transient and depend largely on periods of extensive riverine input and land run-off to surface layers in the coastal area. The seasonal minimum temperature of ca. 6°C generally occurs in late February–early March and rises to ~12–14°C in August (Figure 6.10c). Water movement is generally southerly, with fairly strong tidal currents and a local tidal excursion of ca. 10 km.

The HadISST temperatures modelled for the area are broadly in good agreement with field measurements. This long time-series indicates that sea temperature around the site has increased distinctly over the period since sampling started in 1997 (Figure 6.11).

The origins of the water passing down the Scottish east coast lie mainly north and west of Scotland and are a variable flux of mixed coastal and oceanic Atlantic waters. Throughout late summer and autumn, the sampled salinity and species indicate a variable, but often significant, increase in the proportion of Atlantic water passing the site. The wider northern North Sea has demonstrated a slight warming trend over the past 50 years, with temperatures in recent years being higher than those seen over the past 100 years (Figure 6.11c, red dashed line). From hydrographic data measured directly at the Stonehaven site, temperature tends to vary smoothly, whereas salinity displays considerably more annual variation.

At the temperate Stonehaven site, annual cycles are evident in all of the measured variables. For example, the concentration of nitrate, a vital nutrient, rises as it is replenished during winter (Figure 6.10e), when both light levels and temperature are too low for phytoplankton growth. The nitrate concentration then falls, often abruptly, with the growth of the spring phytoplankton bloom in March–April (Figure 6.10b). This growth uses up nitrate and other nutrients, such as the silicate needed by diatoms, and accelerates as sea temperature increases. Throughout summer, these phytoplankton, which are nitrogen-dependent, rely on regenerated nitrate and ammonia supplied by microbial action and zooplankton excretion.

Zooplankton, in turn, feed on phytoplankton and on each other and increase in abundance after the spring phytoplankton bloom. After a late-summer peak, which coincides with peak temperature in August–September, zooplankton abundance then declines as winter approaches and food again becomes light-limited and scarce. In order to survive winter, some species, such as the large copepod genus *Calanus* and euphausiids, build up oil reserves, whereas others rely on resting eggs. Some common neritic copepods, such as *Temora longicornis* and *Acartia clausi*, lay eggs that lie dormant on the seabed during winter. Other species, such as the copepod *Centropages typicus* and the planktonic mollusc *Limacina retroversa*, are not resident throughout winter, but are reseeded each year, carried by the circulation and influx of mixed coastal and oceanic waters from the north

and from areas south and west of Scotland. Some species simply survive on whatever they find to eat through winter. Although the patterns are broadly consistent, the dynamics of seasonal cycles vary between years for both the environmental and species components of the ecosystem.

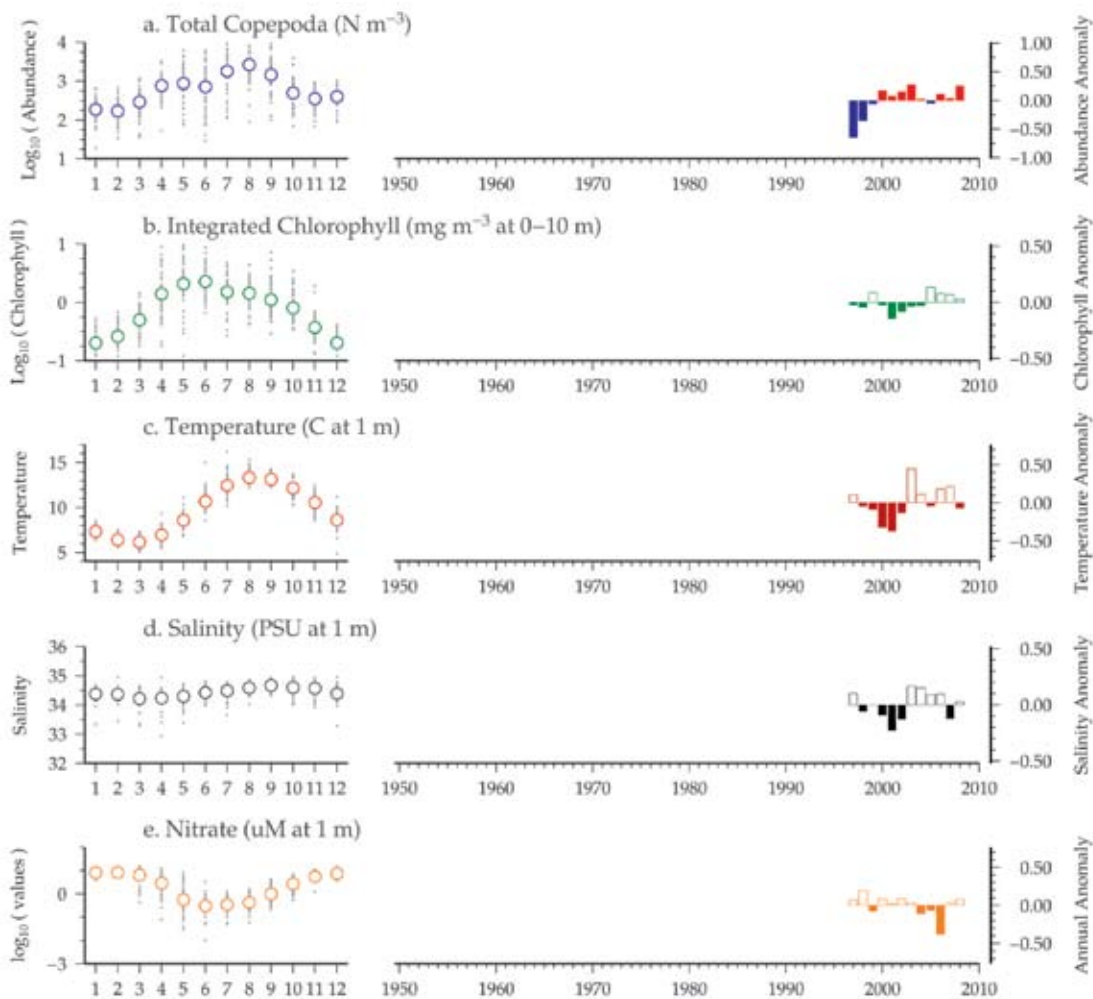
Several zooplankton species are of particular interest because they may be biomass-dominants or indicators of changing conditions. Some demonstrate wide variations in their annual abundance patterns. Overall copepod abundance was lower than average in 1997 and 1998, increased slowly through 2000–2003, and, since 2006, after two more average years in 2004 and 2005, has increased again. An example of this variation is the important copepod genus *Calanus*, which is represented by two species in Scottish seas: *C. finmarchicus* and *C. helgolandicus*. Historically most abundant in spring and summer, the arctic–boreal *C. finmarchicus* is an important species with a large spring influx arising from the winter diapause in deeper waters off the edge of the continental shelf. This species provides food for many fish larvae in spring. However, there has been a 50-year decline in the abundance of *C. finmarchicus*, whereas *C. helgolandicus*, a more southerly species, generally most productive in summer and autumn, has demonstrated increased abundance and productivity in this region, becoming approximately tenfold more abundant than *C. finmarchicus*. Indeed, *C. helgolandicus* had become one of the top ten most numerically abundant species by 2007. Both *Calanus* species have demonstrated increased abundance over the past three years. It is notable that anomalies in the interannual abundance of some plankton predators, such as the copepod genus *Oithona* and the arrow worms (*Chaetognatha*, *Sagitta*), which feed on the copepods and their larvae, follow interannual patterns similar to those of their main prey.

Another example is the copepod species *Eucalanus crassus*, which has been seen regularly in small numbers at Stonehaven since 2003, mainly in autumn. A fairly common species southwest of the UK, it was very rare east of Scotland. This indicates an environmental change that now permits its survival in the area, most probably an increased influx and persistence of warmer Lusitanian waters throughout late summer and into winter. Catches of *Sagitta setosa*, also more common in southern UK seas, have also been present in recent years, again mainly in autumn and early winter.

Copepod abundance at Stonehaven has increased fairly steadily over the past ten years. This is in contrast to the decreasing trend seen in the offshore (open-water) CPR data from the region (Figure 6.11b), particularly since 2005. The causes of this discrepancy are not understood, but it is probably the result of differences in the sampling methods and in the hydrographic influences at the nearshore Stonehaven station, as compared with the much wider and offshore region encompassed by the adjacent CPR survey tracks. It is worth noting that there is more complexity in reality than is evident in the samples. Thus, interpretations must

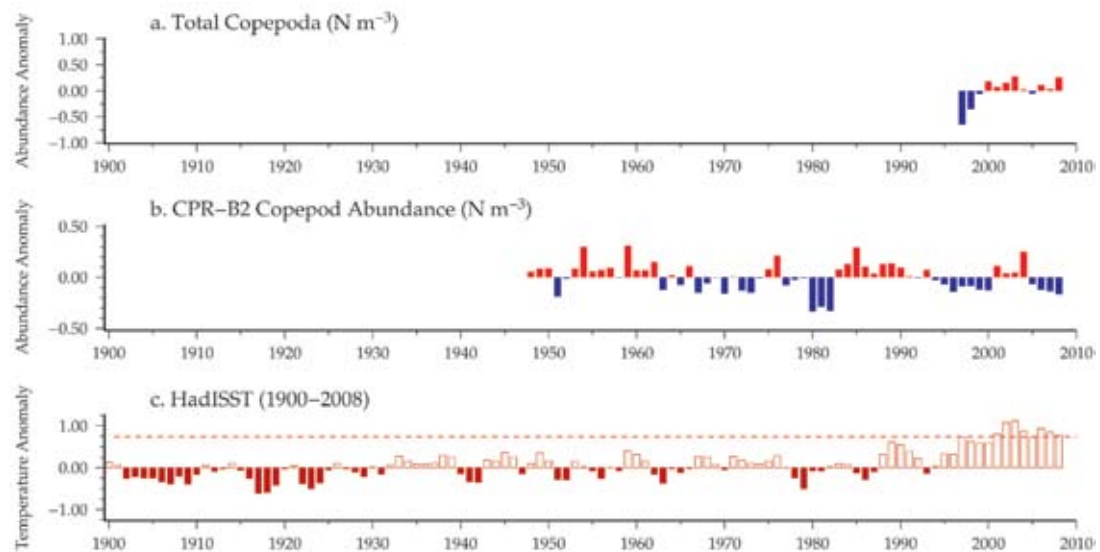
be done carefully and, in future, should employ more integrated and multidisciplinary approaches in order to increase our understanding of marine ecosystems.

Data from the Stonehaven site are regularly processed in a database of Marine Scotland Science (formerly Fisheries Research Services) at the Marine Laboratory Aberdeen (FRS MLA). Some of these data are available online at <http://www.frs-scotland.gov.uk/Delivery/standalone.aspx?contentid=1144>.



**Figure 6.10**  
Seasonal and interannual comparison of select co-sampled variables at Stonehaven (see Section 2.2.2 for an explanation of this figure).

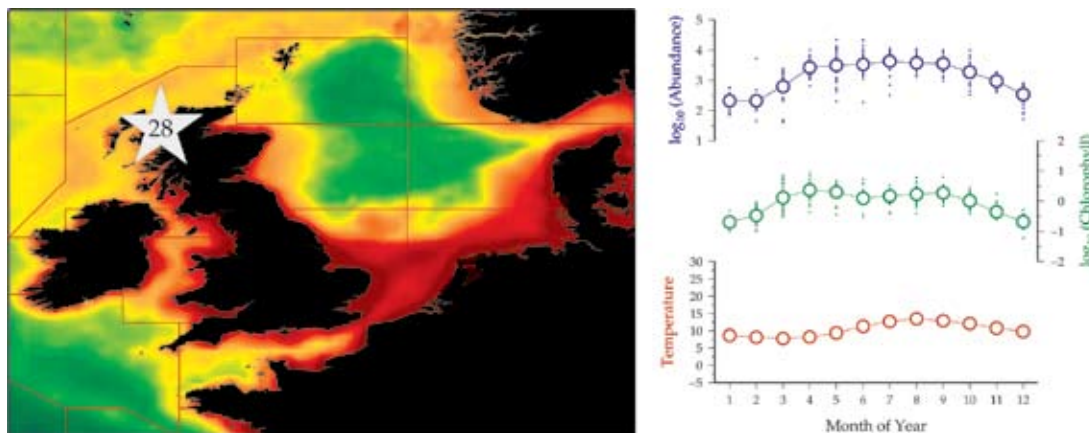
**Figure 6.11**  
Long-term comparison of Stonehaven copepod abundance with copepod abundance in CPR standard area B2 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).





## Site 28: Loch Ewe (northwest Scotland)

Steve Hay



**Figure 6.12**

Location of the Loch Ewe (Site 28) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Loch Ewe sampling site is located at 57°50.99'N 05°38.97'W (Figure 6.12) approximately 0.5 km offshore in a Scottish west-coast sea loch in a water depth of 35–40 m. To the north, the loch opens into the Scottish coastal sea basin of the North Minch and thence to the open eastern Atlantic. Sampling, which began in April 2002, is similar to that at the Stonehaven site and is also carried out by the Marine Scotland Science team from a local boat. Weekly sampling for surface and near-seabed temperature and salinity, and for concentrations of inorganic chemical nutrients, is carried out using water bottles and reversing digital thermometers. For chlorophyll, a Lund tube, integrating 0–10 m, is used. Phytoplankton samples are collected from the Lund tube and preserved in 2% Lugol's iodine in dark bottles.

Zooplankton are collected using a bongo net (40 cm diameter, 200 µm mesh), with flowmeter, in vertical tows from near-bottom to surface and preserved in 4% borax-buffered formaldehyde. Detailed taxonomic analysis is carried out on the mesozooplankton (>200 µm) and phytoplankton samples. Another pair of 40-cm bongo net samples is collected with a fine-mesh (68 µm) net. These fine-mesh samples are currently archived and not analysed, owing to the limited availability of trained staff.

Sampling at the site also supports a variety of time-limited research projects that study aspects of the coastal species or ecology in more detail. The time-series samples are collected consistently and at a relatively high frequency, affording insight into the seasonal dynamics and succession of plankton species throughout the annual cycle. This time-series dataset provides excellent background and

context for more-intensive or focused studies of individual species groups, ecosystem dynamics, rates, and processes. These data also support model development and validation, whereas comparisons with other monitoring sites assess and consider local variability relative to broader patterns of species ecology or ocean-climate change.

The objective of the time-series is to establish a monitoring base for assessing the status of the Scottish coastal ecosystem and gauging responses to climate change. Comparison of the results with other regional data on temperature, salinity, nutrients, and phytoplankton chlorophyll *a* indicates that the site provides a reliable index of the state of the coastal waters in northwest Scotland. The biological data illustrate the consistencies and the variability in seasonal life cycles of plankton species and their abundance. There are significant seasonal and interannual differences. Although this time-series so far is too short for full statistical analysis of interannual patterns, it already provides data on seasonality and can be compared with and contrasted to other longer-term monitoring data.

Most of the water column at the site is well mixed throughout much of the year. However, because it lies in a semi-enclosed sea loch, it is affected by river and land run-off, which is reflected in the surface water as lower salinities, particularly in autumn–winter, when freshwater inputs are high. In summer and early autumn, surface heating and calm weather cause temporary thermoclines to appear. The seasonal minimum temperature of ca. 8°C generally occurs in mid-March and rises to ~12–14°C in August–September (Figure 6.13c, left). The winter temperatures in the loch are generally ca. 1.5°C higher than in the exposed North Sea site

at Stonehaven on the Scottish east coast. It is also noticeable that the sea cools more slowly through autumn and winter in this semi-enclosed loch than at the Stonehaven site. Water movement in this fjordic loch is complex and strongly influenced by wind and tide. The loch faces north and has quite strong tidal currents, with variable exchange with the coastal sea of the North Minch.

The HadISST temperatures modelled for the area are broadly in agreement with field measures. This long time-series indicates that sea temperature in the wider area around the site has increased distinctly since the turn of the century (Figure 6.14c). The origins of the water that exchanges into the loch are not simply the Scottish Coastal Current waters that flow north along the Scottish west coast shelf. The North Minch, which the loch faces, is affected by influxes of oceanic Atlantic water from the northwest, particularly into the deeper basin. When strong, this influx may influence exchange between the loch and the adjacent coastal waters, varying the environment, sometimes quite suddenly, and thus affecting the composition of flora and fauna in the loch.

As at the temperate Stonehaven site, annual cycles are evident in all of the measured variables (Figure 6.13). A spring bloom of mesozooplankton in March–April, which includes many species groups (e.g. copepods, cladocerans, and appendicularians), as well as meroplankton, is increased throughout summer by a variety of predatory species, such as chaetognaths and cnidarians, which consume them and thus limit secondary production. This is sometimes followed by an autumn bloom of varying strength and then a general decline in species abundance as temperature, light, and phytoplankton growth fall through late autumn and winter.

Species such as the large copepod genus *Calanus* and euphausiids build up oil reserves or simply survive on whatever they find to eat through winter, whereas others rely on dormant eggs or resting stages. Some neritic copepods that are common in the loch, such as *Temora longicornis* and *Acartia clausi*, and cladocerans such as *Evadne nordmanni*, lay eggs that lie dormant on the seabed during winter and hatch when conditions improve in spring and summer. Other species, such as the copepods *Centropages typicus* and *Candacia armata*, and the planktonic mollusc *Limacina retroversa*, are not resident throughout winter, but are reseeded each year, carried by the circulation and influx of mixed coastal and oceanic waters from the north, and from areas south and west of Scotland. Patterns are broadly consistent, although the dynamics

of seasonal cycles vary between years for the environmental and species components of the ecosystem.

Several zooplankton species are of particular interest because they may be biomass-dominants or indicators of changing conditions. Some demonstrate wide variations in their annual abundance patterns. Generally, copepod abundance has remained fairly stable in the sea loch over the sampled years, in contrast to the pattern evident from the nearest offshore CPR data from CPR standard area C4, which demonstrates several years of decline in copepod abundance (Figure 6.14b). This contrast is also evident when comparing copepod numbers from the Stonehaven inshore site and from the wider sampling of the CPR in the North Sea. The diversity of species is higher on the west coast of Scotland, owing to the more direct influence of waters and communities of southern origin, and this is reflected in the samples from Loch Ewe, when compared with Stonehaven in the northern North Sea on the Scottish east coast.

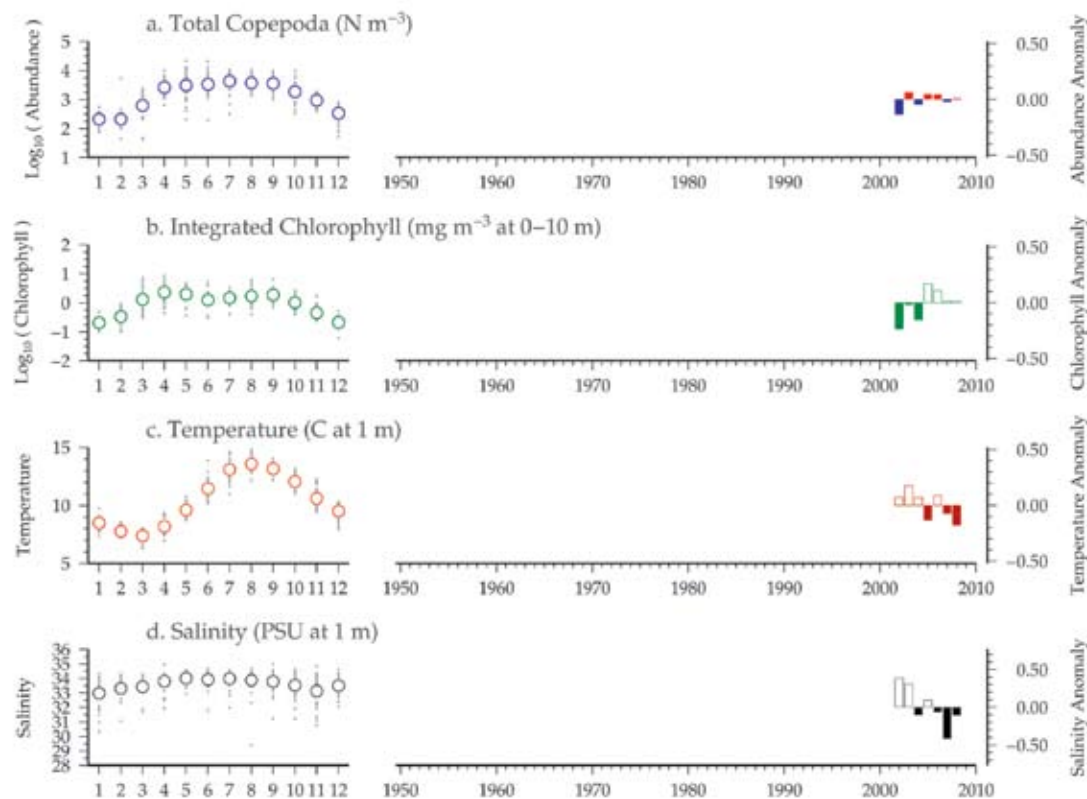
At Loch Ewe, as at Stonehaven, the important copepod genus *Calanus* is represented by two species: *C. finmarchicus* and *C. helgolandicus*. Most abundant in spring and summer, the arctic–boreal *C. finmarchicus* is an important species with a spring influx that arises from the winter diapause in deeper waters off the edge of the continental shelf. This species provides food for the region's many fish larvae in spring; however, there has been a 50-year decline in the abundance of *C. finmarchicus* in the region. *C. helgolandicus*, a more southerly species that does not diapause in winter and is generally most productive in summer and autumn, has demonstrated increased abundance and productivity in this region, becoming considerably more abundant than *C. finmarchicus* over the years. However, both *Calanus* species have demonstrated increased abundance over the past three years at both Stonehaven and Loch Ewe. The recent increase in winter survival of *C. helgolandicus* appears to have enhanced its spring abundance, leading to increased populations, whereas the spring influx and productivity of post-diapause *C. finmarchicus* also seems to have been greater in the past two years. It is also notable that anomalies in the interannual abundance of some plankton predators, such as the copepod genus *Oithona* and the arrow worms (*Chaetognatha*, *Sagitta*) that feed on copepods and their larvae, track the copepod seasonal abundance cycle and follow similar interannual patterns as their main prey. *Cnidarian medusae*, too, can be present in the loch in great abundance, with different species having different seasonal peaks

and adding to the predation pressure on the mesozooplankton, thereby affecting phytoplankton growth and dynamics. As in most coastal seas, and particularly evident in the semi-enclosed sea loch, the diverse larvae of benthic invertebrates are major components of the mesozooplankton biomass and are present throughout the year, with peaks in spring and autumn.

Another example is the copepod species *Eucalanus crassus*, which has been seen regularly in small numbers at Stonehaven since 2003, mainly in autumn, when it has also been found in Loch Ewe. A fairly common species southwest of the UK, it was very rare in Scotland's coastal waters. This

indicates an environmental change that now permits its survival in the area, most probably an increased influx and persistence of warmer Lusitanian waters throughout late summer and into winter. Catches of *Sagitta setosa*, also more common in southern UK seas, have also been taken in recent years, again mainly in autumn and early winter.

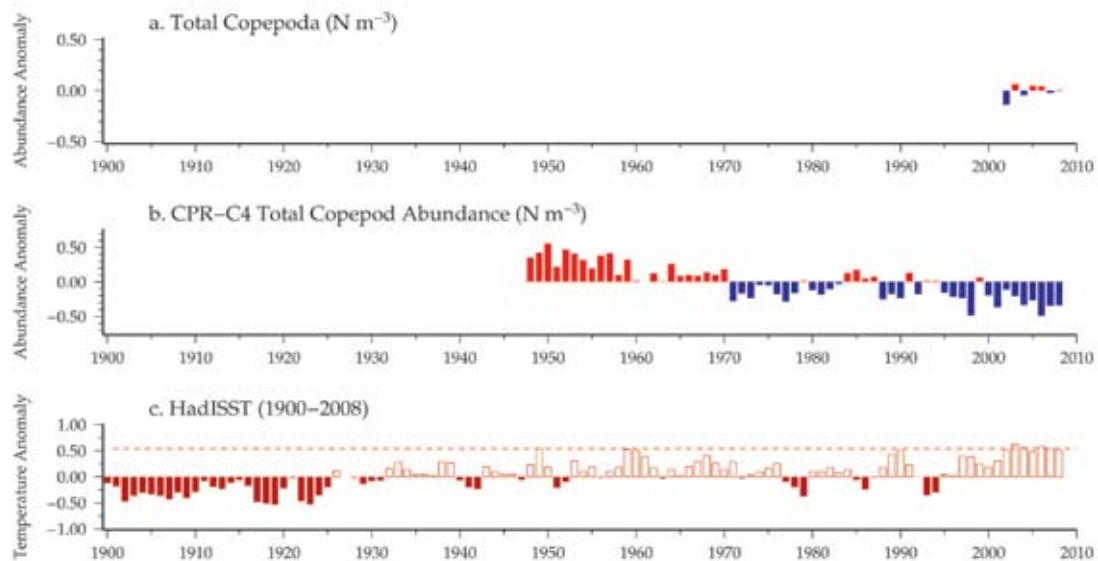
Data from the Loch Ewe site are regularly processed in a database of Marine Scotland Science (formerly Fisheries Research Services) at the Marine Laboratory Aberdeen (FRS MLA). Some of these data are available online at <http://www.frs-scotland.gov.uk/Delivery/standalone.aspx?contentid=1144>.



**Figure 6.13**  
Seasonal and interannual comparison of select co-sampled variables at Loch Ewe (see Section 2.2.2 for an explanation of this figure).

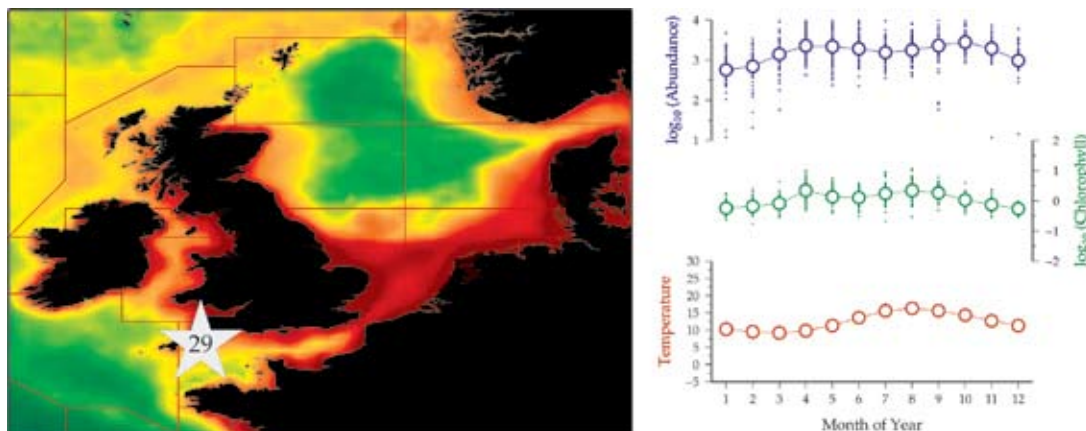
**Figure 6.14**

Long-term comparison of Loch Ewe copepod abundance with copepod abundance in CPR standard area C4 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



## Site 29: Plymouth L4 (English Channel)

Claudia Halsband-Lenk, Tim Smyth, and Roger Harris



**Figure 6.15**

Location of the Plymouth L4 (Site 29) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

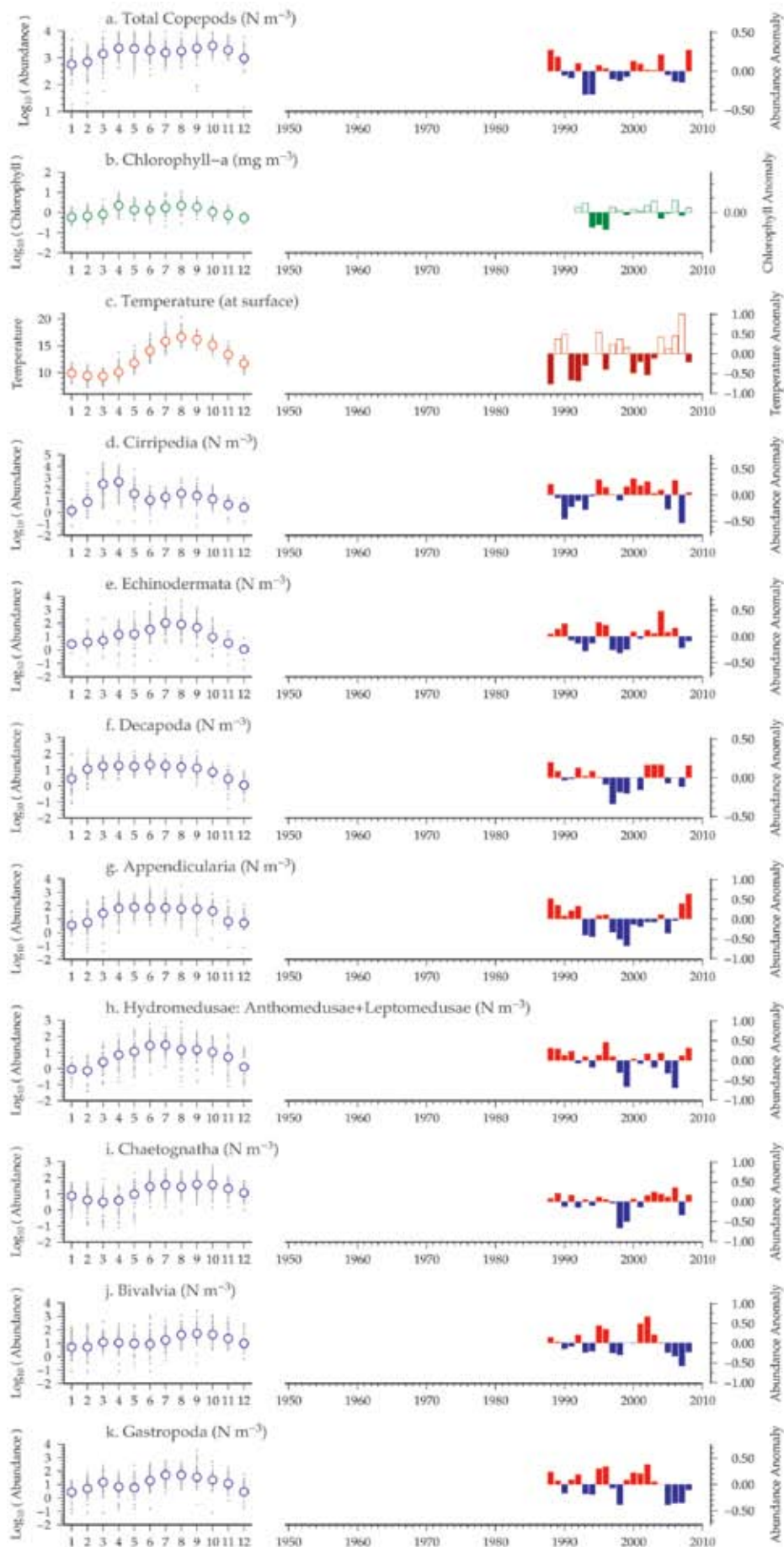
The zooplankton time-series at Plymouth Station L4 (50°15'N 4°13'W) in the western English Channel now spans more than 20 years (Harris, 2010). Weekly samples are taken ca. 16 km southwest of Plymouth (Figure 6.15), using a WP-2 net (56 cm diameter, 200 µm mesh) towed vertically from the seabed at ca. 50-m depth to the surface. The area around L4 is characterized by transitional mixed-stratified waters (Pingree and Griffiths, 1978). Zooplankton samples are split, and organisms are counted and identified to major taxonomic groups and families. For some groups, particularly copepods such as *Calanus helgolandicus*, organisms are identified to species level, partly with additional information on sex and life stages. The sea surface temperature (SST) has been measured using a mercury-in-glass thermometer immersed in an aluminium bucket of water collected at the surface. Since 1992, water samples collected from a depth of 10 m with a Niskin bottle have been analysed to determine abundance and to estimate carbon biomass of phytoplankton and microzooplankton. Organisms are counted and identified at genus or species level using inverted microscopy. At the same time, chlorophyll *a* triplicate measurements are made using a Turner fluorometer after filtering and extraction of sea surface water samples. Nutrient data (nitrate, nitrite, phosphate, and silicate) are also available from 2000 onwards. Since 2002, water-column profiles have been recorded with a conductivity-temperature-depth (CTD) instrument, providing temperature, salinity, and fluorescence data. All L4 data are maintained at the Plymouth Marine Laboratory and are available online at the Western Channel Observatory website (<http://www.westernchannelobservatory.org.uk/>).

In line with observations around the UK shelf seas, the western English Channel has warmed by 0.6°C per decade over the past 20 years. The greatest temperature rises followed a period of reduced windspeeds and enhanced surface solar irradiation in recent years (Smyth *et al.*, 2010). Set in this context, Station L4 is continually affected by the tide, which is associated with an interplay of regular estuarine outflow from Plymouth Sound and oceanic waters coming in with the dominating southwesterly winds. The water column is weakly stratified from mid-April to September and mixed during winter (Pingree and Griffiths, 1978); the minimum and maximum surface temperatures occur in March (9.1°C) and August (16.4°C), respectively. The seasonal cycle of the phytoplankton community is characterized by spring diatom and autumn dinoflagellate blooms, but there is high interannual variability in abundance and floristic composition (Widdicombe *et al.*, 2010). Since 1992, diatoms and *Phaeocystis* sp. have decreased, whereas coccolithophores reveal an increasing trend.

The seasonal cycle of zooplankton is characterized by a maximum peak in abundance in April, followed by a slight decrease until August, when the summer phytoplankton bloom leads to a second increase in zooplankton abundance (Figure 6.16a). Zooplankton abundance remains variable until October and is followed by a decrease in November–December; the lowest abundance occurs in January–February, which also corresponds to the lowest values in chlorophyll *a* and phytoplankton abundance (Figure 6.16b).



**Figure 6.16**  
Seasonal and interannual comparison of select co-sampled variables at Plymouth L4 (see Section 2.2.2 for an explanation of this figure).

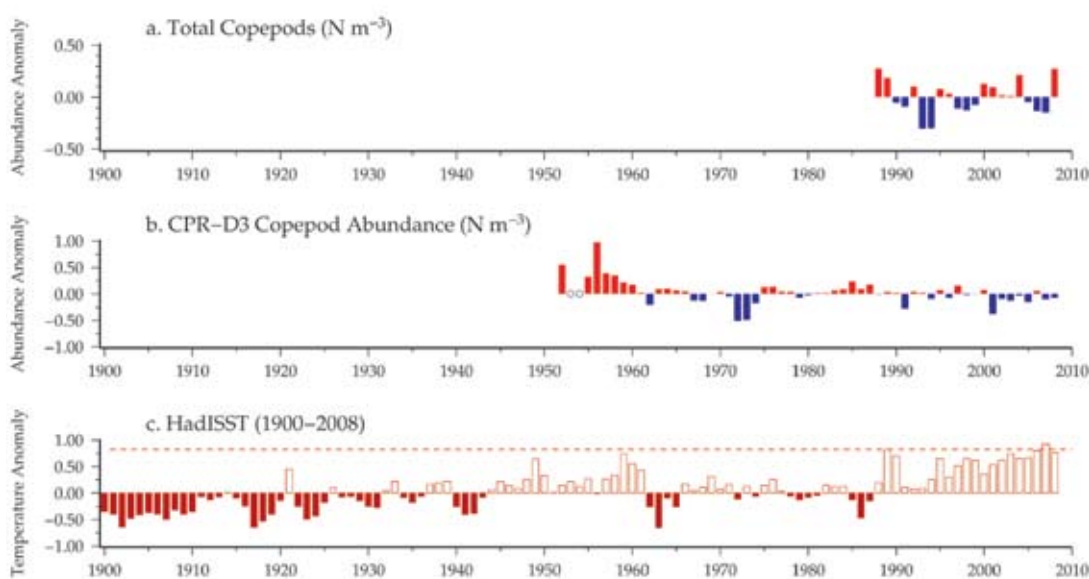


The mesozooplankton community at L4 is dominated by copepods, which represent 69–74% of the total zooplankton abundance and include the most abundant species in the top-ten ranking (Eloire *et al.*, 2010). Copepod abundance does not seem to be related to temperature or phytoplankton variations. Furthermore, zooplankton abundance observed at L4 is not synchronized with the CPR abundance observed for the corresponding area (Figure 6.17b), suggesting that Station L4 may be influenced by the nearshore and currents. Although correlations between phytoplankton and zooplankton components were generally not significant, it is possible that copepod abundance responds to phytoplankton abundance, with a 1- to 2-year time-lag. More detailed investigations of relationships between phyto- and zooplankton phenological patterns are needed to understand predator–prey relationships and their impact on abundance variability.

Meroplankton larvae play an important role at L4 in certain seasons. Cirripedes are abundant in March and April (Figure 6.16d) and can account for up to 42.5% of the total zooplankton community following spawning events linked to phytoplankton blooms (Highfield *et al.*, 2010). Echinoderms reach large numbers in July and August (Figure 6.16e), whereas lamellibranches peak in September and October (not shown). Little evidence was found for any major trends of change in the meroplankton community (at the taxonomic level examined) over the past 20 years.

Although the community composition seems to be stable, the interannual variation in zooplankton abundance is important but does not demonstrate any long-term trend. Nevertheless, periods with high abundance are observable, e.g. in the late 1980s and 2000–2004 (Figure 6.16a). The most recent year of the series, 2008, also demonstrates positive anomalies for copepods and other taxa (e.g. decapod larvae and appendicularians; Figure 6.16f and g). This enhanced food supply may have provided favourable conditions for planktonic predators. For example, *Sagitta setosa* is an important predator of *Calanus helgolandicus* at L4 (Bonnet *et al.*, 2010) and the abundance of medusae and chaetognaths was above average in 2008 (Figure 6.16h and i). In contrast, the abundance of larvae of benthic animals (echinoderms, bivalves, and gastropods) continued a negative trend (Figure 6.16e, j, and k).

The reversal of the negative trend in the abundance of copepods, and thus of overall zooplankton, in 2008 is paralleled by relatively cooler temperatures in the Plymouth L4 area and a slightly positive chlorophyll anomaly (Figure 6.16a–c). This result strengthens the hypothesis that high-temperature years correspond to below-average copepod abundance, a trend also seen in local CPR data (Figure 6.17b). Prior to 2008, the years 2005–2007 had been especially warm, with temperatures at or above any recorded in the past 100 years (Figure 6.17c, red dashed line).



**Figure 6.17**  
Long-term comparison of Plymouth L4 copepod abundance with copepod abundance in CPR standard area D3 and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## 7. ZOOPLANKTON OF THE NORTHWEST IBERIAN PENINSULA

*Juan Bueno, Angel Lopez-Urrutia, Carmen Rodriguez, Maite Alvarez-Ossorio, Antonio Bode, Ana Miranda, Antonina dos Santos, and A. Miguel P. Santos*

The oceanography of the north and northwest coasts of the Iberian peninsula fits the classical pattern of temperate seas, with a period of water-column stratification in summer and relatively strong mixing during winter. This region is an ideal ecological study area, owing to the gradient of environmental changes found from the Galician coasts to the inner Bay of Biscay. These gradual changes allow research into the effects of different ecological variables on the plankton community. An example of these environmental gradients is the influence of the upwelling events characteristic of the coasts of Portugal and Galicia during spring and summer. These events break the stratified upper layers of the water column, and their influence can be noticed along the Cantabrian Sea, with an eastward-decreasing intensity (Cabal *et al.*, 2008). Another important hydrographic element is the Iberian Poleward Current (IPC), north-flowing, warm saline water from the Portuguese continental

shelf, usually during December, which turns eastwards and follows the Galician coast to reach the Cantabrian Sea (González-Nuevo and Nogueira, 2005). Other important hydrographic features that affect the plankton community and dynamics are slope-water, oceanic, anticyclonic eddies (Isla *et al.*, 2004), and the subsurface front between the subtropical and subpolar modes of the Eastern North Atlantic Central Water (ENACW) off Cape Fisterra (Pérez *et al.*, 1993). The project RADIALES of the Instituto Español de Oceanografía (<http://www.seriestemporales-ieo.net>) was established in 1991 and conducts five monthly transects perpendicular to the coast along the north and northwest coasts of Spain.



**Figure 7.1**  
Locations of the northwest Iberian peninsula survey areas (Sites 30–34) plotted on a map of average chlorophyll a concentration (see Section 2.3.2).

The southwest region of the Iberian peninsula features many of the same hydrographic features described for the northwest Iberian coast, most notably upwelling events during spring and summer, with additional influences of buoyant river plumes (Peliz *et al.*, 2002). The seasonal plankton cycle in this region does not follow the classical pattern for temperate seas. The local pattern is transitional between the temperate and the tropical type, presenting fairly constant values almost year-round. The factors that contribute to this pattern are

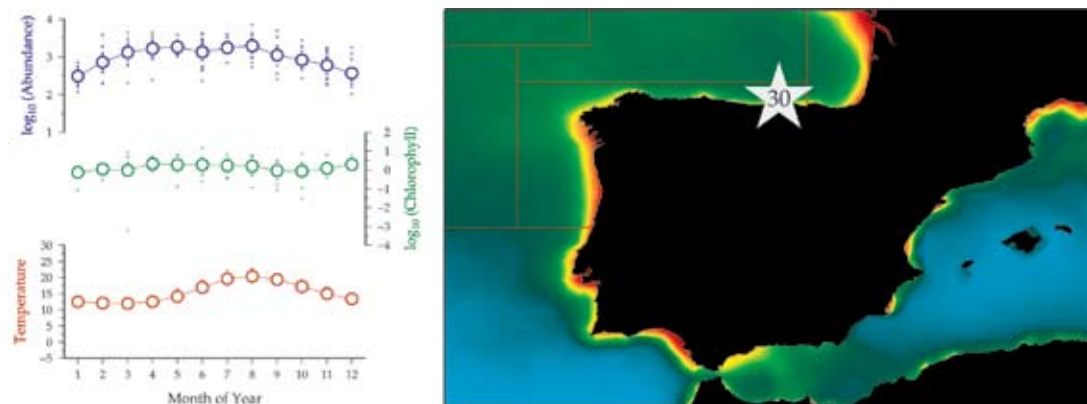
probably related to the location of the area, which is in an upwelling shadow (Moita *et al.*, 2003) that is considered to give some stability during upwelling-favourable winds, as well as being subject to the influence of the Tejo River estuary.

## Site 30: Santander transect (southern Bay of Biscay)

*Carmen Rodriguez*

**Figure 7.2**

Location of the Santander transect (Site 30) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



This monthly transect carried out off the coast of Santander (Figure 7.2) is part of the temporal dataserries project RADIALES (Instituto Español de Oceanografía; <http://www.seriestemporales-ieo.net>).

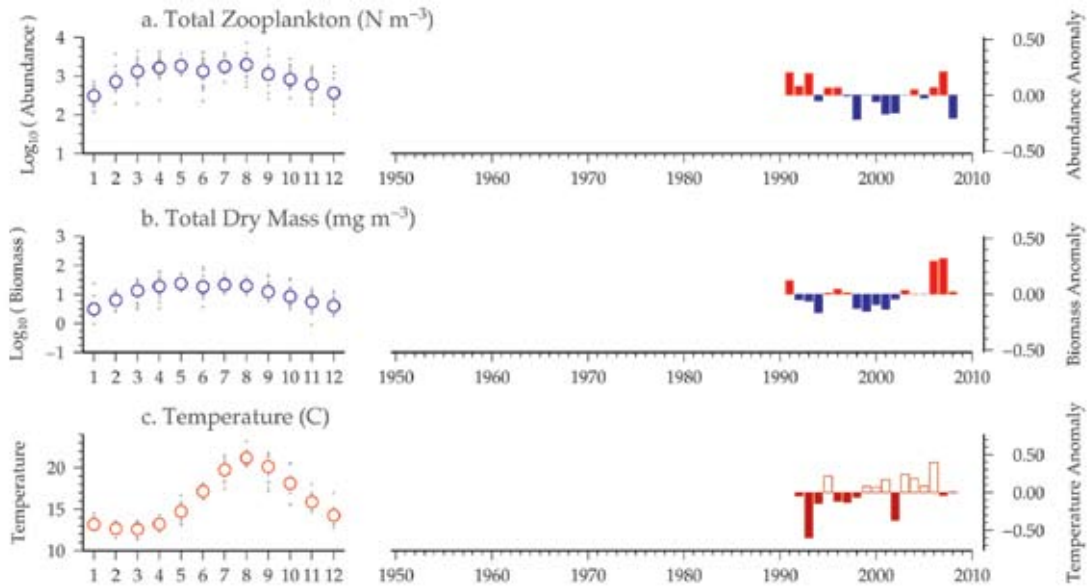
Since 1991, zooplankton samples have been collected at four stations, from 50 m to surface, in oblique hauls using a Juday–Bogorov net (50 cm diameter, 250  $\mu$ m mesh). Once on board, samples were preserved with 4% formalin in sodium borate-buffered seawater for analysis in the laboratory. To estimate total zooplankton biomass, samples were rinsed with 0.2  $\mu$ m filtered seawater, filtered onto pre-combusted (450°C, 24 h), pre-weighed Whatman GF/A filters, and dried at 60°C. After 24 h, total dry weight was measured with a Sartorius microbalance. The data used in this site report come from Station 4 of the transect (43°34.4'N 3°47.0'W).

At Santander, both zooplankton abundance and biomass demonstrate a yearly unimodal distribution, with a sustained high production between March and September, which suffers a slight drop in summer, suggesting the possibility of a bimodal cycle (Figure 7.3a and b). Although there is no clear trend in zooplankton abundance or biomass during the years of sampling at Santander, both variables have a low-frequency (5- to 6-year) interannual cycle. This cycle is also visible in the Continuous Plankton Recorder (CPR) copepod abundance data (Figure 7.4c) from the adjacent standard CPR standard area E4.

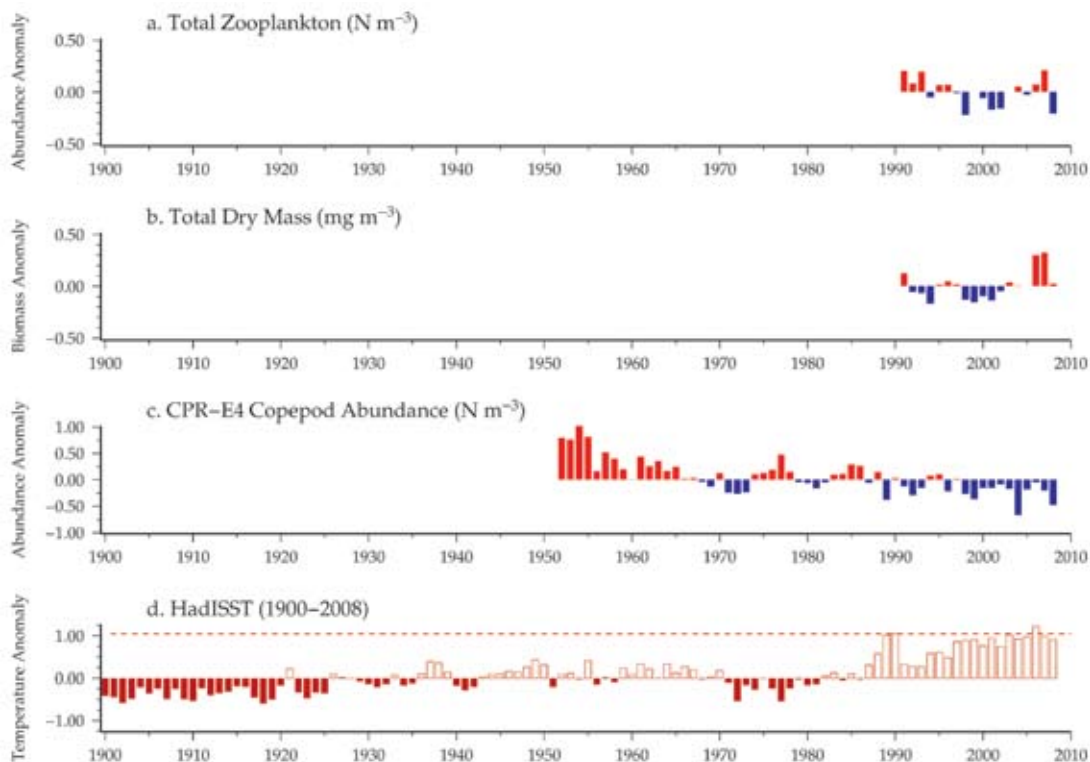
Sea surface temperatures (SST) during the period of the Santander survey (Figure 7.3c), and from the past 100 years (Figure 7.4d), demonstrate an unequivocal upward trend. In contrast, the CPR data for the region demonstrate a clear decreasing trend in copepod abundance over the past 50 years (Figure 7.4c). The Cantabrian Sea is typical of temperate-region oceans, with a summer-stratification–winter-mixing cycle. The onset and strength of the summer stratification, which are influenced by water temperatures, limit the influx of nutrients from deeper water to the surface and this, in turn, limits phytoplankton production. Lavin *et al.* (1998) reported an increasing trend in the stratification index for this region, to which the decreasing trend in zooplankton abundance was attributed by Valdés *et al.* (2007).

Over the last two decades, the increase in local water temperature, added to the transport from southern waters, has also been associated with the greater occurrence of warm-water-adapted species and a decrease in species typical of upwelling zones in the Cantabrian Sea (Bode *et al.*, 2009). Bode *et al.* (2010) found an upward trend in copepod abundance and diversity. In addition to temperature, other oceanographic features, such as intrusions of high-salinity water during mixing or small-scale coastal upwellings, have been reported as important determinants of the variability and the ecology of the planktonic community in the region (Huskin *et al.*, 2006).





**Figure 7.3**  
Seasonal and interannual comparison of select co-sampled variables at Santander (see Section 2.2.2 for an explanation of this figure).



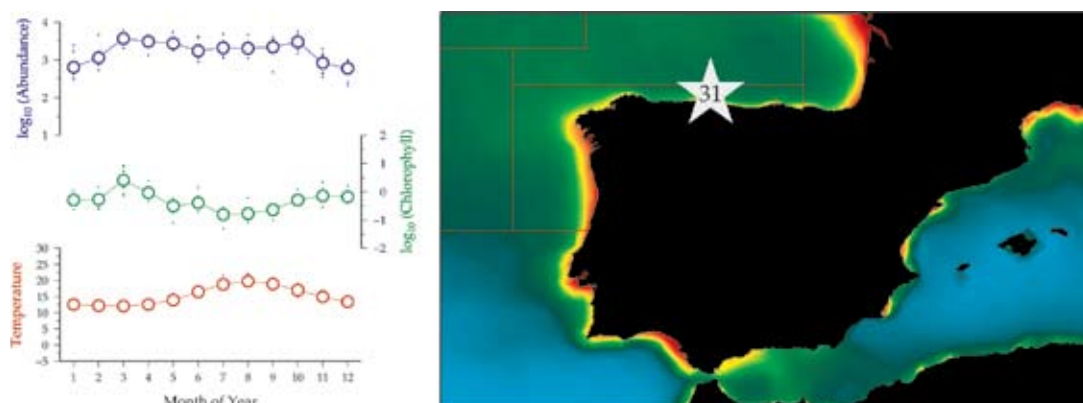
**Figure 7.4**  
Long-term comparison of Santander zooplankton abundance and total dry mass with CPR standard area E4 copepod abundance and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## Site 31: Gijón transect (southwestern Bay of Biscay)

*Angel Lopez-Urrutia*

**Figure 7.5**

Location of the Gijón transect (Site 31) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



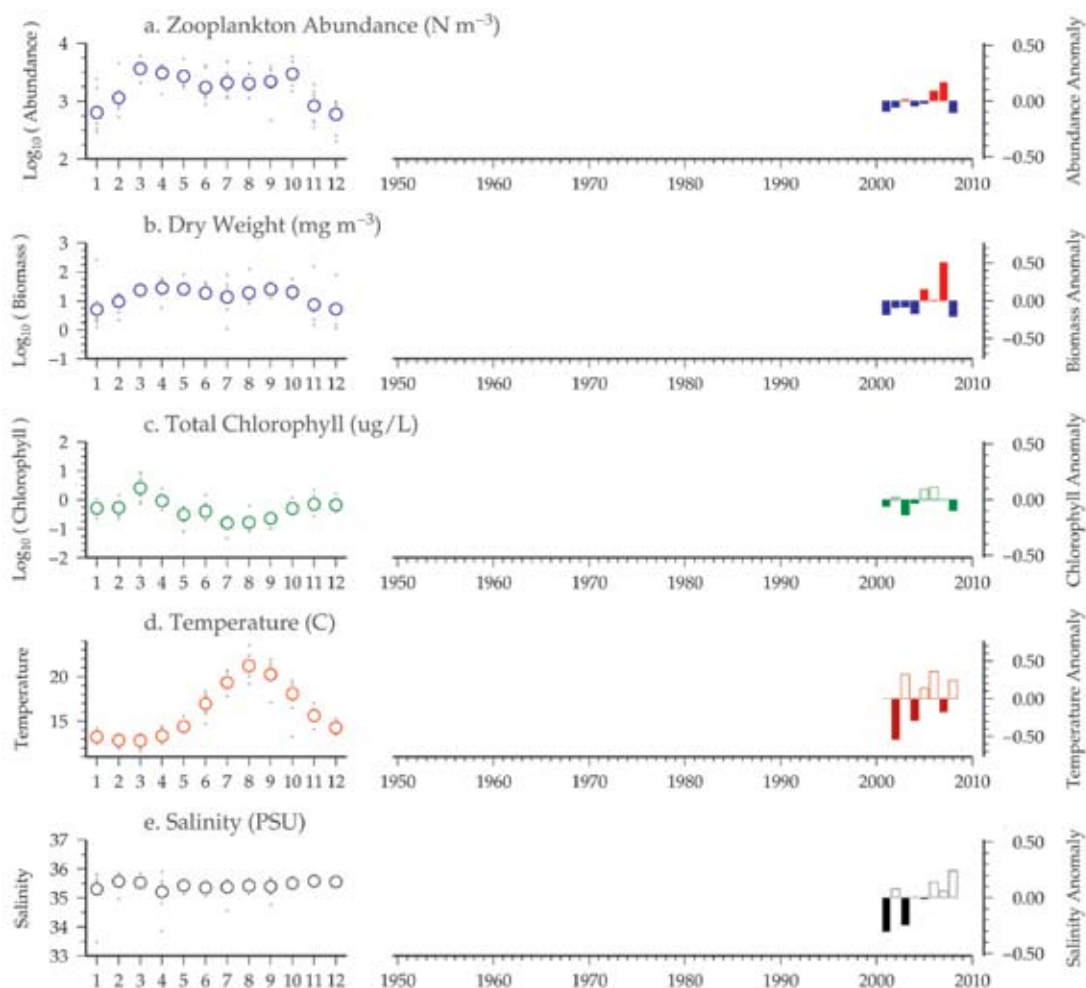
Gijón (Figure 7.5), where sampling started in 2001, is the latest station to be added to the temporal dataserie project RADIALES (Instituto Español de Oceanografía; <http://www.seriestemporales-ieo.net>). This monthly survey consists of three sampling stations, of which only Station 3 (43°46.7'N 5°30.3'W) data were used for this site summary.

Zooplankton samples were collected on board RV “José de Rioja” by means of vertical hauls from 100 m to the surface using a triple WP-2 net (38 cm diameter, 200 µm mesh) and then preserved with 4% formalin in sodium-borate-buffered seawater for posterior laboratory analysis. To estimate total zooplankton biomass, samples were divided into three size ranges (200–500 µm, 500–1000 µm, and >1000 µm) using sieve cups equipped with Nitex screens. The samples were rinsed with 0.2 µm filtered seawater, filtered onto pre-combusted (450°C, 24 h), pre-weighed Whatman GF/A filters, and dried at 60°C. After 24 hours, total dry weight is measured with a Sartorius microbalance.

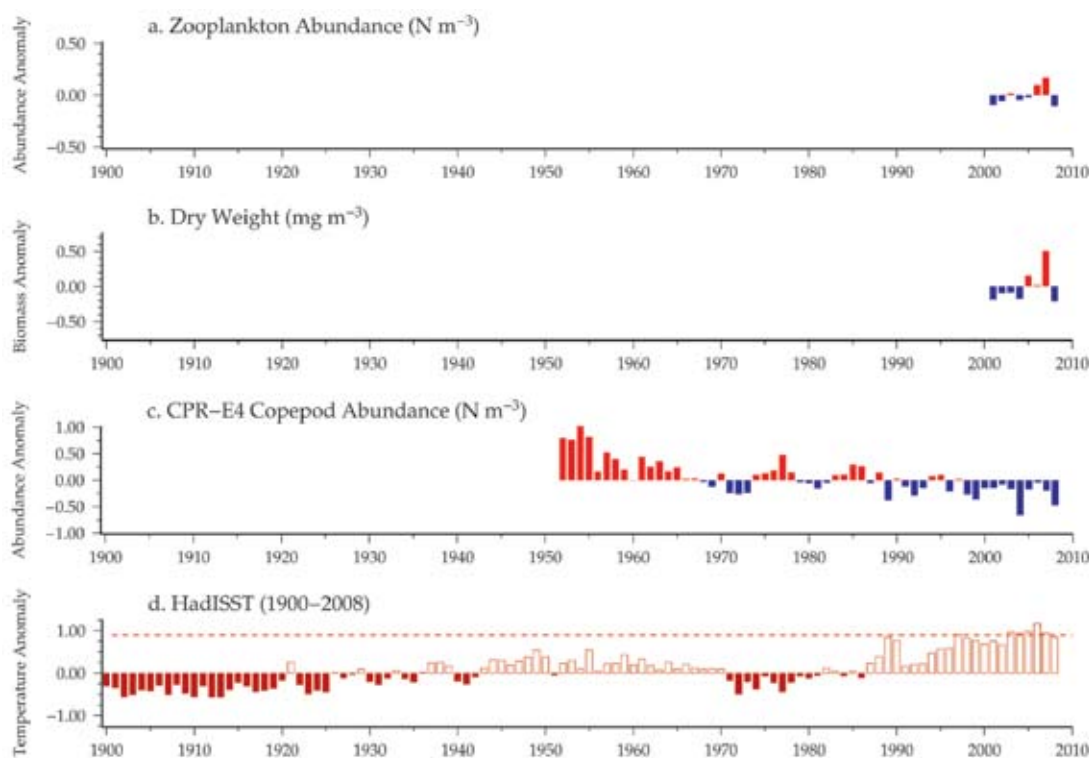
The hydrographic conditions in the northern Iberian coast demonstrate a marked seasonality, driven by the cycle of mixing–stratification that is characteristic of temperate seas. Additionally, other specific oceanographic structures influencing the planktonic dynamics can be found, such as the warm, saline IPC flowing east during winter along the Cantabrian continental shelf and slope, or the entrainment of waters from the subtropical (colder and saltier) and Subpolar gyres of the Northeast Atlantic.

Total zooplankton abundance demonstrates a bimodal distribution, in which spring (March–May) and autumn (September–October) peaks are separated by summer intermediate and winter low values (Figure 7.6a). The rise in both zooplankton abundance and dry weight is already apparent in February (Figure 7.6a and b), although abundance values peak a month earlier than biomass, coinciding with the chlorophyll maximum of March (Figure 7.6c).

Temperature and salinity have been steadily increasing off Gijón since the start of this time-series (Figure 7.6d and e). The increase in salinity may be the result of a generalized decrease in the pattern of rains on the Cantabrian coasts, diminishing the discharge of water from the coastal rivers, combined with the pattern of upwelling events in late autumn (Rodríguez *et al.*, 2009).



**Figure 7.6**  
Seasonal and interannual comparison of select co-sampled variables at Gijón (see Section 2.2.2 for an explanation of this figure).



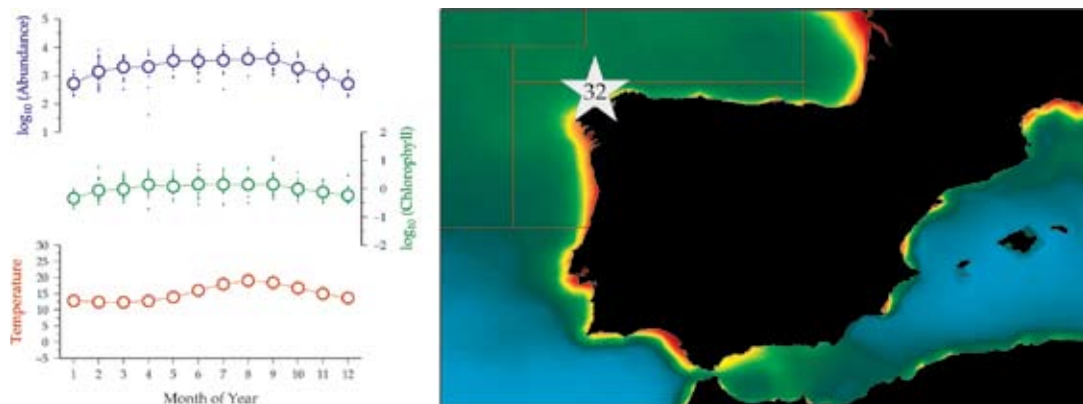
**Figure 7.7**  
Long-term comparison of Santander zooplankton abundance and dry weight with CPR standard area E4 copepod abundance and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## Site 32: The A Coruña transect (northwest Iberian peninsula)

*Maite Alvarez-Ossori and Antonio Bode*

**Figure 7.8**

Location of the A Coruña transect (Site 32) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



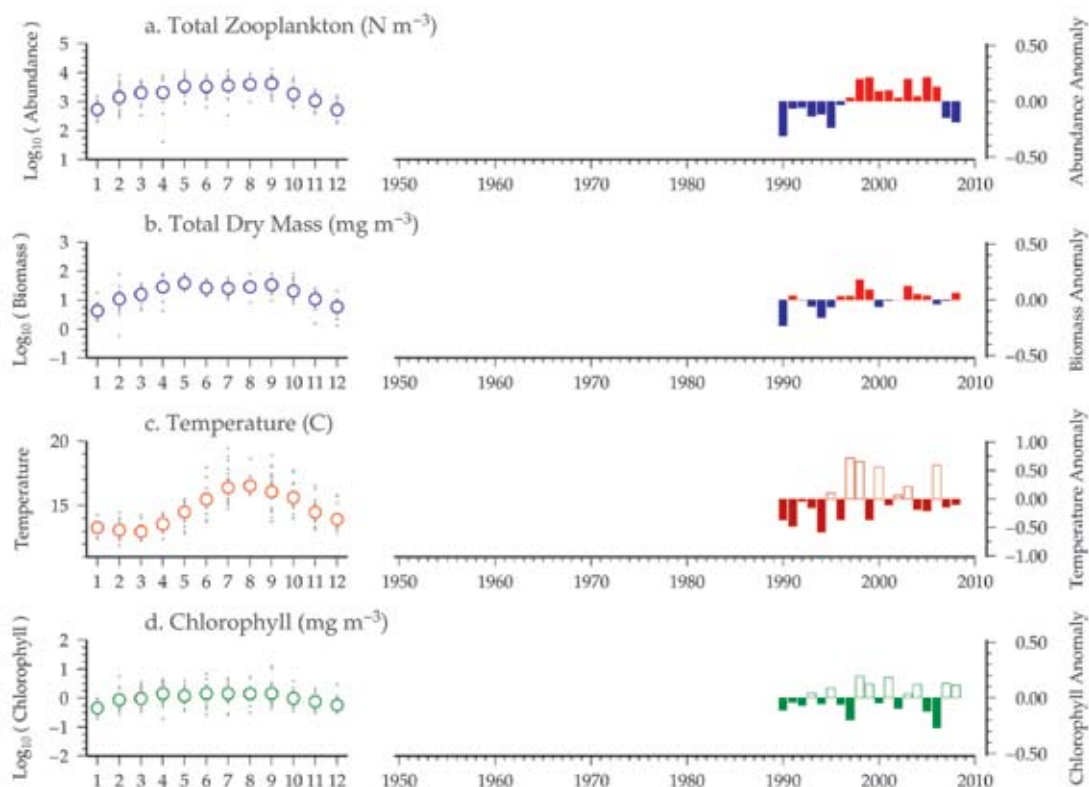
The A Coruña survey has been carried out since 1988 as part of the temporal dataserie project RADIALES (Instituto Español de Oceanografía; <http://www.seriestemporales-ieo.net>), and consists of a monthly transect off A Coruña (northwest Iberian peninsula; Figure 7.8).

Zooplankton samples were collected from 65 m to the surface in oblique hauls by means of a Juday–Bogorov net (50 cm diameter, 200 µm mesh). Once on board, the samples were preserved in 4% formalin sodium-borate-buffered seawater for analysis in the laboratory. To estimate total zooplankton biomass, samples were rinsed with 0.2 µm filtered seawater, filtered onto pre-combusted (450°C, 24 h), pre-weighed Whatman GF/A filters and dried at 60°C. After 24 hours, total dry weight was measured with a Sartorius microbalance. The data used in this site report come from Station 2 of the transect (43°25.3'N 8°26.2'W).

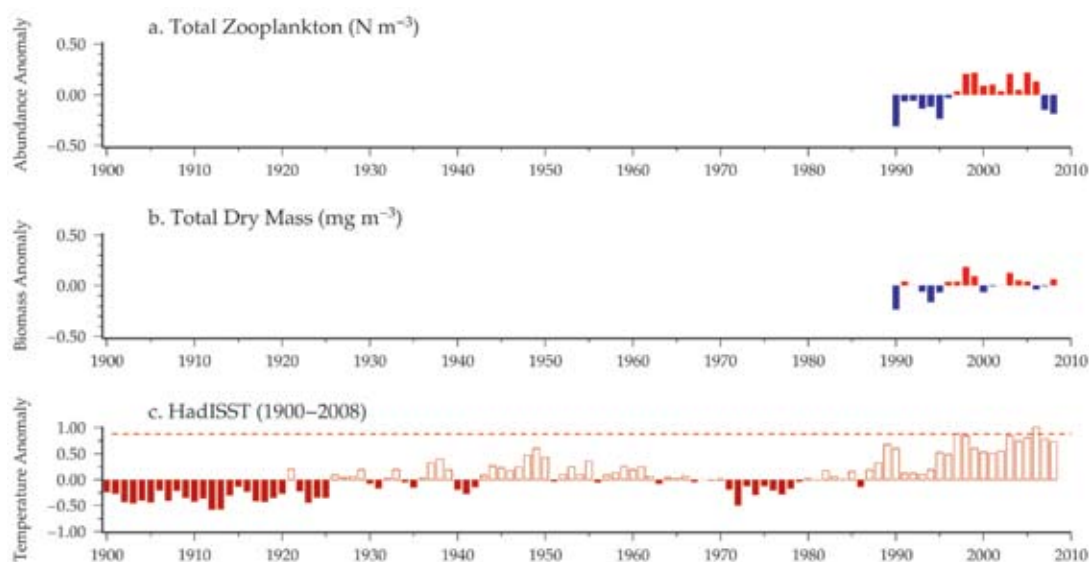
The hydrographic region off A Coruña, as well as the rest of the Atlantic coast of Galicia and Portugal, is characterized by the occurrence of upwelling events during spring and summer (May–September). These upwelling events break up the summer stratification of the water column, and the resulting influx of nutrients from deeper waters enhances plankton productivity during summer. This region is therefore generally more productive than other temperate seas, where strong summer stratification and nutrient limitations reduce productivity. The influence and occurrence of these upwelling events is apparent in the variability of the temperature and chlorophyll annual anomalies (Figure 7.9c and d).

The seasonal cycle of zooplankton abundance off A Coruña demonstrates a continued increasing pattern from February until September, with the lowest values in December and January (Figure 7.9a). The biomass pattern is similar, with two peaks in May and September and a slight drop from June to August that suggests a bimodal cycle (Figure 7.9b). Bode *et al.* (2009) discuss environmental factors that influence interannual variability in zooplankton production, most notably the intensity of the summer upwelling events.

There is a weak increasing trend in water temperature, driven mainly by the diminishing amplitude of the negative annual anomalies found since 1994 (Figure 7.9c). This temperature rise also agrees with the temporal dataserie of HadISST for the past 20 years (Figure 7.10c), which extends the increasing trend over the past 100 years. Current water temperatures are at or above the 100-year maximum for this region (Figure 7.10c, red dashed line).



**Figure 7.9**  
Seasonal and interannual comparison of select co-sampled variables at A Coruña (see Section 2.2.2 for an explanation of this figure).



**Figure 7.10**  
Long-term comparison of A Coruña zooplankton biomass and abundance with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

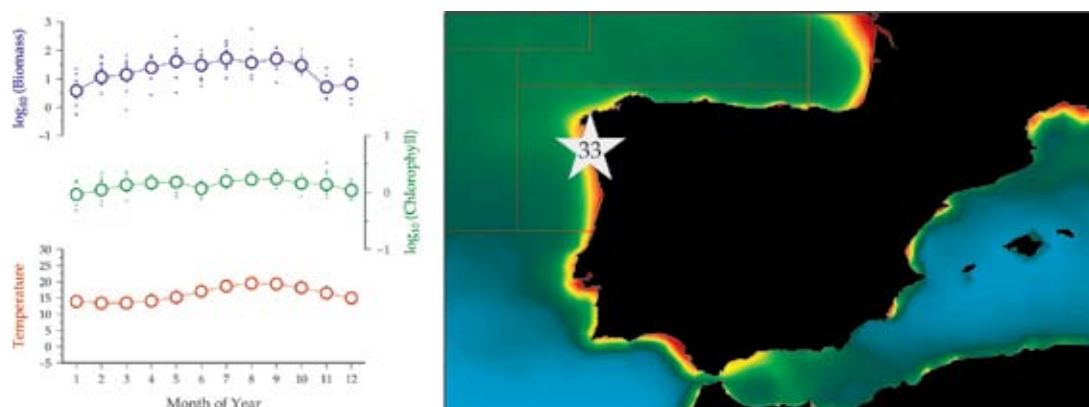


## Site 33: Vigo transect (west Iberian peninsula)

Ana Miranda

**Figure 7.11**

Location of the Vigo transect (Site 33) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



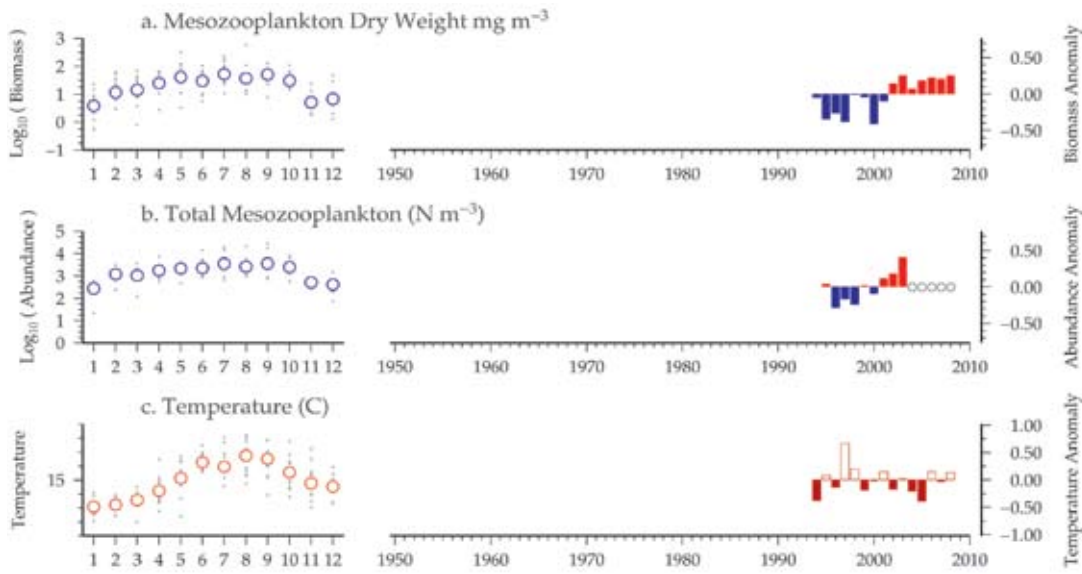
The Vigo transect has been sampled since 1994 as part of the time-series project RADIALES (Instituto Español de Oceanografía; <http://www.seriestemporales-ieo.net>). Station 3 of the Vigo transect, which was used for this summary, is located off the northwest Iberian coast (42°8.5'N 8°57.5'W; Figure 7.11) at a depth of 97 m.

Zooplankton samples were collected from near bottom to the surface (oblique hauls) on a monthly basis with a bongo net (40 cm diameter, 200 µm mesh). Once on board, samples were preserved in 4% formalin sodium-borate-buffered seawater and examined post-cruise at the laboratory for identification and counting of mesozooplankton. Biomass samples were frozen and quantified as dry weight (dried at 60°C for 24 h) post-cruise in the laboratory.

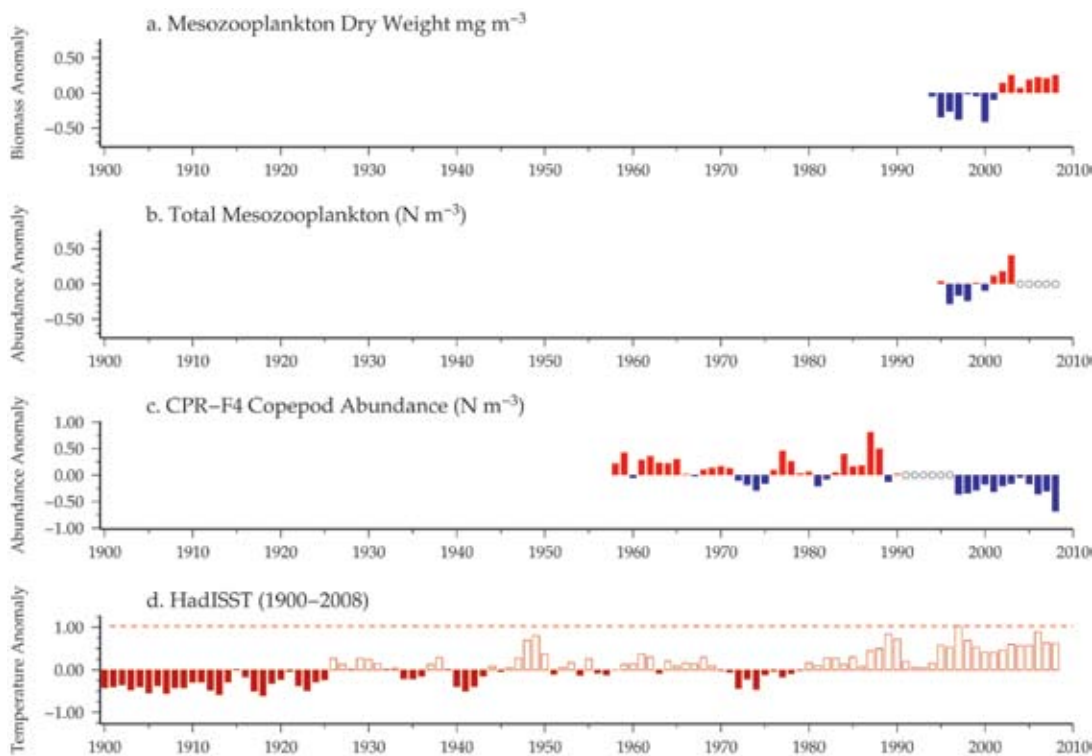
In the coastal region off Galicia (northwest Spain), the classic temperate pattern of seasonal stratification of the water column is masked by upwelling events from April to September. These upwelling events provide zooplankton populations with favourable conditions (influx of nutrients and phytoplankton production) in which to develop during summer, which is the opposite of what occurs in other temperate seas during this season. Nevertheless, upwelling is highly variable in intensity and frequency, with substantial year-to-year variability.

The seasonal cycle of zooplankton biomass is characterized by high values from April to October, with a slight reduction in June and August and a clear reduction in winter (Figure 7.12a and b). Interannual biomass anomalies reveal an increasing trend, although decreases in biomass were observed in 1997, 2000, and 2004. During these years, the monthly biomass was relatively low, but the decrease was not accompanied by a drop in abundance, which suggests an increased prevalence of small organisms during these periods. There are two copepod species typical of the warm Vigo waters: *Temora stylifera*, which typically dominates the zooplankton samples during warmer periods (e.g. 1997–1998 and 2001–2002); and *Oncaea mediterranea*, which used to be a fairly rare species, but has been increasing in abundance over the past few years.

*In situ* temperature at the site reveals no trend over the 15 years of the time-series (Figure 7.12c). To investigate longer-term trends of both temperature and zooplankton at the site, data were compared with long-term data from CPR and SST. Long-term temperatures in the region (Figure 7.13d) reveal an increase of almost 1°C in SST during the last half-century. The increase in zooplankton biomass recorded at Vigo during the past 15 years is not reflected in the period of below-average copepod abundance in CPR standard area F4.



**Figure 7.12**  
Seasonal and interannual comparison of select co-sampled variables at Vigo (see Section 2.2.2 for an explanation of this figure).



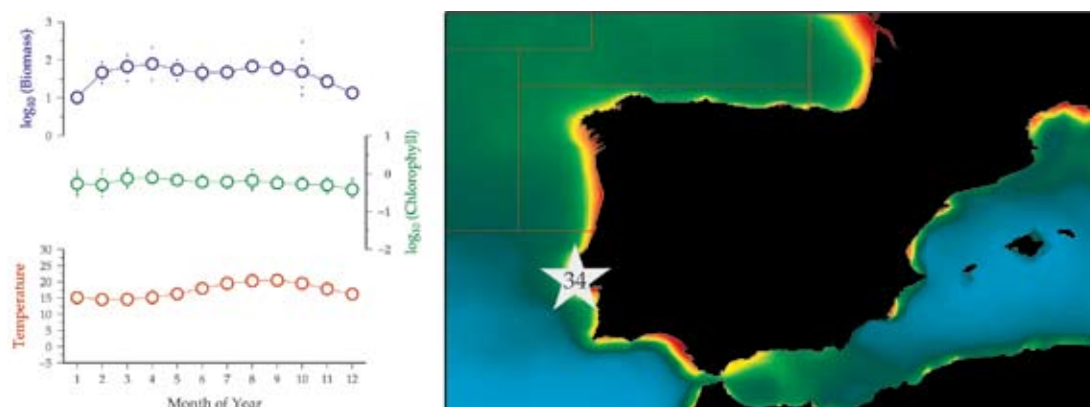
**Figure 7.13**  
Long-term comparison of Vigo zooplankton biomass and abundance with CPR standard area F4 copepod abundance and HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## Site 34: Cascais (southwest Iberian peninsula)

*Antonina dos Santos and A. Miguel P. Santos*

**Figure 7.14**

Location of Cascais (Site 34) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



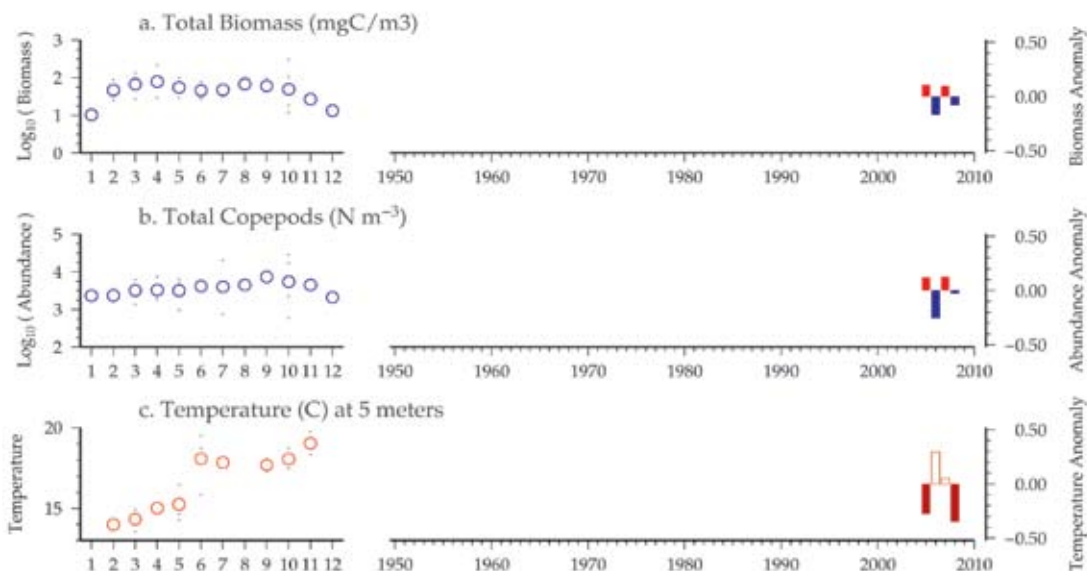
The Cascais monitoring site is a station of the time-series CASCAIS-WATCH, the oceanographic observation programme of the Oceanography and Plankton Group of the Instituto Nacional de Recursos Biológicos, Instituto de Investigação das Pescas e do Mar (INRB-IPIMAR). The station is located off Cascais Bay, outside the Tejo River estuary at 38°40'N 09°26.2'W (Figure 7.14).

Zooplankton samples were collected from 30 m to the surface (oblique hauls) on a monthly basis with a WP2 net (50 cm diameter, 200 µm mesh). Samples were divided into two with a Folsom plankton splitter: one half was preserved in 4% borax-buffered formaldehyde in seawater and later examined for identification and counting of mesozooplankton, and the other half was lyophilized and weighed for biomass determination.

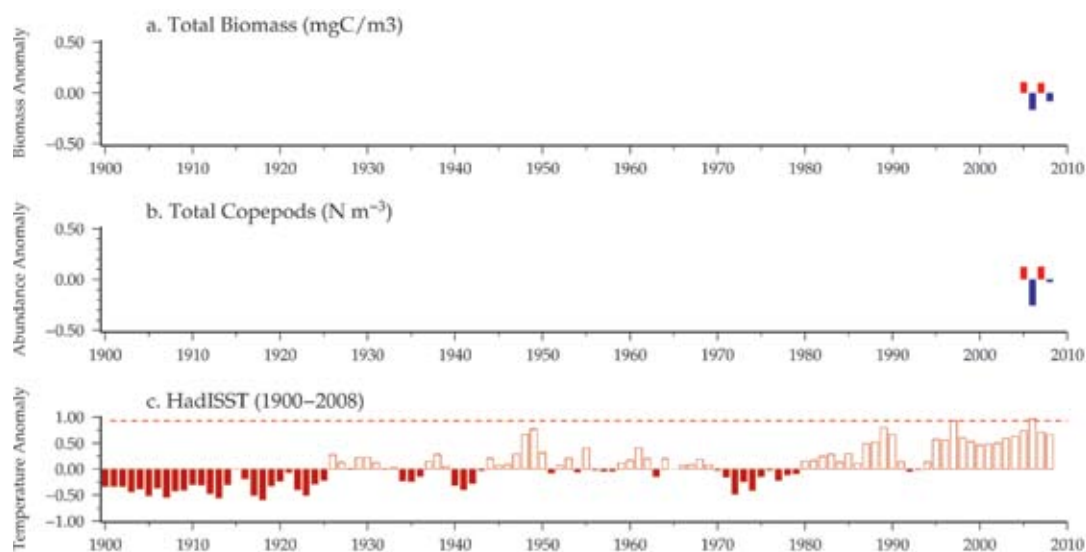
The short length of this time-series limits its interannual analysis. The seasonal cycle of zooplankton biomass is characterized by a bimodal pattern, with peak biomass in April and August (Figure 7.15a). Copepod abundance remains high throughout the season, with highest abundance from August through November (Figure 7.15b). Copepods at Cascais are mainly represented by the genera *Acartia*, *Paracalanus*, *Oncaea*, and *Oithona*. Other species (*Temora stylifera*, *T. longicornis*, and *Centropages* spp.) are also important but occur later in the season, which explains the high copepod abundance late in the year.

The Cascais site is thought to be under the influence of the Eastern North Atlantic Upwelling System in spring and summer. This seasonal upwelling is responsible for the high phytoplankton production that promotes the stable zooplankton abundance through the year (Santos *et al.*, 2007). *In situ* temperatures at Cascais demonstrate a two-tier seasonal pattern, usually below 16°C during winter and spring, and at or above 18°C in June–November (Figure 7.15c). This pattern is attributed to the station being located in an upwelling shadow (Moita *et al.*, 2003), where winds favourable to upwelling can promote local water stratification and stability.

The long-term temperature record for this region demonstrates that SSTs are currently at the high end of those seen in the past 100 years (Figure 7.16). Although the Cascais site is located just south of the CPR standard area F4, CPR copepod abundance has been consistently decreasing just north of Cascais and along the entire northwest Iberian peninsula (see Santander, Site 30, Figure 7.4c; Vigo, Site 33, Figure 7.13c), whereas temperatures have been consistently at the high end of their 100-year record (Santander, Site 30, Figure 7.4d; Vigo, Site 33, Figure 7.13d; and this site, Figure 7.16c).



**Figure 7.15**  
Seasonal and interannual comparison of select co-sampled variables at Cascais (see Section 2.2.2 for an explanation of this figure).



**Figure 7.16**  
Long-term comparison of Cascais zooplankton biomass and total copepods with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).

## 8. ZOOPLANKTON OF THE MEDITERRANEAN SEA

*Delphine Bonnet, Lidia Yebra, Serena Fonda-Umani, Gabriel Gorsky, Maria Grazia Mazzocchi, Maria Luz Fernández de Puellas, Ioanna Siokou-Frangou, Lars Stemann, Olja Vidjak, and Soultana Zervoudaki*

In contrast to the North Atlantic, which has several highly productive sea areas around its continental shelf margins, the Mediterranean Sea is oligotrophic, similar to the subtropical central North Atlantic. The seasonal cycles of primary and secondary production are more or less similar for both regions, driven by physical processes that affect the stability of the upper layers of the water column and the supply of nutrients from the deeper layers into the photic zone.

Most zooplankton species present in the Mediterranean Sea are of Atlantic origin. Both the North Atlantic and the Mediterranean Sea have deep oceanic basins that serve as overwintering sites for ontogenetically migrating zooplankton. Dominant species are common in both areas at the same latitude in the epi- and mesopelagic layers, whereas the bathypelagic species of the North Atlantic are excluded in the Mediterranean Sea by the Strait of Gibraltar sill. Interestingly, marginal seas of the North Atlantic and the Mediterranean Sea, such as the Baltic and Black seas, have common characteristics (low salinity, anoxic bottom layer, high productivity) and all face strong challenges to local ecology from exotic/introduced species. The larger shelf seas, such as the North Sea and shelf regions of the Mediterranean, are also not immune.





**Figure 8.1**  
Locations of Mediterranean survey areas (Sites 35–40) plotted on a map of average chlorophyll concentration (see Section 2.3.2).

Although several studies have demonstrated that the large climatic signals, such as the North Atlantic Oscillation (NAO), could affect the zooplankton communities and structures in the western Mediterranean Sea (Molinero *et al.*, 2005), the specific nature of this basin is probably reflected in its capacity to allow alien-species development. This basin is a converging point of different water masses (Atlantic Ocean, Red Sea, Black Sea) and it is a very active place for commercial transport (ballast-water transport and release). The number of alien species in European waters is increasing at the rate of one introduction every nine days, with 8% being zooplankton (Zenetos *et al.*, 2008). However, small invertebrate species such as copepods, although critical components of marine ecosystems, are rarely listed in invasive-species databases (Zenetos *et al.*, 2006, 2008). Therefore, the continued monitoring of coastal waters in the Mediterranean basin is of primary importance from both economic and ecological points of view.

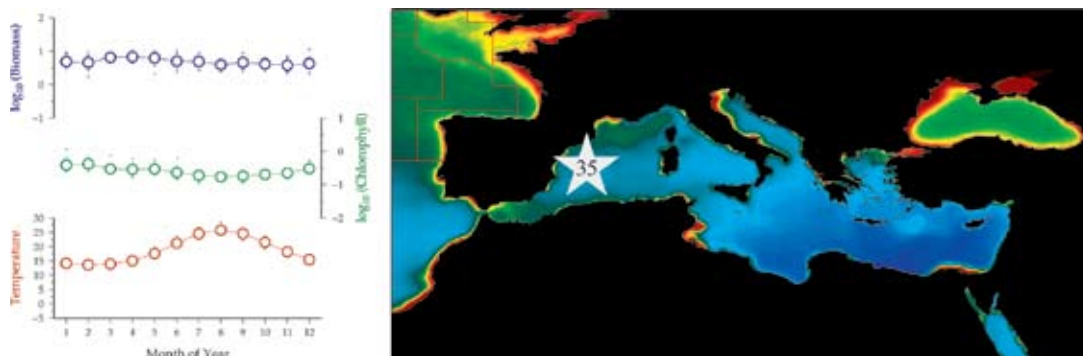
Several research programmes have recently focused on the expansion and blooms of gelatinous plankton that have exhibited marked economic impacts, especially the ctenophore *Mnemiopsis leidyi*, which is now established in the Mediterranean, and some cnidarians (e.g. the scyphozoan jellyfish *Pelagia noctiluca* and *Chrysaora* spp.). Studies such as those of Molinero *et al.* (2005) note that warmer water temperatures (and subsequent water-column stability) tend to favour higher jellyfish abundance. This is a growing concern, considering that the long-term temperature records for all six of the Mediterranean zooplankton sites are near to and often above the 100-year SST averages in each of their respective areas.

## Site 35: Balears Station (Balearic Sea)

*Maria Luz Fernández de Puelles*

**Figure 8.2**

Location of the Balears Station (Site 35) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



The Balearic sampling site is located southwest of the island of Mallorca at 39°29'N 2°25'W, with a bottom depth of 77 m (Figure 8.2). Starting in 1994, the station was sampled every ten days until December 2005, after which it was sampled seasonally only four times a year. Zooplankton was sampled by means of oblique hauls from a depth of 75 m to the surface with a bongo net (40 cm diameter, 250 µm mesh). A full description of the methodology is given in Fernández de Puelles and Molinero (2007).

The Balearic Sea is characterized by complex mesoscale features resulting from the interaction between the saline and colder northern waters of the western Mediterranean and the southern, less saline, and warmer water from the Alboran Sea. This ecologically important region encompasses major spawning areas of pelagic fish, possibly owing to an “island stirring” effect that may produce concentrated plankton biomass around the islands. Overall, the annual circulation pattern consists of cool, south-flowing waters of northern origin during the first part of the year, changing to warm, north-flowing waters of Atlantic origin in the second part. Circulation within the region becomes very complex because of the permanent mesoscale activity and the north Balearic front (Pinot *et al.*, 2002). Depending on the influence of these structures, the region can undergo mixing or incursions of different water masses, forming frontal systems or eddies that drive the planktonic community dynamics (Fernandez de Puelles *et al.*, 2009).

Chlorophyll concentrations are highest from December through February (Figure 8.2), before the onset of warmer water temperatures and

stratification. Seasonal temperature cycles indicate a mixing period during colder months and a stratification period from June to October (Figure 8.3d). Mean surface water temperatures have a seasonal difference of up to 14°C, with a winter minimum of ca. 13°C and a summer maximum as high as 27°C. At a depth of 75 m, this seasonal difference is only 3°C: from 13°C (in March) to 16°C (in October). In general, this area has low nutrient concentrations and low primary production because of the development of the thermocline, which acts as a barrier to the supply of nutrients to the photic layer.

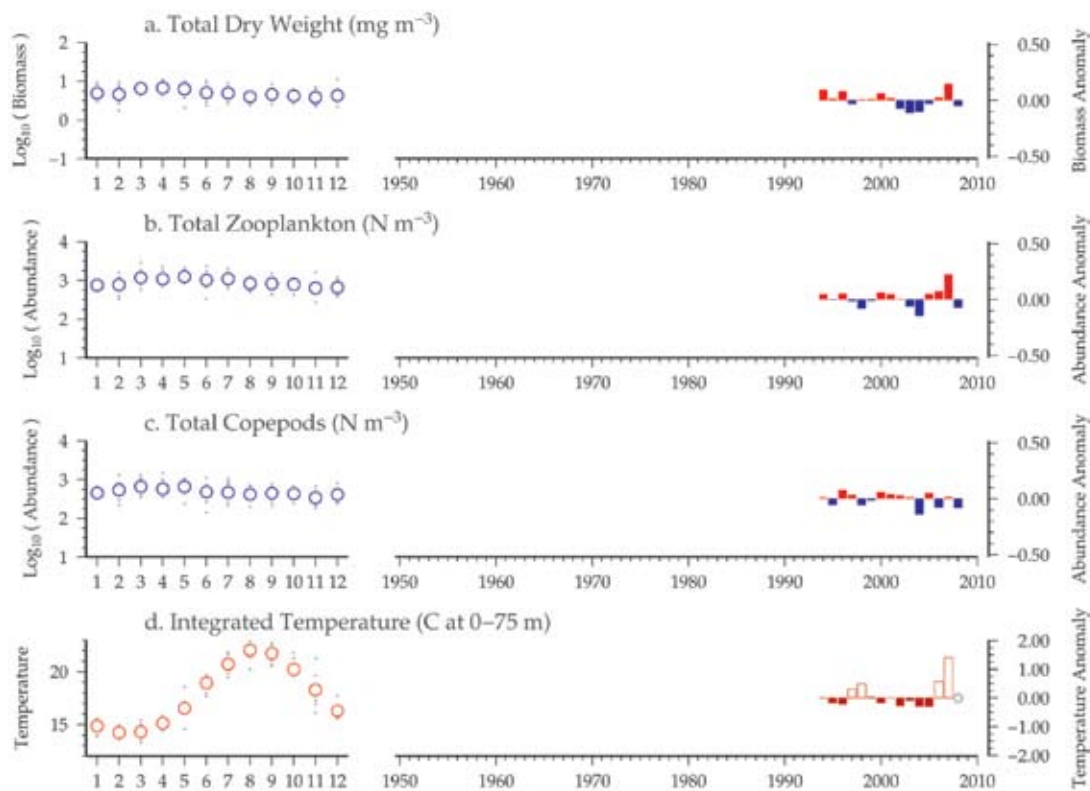
Zooplankton biomass (total dry weight; Figure 8.3a) demonstrates a seasonal pattern, with higher mean biomass in the first half of the year (maximum in April) and lower biomass in the second half of the year (minimum in August). The Balearic area is characterized by the presence of relatively small organisms. Large gelatinous zooplankton did not appear in great quantities in the samples. The zooplankton peak in March was related to a period of vertical mixing, when the cold, dense, nutrient-rich waters reach the surface, a widespread event in the Mediterranean. This early-spring zooplankton maximum seems to occur yearly in response to the previous winter phytoplankton bloom. During spring, when the thermocline is developing, the inputs of offshore waters and the proximity of frontal systems usually enhance the zooplankton abundance.

Copepods (Figure 8.3c) were the most abundant and perennial group in the zooplankton samples (56% of the total). Other important groups were gelatinous zooplankton (23%, consisting primarily of 17% appendicularians, 5% doliolids, and 1%

salps), cladocerans (10%), and meroplankton (4%). Nevertheless, siphonophores (3%), chaetognaths (2%), ostracods (1%), and pteropods (1%) were also found in the area. More than 80 copepod species were identified during the entire study period, of which ten accounted for 60% of the total. The group of *Clausocalanus* was the most abundant (*C. arcuicornis*, *C. furcatus*, *C. pergens*, and *C. paululus*; 27%), followed by *Oithona* spp. (25%). Some species had very low abundance during short periods, such as *Calanus helgolandicus* in winter or *Acartia danae* in late summer.

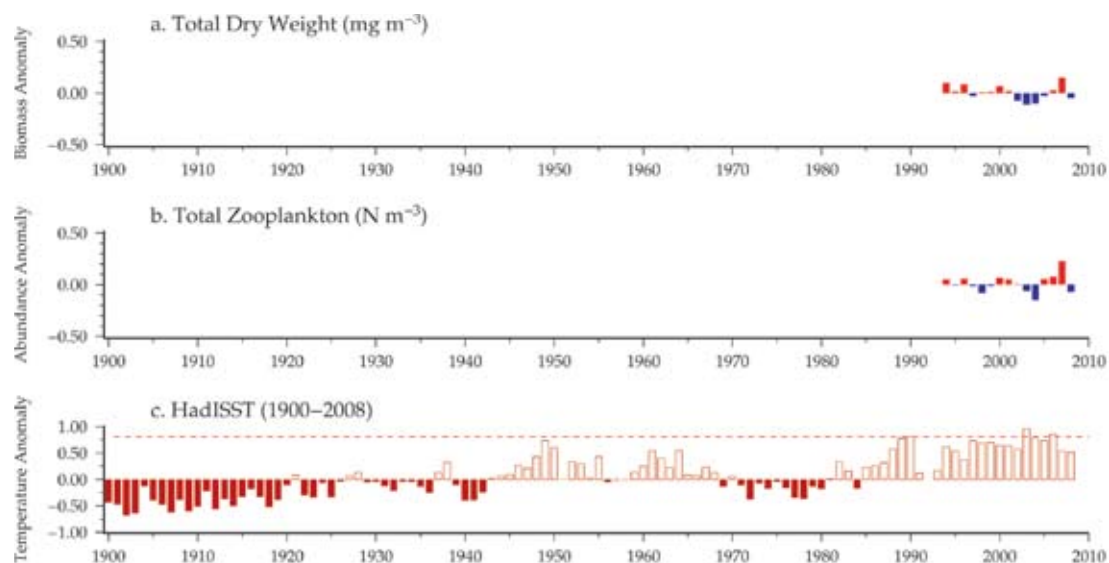
The SSTs in the region have been above the 100-year average since 1985 and, since 2000, have often

been the warmest seen in the region for the past 100 years (Figure 8.4c). Although no significant zooplankton biomass decrease was observed during this time-series, a correlation of copepods with temperature (negative) and salinity (positive) indicated their direct relation to the presence of the different surface water masses; when colder and saltier Mediterranean waters prevailed in the area, higher zooplankton biomass values were observed. Factors other than temperature and salinity could contribute to the plankton pattern observed, but the recognition of large-scale dependence on the physical environment is a first and necessary step to understanding zooplankton distribution in the western Mediterranean.



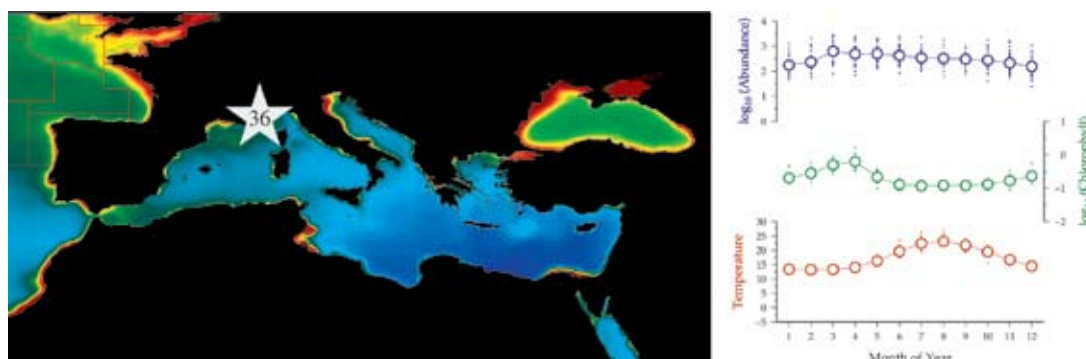
**Figure 8.3**  
Seasonal and interannual comparison of select co-sampled variables at Balears Station (see Section 2.2.2 for an explanation of this figure).

**Figure 8.4**  
Long-term comparison of Balears Station zooplankton with HadISST sea surface temperatures for the region (see Section 2.2.3 for an explanation of this figure).



## Site 36: Villefranche Point B (Côte d'Azur)

Lars Stemann, Gabriel Gorsky, and Franck Prejger

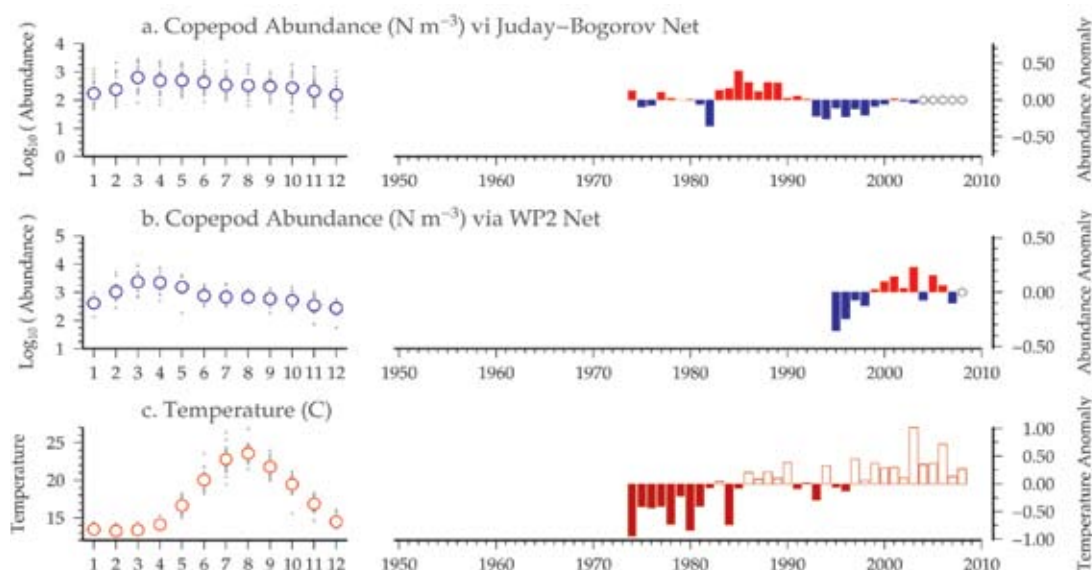


**Figure 8.5**  
Location of the Villefranche Point B (Site 36) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Villefranche Point B dataset consists of more than 30 years of samples collected off Villefranche at 43°41'N 07°19'E (Figure 8.5). Samples were collected by a vertical tow from bottom to surface (75–0 m), using a Juday–Bogorov net (330  $\mu$ m mesh; Figure 8.6a) from 1966 to 2003, a Regent net from 1966 to 2010 (690  $\mu$ m mesh), and a WP-2 net from 1995 to 2010 (56 cm diameter, 200  $\mu$ m mesh; Figure 8.6b). Sample processing is still underway, so not all years were available for this report. Here, we report copepod abundance using Juday–Bogorov and WP-2 nets, counted using the wet-bed image scanning technique of ZooScan (Grosjean *et al.*, 2004) and a semi-automatic recognition method (Gorsky *et al.*, 2010). Zooplankton sample analysis

is performed by the RADEZOO service at the Oceanologic Observatory of Villefranche-sur-Mer. Only total copepod abundance is reported here. Other taxa are counted. A complete list of taxa is available online at <http://www.obs-vlfr.fr/Rade/RadeZoo/RadZoo/Accueil.html>.

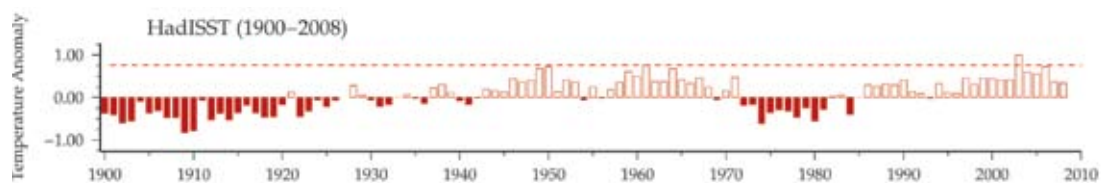
Copepod abundance tends to be highest during years when cold and saline surface waters lead to strong convection, such as occurred in the 1980s and early 2000s (Figure 8.5 and 8.6a and b), and decline during warmer, low-salinity periods, which prevents the success of winter convection. The SSTs in the region have been warmer than the 100-year, long-term average since 1985 (Figure 8.7).



**Figure 8.6**  
Seasonal and interannual comparison of select co-sampled variables at Villefranche Point B (see Section 2.2.2 for an explanation of this figure).

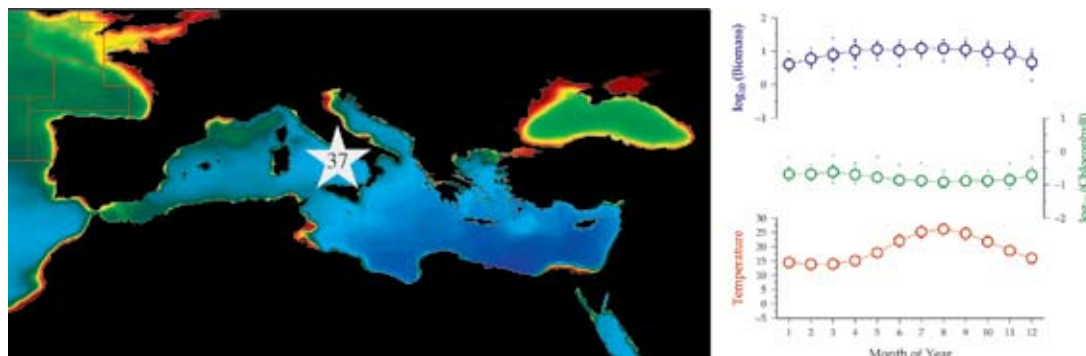


**Figure 8.7**  
 Long-term HadISST sea surface  
 temperatures at Villefranche  
 Point B (see Section 2.2.3 for an  
 explanation of this figure).



## Site 37: MareChiara LTER (Gulf of Naples)

*Maria Grazia Mazzocchi*



**Figure 8.8**  
Location of the MareChiara LTER (Site 37) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Gulf of Naples, located in the Tyrrhenian Sea at the border between the central and southern regions of the western Mediterranean, has been a study site for investigations on zooplankton taxonomy and distribution since the 19th century (Giesbrecht, 1892). However, only regular sampling, begun in 1984 for the MareChiara time-series, has started to unveil aspects of zooplankton temporal evolution and recurrences in this typical Mediterranean embayment (Mazzocchi and Ribera d'Alcalà, 1995). This long-term time-series focuses on characterizing the structure of plankton communities, in terms of standing stocks and species composition, and on following their variability at different temporal scales in relation to environmental conditions. Since 2006, the MareChiara time-series has been part of the International network of Long Term Ecological Research (I-LTER; <http://www.ilternet.edu>).

The sampling site is located ca. 3 km from the coastline, near the 75 m isobath (40°48.5'N 14°15'E), and at the boundary between two subsystems whose exchanges are very dynamic: the coastal eutrophic area, influenced by the land run-off from a very densely populated region, and the offshore oligotrophic area, similar to the open Tyrrhenian waters (Figure 8.8). Sampling has been ongoing since January 1984, with a major interruption from 1993 to 1994. The sampling frequency was fortnightly until 1990 and weekly from 1995 to present (Ribera d'Alcalà *et al.*, 2004). Zooplankton samples were collected with two successive vertical tows from

a depth of 50 m to the surface with a Nansen net (113 cm diameter, 200 µm mesh). One fresh sample was processed for biomass measurements as dry mass, whereas the other sample was fixed with buffered formaldehyde (2–4% final concentration) for the determination of species composition and abundance.

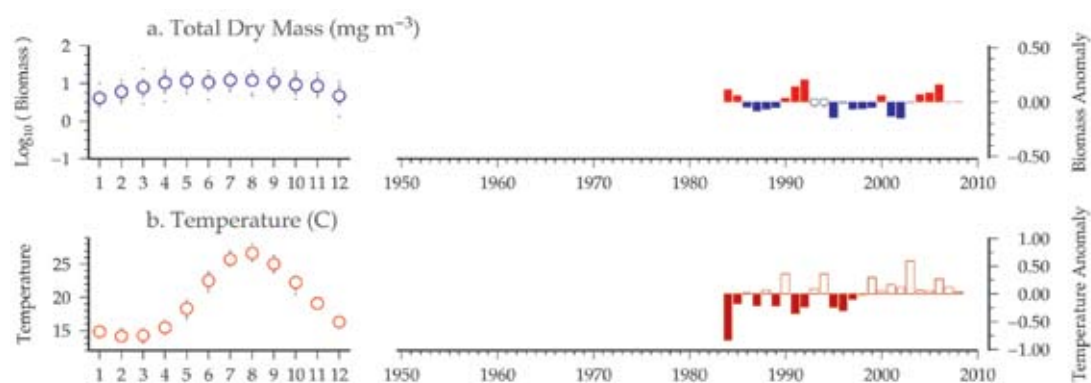
The water column at the site is thoroughly mixed from December to March and stratified during the rest of the year. The annual cycle of depth-integrated temperature (not shown) is characterized by lowest values in March (~14°C) and highest values in September–October (~20°C). Temperature, salinity, and chlorophyll demonstrate high interannual variability. Significant trends during the period 1984–2006 have been recorded in the increasing summer temperatures and in the decreasing annual chlorophyll *a* concentrations (Modigh and Castaldo, 2002; Ribera d'Alcalà *et al.*, 2004; Zingone *et al.*, 2010; M. G. Mazzocchi, pers. comm.). The temperature trends can be seen in the HadISST date-matched and long-term anomalies (Figures 8.9b and 8.10).

The average annual cycles of zooplankton biomass and abundance reveal minima in January and an extended season of high values from April through October, with major peaks in midsummer (Figure 8.9a). The interannual variability of abundance was more pronounced in the first period (1984–1990) than in the second period (1995–2006) of the time-series, although interannual averages were similar in magnitude. The zooplankton community is numerically dominated by copepods, which account for 61–78% of annual abundance. Cladocerans (with high and steep peaks in summer), tunicates (mainly appendicularians), meroplankton (mainly decapod larvae), and chaetognaths follow the copepods in rank order of abundance. Various other taxonomic groups (e.g. amphipods, ostracods, cnidarians) occur in much smaller numbers and lower frequency.

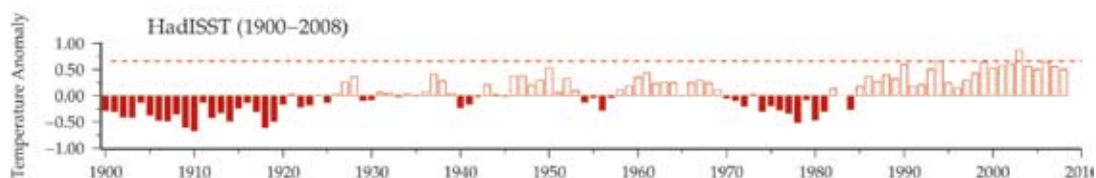
The MareChiara copepod assemblages are highly diversified, with 136 identified species so far and a few unidentified harpacticoids and monstriloids. The bulk of the copepod abundance consists of small individuals ( $\leq 1$  mm). The species composition changes throughout the year, acquiring a strong

seasonal signature (M. G. Mazzocchi, pers. comm.). From spring through autumn, four abundant species peak in succession: *Acartia clausi* and *Centropages typicus* in spring–early summer, *Pseudocalanus parvus* in full summer–early autumn, and *Temora stylifera* in late summer–autumn. These four calanoids occur throughout the year and, together, represent a fairly stable component of copepod assemblages that account for 47.7% ( $\pm 6.7\%$ ) of total copepod abundance from May to October. In late autumn–early spring, when the annual minimal abundance is recorded, copepod assemblages are more diversified than during the rest of the year. The most common genera in this period are the small calanoids *Clausocalanus*, *Calocalanus*, and *Ctenocalanus vanus*, the cyclopoid *Oithona*, oncaeids, and corycaeids. The winter–early spring copepod assemblages are further enriched by the regular, although numerically negligible, occurrence of large calanoid species ( $>1.5$  mm total length) that belong to various families that thrive in offshore deeper waters (mainly *Nannocalanus minor*, *Candacia* spp., and *Pleuromamma* spp.).

**Figure 8.9**  
Seasonal and interannual comparison of select co-sampled variables at MareChiara (see Section 2.2.2 for an explanation of this figure).

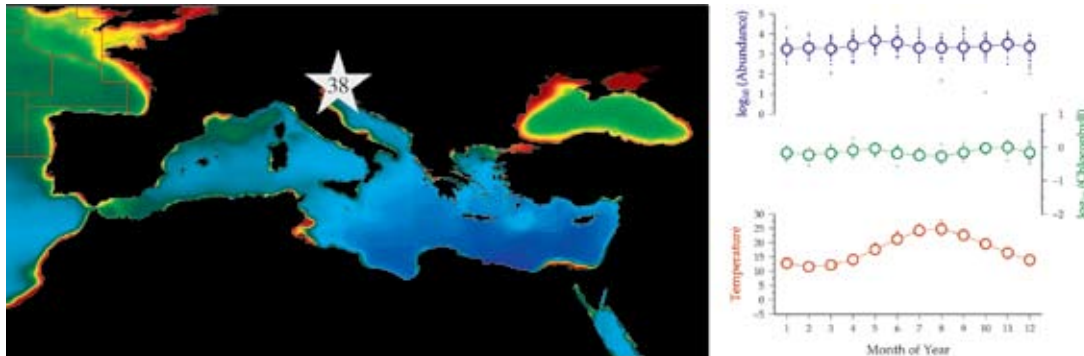


**Figure 8.10**  
Long-term HadISST sea surface temperatures at MareChiara (see Section 2.2.3 for an explanation of this figure).



## Site 38: Gulf of Trieste (northern Adriatic Sea)

Serena Fonda-Umani



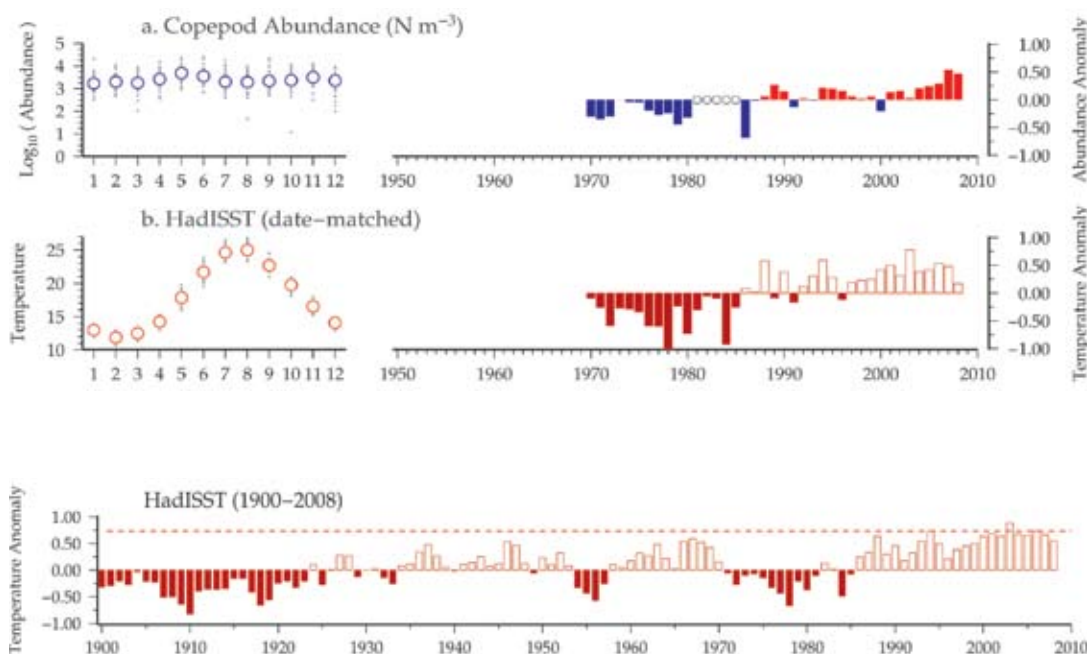
**Figure 8.11**  
Location of the Gulf of Trieste (Site 38) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).

The Gulf of Trieste is the northernmost, landlocked shallow bay of the Adriatic Sea (Figure 8.11). It is characterized by large and variable freshwater input. Zooplankton are collected by vertical hauls from the bottom (18 m) to the surface using a WP-2 net (56 cm diameter, 200 µm mesh). The data have been collected monthly since April 1970, with a 5-year gap from January 1981 to February 1986, inclusive.

The mesozooplankton community in the Gulf of Trieste is characterized by a small number (approximately 30) of coastal and estuarine species, which can exhibit high dominance. Copepods dominate in all months except June and July, when cladocerans (especially *Penilia avirostris*) take over.

The calanoid copepod *Acartia clausi* is dominant for most of the year, but recently its average percentage abundance has decreased. Over the more than 30-year time-series, a regular peak in total copepod abundance was present in May, with a smaller second peak in November.

Since 1987 (Conversi *et al.*, 2009, 2010; Figure 8.12b), a significant increase in temperature (particularly in summer and autumn) was observed, as well as a general increase in total copepod abundance (Figure 8.12a). The SSTs in the region have been above the 100-year average since 1986 and, since 2000, have often been the warmest seen for the past 100 years (Figure 8.13).



**Figure 8.12**  
Seasonal and interannual comparison of select co-sampled variables at Gulf of Trieste (see Section 2.2.2 for an explanation of this figure).

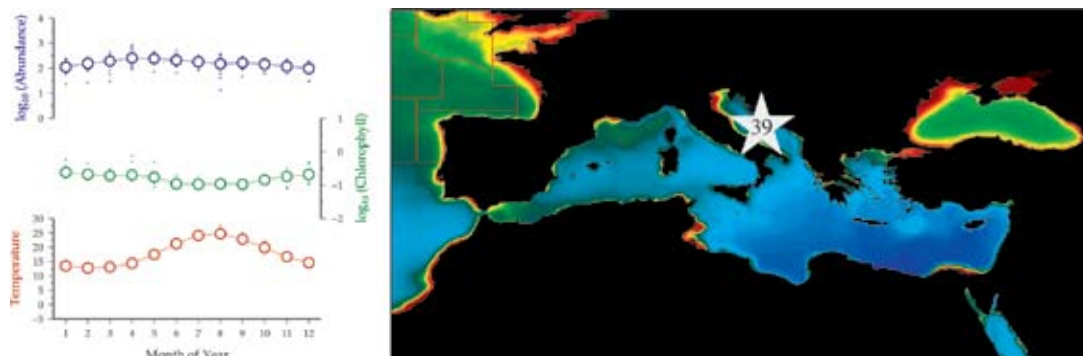
**Figure 8.13**  
Long-term HadISST sea surface temperatures at Gulf of Trieste (see Section 2.2.3 for an explanation of this figure).

## Site 39: Stončica (central Adriatic Sea)

*Olja Vidjak*

**Figure 8.14**

Location of the Stončica (Site 39) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



The offshore station of Stončica is located at 43°02'38"N 16°17'7"E in the central Adriatic Sea (Figure 8.14) at a maximum depth of 107 m and with a detrital and slightly muddy bottom. The annual dynamics of the surface temperature are characterized by a peak in August and minimum in March (Figure 8.15b). Based on long-term monitoring of the chemical and biological parameters, the area is designated as an oligotrophic open sea, characterized by high transparency and decreased phytoplankton and zooplankton abundance, compared with the more productive coastal areas around the central Adriatic. The station is strongly influenced by the incoming Mediterranean water masses known as the Levantine Intermediate Water (LIW).

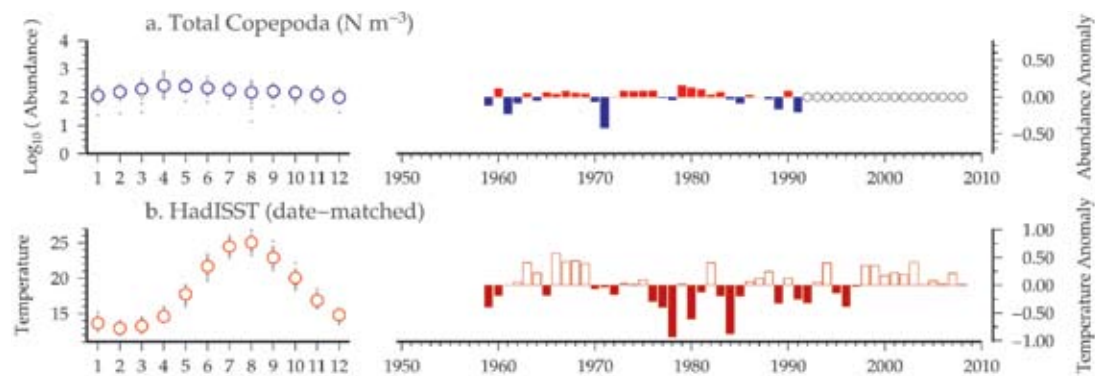
Regular zooplankton sampling at this permanent monitoring site was started in 1959 and performed at approximately monthly intervals using a Hensen net (73 cm diameter, 330 µm mesh) towed vertically from near-bottom to the surface (100–0 m). Special emphasis was given to copepods, because they are generally the most important net zooplankton component and are significant prey to the commercially important planktivorous fish. Approximately 90 copepod species have been registered in this area, where, apart from the open-sea species, the surface waters also host many neritic copepods. These are distributed either from the shallow northern Adriatic area via south-flowing surface currents during summer, or through the spreading of coastal waters towards the open sea.

The same sampling methodology was consistent until 1991; during 1991–1994, the sampling programme was interrupted. In January 1995, the programme was resumed, but the samples have not yet been processed and are stored in the Institute of Oceanography and Fisheries (IZOR). From the end of the 1990s, the research interests within the Institute shifted towards the role of smaller fractions of the zooplankton, such as tintinnids, radiolarians, copepod developmental stages, and small copepod species. Consequently, samplings with finer plankton nets are currently performed regularly at this site.

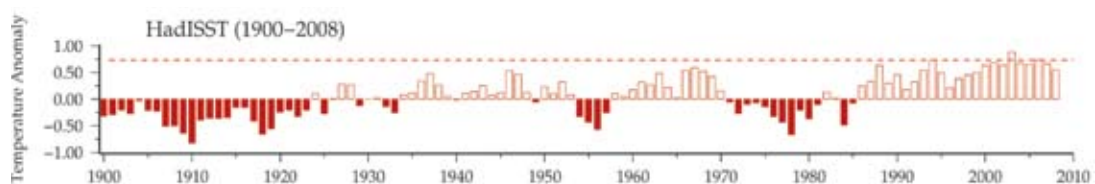
Long-term zooplankton data from Stončica have been analysed in several papers (Regner, 1981, 1985, 1991; Baranović *et al.*, 1993; Šolić *et al.*, 1997). The analyses of copepod abundance identified the dominant seasonal pattern, with the appearance of a strong peak in April (Figure 8.15a); on the interannual scale, a slight decrease in abundance was observed after the 1980s.

The SSTs in the region have been above the 100-year average since 1986 and, since 2000, have often been the warmest seen for the past 100 years (Figure 8.16).





**Figure 8.15**  
Seasonal and interannual comparison of select co-sampled variables at Stončica (see Section 2.2.2 for an explanation of this figure).



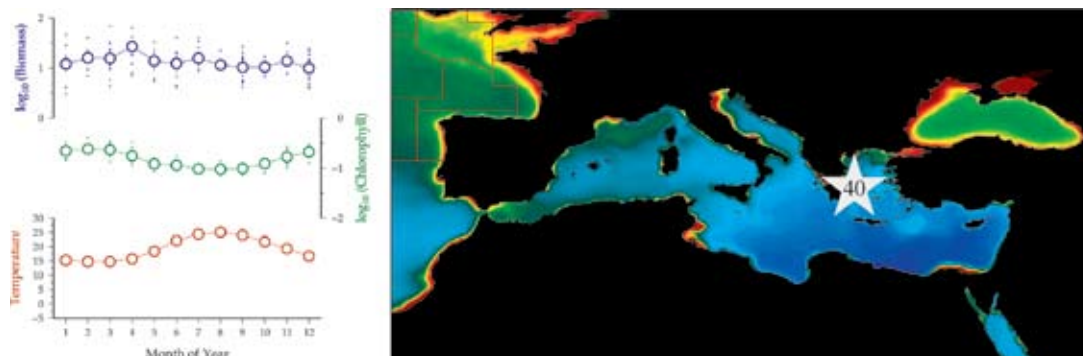
**Figure 8.16**  
Long-term HadISST sea surface temperatures at Stončica (see Section 2.2.3 for an explanation of this figure).

## Site 40: Saronikos S11 (Aegean Sea)

*Ioanna Siokou-Frangou and Soultana Zervoudaki*

**Figure 8.17**

Location of the Saronikos S11 (Site 40) survey area and the seasonal summary plots for zooplankton, chlorophyll, and surface temperature in this area (see Section 2.2.1 for an explanation of this figure).



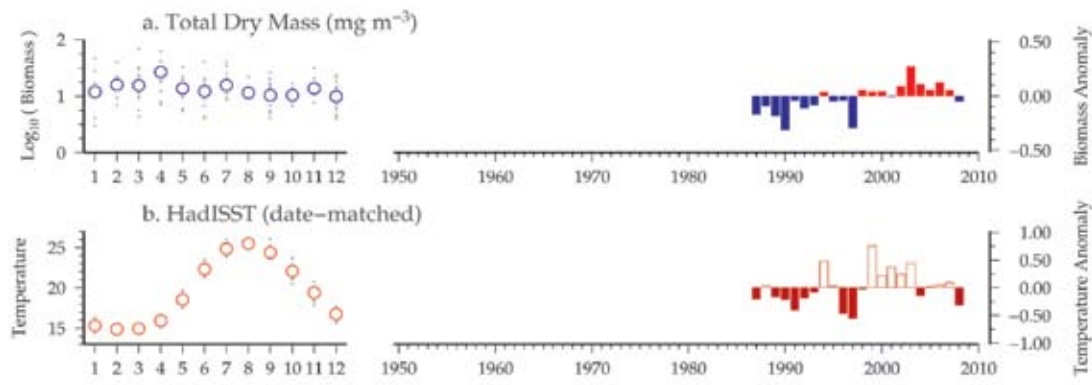
Saronikos Station 11 (Saronikos S11) is located in the Saronikos Gulf at 37°52.36'N 23°38.30'E (Figure 8.17), with a bottom depth of 78 m. Zooplankton were sampled with a WP-2 net (56 cm diameter, 200 µm mesh) from a depth of 75 m to the surface. Monitoring of zooplankton and abiotic parameters started in 1987, with variable (monthly or seasonal) sampling frequency and periodic gaps.

Zooplankton biomass (total dry mass) was highest during the well-mixed winter period, with maxima in April, followed by a general decline accompanying increasing water temperatures and stratification (Figure 8.18a). Saronikos S11 surface temperature peaks in August and has a minimum in February–March (Figure 8.18b). Salinity ranges between 38 and 39 psu, depending on the variable inflow of Aegean water (Kontoyiannis *et al.*, 2005).

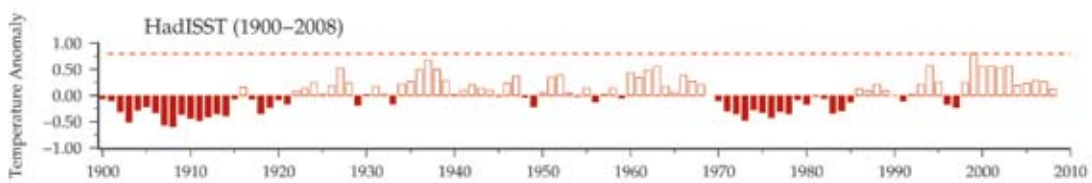
Saronikos S11 is located 7 km from the Athens domestic sewage outfall. Prior to 1994, untreated wastewater was disposed at the sea surface. In 2004, primary-treated wastewater was disposed at a depth of 60 m, below the seasonal thermocline. Since 2004, this wastewater has been further treated in order to eliminate its organic load and to greatly

reduce its nutrient content. In spite of additional treatment, nutrient concentrations increased during the period 1987–2004, related to an increase in sewage volume. During this period, phytoplankton biomass decreased until 2002, probably because of the availability of nutrients at depth after 1994 and the competition with bacteria (Siokou-Frangou *et al.*, 2007; Zeri *et al.*, 2009). In contrast, zooplankton biomass revealed a clear increasing trend from 1987 to 2003, followed by a slight decrease (Figure 8.18a).

Despite an apparent covariability of seawater temperature and zooplankton biomass anomalies, no correlation was found between climate indices and zooplankton groups (Berline *et al.*, In press). Nevertheless, investigation at the species level could provide more information for the study area. The combination of several driving forces affecting the area and the lack of data makes the investigation of zooplankton variability quite difficult. Continuation of the monitoring without gaps and greater stability obtained in anthropogenic factors could permit a better understanding of zooplankton dynamics in future.



**Figure 8.18**  
Seasonal and interannual comparison of select co-sampled variables at Sarónikos S11 (see Section 2.2.2 for an explanation of this figure).



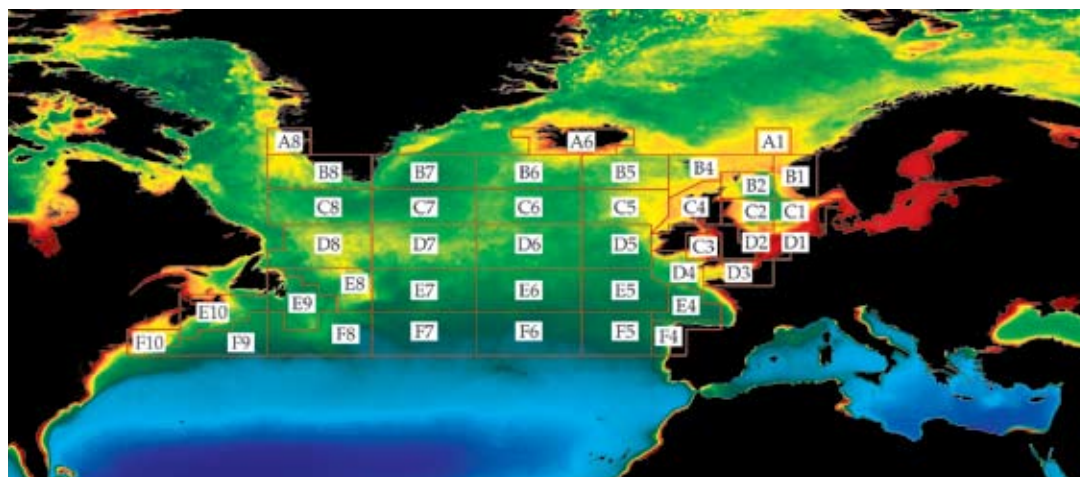
**Figure 8.19**  
Long-term HadISST sea surface temperatures at Saronikos S11 (see Section 2.2.3 for an explanation of this figure).

## 9. ZOOPLANKTON OF THE NORTH ATLANTIC BASIN

*Priscilla Licandro*

The Continuous Plankton Recorder (CPR) survey, operated by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS; <http://www.SAHFOS.org>), has been sampling plankton in the North Atlantic and North Sea for more than 70 years. The CPR instrument is towed at the surface behind volunteer-operated vessels (ships of opportunity), sampling plankton onto a moving 270  $\mu$ m band of net silk as the vessel and CPR unit traverse the North Atlantic and/or North Sea. Within the CPR instrument, the net silk and its captured plankton are preserved in formalin until they are returned to SAHFOS. During the processing, the net silk is divided into sections representing 10 nautical miles of towing, and each section is analysed for plankton composition and abundance.

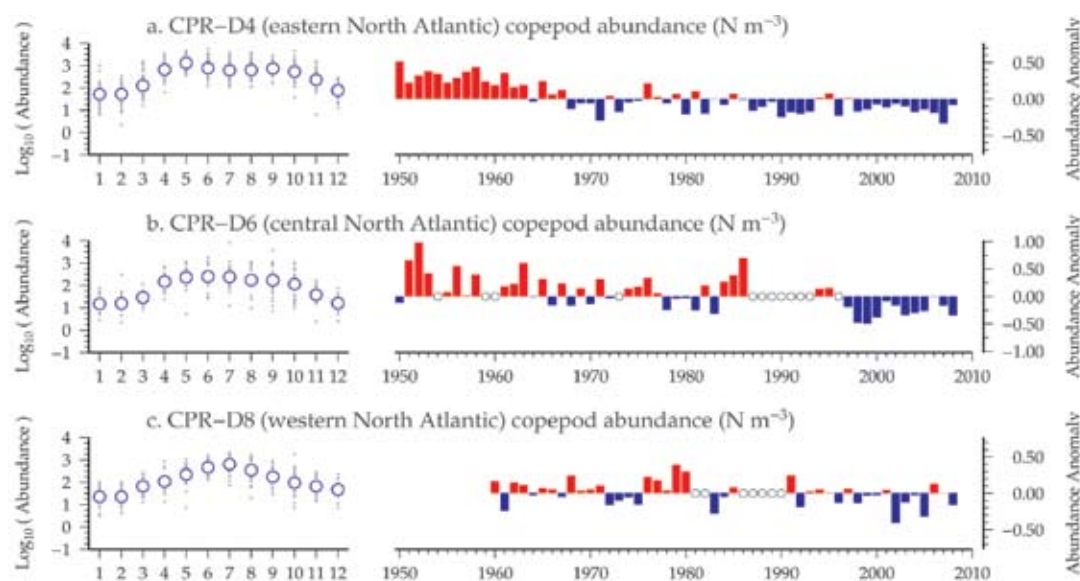
The North Atlantic CPR database contains more than 5 million plankton observations analysed from more than 200 000 silk sections. By representing the midpoint of each silk section with a grey dot, the spatial coverage of the North Atlantic area of the CPR survey is shown in Figure 9.2. This area is further divided into 40 geographic regions, known as CPR standard areas (Figures 9.1 and 9.2; red boxes) and referred to by alpha-numerical identifiers (e.g. A1, E6).



**Figure 9.1**  
Locations of CPR standard areas plotted on a map of average chlorophyll concentration (see Section 2.3.2).



**Figure 9.2**  
Locations of CPR plankton samples (grey dots) with an overlay (red lines) indicating the CPR standard areas.



**Figure 9.3**  
Seasonal and interannual comparison of three CPR standard area boxes from the (a) eastern, (b) central, and (c) western North Atlantic (see Section 2.2.2 for an explanation of this figure).



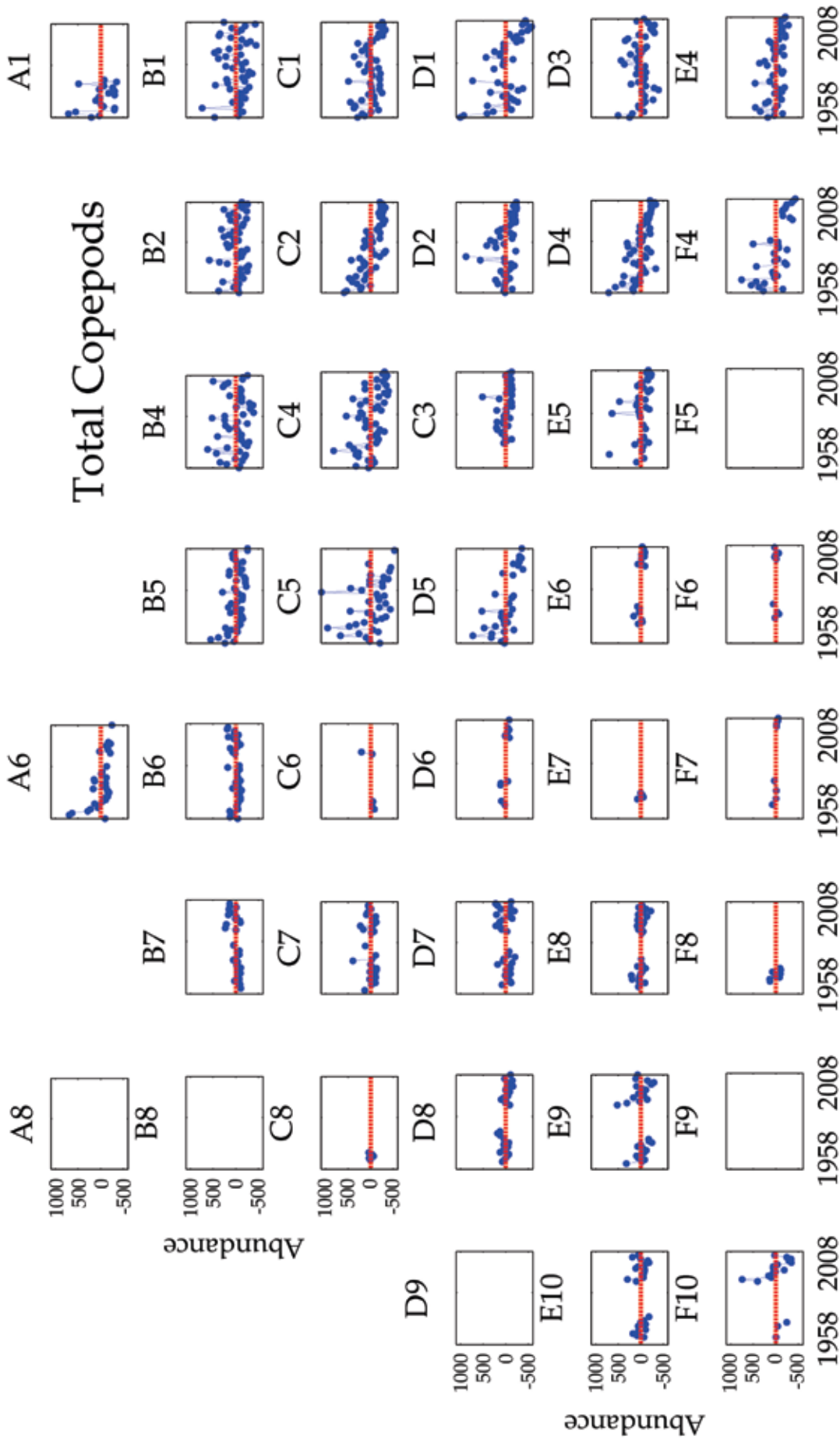
Although standard WGZE figures (*sensu* Figure 9.3) could be created for all 40 CPR sites, it would not necessarily provide a coherent spatial picture of the North Atlantic Basin. For better visualization of this large data collection, spatial compilation maps were created to represent the entire North Atlantic and North Sea time-series data collection. Applying this to the CPR copepod abundance time-series data, Figure 9.4 shows the cross-basin results for each of the CPR standard areas. It is important to note that this figure differs from the standard WGZE anomaly figures in that the values represent annual anomalies based on non-log-transformed values. In each subfigure, blue dots indicate annual anomaly values, while a solid red line indicates the zero-value anomaly (i.e. the climatology).

In most areas of the Northeast Atlantic (e.g. Figures 9.3a and 9.4), total copepod abundance has been decreasing since the beginning of the time-series. Between 2007 and 2008, copepods increased slightly in the English Channel and in the southeast North Sea, whereas very low concentrations were recorded over the northwest European shelf south of Iceland. In the western North Atlantic (Figures 9.3c and 9.4), copepod abundance has remained relatively stable or has increased, particularly in the region around and south of Newfoundland.

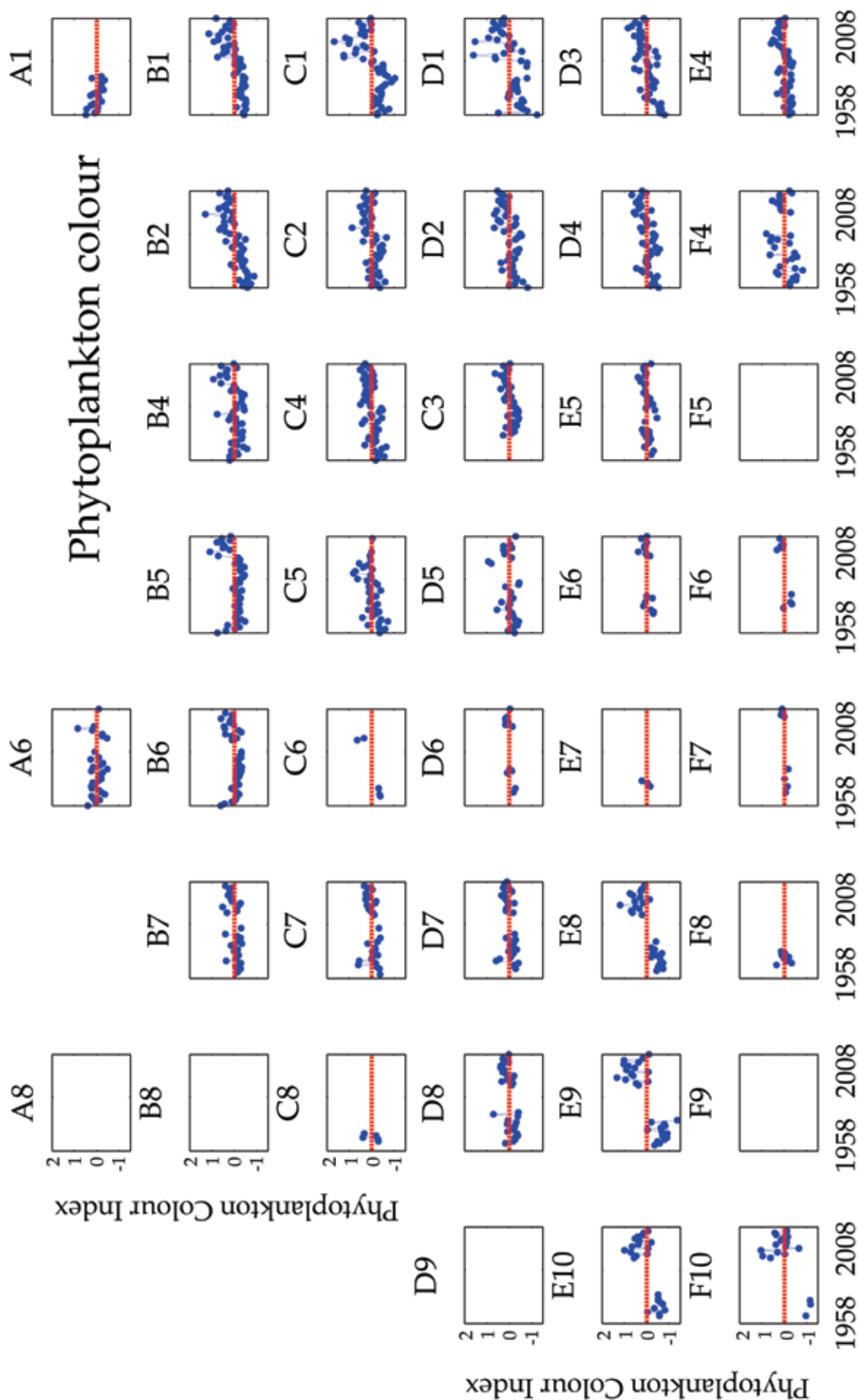
To understand long-term changes in zooplankton populations, it is essential to understand the changes occurring in the lower trophic levels. The CPR phytoplankton colour index (PCI) was used to investigate changes in phytoplankton in the North Atlantic. The PCI is the degree of greenness of the CPR silk. It includes the chloroplasts of unbroken

and broken cells, as well as small, unarmoured flagellates, which tend to disintegrate on contact with the net. The phytoplankton colour on the silk is a good index of total chlorophyll content (Hays and Lindley, 1994) and is closely related to phytoplankton biomass estimates from satellite observations (Batten *et al.*, 2003; Raitos *et al.*, 2005). Long-term interannual values of phytoplankton colour in CPR standard areas in the North Atlantic from 1958 to 2008 are shown in Figure 9.5. There has been a large increase in the PCI since the late 1980s in most regions, particularly in the Northeast Atlantic and the Newfoundland Shelf. In 2007–2008, the values of PCI were still above the long-term mean, but a slight decrease in the PCI was recorded over the western European shelf south of Ireland and in the region around and south of Newfoundland.

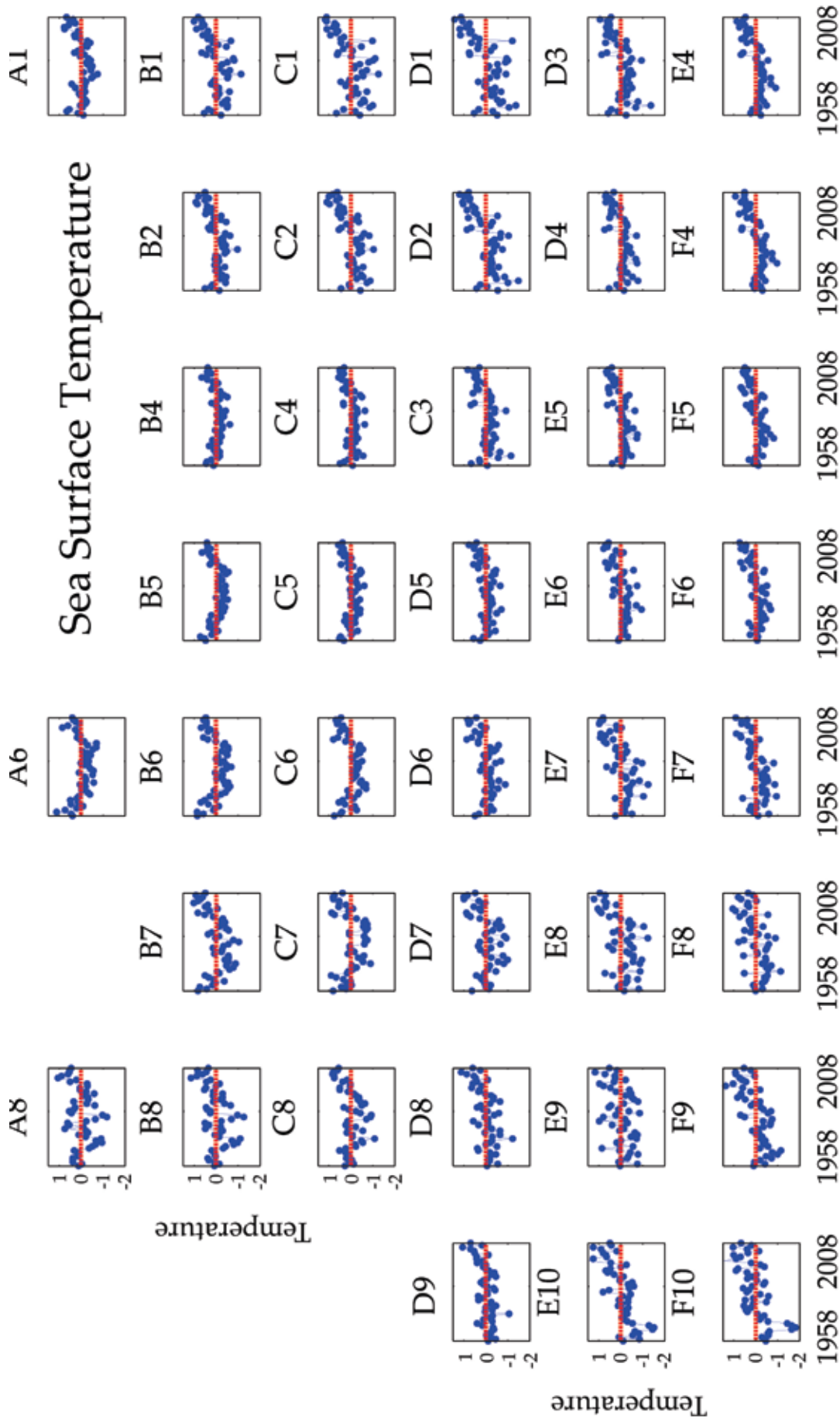
The sea surface temperature (SST) time-series from 1958 to 2008 for CPR standard areas increased overall since the early 1970s for the whole of the North Atlantic (Figure 9.6). Surface temperatures in 2007–2008 were above the long-term mean in all regions, but a relative decrease in SST was recorded in 2008 in the central North Atlantic.



**Figure 9.4**  
Annual anomalies of total copepod  
abundance in CPR standard  
areas across the North Atlantic  
(see Figure 9.1 for a map of CPR  
standard area locations).



**Figure 9.5** Annual anomalies of phytoplankton colour index (PCI) in CPR standard areas across the North Atlantic (see Figure 9.1 for a map of CPR standard area locations).



**Figure 9.6**  
Annual anomalies of sea surface temperature (SST) in CPR standard areas across the North Atlantic (see Figure 9.1 for a map of CPR standard area locations).









Copepods are the dominant species in many pelagic zooplankton communities.  
Photo by M. G. Mazzocchi.

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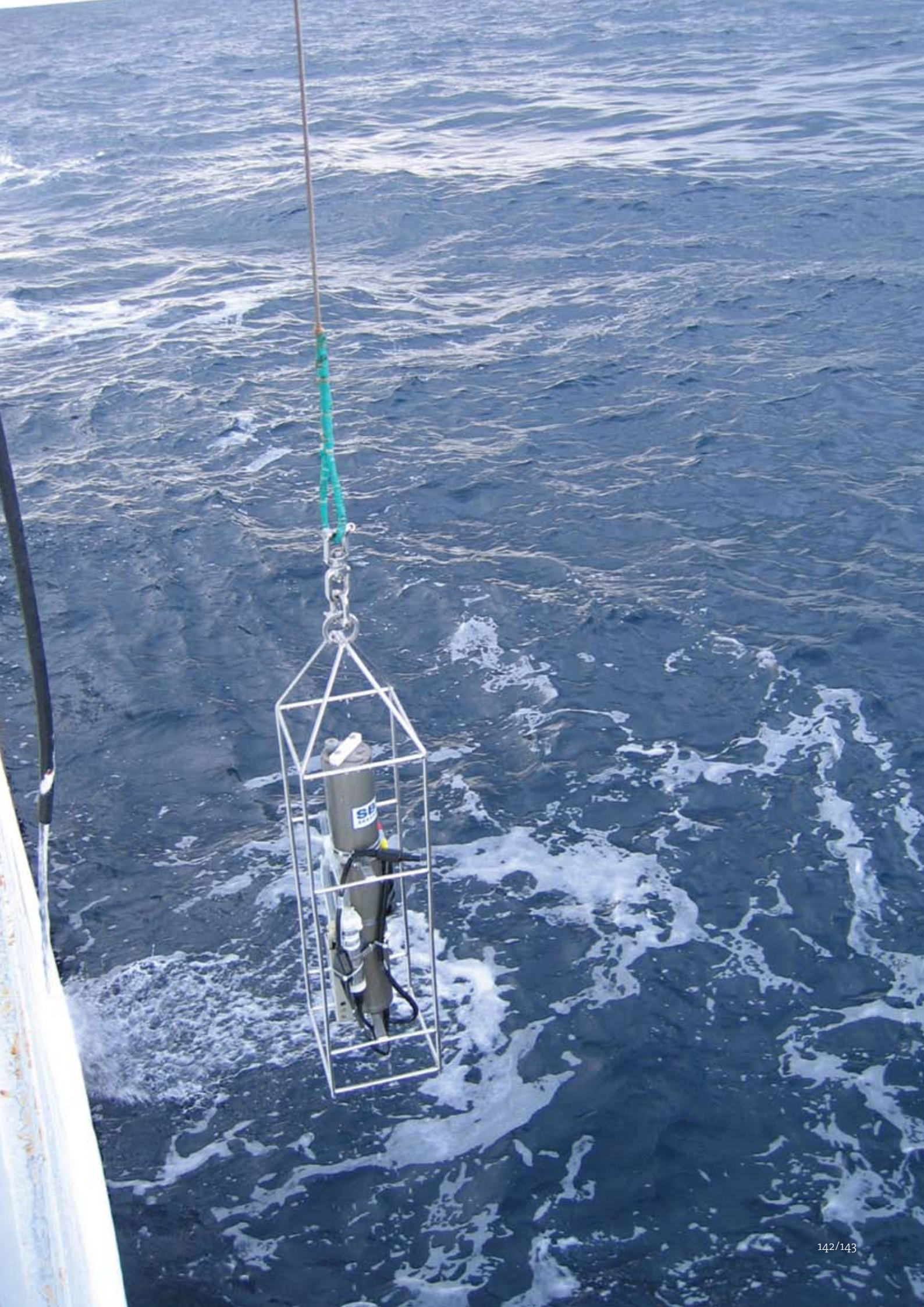
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**Right.** A CTD being deployed off Cascais, Portugal (report site #34). Photo by A. dos Santos.







# 11. METADATA: CHARACTERISTICS OF THE COLLECTIONS USED

Ocean region	Western North Atlantic								
Country	USA					Canada			
Sampling/ monitoring programme	NMFS–NEFSC				BIOS	AZMP			
Sampling site name	MAB	SNE	GOM	GB	BATS	Prince 5	Halifax Line 2	Anticosti Gyre and Gaspé Current	Station 27
WGZE site number	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>9</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>
Sampling location	Mid- Atlantic Bight	Southern New England	Gulf of Maine	Georges Bank	Sargasso Sea	Bay of Fundy	Scotian Shelf	Gulf of St Lawrence	Newfoundland Shelf
Sampling duration	1977– present	1977– present	1977– present	1977– present	1994– present	1999– present	1999– present	1999– present	1999 present
Sampling frequency	Cross-monthly surveys six times per year				Monthly/ biweekly	Monthly/biweekly			
Sampling gear (diameter)	Bongo net				Ringnet (100 cm)	Ringnet (75 cm)			
Sampling mesh (µm)	333 µm				202 µm	200 µm			
Sampling depth (m)	0–200 (or bottom)				0–200	0–bottom			
Contact person	Jon Hare				Debbie Steinberg	Erica Head	Michel Harvey		Pierre Pepin
Contact's email address	Jon.Hare@noaa.gov				DebbieS@ vims.edu	Erica.Head@ dfo-mpo.gc.ca	Michel.Harvey@ dfo-mpo.gc.ca		Pierre.Pepin@ dfo-mpo.gc.ca



Ocean region	Nordic and Barents Seas					
Country	Iceland		Faroe Islands	Norway		
Sampling / monitoring programme	MRI-Iceland		FMRI-Faroe Islands	IMR-Bergen		
Sampling site name	Selvogsbanki transect	Siglunes transect	Faroe Islands (southern Norwegian Sea)	Svinøy transect	Fugløya-Bjørnøya transect	Vardø-Nord transect
WGZE site number	<b>10</b>	<b>11</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>15</b>
Sampling location	South Iceland	North Iceland	Southern Norwegian Sea, Faroe Shelf	Norwegian Sea	Western Barents Sea	Eastern Barents Sea
Sampling duration	1971–present	1961–present	1990–present	1996–present	1994–present	1994–present
Sampling frequency	Annually (May–June)		Annually (late May)	4–6 times per year	3–6 times per year	3–4 per year
Sampling gear (diameter)	1971–1991, Hensen net; 1992–present, WP-2 net		1990–1991, Hensen net; 1992–present, WP-2 net	WP-2 net (56 cm)		
Sampling mesh (µm)	200 µm		200 µm	180 µm		
Sampling depth (m)	0–50		0–50	0–200	0–100	0–100
Contact person	Astthor Gislason		Eilif Gaard	Webjørn Melle		
Contact's e-mail address	astthor@hafro.is		eilifg@frs.fo	webjorn@imr.no		

Ocean region	Baltic Sea								
Country	Finland				Estonia		Latvia		Germany
Sampling / monitoring programme	HELCOM Monitoring				HELCOM Monitoring		National Monitoring Programme of Latvia	LatFRA–Monitoring	IOW
Sampling site name	Bothnian Bay	Bothnian Sea	Gulf of Finland	The Baltic Proper	Tallinn Bay	Pärnu Bay	Station 121	Eastern Gotland Basin	Arkona Basin
WGZE site number	<b>16</b>	<b>17</b>	<b>19</b>	<b>23</b>	<b>18</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>24</b>
Sampling location	Northern Baltic Sea	Northern Baltic Sea	Eastern Baltic Sea	Central Baltic Sea	Gulf of Finland	Northeast Gulf of Riga	Gulf of Riga	Central Baltic Sea	Southern Baltic Sea
Sampling duration	1979–present	1979–present	1979–present	1979–present	1993–present	1957–present	1993–present	1960–present	1979–present
Sampling frequency	August				Up to 10 times per year	Monthly to weekly in non-ice months	At least 3 times per year	Seasonally	Seasonally
Sampling gear (diameter)	WP-2 net (56 cm)				Juday net (36 cm)		WP-2 net	Juday net (36 cm)	WP-2 net
Sampling mesh (µm)	100 µm				90 µm		100 µm	160 µm	100 µm
Sampling depth (m)	0–bottom				0–bottom		0–50	0–100	0–25
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Ocean region	North Sea and English Channel				
Country	Norway	Germany	UK		
Sampling / monitoring programme	IMR	BSH and DZMB	FRS–MLA		PML
Sampling site name	Arendal Station 2	Helgoland Roads	Stonehaven	Loch Ewe	Plymouth L4
WGZE site number	<b>25</b>	<b>26</b>	<b>27</b>	<b>28</b>	<b>29</b>
Sampling location	Northern Skagerrak	Southeastern North Sea	Northwestern North Sea	Northwest Scotland	English Channel
Sampling duration	1994–present	1975–present	1997–present	2002– present	1988–present
Sampling frequency	Twice per month	Every Monday, Wednesday, and Friday	Weekly (52 weeks per year)		Weekly (~40 weeks per year)
Sampling gear (diameter)	WP-2 net	Hydrobios and Calcofi	Bongo net (40 cm)		WP-2 net
Sampling mesh (µm)	180 µm	150 µm, 500 µm	200 µm		200 µm
Sampling depth (m)	0–50	0–bottom	0–50	0–35	0–50
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Ocean region	Bay of Biscay and Iberian Coast				
Country	Spain				Portugal
Sampling / monitoring programme	IEO–Spain				IPIMAR
Sampling site name	Santander	Gijón	A Coruña	Vigo	Cascais
WGZE site number	<b>30</b>	<b>31</b>	<b>32</b>	<b>33</b>	<b>34</b>
Sampling location	Southern Bay of Biscay	Southwestern Bay of Biscay	Northwest Iberian peninsula	West Iberian peninsula	Southwest Iberian peninsula
Sampling duration	1991–present	2001–present	1990–present	1994–present	2005–present
Sampling frequency	Monthly	Monthly	Monthly	Monthly	Monthly
Sampling gear (diameter)	Juday net (50 cm)	WP-2 net (38 cm)	Juday net (50 cm)	Bongo net (40 cm)	WP-2 net (50 cm)
Sampling mesh (µm)	250 µm	200 µm	1971–1996, 250 µm; 1996–present, 200 µm	200 µm	200 µm
Sampling depth (m)	0–50	0–100	0–50	0–95	0–30
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Ocean region	Mediterranean Sea					
Country	Spain	France	Italy		Croatia	Greece
Sampling / monitoring programme	IEO–Spain	LOV–France	SZN–Italy	UNITS–Italy	IZOR–Croatia	HCMR–Greece
Sampling site name	Baleares Station	Villefranche Point B	MareChiara LTER	Gulf of Trieste	Stoncića	Saronikos S11
WGZE site number	<b>35</b>	<b>36</b>	<b>37</b>	<b>38</b>	<b>39</b>	<b>40</b>
Sampling location	Balearic Sea	Cote d'Azur	Gulf of Naples	Northern Adriatic Sea	Central Adriatic Sea	Aegean Sea
Sampling duration	1994–present	1974–present	1984–present	1970–present	1959–1991; 1995–present (unprocessed)	1987–present
Sampling frequency	Monthly (until 2006)	Monthly	Monthly	Monthly	Monthly (with gaps)	Seasonally (1987–1998); monthly after 1999
Sampling gear (diameter)	Bongo net (20 cm)	Juday–Bogorov net	Nansen net (113 cm)	WP-2 net	Hensen net (73 cm)	WP-2 net
Sampling mesh (µm)	100/250 µm	330	µm 200 µm	200 µm	330 µm	200 µm
Sampling depth (m)	0–100	0–75	0–50	0–18	0–100	0–75
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Ocean region	North Atlantic Basin
Country	UK
Sampling / monitoring programme	Continuous Plankton Recorder
Sampling site name	CPR surveys
WGZE site number	<b>CPR standard areas*</b>
Sampling location	Trans-Atlantic Basin
Sampling duration	1946–present
Sampling frequency	Monthly (with gaps)
Sampling gear (diameter)	CPR (1.24 cm)
Sampling mesh (µm)	270 µm
Sampling depth (m)	Subsurface (7–10 m)
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\* See Figure 9.1.

## 12. LIST OF ABBREVIATIONS

AW	Atlantic water
BATS	Bermuda Atlantic Time-series Study
CPR	Continuous Plankton Recorder
CTD	conductivity–temperature–depth
DFO	Department of Fisheries and Oceans Canada
EIW	East Icelandic Water
FIMR	Finnish Institute of Marine Research; now the Finnish Environment Institute
GlobColour	GlobColour Project chlorophyll- <i>a</i> concentration merged level-3 dataset
HadISST	Hadley Centre Global Sea Ice Coverage and Sea Surface Temperature dataset
HELCOM	Helsinki Commission
IMR	Norwegian Institute of Marine Research
IPC	Iberian Poleward Current
NAO	North Atlantic Oscillation
NMFS	National Marine Fisheries Service (under NOAA)
NOAA	National Oceanic Atmospheric Administration (USA)
PCI	the CPR phytoplankton colour index
PROBE	PROgram for Boundary layers in the Environment
SST	sea surface temperature
WGZE	Working Group on Zooplankton Ecology

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