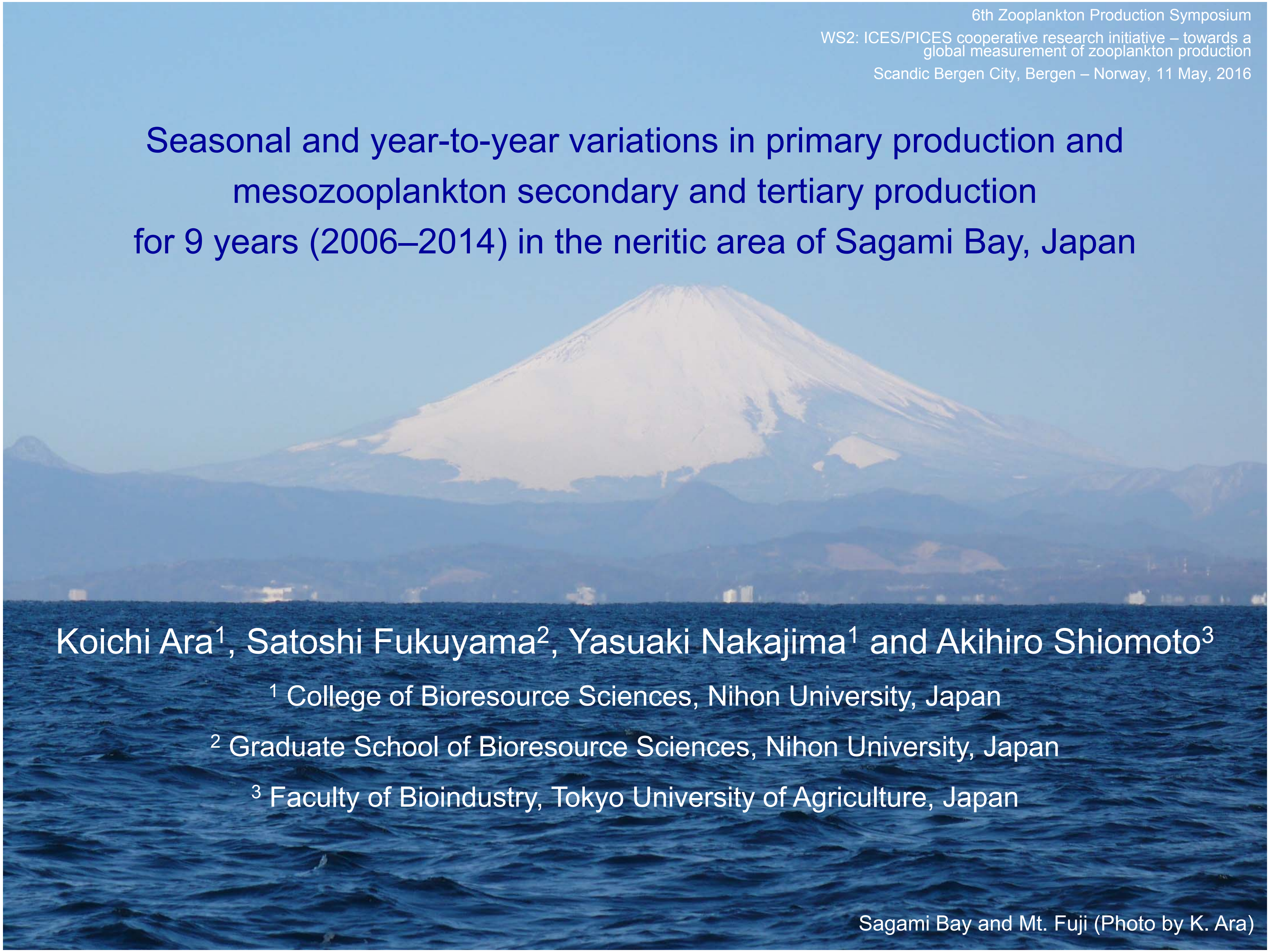
6th Zooplankton Production Symposium
WS2: ICES/PICES cooperative research initiative – towards a global measurement of zooplankton production
Scandic Bergen City, Bergen – Norway, 11 May, 2016

Seasonal and year-to-year variations in primary production and mesozooplankton secondary and tertiary production for 9 years (2006–2014) in the neritic area of Sagami Bay, Japan



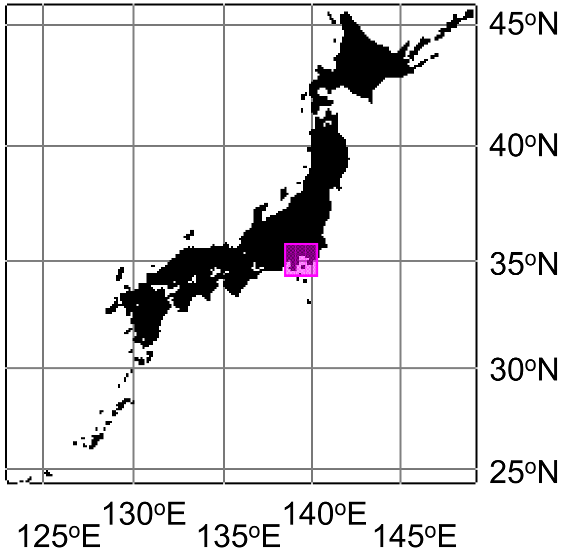
Koichi Ara[1], Satoshi Fukuyama[2], Yasuaki Nakajima[1] and Akihiro Shiomoto[3]

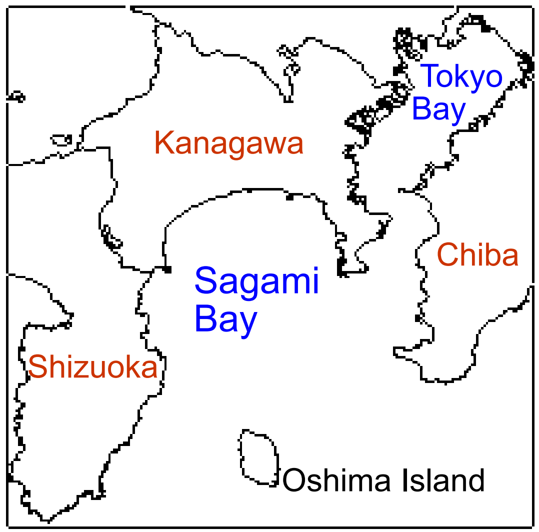
[1] College of Bioresource Sciences, Nihon University, Japan

[2] Graduate School of Bioresource Sciences, Nihon University, Japan

[3] Faculty of Bioindustry, Tokyo University of Agriculture, Japan

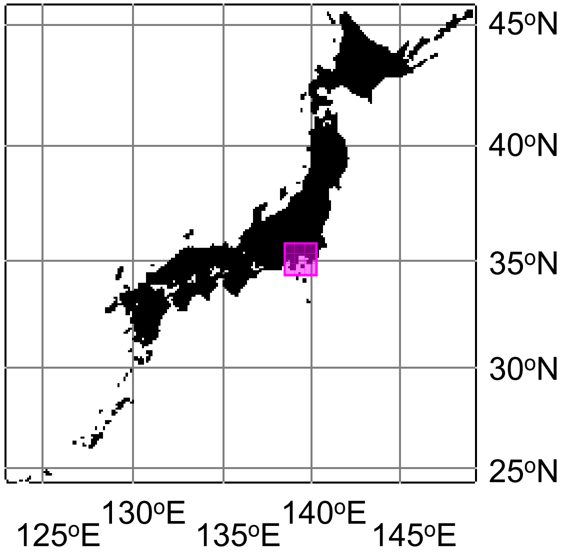
Sagami Bay and Mt. Fuji (Photo by K. Ara)

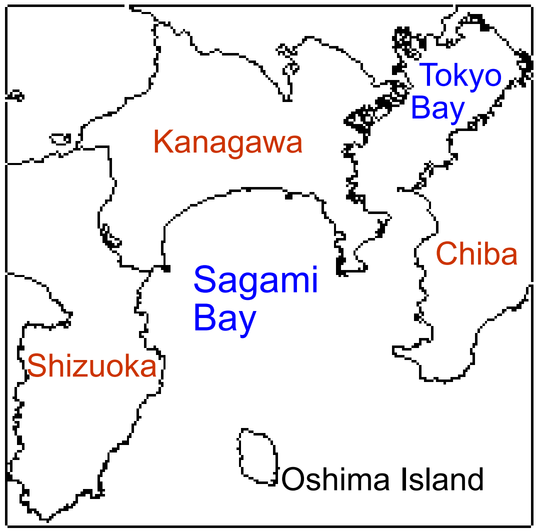




(1) Sagami Bay is traditionally well known for its beautiful natural environment and richness of marine organisms with high biodiversity.

(2) Since at least the 1960s until now, the total annual fishery capture in Sagami Bay has been maintained at ca. 30,000 tons wet weight year^{-1}, and most of this has been caught in the shallow (<250 m depth), coastal and neritic waters.



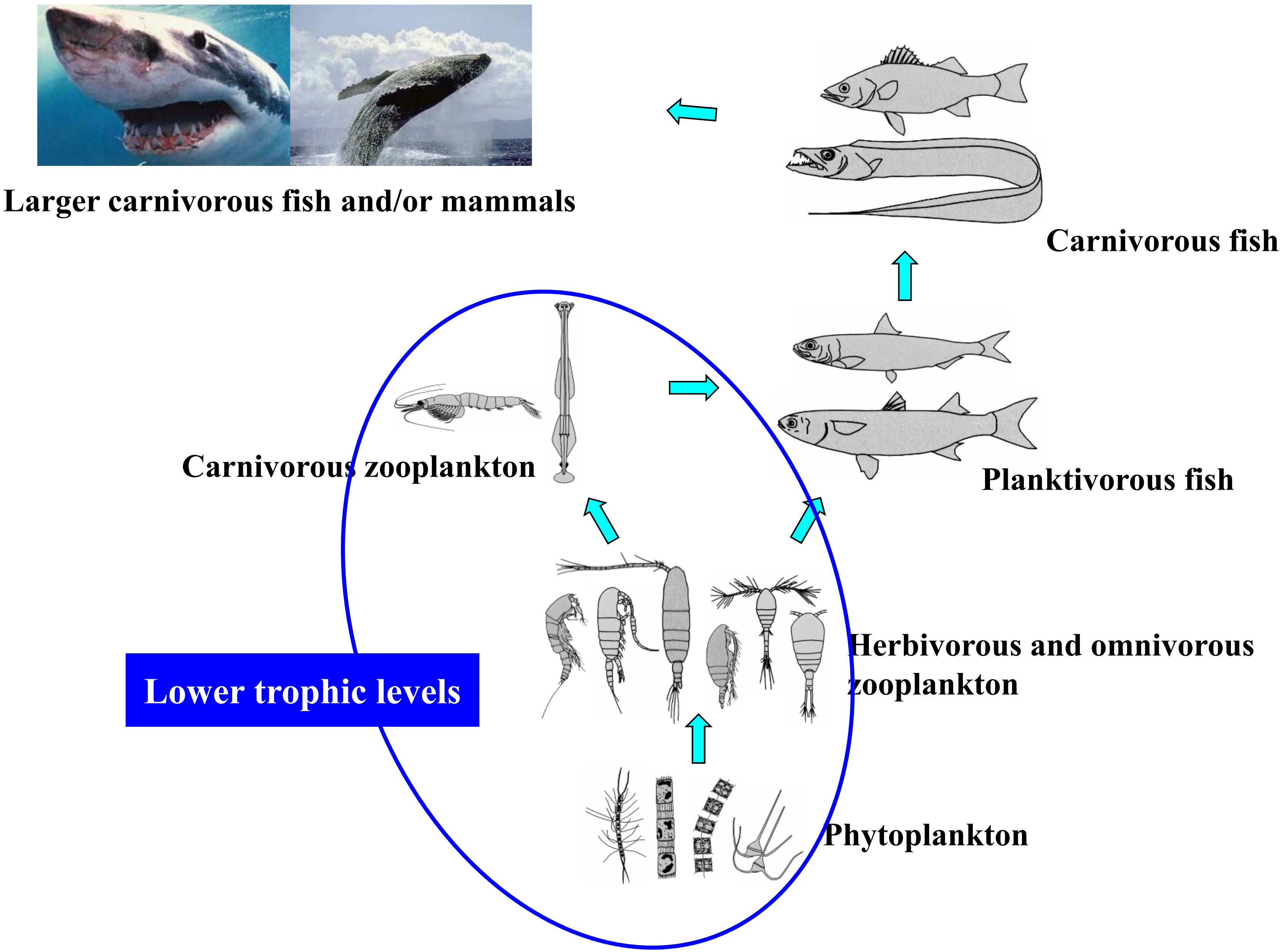


(1) Sagami Bay is traditionally well known for its beautiful natural environment and richness of marine organisms with high biodiversity.

(2) Since at least the 1960s until now, the total annual fishery capture in Sagami Bay has been maintained at ca. 30,000 tons wet weight year^{-1}, and most of this has been caught in the shallow (<250 m depth), coastal and neritic waters.




Marine ecosystem: traditional grazing food chain



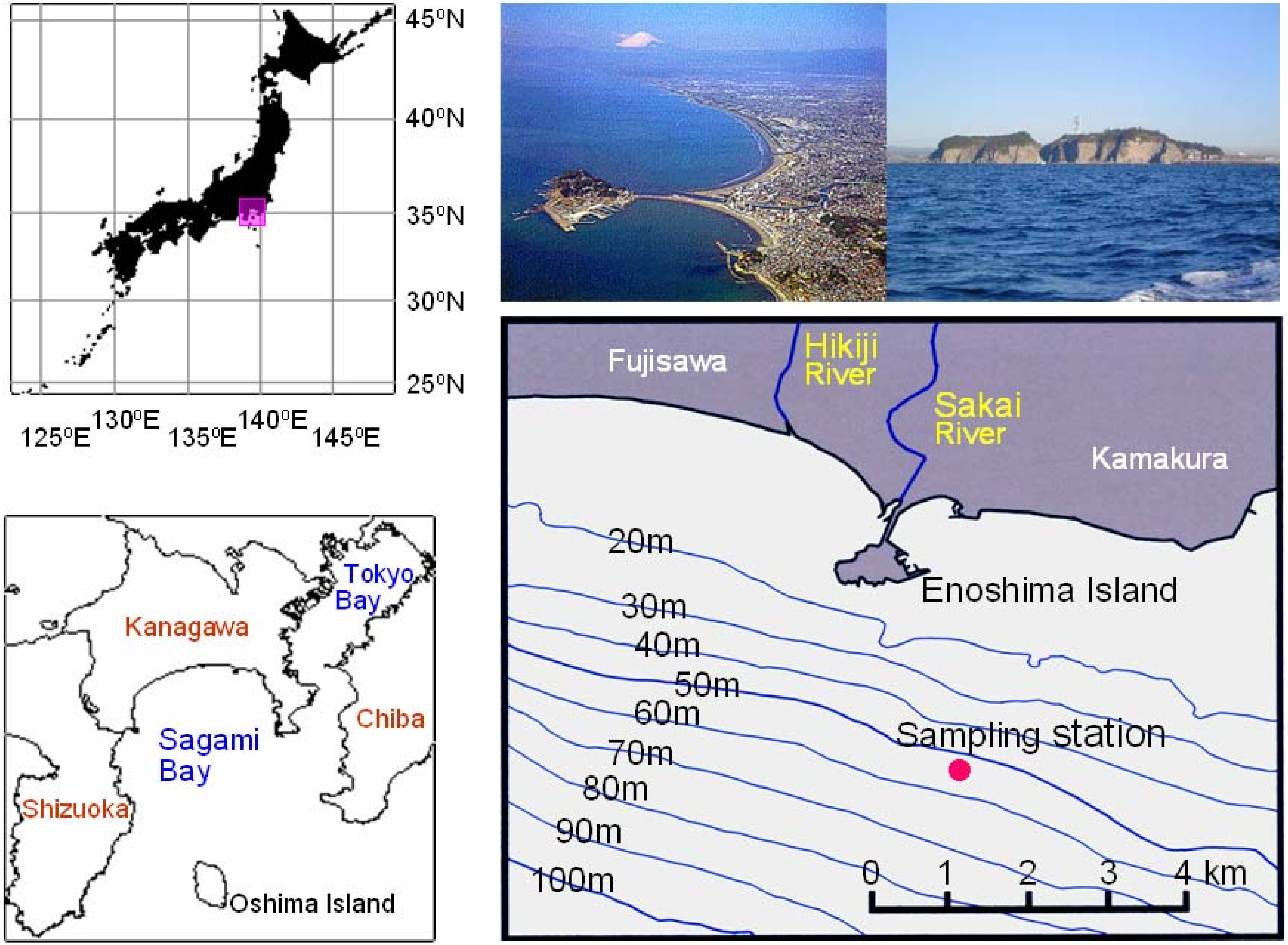


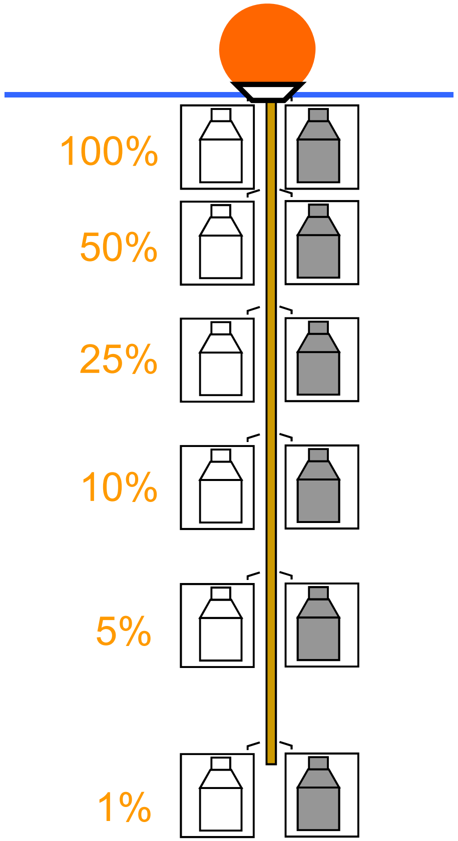
Figure 1 Map showing the study area in Sagami Bay.

Materials and methods

Sampling period and frequency	• From January 2006 to December 2014 • Mostly every 2 weeks on 217 occasions
Water temperature and salinity	• Memory STD (Alec Electronics, AST1000-PK), • Every 1 m from the surface to the bottom
Primary production	• *In situ* ^{13}C incubation for 24 hrs (Hama *et al.* 1983)
Mesozooplankton	• Plankton net (mouth diameter: 45 cm, mesh opening size: 200 μm) equipped with a flowmeter (Rigosha) • Vertical tows from the bottom to the surface • Immediately preserved in 5–10% (final concentration) buffered formalin seawater solution • Identification Copepods: species, stage (CI–CVI) and sex Other non-copepods: taxonomic group • Count (>500 individuals) and measurement of body length

Primary production: *in situ* ^{13}C method

1. Water samples: from six depths (100, 50, 25, 10, 5 and 1% photon fluxes just above the sea surface), using a Niskin bottle.
2. Large zooplankton: removed by sieving through a 200 µm mesh.
   Seawater samples: into polycarbonate bottles (two light bottles and one dark bottle at each depth).
3. Add $NaH^{13}CO_3$ (ca. 10% of total inorganic carbon in ambient water).
   Bottles: placed at the same depths at which water samples were taken, and incubated *in situ* for 24 h.
4. Samples: filtered through pre-combusted (at 450°C for 4 h) filters.
   Filters: dried at 60°C for 1–2 h, fumed with HCl for 3 h, dried at 60°C, and stored in a desiccator.
5. Isotopic ratio of $^{13}C/^{12}C$: determined by a quadruple mass-spectrometer (Europe Scientific ANCA-SL).
6. Primary productivity: calculated according to Hama *et al*. (1983).
7. Depth-integrated primary production: as integral of primary productivities in the photic zone.



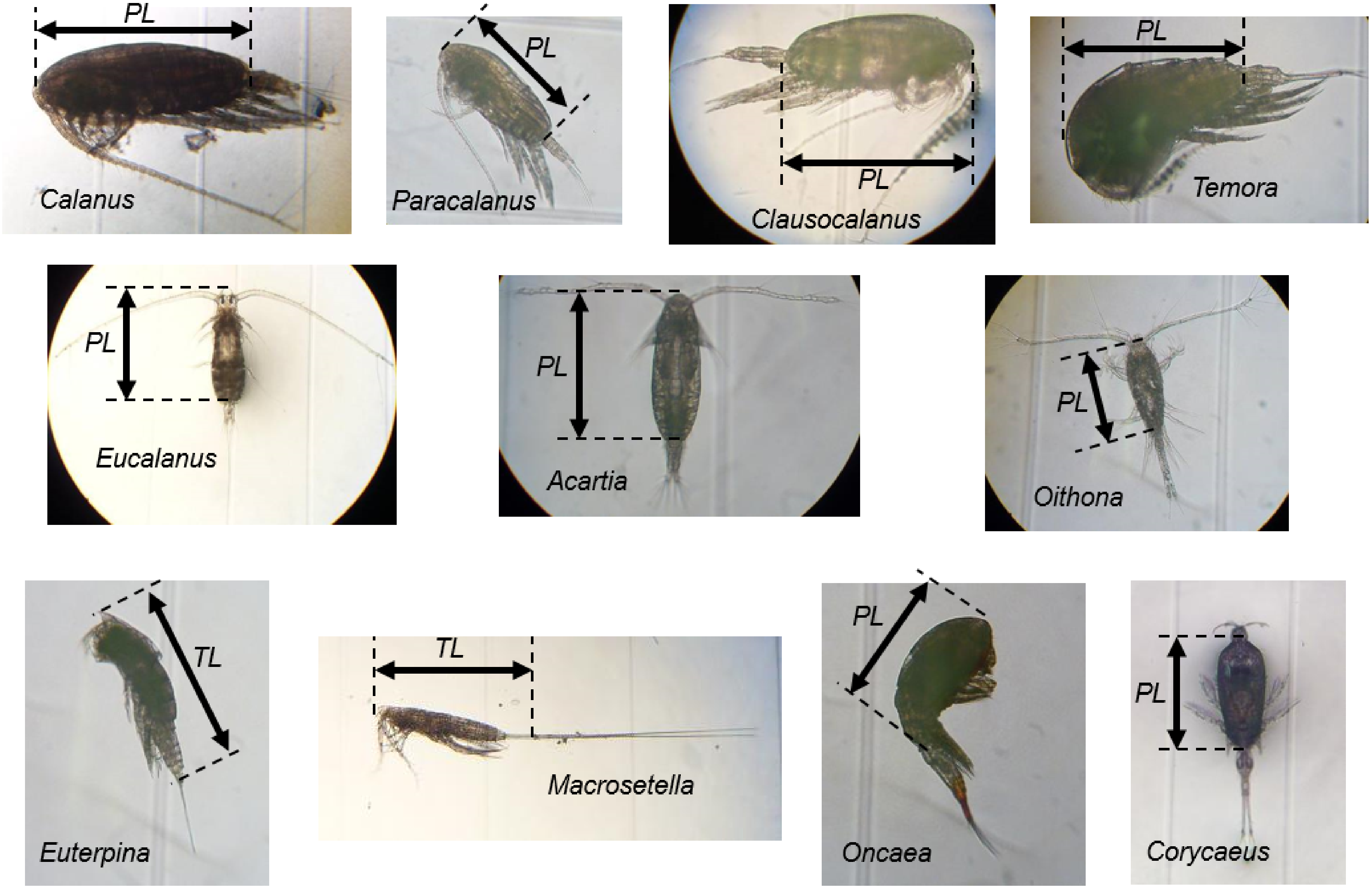


Figure 2 Measurements of body lengths for copepods. *PL*: prosome length; *TL*: total body length.

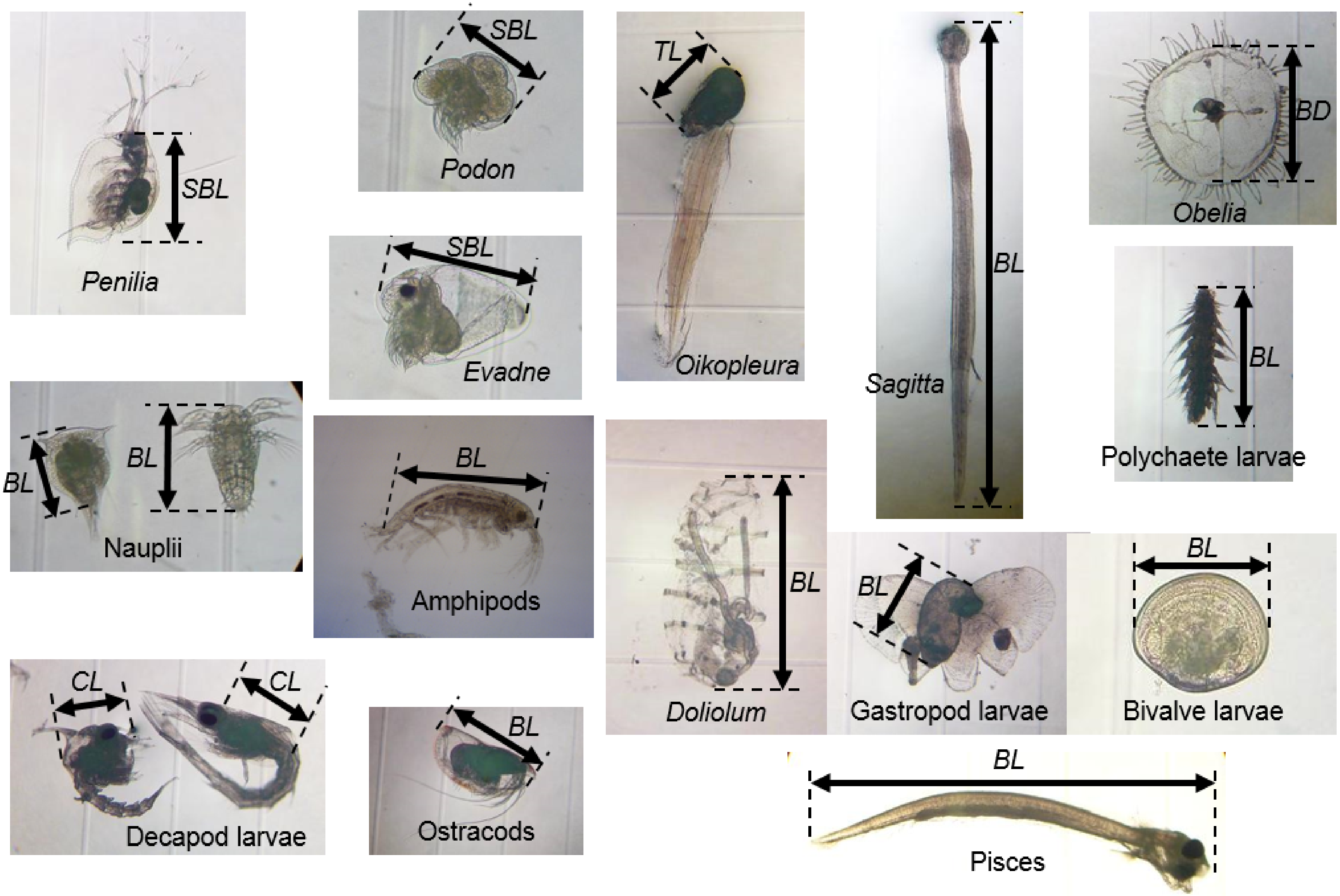


Figure 3 Measurements of body lengths for non-copepods. *BL*: body length; *SBL*: standard body length; *CL*: carapace length; *TL*: trunk length; *BD*: bell diameter.

- Abundance (A, inds. m^{-3})

- Biomass (B, mg C m^{-3}): $B = \sum A \times Wc$
  where Wc: individual weight (µg C).

- Daily production rate (PR, mg C m^{-3} d^{-1}): $PR = \sum A \times Wc \times G$
  where G: individual specific growth rate (d^{-1}).

- Food requirement (FR, mg C m^{-3} d^{-1}): $FR = Res / (As - Gr)$
  where Res: respiration rate (µL O_2 ind.$^{-1}$ h^{-1}), As (assimilation rate): 0.7 (Ikeda & Motoda 1978),
  Gr (gross growth efficiency): 0.3 (Ikeda and Motoda 1978), respiratory quotient: 0.97 (Gnaiger 1983)

Appendicularians (T: 15°C): $\log_{10} Res = -1.38 + 0.81 \log_{10} W$ (Gorsky *et al*. 1987)
(T: 20°C): $\log_{10} Res = -1.27 + 0.88 \log_{10} W$
(T: 24°C): $\log_{10} Res = -1.27 + 0.88 \log_{10} W$
where W: individual weight (µg DW), Q_{10}: 2.45 (15–20°C), 3.75 (20–24°C).

Copepods: $\ln Res = 0.124 + 0.78 \ln Wc + 0.073T$ (Ikeda *et al*. 2001)
Others: $\ln Res = 0.524 + 0.8354 \ln Wc + 0.0601T$ (Ikeda 1985)
where Wc: individual weight (mg C).

Table 1 Length-weight regression equations employed to estimate carbon weight for mesozooplankton.

Taxonomic group	Regression equation	Units	Reference
Copepods			
Calanus	$Wc = 3.84 \times 10^{-10}\ PL^{3.378}$	µg C, µm	Uye (1988)
Paracalanus	$Wc = 3.54 \times 10^{-9}\ PL^{3.128}$	µg C, µm	Uye (1991)
Acartia	$Wc = 3.09 \times 10^{-9}\ PL^{3.08}$	µg C, µm	Uye (1982)
Centropages	$Wc = 6.46 \times 10^{-9}\ PL^{2.97}$	µg C, µm	Uye (1982)
Euchaeta	$Wc = 5.62 \times 10^{-7}\ PL^{2.45}$	µg C, µm	Uye (1982)
Oithona	$Wc = 1.83 \times 10^{-6}\ PL^{2.05}$	µg C, µm	Uye & Sano (1998)
other calanoids, cyclopods and poechilostmatoids	$Wc = 4.27 \times 10^{-9}\ PL^{3.07}$	µg C, µm	Uye (1982)
Microsetella	$Wc = 2.65 \times 10^{-6}\ TL^{1.95}$	µg C, µm	Uye *et al*. (2002)
other harpacticoids	$Wc = 8.51 \times 10^{-10}\ TL^{3.26} \times 0.457$	µg C, µm	Hirota (1986)
Crustacean nauplii	$Wc = 1.51 \times 10^{-5}\ BL^{2.94}$	ng C, µm	Uye *et al*. (1996)
Cladocerans			
Penilia	$Wc = 1.82 \times 10^{-13}\ TCL^{4.51}$	µg C, µm	Uye (1982)
Podon, *Evadne*	$Wc = 7.08 \times 10^{-12}\ TCL^{4.15}$	µg C, µm	Uye (1982)
Ostracods	$Wc = 7.08 \times 10^{-12}\ TCL^{4.15}$	µg C, µm	Uye (1982)
Decapod larvae	$Wc = 9.12 \times 10^{-9}\ CL^{3.28} \times 0.416$	µg C, µm	Hirota (1986)
Lucifer	$Wc = 3.09 \times 10^{2}\ PBL^{2.489} \times 0.1 \times 0.416$	µg C, mm	Vega-Pérez *et al*. (1996), Hirota (1986)
Mysids	$Wc = 6.81 \times 10^{-1}\ CL^{3.10}$	µg C, mm	Uye (1982)
Amphipods	$Wc = 4.85 \times 10^{-3}\ BL^{2.957} \times 0.3693$	mg C, mm	Ikeda (1990, 1991)

Table 1 Length-weight regression equations employed to estimate carbon weight for mesozooplankton (continued).

Taxonomic group	Regression equation	Units	Reference
Cirriped nauplii	$Wc = 2.88 \times 10^{-7}\ BL^{2.65} \times 0.434$	µg C, µm	Hirota (1986)
Appendicularians *Oikopleura*	$Wc = 2.62 \times 10^{-8}\ TRL^{2.83}$	µg C, µm	Sato *et al*. (2001)
Thaliaceans *Doliolum*	$Wc = 1.15 \times 10^{-7}\ BL^{2.54} \times 0.0782$	µg C, µm	Hirota (1986), Madin *et al*. (1981)
Chaetognaths	$Wc = 5.13 \times 10^{-2}\ BL^{3.16}$	µg C, mm	Uye (1982)
Bivalve larvae	$Wc = 2.00 \times 10^{-3}\ SL^{1.47} \times 0.177$	µg C, µm	Hirota (1986)
Gastropod larvae	$Wc = 7.94 \times 10^{-6}\ SL^{2.46} \times 0.177$	µg C, µm	Hirota (1986)
Polychaete larvae	$Wc = 2.09 \times 10^{-6}\ BL^{2.10} \times 0.512$	µg C, µm	Hirota (1986)
Cnidarians *Obelia*	$Wc = 2.14 \times 10^{-8}\ BD^{2.75} \times 0.089$	µg C, µm	Hirota (1986), Larson (1986)
Fish larvae	$Wc = 2.045 \times 10^{-4}\ BL^{3.385} \times 0.425$	mg C, mm	Shoji (2000), Uye (1982)

Table 2 Regression equations to estimate growth rate (G: d^{-1}) for mesozooplankton.

Taxonomic group	Body size or stage	Regression equation	Reference
Copepods	C1–C6	$\log_{10}G = 0.0246T - 0.2962 \log_{10}Wc - 1.1355$	Hirst & Sheader (1997)
Other crustaceans (Non-copepods)	Wc: ~10 μg C ind.$^{-1}$ Wc: 10–100 μg C ind.$^{-1}$	$\log_{10}G = -1.232 + 0.0246T$ $\log_{10}G = -1.405 + 0.0337T$	Hirst *et al*. (2003)
Appendicularians	All	$G = 0.21 \times e^{0.0815T}$	López-Urrutia (2003)
Thaliaceans	All	$\log_{10}G = 0.0645T + 0.138 \log_{10}Wc - 2.070$	Hirst *et al*. (2003)
Chaetognaths	All	$\log_{10}G = -1.851 + 0.0367T$	Hirst *et al*. (2003)
Others*	Wc: ~10 μg C ind.$^{-1}$ Wc: 10–100 μg C ind.$^{-1}$ Wc: >100 μg C ind.$^{-1}$	$\log_{10}G = -1.067 + 0.0206T$ $\log_{10}G = -1.406 + 0.0326T$ $\log_{10}G = -1.779 + 0.0364T$	Hirst *et al*. (2003)

Others*: molluscan (bivalve and gastropod) larvae, polychaete larvae, cnidarians and fish larvae.

Table 3 Feeding habits of mesozooplankton.

Feeding habit	Copepods	Non-copepods
Herbivorous (HER)	*Calanus, Acrocalanus, Calocalanus, Canthocalanus, Clausocalanus, Ctenocalanus, Eucalanus, Microcalanus, Nannocalanus, Rhincalanus, Paracalanus, Pseudocalanus, Calanoides, Pseudodiaptomus, Undinula, Clytemnestra, Euterpina, Macrosetealla, Microsetella*	Appendicularians, Cladocerans, Crustacean (non-copepod) nauplii, Molluscan (Bivalve and Gastropod) larvae, Polychaet larvae, Thaliaceans
Omnivorous (OMN)	*Acartia*, *Aetideus, Bradyidius, Centropages*, *Chiridius, Gaidius, Lucicutia, Metridia, Oithona, Oncaea*, *Pleuromamma, Scolecithricella, Scolecithrix, Scottocalanus*, *Temora*	Malacostracans (Decapod larvae, Mysids, Amphipods), Ostracods
Carnivorous (CAR)	*Calanopia*, *Candacia*, *Corycaeus, Copilia, Euchaeta*, *Paraeuchaeta*, *Heterorhabdbus, Labidocera*, *Pontellina, Phaenna, Farranula, Sapphirina*	Decapod *Lucifer*, Chaetognaths, Cnidarians, Fish larvae

Daily production rate (PR, mg C m^{-3} d^{-1})

- Secondary production (PR_{SP}): $PR_{SP} = PR_{HER} + 0.5 \times PR_{OMN}$
- Tertiary production (PR_{TP}): $PR_{TP} = PR_{CAR} + 0.5 \times PR_{OMN}$

Food requirement (FR, mg C m^{-3} d^{-1})

- Secondary producers (FR_{SP}): $FR_{SP} = FR_{HER} + 0.5 \times FR_{OMN}$
- Tertiary producers (FR_{TP}): $FR_{TP} = FR_{CAR} + 0.5 \times FR_{OMN}$

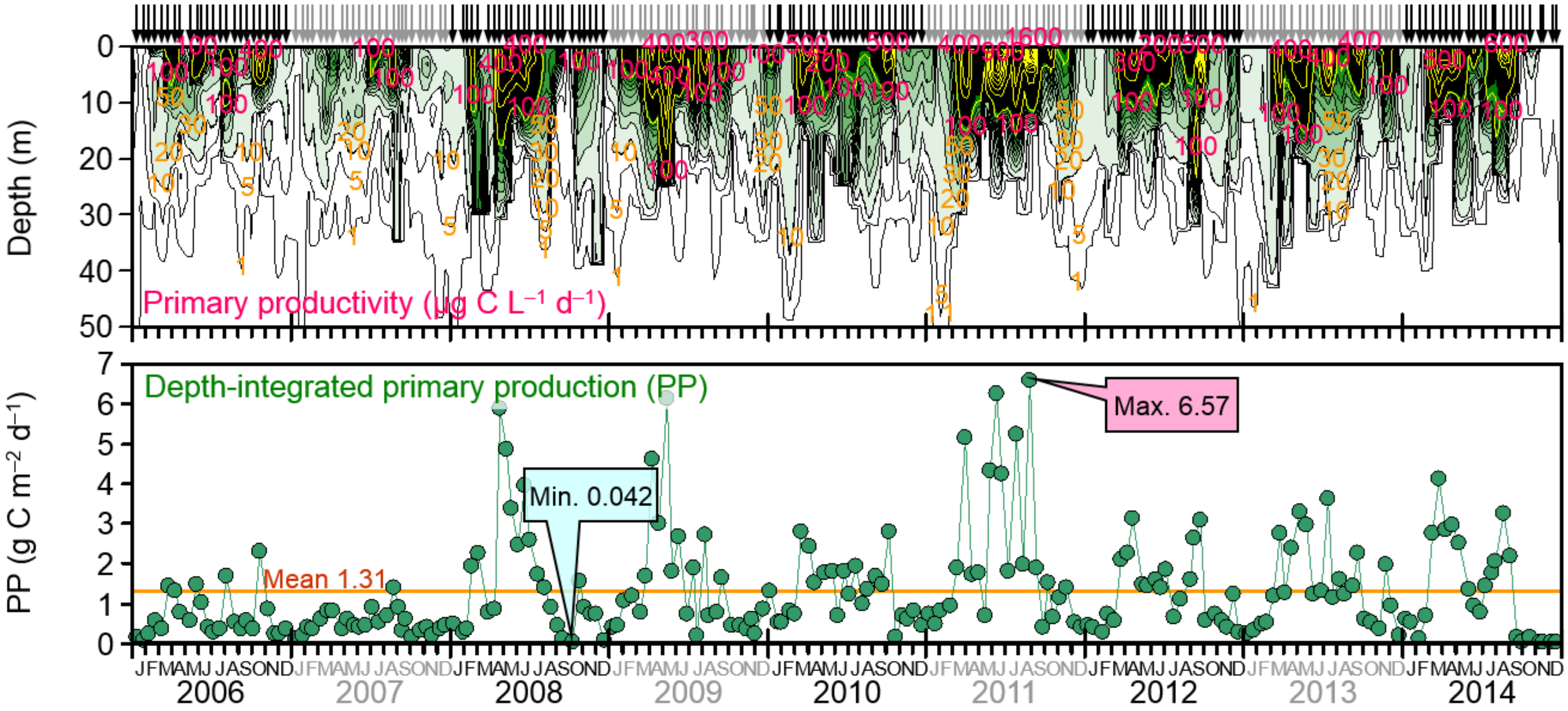


Figure 4 Seasonal and year-to-year variations in phytoplankton primary productivity (upper) and depth-integrated primary production (PP) in the euphotic zone (lower) in Sagami Bay, from January 2006 to December 2014. Arrows denote sampling dates.

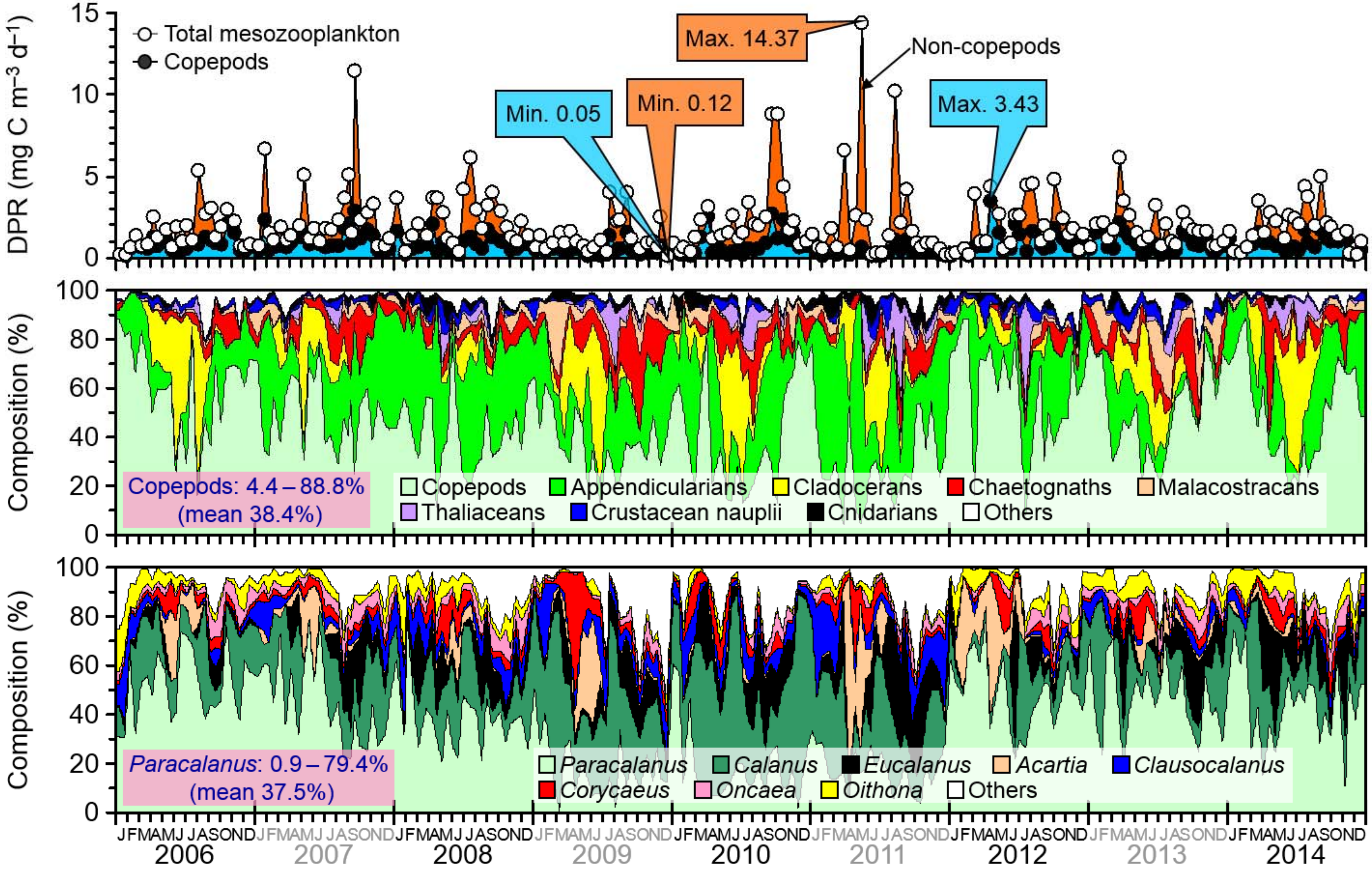


Figure 5 Seasonal and year-to-year variations in daily production rate (DPR) of the total mesozooplankton and copepods (upper) and composition (middle and lower) in Sagami Bay, from January 2006 to December 2014.

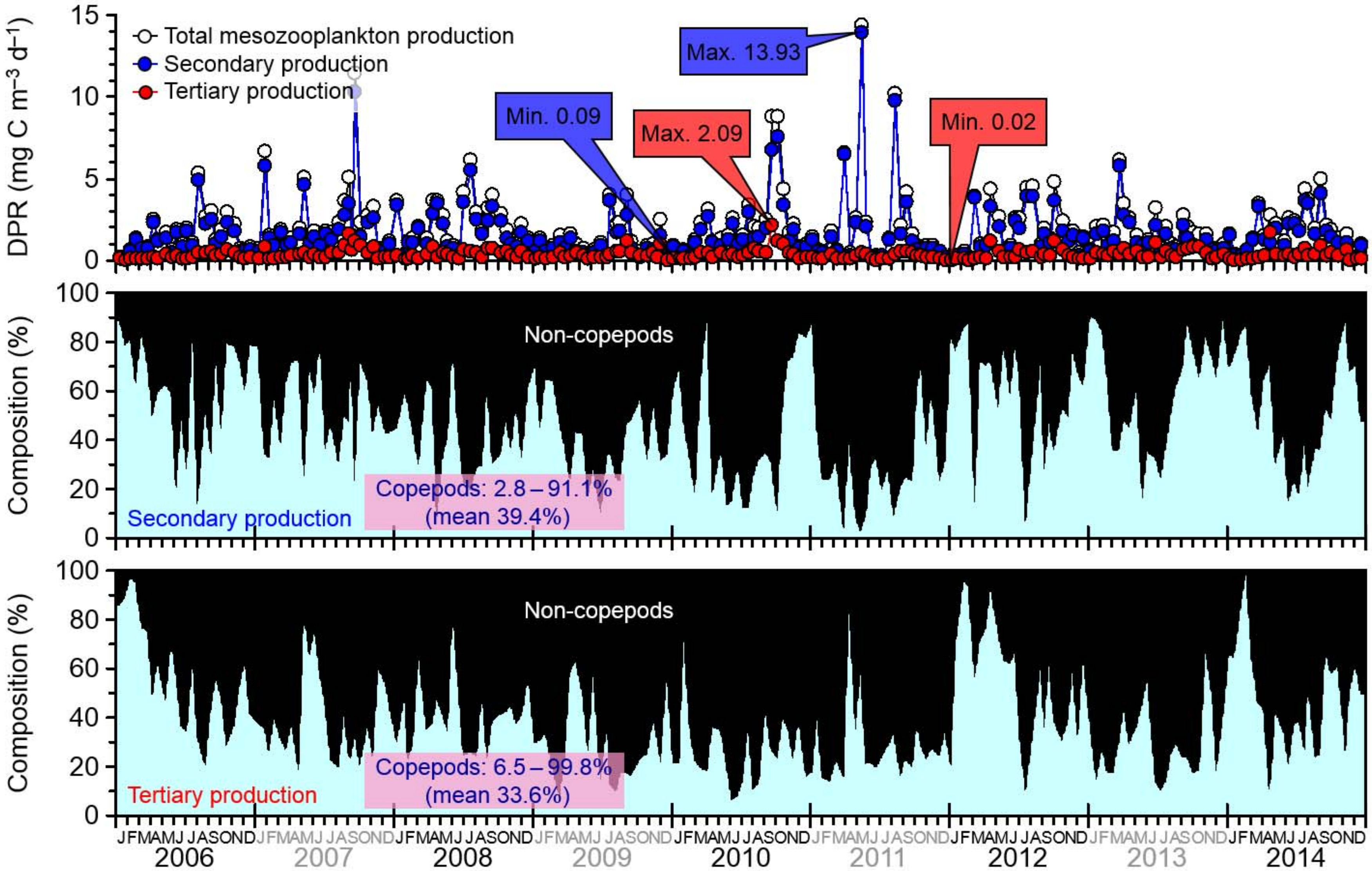


Figure 6 Seasonal and year-to-year variations in mesozooplankton secondary and tertiary production (upper) and composition (middle and lower) in Sagami Bay, from January 2006 to December 2014.

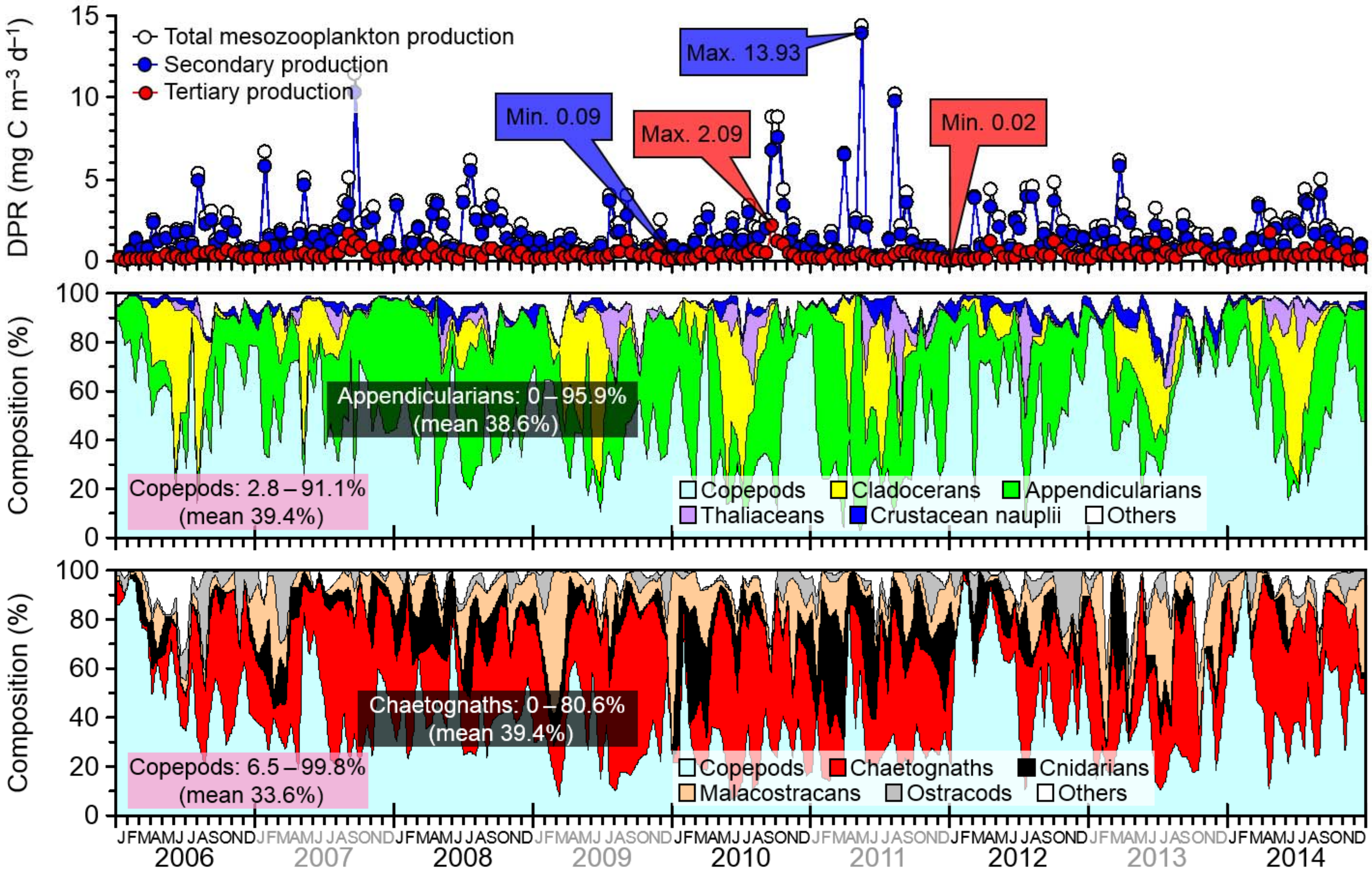


Figure 6 Seasonal and year-to-year variations in mesozooplankton secondary and tertiary production (upper) and composition (middle and lower) in Sagami Bay, from January 2006 to December 2014.

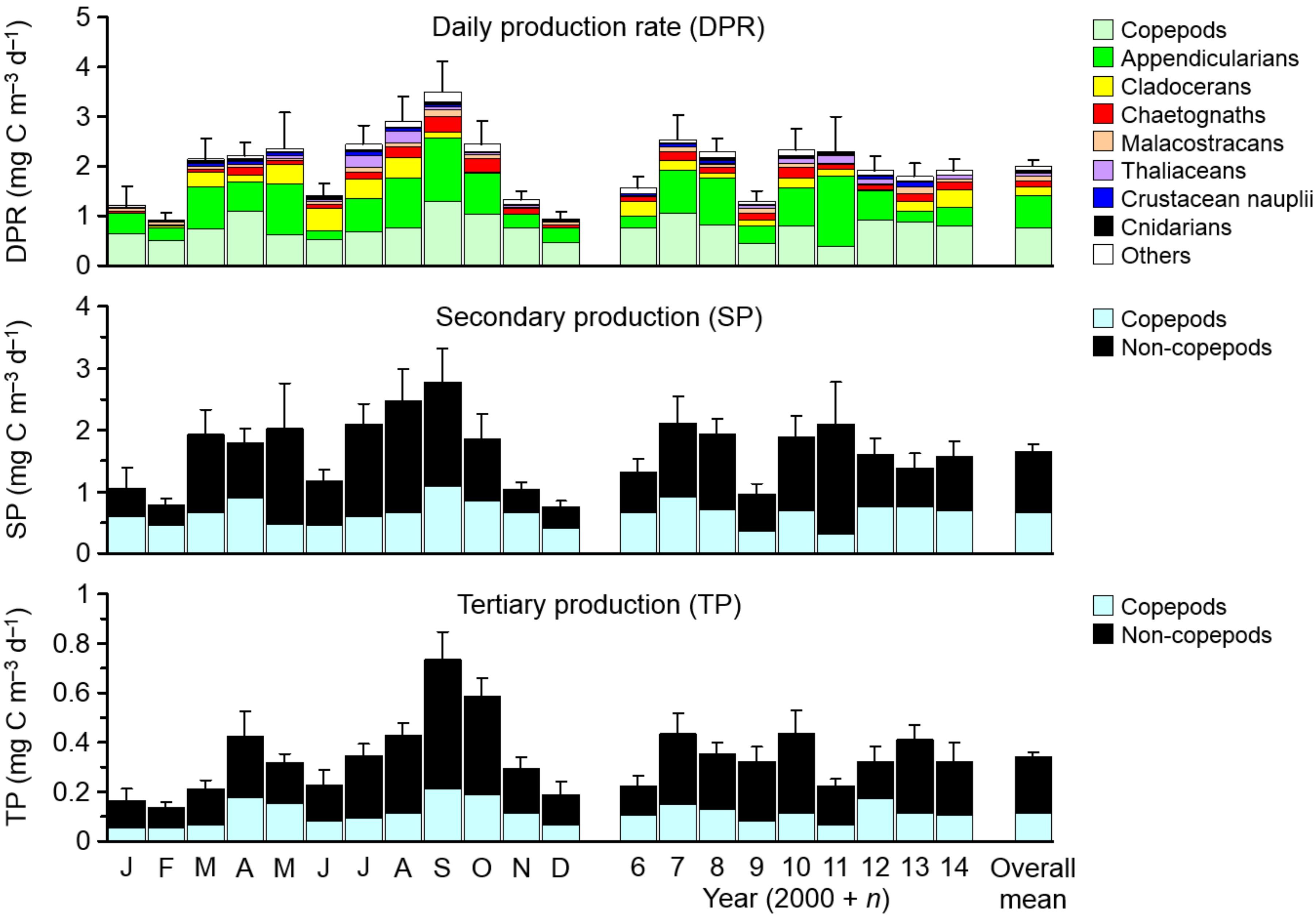


Figure 7 Monthly, yearly and overall mean of mesozooplankton daily production rate (DPR), secondary and tertiary production (SP, TP) in Sagami Bay, from January 2006 to December 2014. Error bars denote SE.

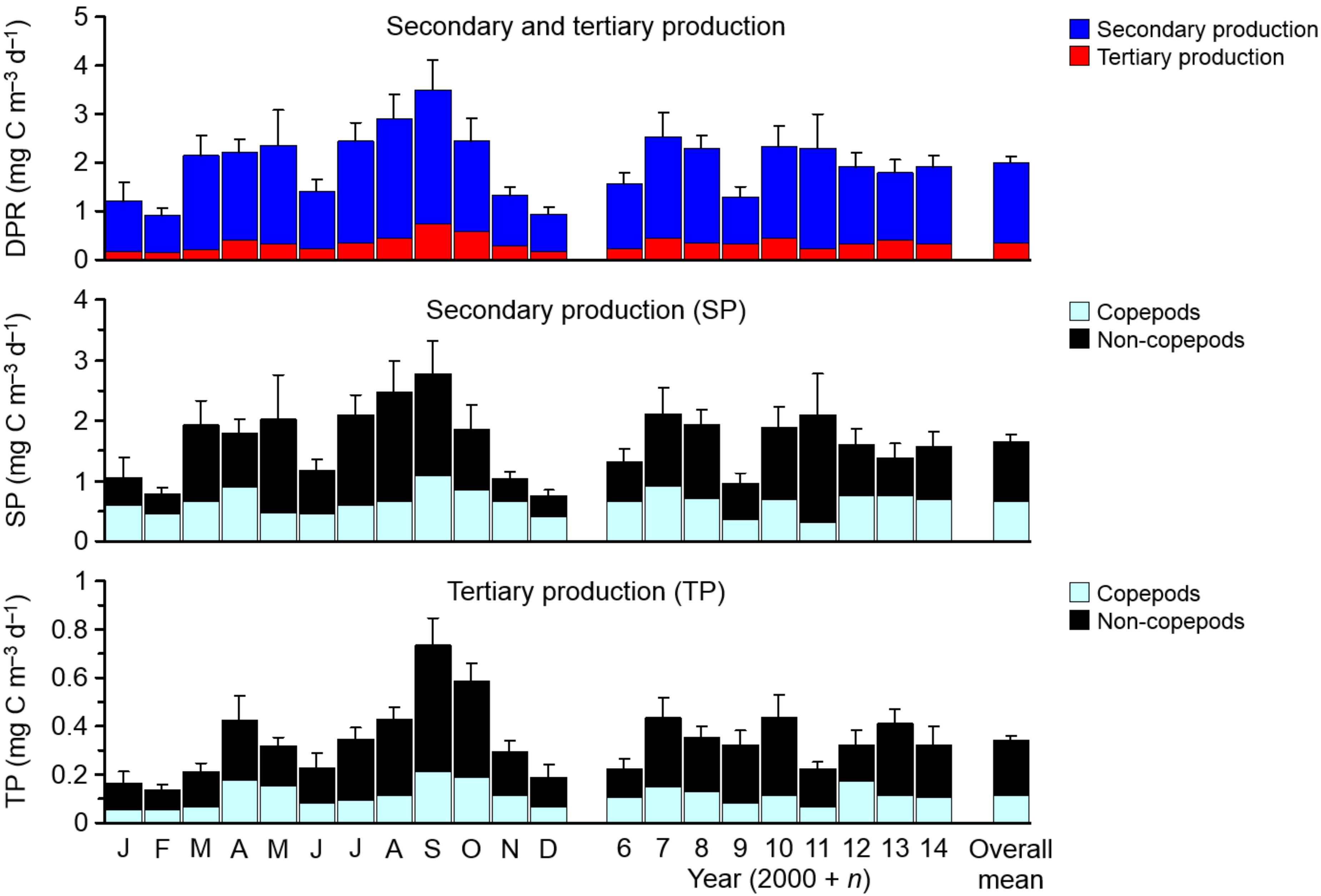


Figure 8 Monthly, yearly and overall mean of mesozooplankton secondary and tertiary production (SP, TP) in Sagami Bay, from January 2006 to December 2014. Error bars denote SE.

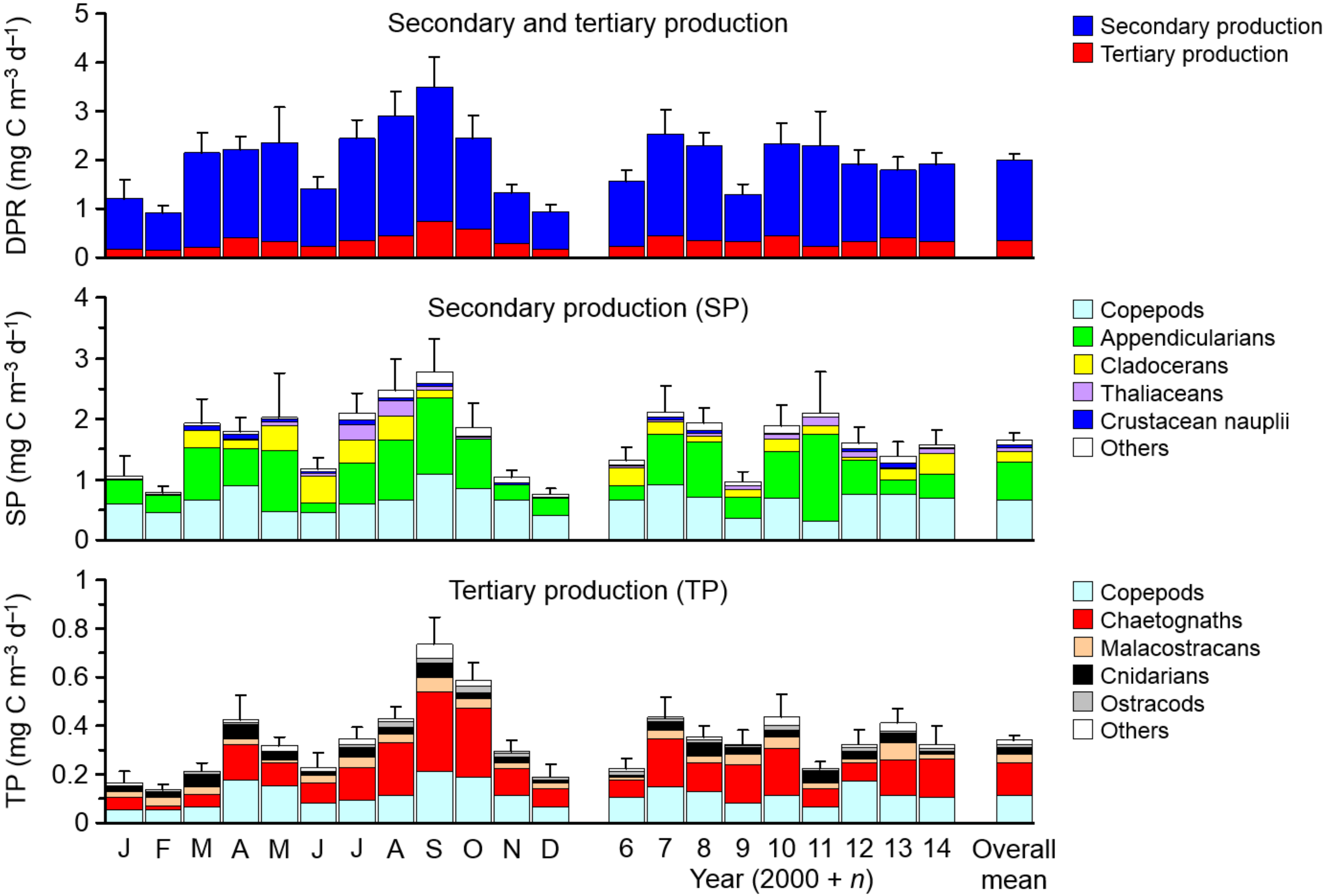


Figure 8 Monthly, yearly and overall mean of mesozooplankton secondary and tertiary production (SP, TP) in Sagami Bay, from January 2006 to December 2014. Error bars denote SE.

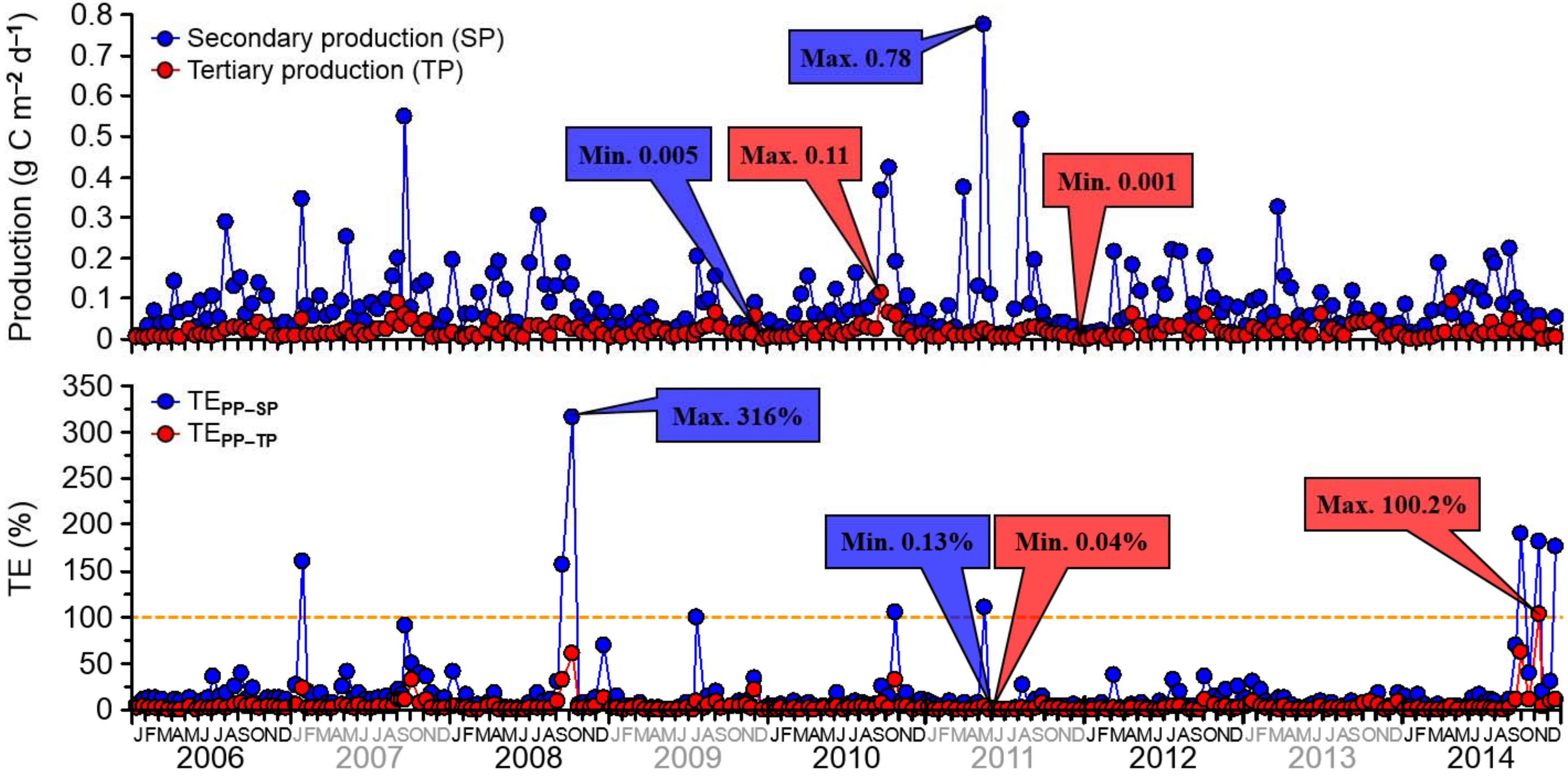


Figure 9 Seasonal and year-to-year variations in depth-integrated mesozooplankton secondary and tertiary production (SP, TP) (upper) and in transfer efficiency from primary production (PP) to mesozooplankton secondary and and tertiary production (TE_{PP-SP}, TE_{PP-TP}) (lower) in Sagami Bay, from January 2006 to December 2014.

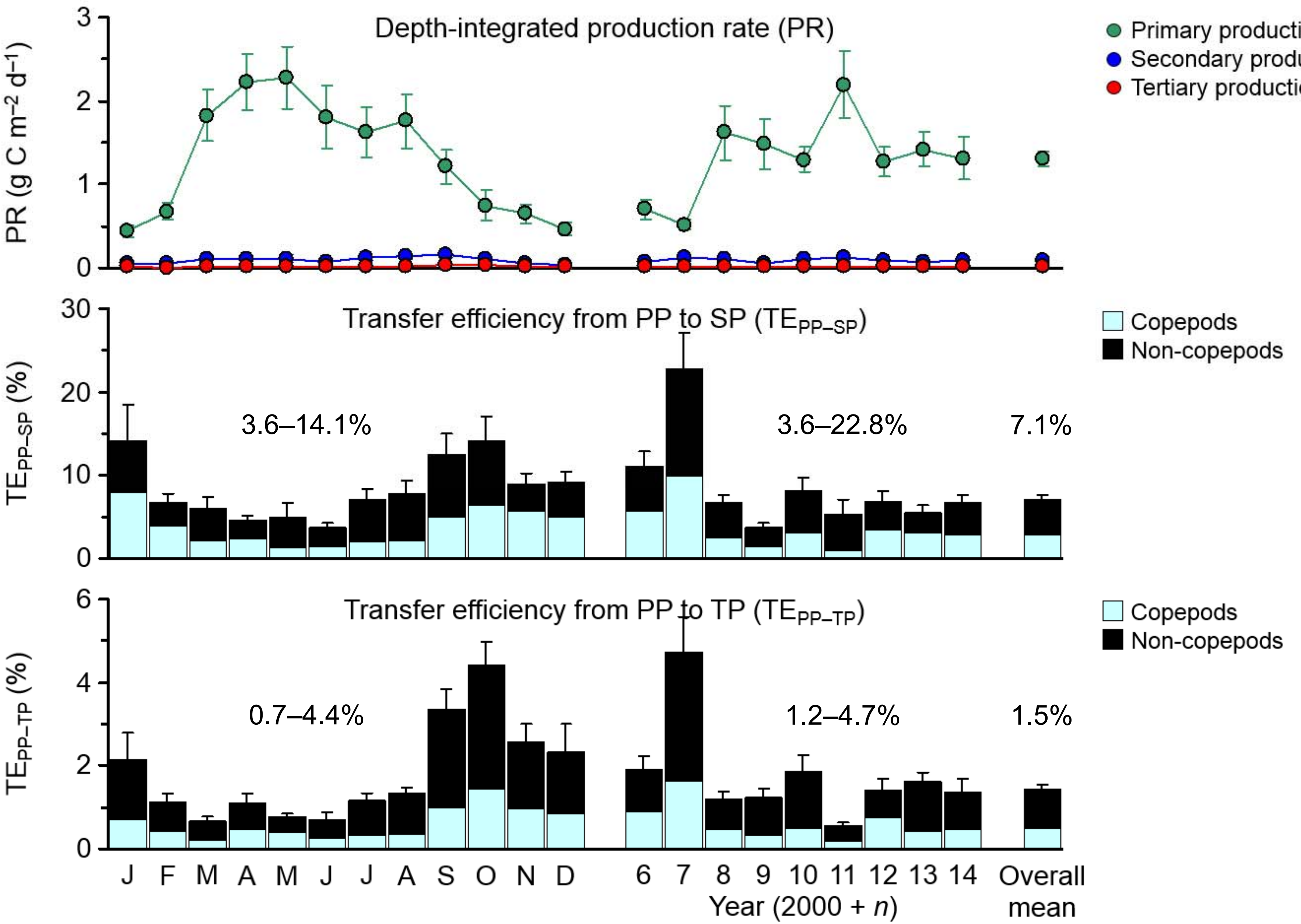


Figure 10 Mean depth-integrated production rate (PR) and transfer efficiency from primary production to secondary and tertiary production (TE_{PP-SP}, TE_{PP-TP}) in Sagami Bay, from January 2006 to December 2014.

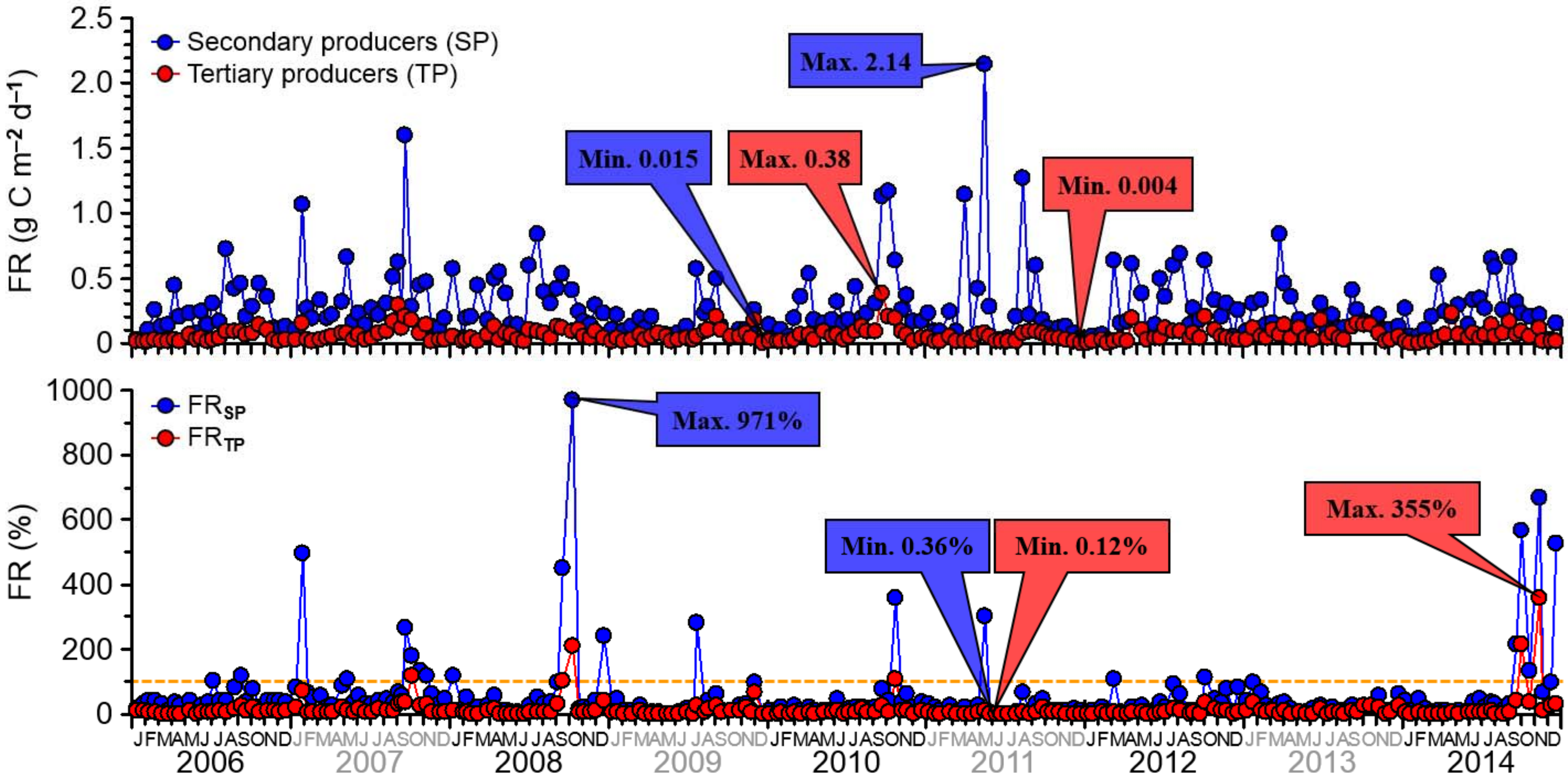


Figure 11 Seasonal and year-to-year variations in depth-integrated food requirement by mesozooplankton secondary and tertiary producers (SP, TP) (upper) and in the ratio of food requirement by mesozooplankton secondary and tertiary producers to primary production (FR_{SP}, FR_{TP}) (lower) in Sagami Bay, from January 2006 to December 2014.

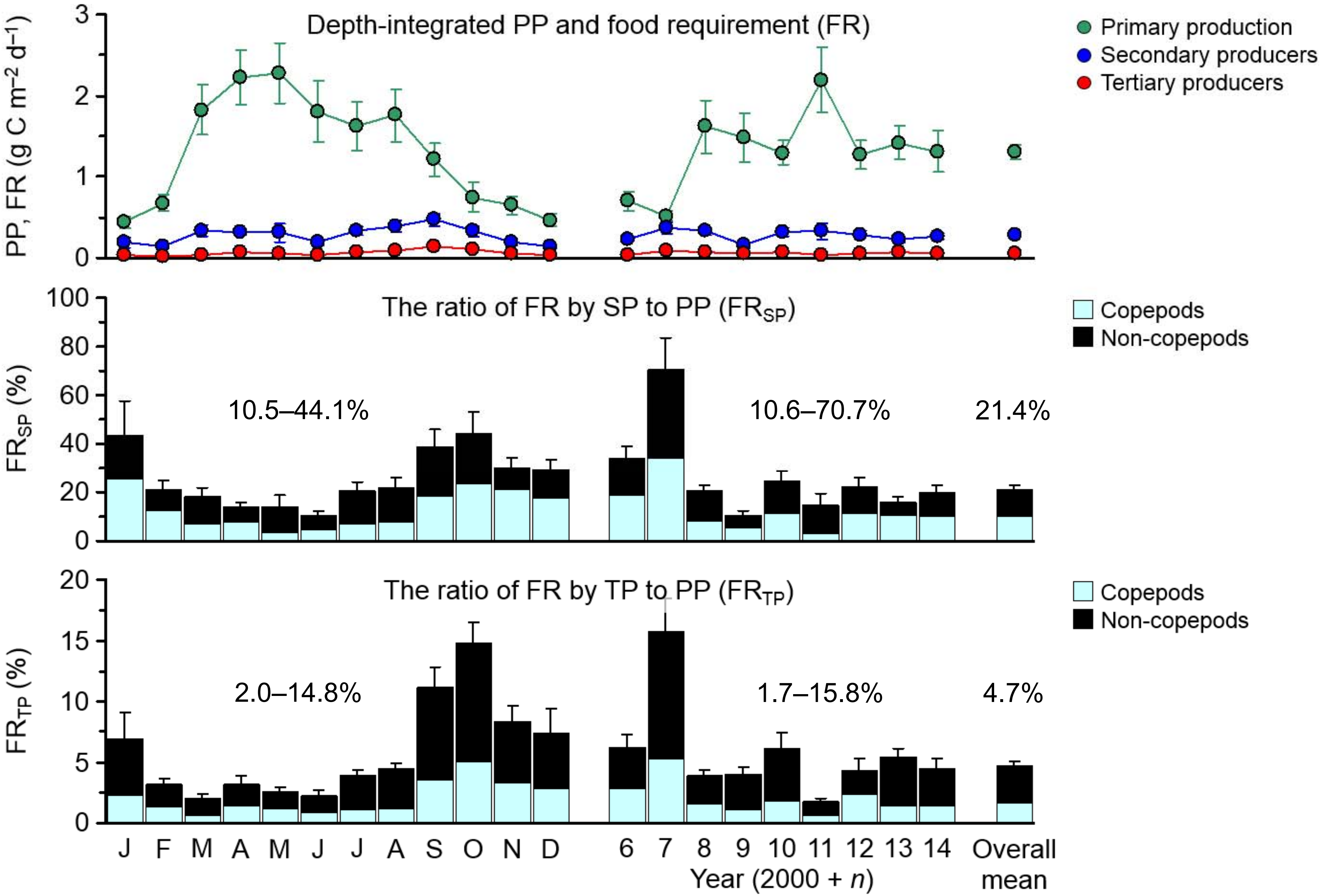


Figure 12 Mean depth-integrated food requirement (FR) and the ratio of food requirement by secondary and tertiary producers to primary production (FR_{SP}, FR_{TP}) in Sagami Bay, from January 2006 to December 2014.

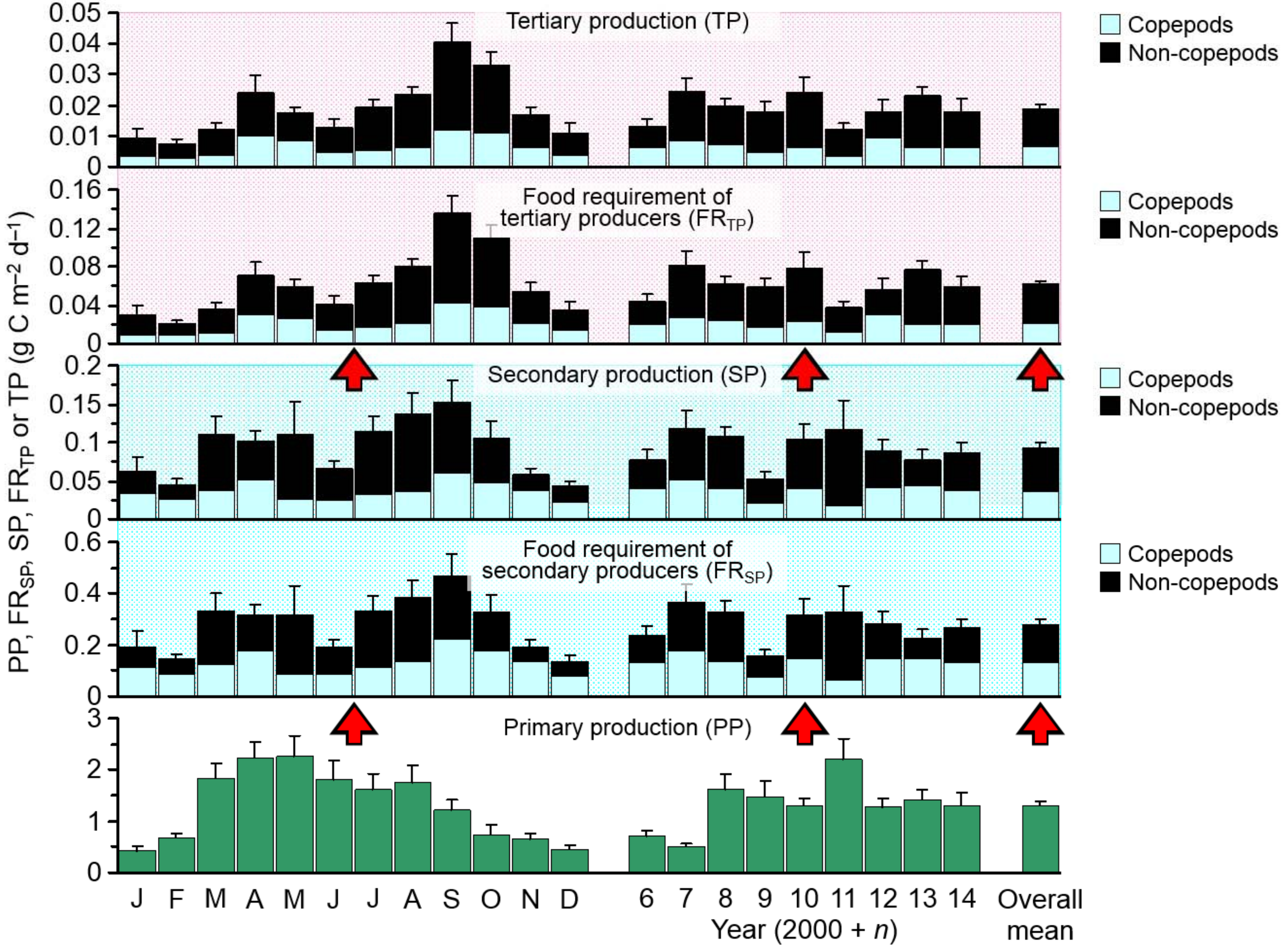


Figure 13 Carbon flow based on production (PR) and food requirement (FR) from primary production (PP) to secondary and tertiary production (SP, TP) in Sagami Bay, from January 2006 to December 2014.

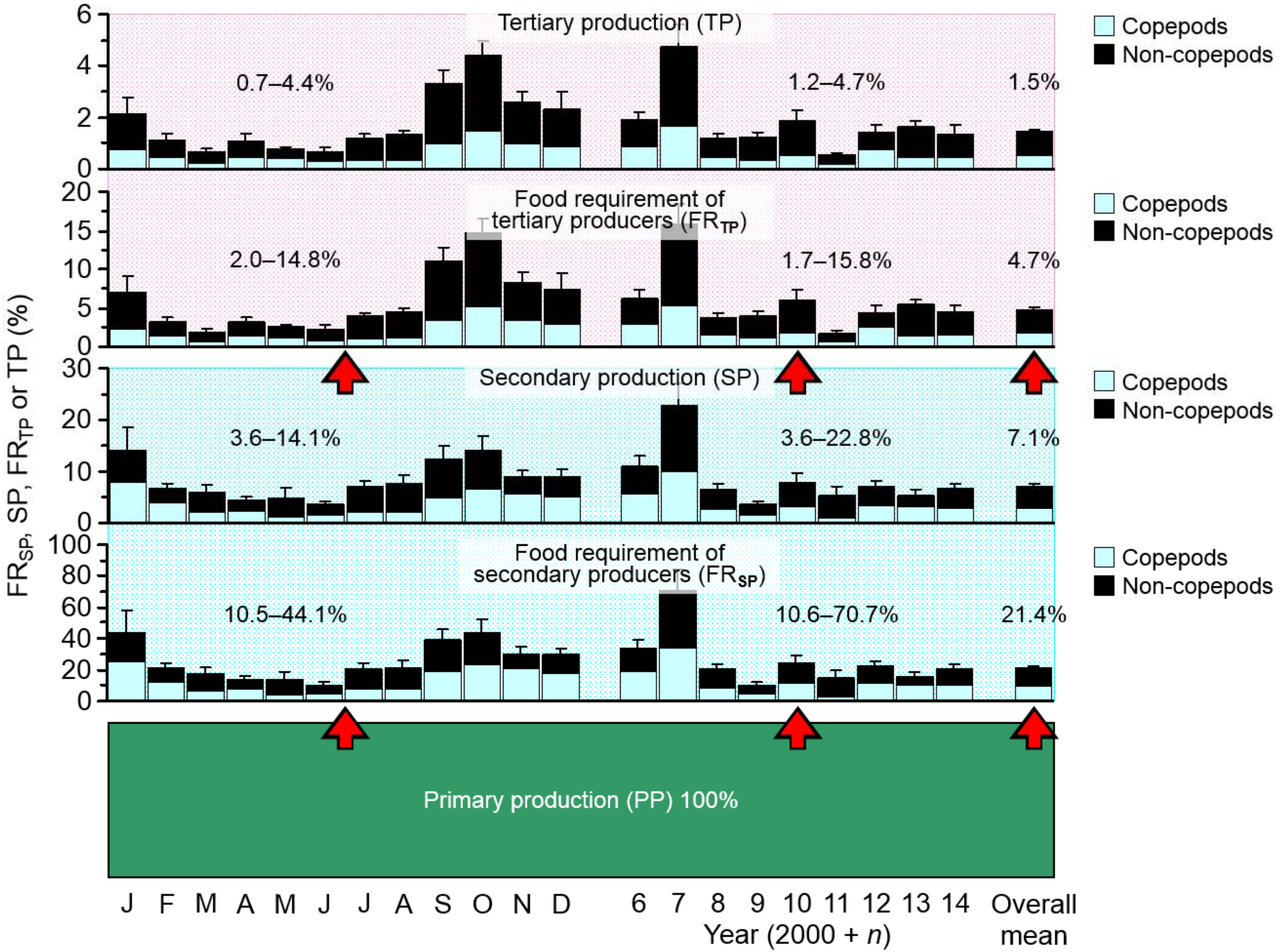


Figure 14 Carbon flow based on production (PR) and food requirement (FR) from primary production (PP) to secondary and tertiary production (SP, TP) in Sagami Bay, from January 2006 to December 2014.