Supplements

Supplement 1. Model description

The ocean model in use was the three-dimensional baroclinic Regional Ocean Modelling System (ROMS) version 2.1, described by Shchepetkin & McWilliams (2005), and references therein. The model domain covers the Barents Sea, the Norwegian Sea and the North Sea (Figure 1 in the main text). The atmospheric forcing was obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996). The ice–ocean model system is run at high spatial resolution for a multi-year simulation and validated against available observations (Budgell 2005, Lien et al. 2006).

The nutrients−phytoplankton−zooplankton−detritus (NPZD) model was developed by Skogen et al. (1995) and Skogen & Søiland (1998), and coupled to the physical model through light, hydrography and horizontal and vertical movements of the water masses. The prognostic variables include dissolved inorganic nitrogen, phosphorous, silicate, two functional types of phytoplankton (diatoms and flagellates), two classes of zooplankton (meso and micro), two classes of detritus pools (dead organic nitrogen and phosphorous), diatom skeleton (biogenic silica) and oxygen. The simulated processes involve primary and secondary production, grazing by zooplankton on phytoplankton and detritus, respiration, mortality, remineralization of dead organic matter, self-shading, turbidity, sedimentation, resuspension, sedimental burial, and denitrification. It has been validated by comparison with field data in the North Sea/Skagerrak (Skogen et al. 1997, 2004, 2007, Søiland & Skogen 2000, Hjøllo et al. 2009), as well as in the Nordic Seas and Barents Sea (Hjøllo et al. 2012, Skaret et al. 2014, Dalpadado et al. 2014).

The *Calanus finmarchicus* individual-based model is two-way coupled to the NPZD-model. A complete, detailed description of the *C. finmarchicus* individual-based model following the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006) is provided in Huse et al. (2018), and also given in Hjøllo et al. (2012). In the following, an ODD summary following Grimm et al. (2020) is provided.

The purpose of the model was to apply a physiological model and a detailed description of the environment in order to understand *C. finmarchicus*'s behavioral and life-history strategies and their effect on population dynamics. Specifically, in this paper we are addressing the following question: How will a suite of sampling patterns influence the estimate of biomass of the spatial-temporal varying *C. finmarchicus* population?

To consider our model realistic enough for its purpose, we used patterns of population dynamics, including quantitative patterns of age-specific population changes over time (see Section 3 in the main text and Supplement 2). The model's ability to reproduce a variety of patterns has been demonstrated by Hjøllo et al. (2012) in the Norwegian Sea, and by Dalpadado et al. (2014) and Skaret et al. (2014) in the Barents Sea.

The model included the following entities: *C. finmarchicus* individuals and their 3D environments. The model addresses the entire life cycle of *C. finmarchicus* simulated using the super-individual approach, where a super-individual represents many (~10^{12}) identical individuals (Scheffer et al. 1995). The state variables and attributes characterizing these entities are listed in Table S1. The attribute vector (Chambers 1993) for super-individuals consist of 13 different states; among other their stage, internal number (number of *C. finmarchicus* individuals represented by the super-individual), weight, fat level, age, and position. The strategy vector (Huse et al. 2018), contains all the life history and behavioral strategies of individuals and comprises six behavioral and life-history traits.

The most important processes of the model, which are repeated daily, are movement, growth, mortality including predation, and reproduction of *C. finmarchicus*. The feeding and growth model is adapted from Carlotti & Wolf (1998), and it is assumed here that the copepod feeds on phytoplankton and microzooplankton. The copepod goes through 13 different stages including an egg stage, six nauplii stages N1-N6, five copepodite stages CI-CV, and an adult stage CVI (Table S2). The copepod is assumed to change stage when a stage specific critical weight is achieved. Reproduction of adults can take place when their weight is above a threshold value and they have attained enough fat reserves to spawn a batch of eggs. For the egg and nauplii stages, mortality consists of tactile predation and a daily background mortality rate. For the copepodite and adult stages, mortality is attributed to predation from pelagic fish (herring, blue whiting, and mackerel), mesopelagic fish and tactile predators, starvation when the weight goes below the critical weight, and exhaustion when number of eggs spawned exceed a threshold value. In addition, slightly increased autumn background mortality for super-individuals not in the overwintering stage is added. The movement of egg-N2 are passive drifting with the horizontal flow with an additional random walk component to represent sub grid "diffusion" processes. In the vertical, movement is calculated either as a function of turbulence and sinking (stages <N3) or by adapted rules. For individuals in diapause, no vertical movement is calculated.

The most important design concepts of the model are the collectives (super-individuals) with emergent properties (mortality, growth, reproduction, and spatial dynamics) that sense (chlorophyll density, day/night and inherited day of start and end of diapause) and interact (indirectly through random cross over in the strategy vectors during reproduction, where an offspring inherits the strategy vector from its parent).

Table S1. Attributes and strategy vectors

Attribute	**Description**
Mynumb	Unique identifier for each super-individual (SI)
Alive	Dead = 0, alive = 1
Inumb	Number of identical siblings represented by SI
Stage	Egg, nauplia (NI-NVI), Copepodites (CI-CVI)
Age	Age in days
Lstage	Stage longevity in days
Sweight	Structural weight (excluding fat reserves) in µg
Fat	Fat reserves in µg (for CIII to adults)
Moult	Moult cycle fraction (for eggs and N1-N2)
Maxegg	Number of eggs to be spawned
Cumeggs	Accumulated number of eggs spawned
Position	Grid position (x, y, z)

Activity level	0 = diapause, 1 = active, 2 = descending, 3 = ascending
Parent	Identity number of parent SI
Sex	0 = male, 1 = female (only for adult stage)
Death	Spawned out, out of map, stage longevity, internal number <1, unproductive sex (male)
OWD	Overwintering depth (initial 300-1100m)
WUD	Wake-up-day from diapause (initial day 60 ± 30 d)
AFD	Allocation-to-fat-day (WUD + 60 ± 30 d)
FSR	Fat to soma ratio (0.4 ± 0.2)
VM_1 VM_2	Parameters used for defining size-based vertical position during daytime. VM_1: 13 VM_2: 20500.

Table S2. Overview of model parameters

Parameters	**Value**	**Reference**
N1-N2 stage specific weight	0.05 µgC	Carlotti & Wolf (1998)
N3	0.2 µgC	Carlotti & Wolf (1998)
N4	0.3 µgC	Carlotti & Wolf (1998)
N5	0.45 µgC	Carlotti & Wolf (1998)
N6	0.75 µgC	Carlotti & Wolf (1998)
CI	1.1 µgC	Carlotti & Wolf (1998)
CII	2.5 µgC	Carlotti & Wolf (1998)
CIII	7 µgC	Carlotti & Wolf (1998)
CIV	15 µgC	Carlotti & Wolf (1998)
CV	40 µgC	Carlotti & Wolf (1998)
CVI	90 µgC	Carlotti & Wolf (1998)
Mortality egg-N2	0.3 d^{-1}	Ohman et al. (2004)
Mortality N1-C2	0.05 d^{-1}	Ohman et al. (2004)
Mortality C3-CIV	0 d^{-1}	Ohman et al. (2004)
Egg stage longevity parameter	595	Lynch et al. (1998)

N1 –«-	387	Lynch et al. (1998)
N2	582	Lynch et al. (1998)
N3	1387	Lynch et al. (1998)
N4	759	Lynch et al. (1998)
N5	716	Lynch et al. (1998)
N6	841	Lynch et al. (1998)
C1	966	Lynch et al. (1998)
C2	1137	Lynch et al. (1998)
C3	1428	Lynch et al. (1998)
C4	2166	Lynch et al. (1998)
C5	4083	Lynch et al. (1998)
Cad	4083	Lynch et al. (1998)
Maximum numbers of eggs	800	Carlotti & Wolf (1998)
Minimum structural spawning weight	90 µgC	Carlotti & Wolf (1998)
Eggweight	0.23 µgC	Carlotti & Wolf (1998)
Eggfat	0.115 µgC	Carlotti & Wolf (1998)
Clutch size	50 eggs	Lynch et al (1998)
Maximum ingestion I_{max}	0.7 d^{-1}	Campbell et al. (2001)
Q_{10}	2.1 wd	Carlotti & Wolf (1998)
QR_{10}	3.4 wd	Carlotti & Wolf (1998)
Diapause metabolism	0.1% d^{-1}	Fiksen (2000)

Supplement 2. *Calanus finmarchicus* module: abundance validation

Horizontal fields:

1995 is the starting year of the simulation. Modelled mean abundance in May 1995 is shown in Figure S1, and three core areas at 65°N/5°E, 71°N/8°E and north of 72°N with abundance of the order 150000-200000 individuals m^{-2} can be seen. Two tongues stretching towards Jan Mayen are also visible, as well as high abundance along the west of Svalbard. Westward of 0°E and in the coastal waters of Norway the abundance is very low. From Broms et al.'s (2009) Figure 2A, the outer limit for abundance is approximately the same. The two southern cores are also seen, while the northern core is covered by only 1 observation, which shows abundance of 50000-100000 ind m^{-2}, corresponding well to values from the model (~100000 ind m^{-2}).

Seasonal cycle:

Bi-weekly averaged modelled *C. finmarchicus* abundance and distribution among stages for 5 different positions are shown in Figure S2. At all stations, the abundance in January and February is low and dominated by CV, before adults appear in March and reproduction starts. Young copepods can be found in varying amounts until September on all stations, but at the end of the year mostly CVs are found. Several peaks in abundance at the Atlantic, Coastal and Saltenfjord stations are seen, but the maximum in abundance occurs in June for all stations except at StM and Arctic, where the maximum occurs 1 month later. The abundance maximum varies between 15000 (Saltenfjord) and 600000 (Atlantic). From Melle et al.'s (2014) Figures A5 and A6, observed abundance is generally considerably lower (except at Saltenfjord where modelled abundance is the lowest), the maximum occurs earlier in spring, and the high summer abundance found in the model is not visible.

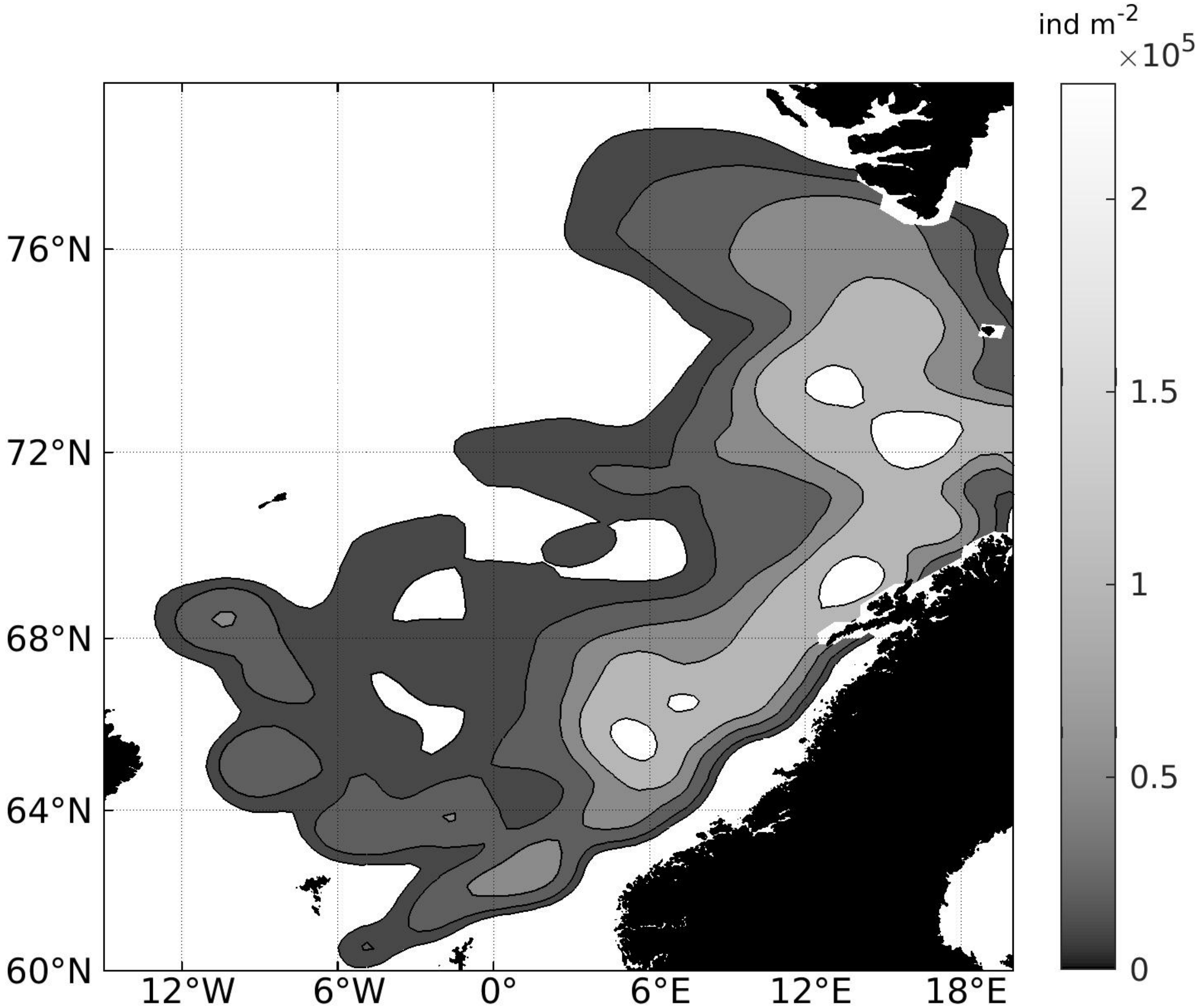

Figure S1. Modelled *C. finmarchicus* abundance May 1995, upper 200 m. Units are number of individuals per square meter (ind m^{-2}).

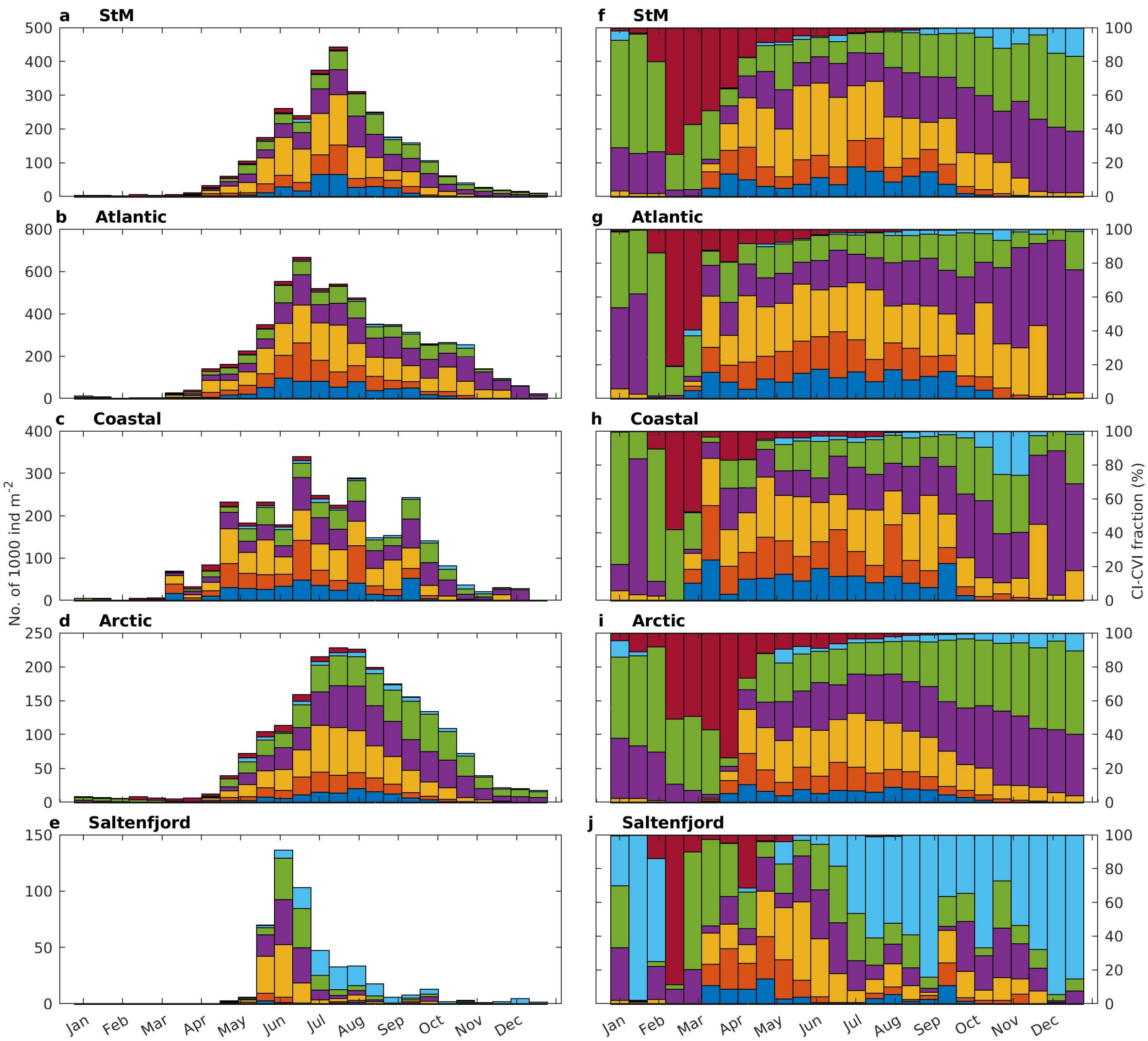

Figure S2. Stage resolved bi-weekly averaged upper 200 meters *C. finmarchicus* abundance (number of 1000 ind m^{-2}) to the left, stage fraction to the right, for the period 1996-2005 at five positions in the Norwegian Sea: Station M (66.0°N, 2 °E); Svinøy section, Atlantic part (63.52°N, 2.66°E); Svinøy section, coastal water (62.82°N,4.21°E); Svinøy section, Arctic part (64.51°N, 0.36°E; Saltenfjord (67.23°N,13.65°E)

Vertical distribution and stage development:

The vertical distributed monthly mean abundance at two selected sites, representing Atlantic Waters and the Atlantic/Coastal Water front respectively, for a single year (1997) is shown in Figure S3. In July, both stations are dominated by CIII and CIV in the upper 200 m, and at the coastal station descent of CV into deeper water is seen. From Head et al.'s (2013) Figure 14 (top row), the same pattern is seen, although at the coastal front, a larger number of CIV and CV-individuals are found at depth. In October, from the model both stations have CV-dominated abundance in the upper 200 m, but also significant amounts of CV in overwintering stage and descending into depth, while observations from Head et al. (2013) showed higher concentrations of CV in depth. The total water column abundance in the model is remarkably similar to what is observed (71000 and 131000 vs 70000 and 136000 ind m^{-2} in July; 24000 and 28000 vs 22000 and 47000 ind m^{-2} in October).

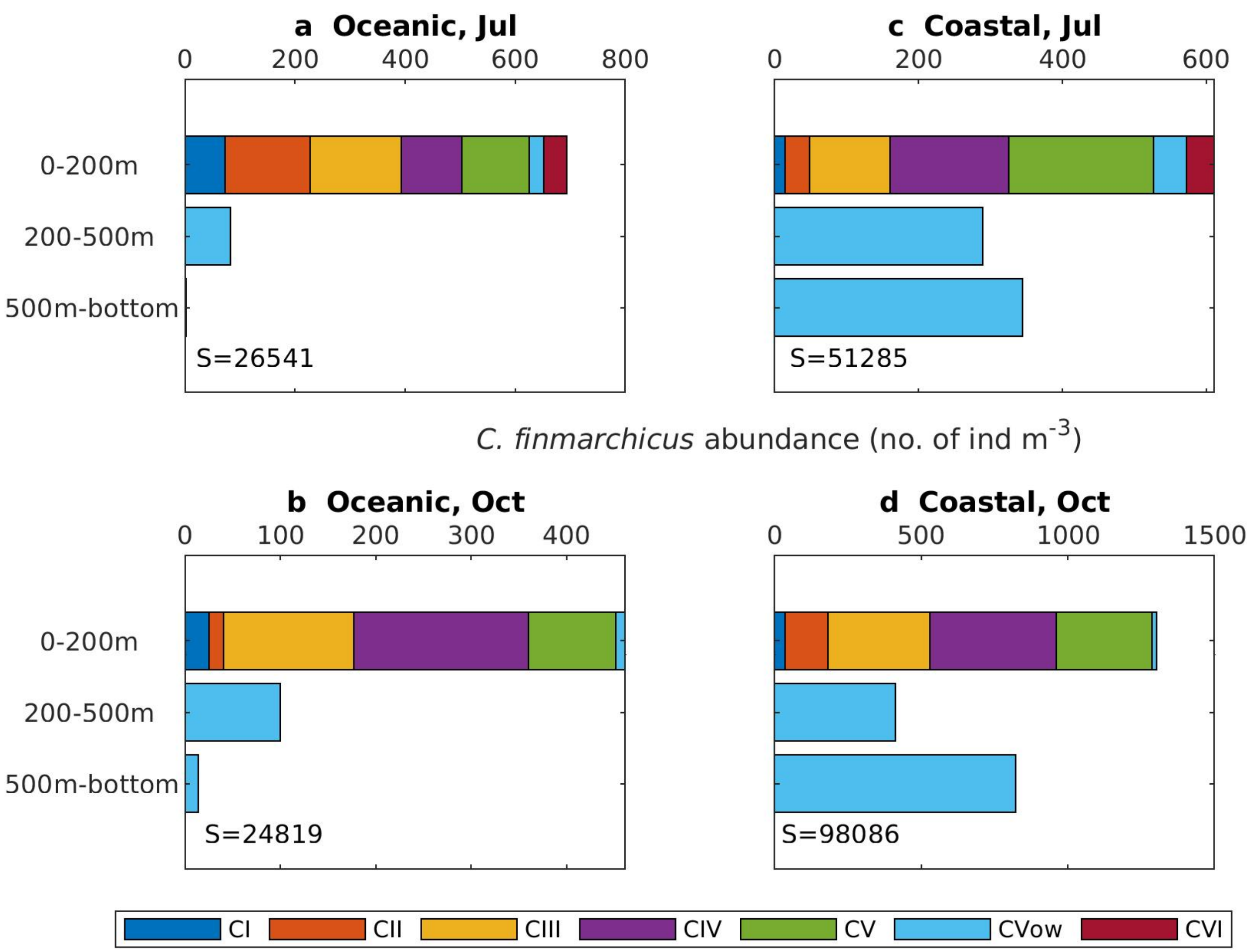

Figure S3. Vertical profiles of modelled mean C. *finmarchicus* abundance (number of individuals m^{-3}) by stage in July (a,c) and October (b,d) in 1997 for the (a,b) oceanic and (c,d) coastal part of the Svinøy section. S is total water column abundance. Oceanic position: 64.67°N, 0°E, depth 2746 m, coastal position: 63.10°N, 4.0°E, depth 767 m

Modelled upper ocean abundance and biomass in two areas roughly corresponding to the Atlantic part of two Continuous Plankton Recorder (CPR)-sections as presented in Strand et al. (2020) are shown in Figure S4. In the northern sector, both adult and young copepodites as well as biomass are found in two distinct peaks: April/May and September (clearly highest values), while in the central Norwegian Sea, a broader peak in abundance and thus biomass is seen from April until October/November. In Strand et al.'s (2020) Figures 10 and 12, for the northern section, spring peak values in abundance is found in Apr (May) for CV-CVI (CV-CVI), similar as in the model, while the observed mid-summer peak is missing in the model or delayed until a strong September peak. The observed maximum biomass values of 35 mg ww m^{-3} corresponds to modelled values of 42 mg ww m^{-3}. In the central Norwegian Sea, elevated levels of abundance and biomass with spring (April-June) and autumn (October) peaks are found both in model and the CPR-observations. Lower maximum biomass than in the northern section is found both for observations (25 mg ww m^{-3}) and model (23 mg ww m^{-3}). The number of CI-CIV copepodites is 5 times higher than the number of CV-CVI individuals both in the model and in the CPR observations.

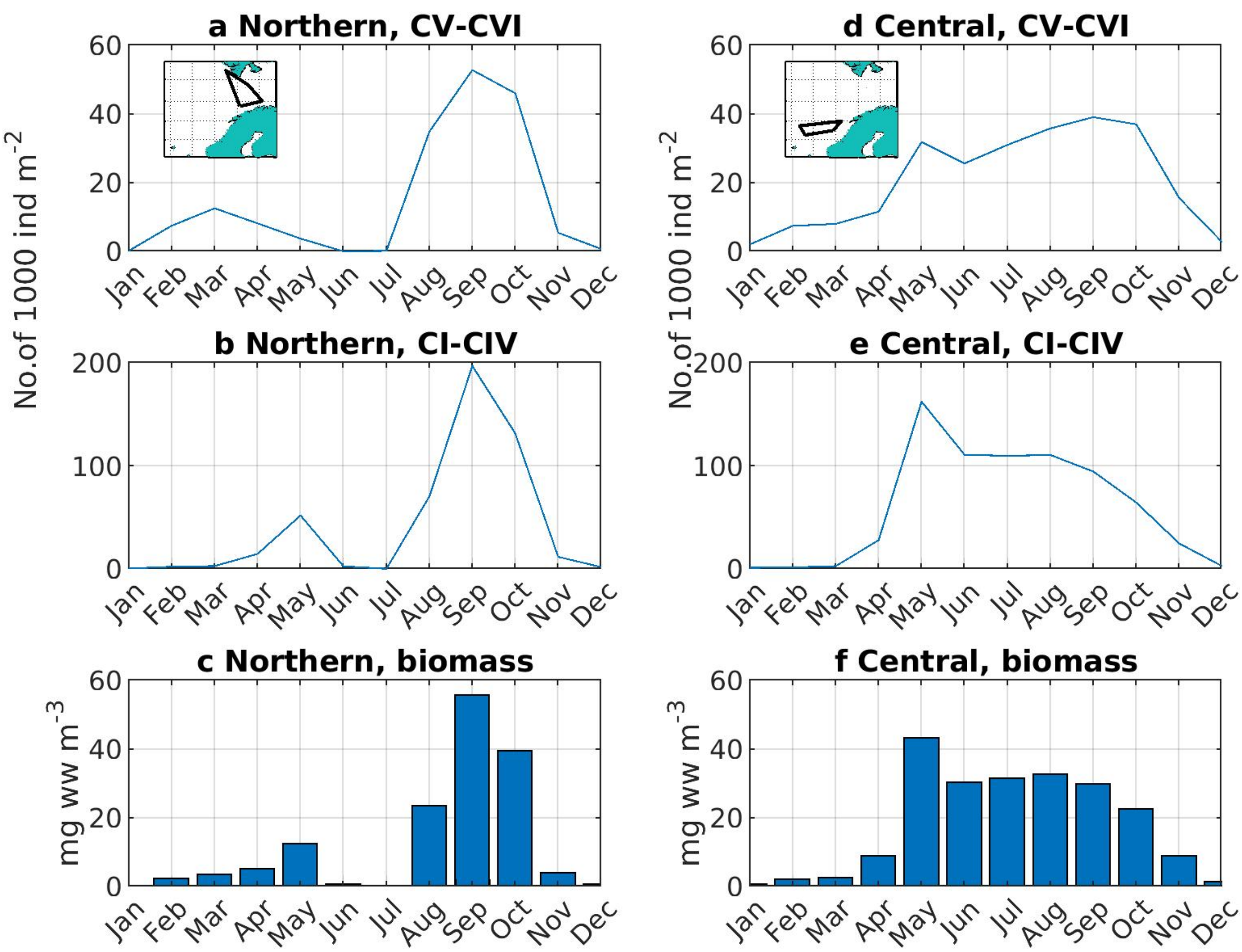

Figure S4. Modelled monthly mean number of *C. finmarchicus* (a,d) CV-CVI individuals, (b,e) CI-CIV individuals, and (d,f) biomass for the (a-c) northern and (d-f) central region in the Norwegian Sea (see map inserts in a and d) in the upper 30 m of the water column for the period 1995-2004. The two regions are chosen to represent the Atlantic water sections as used in Strand et al. (2020)

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