

Table 1. Size range and descriptions of PFT groups used in PlankTOM11. Adapted from Le Quéré et al. (2016).

Name	Abbreviation	Size Range μm	Description/Includes
Autotrophs			
Pico-phytoplankton	PIC	0.5 – 2	Pico-eukaryotes and non N ₂ -fixing cyanobacteria such as <i>Synechococcus</i> and <i>Prochlorococcus</i>
N ₂ -fixers	FIX	0.7 – 2	<i>Trichodesmium</i> and N ₂ -fixing unicellular cyanobacteria
Coccolithophores	COC	5 – 10	
Mixed-phytoplankton	MIX	2 – 200	e.g. autotrophic dinoflagellates and chrysophytes
Diatoms	DIA	20 – 200	
<i>Phaeocystis</i>	PHA	120 – 360	Colonial <i>Phaeocystis</i>
Heterotrophs			
Bacteria	BAC	0.3 – 1	Here used to subsume both heterotrophic <i>Bacteria</i> and <i>Archaea</i>
Protozooplankton	PRO	5 – 200	e.g. heterotrophic flagellates and ciliates
Mesozooplankton	MES	200 – 2000	Predominantly copepods
Macrozooplankton	MAC	>2000	Euphausiids, amphipods, and others, known as crustacean macrozooplankton
Jellyfish zooplankton	JEL	200 – >20,000	Cnidaria medusae, ‘true jellyfish’

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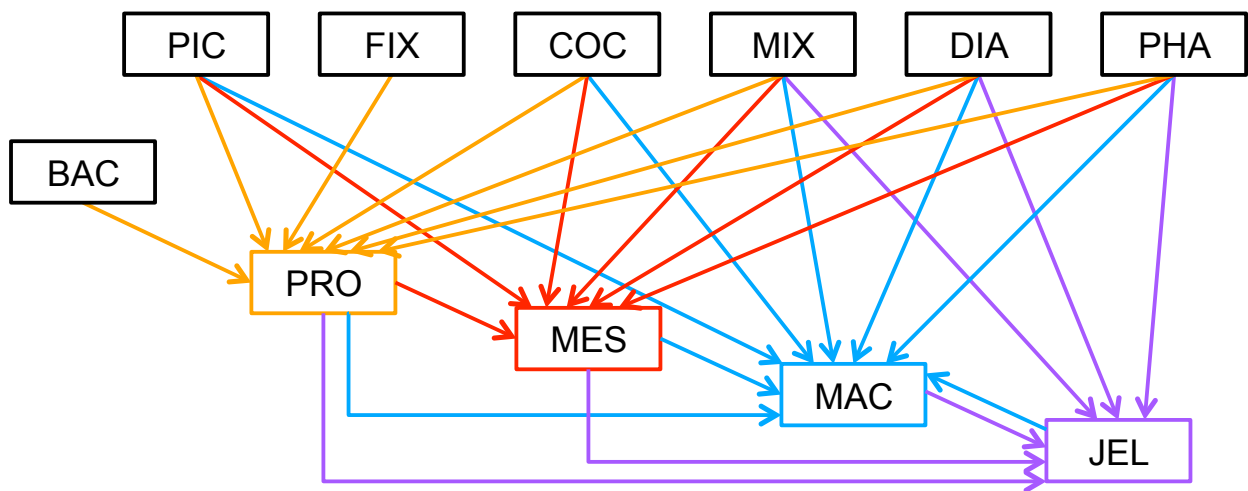
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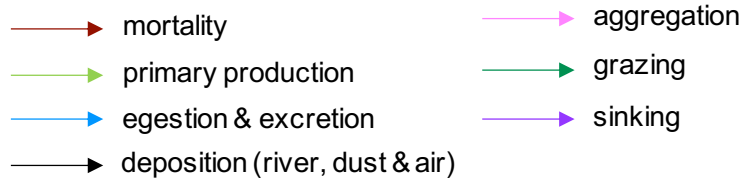
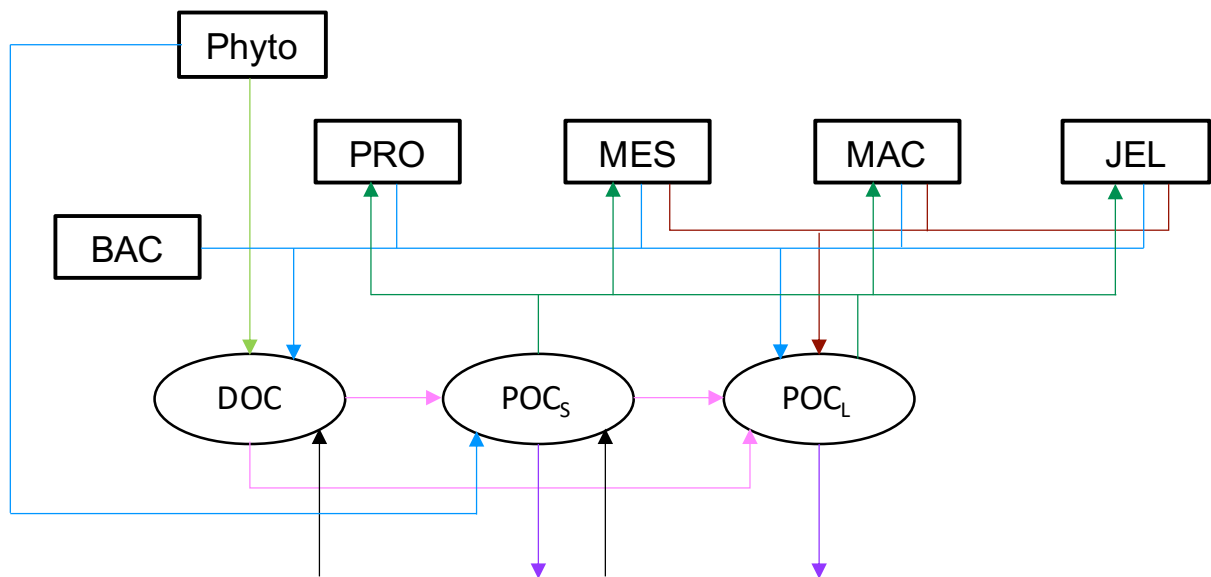
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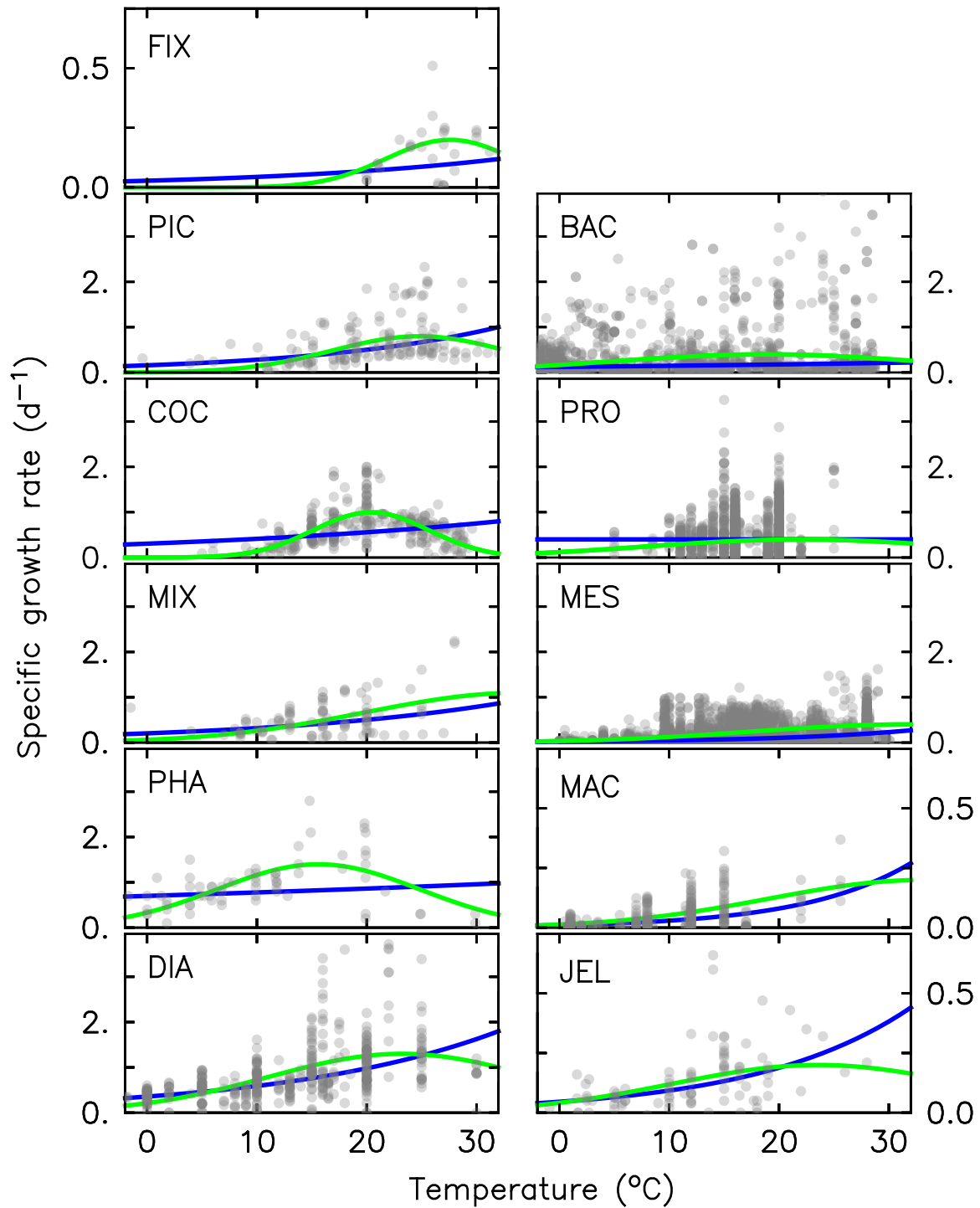
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773 **Figure 1.** Schematic representation of the PlankTOM11 marine ecosystem model (see Table 1 for
774 PFT definitions). **(a)** The plankton food web, arrows represent the grazing fluxes by protozooplankton
775 (orange), mesozooplankton (red), macrozooplankton (blue) and jellyfish zooplankton (purple). Only
776 fluxes with relative preferences above 0.1 are shown (see Table 3). **(b)** Source and sinks for dissolved
777 organic carbon (DOC) and small (POC_S) and large (POC_L) particulate organic carbon.

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Table 2. Parameters used to calculate PFT specific growth rate with three-parameter fit (Eq. 3) in PlankTOM11.

PFT	μ_{\max} (d ⁻¹)	T _{opt} (°C)	dT (°C)
FIX	0.2	27.6	8.2
PIC	0.8	24.8	11.2
COC	1.0	20.4	7.4
MIX	1.1	34.0	20.0
PHA	1.4	15.6	13.0
DIA	1.3	23.2	17.2
BAC	0.4	18.8	20.0
PRO	0.4	22.0	20.0
MES	0.4	31.6	20.0
MAC	0.2	33.2	20.0
JEL	0.2	23.6	18.8



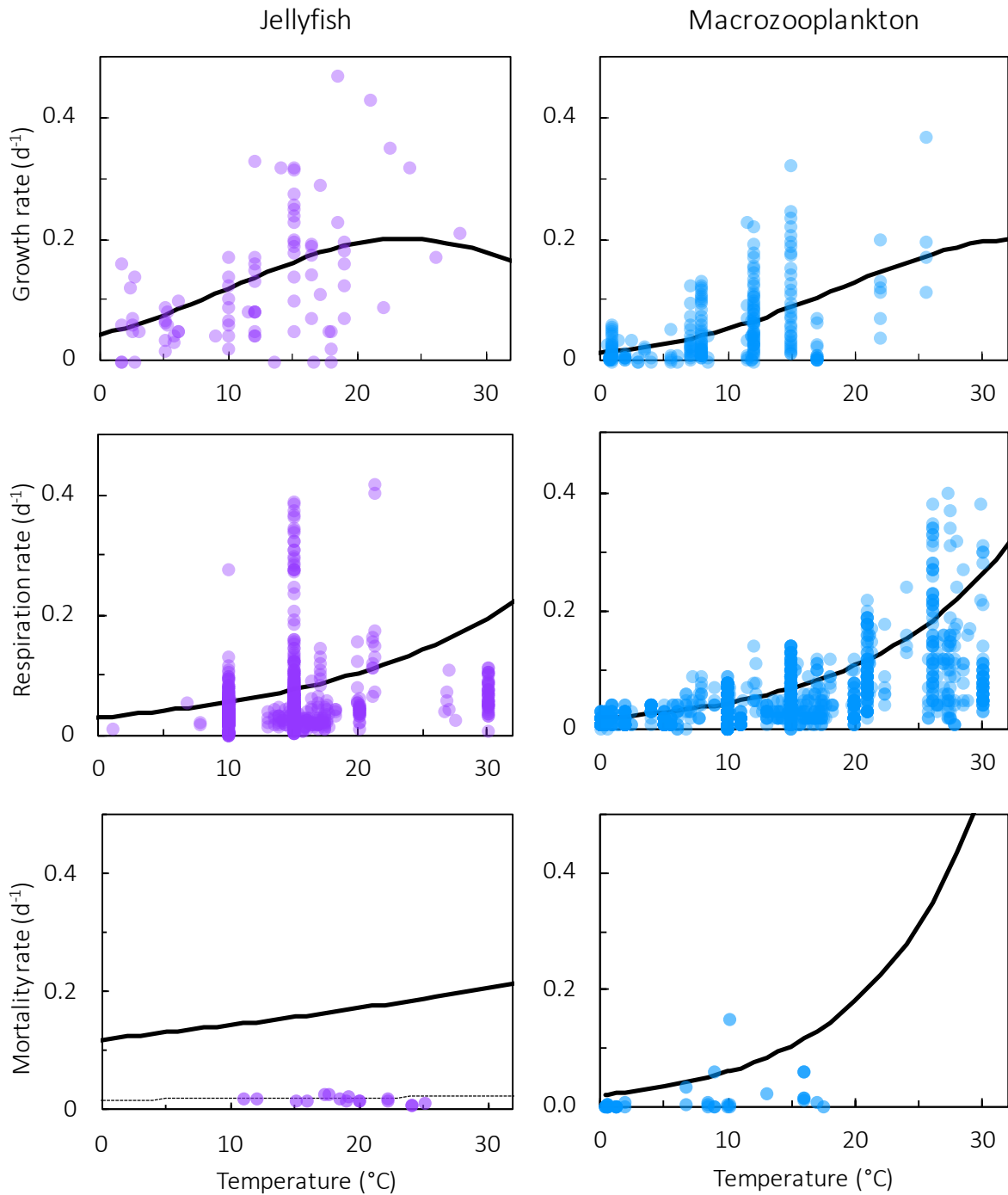
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781 **Figure 2.** Maximum growth rates for the 11 PFTs as a function of temperature from observations
 782 (grey circles). The three-parameter fit to the data is shown in green and the two-parameter fit is shown
 783 in blue, using the parameter values from Table 2. For full PFT names see Table 1. The R^2 for both fits
 784 to the data are given in Appendix Table A2.

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Table 3. Relative preference, expressed as a ratio, of zooplankton for food (grazing) used in PlankTOM11. For each zooplankton the preference ratio for diatoms is set to 1.

PFT	PRO	MES	MAC	JEL
Autotrophs				
FIX	2	0.1	0.1	0.1
PIC	3	0.75	0.5	0.1
COC	2	0.75	1	0.1
MIX	2	0.75	1	1
DIA	1	1	1	1
PHA	2	1	1	1
Heterotrophs				
BAC	4	0.1	0.1	0.1
PRO	0	2	1	7.5
MES	0	0	2	10
MAC	0	0	0	5
JEL	0	0	0.5	0
Particulate matter				
Small organic particles	0.1	0.1	0.1	0.1
Large organic particles	0.1	0.1	0.1	0.1



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788 **Figure 3.** Maximum growth rates (top), respiration rates (middle) and mortality rates (bottom) for
 789 jellyfish (left; purple) and macrozooplankton (right; blue) PFTs as a function of temperature. The fit
 790 to the data is shown in black, using the parameter values from Table 2 and Table 4. Growth rates are
 791 the same as shown in Fig. 2, on a different scale. For jellyfish mortality the thin dashed line is the fit
 792 to data and the solid line is the adjusted fit (Table 4).

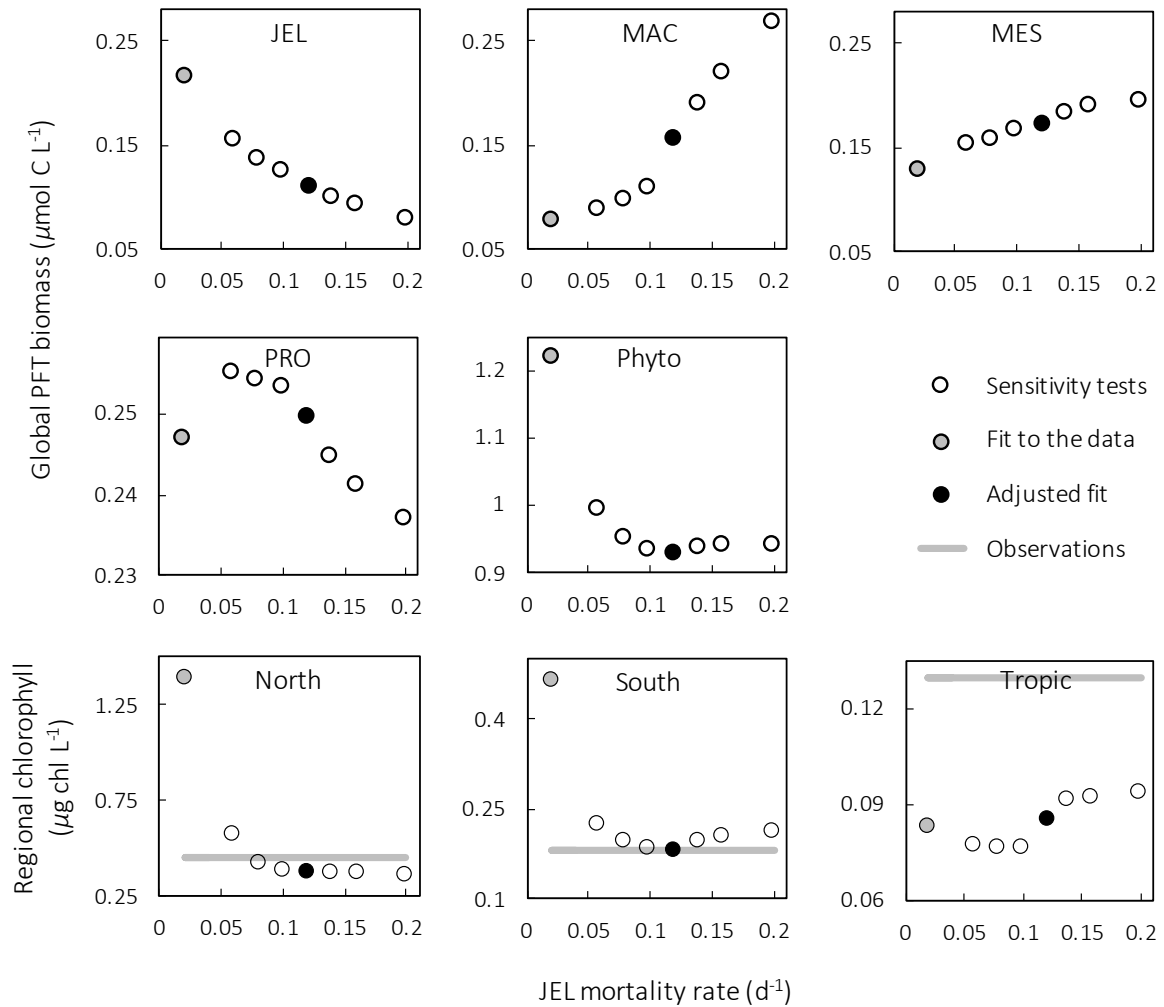
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Table 4. PlankTOM11 parameter values for macrozooplankton and jellyfish, with the associated equation.

Parameters	JEL	MAC	Equation
Respiration			
$R_{0^{\circ}}^{Z_j}$ (d ⁻¹)	0.03	0.01	Eq. 1
d_{Z_j}	1.88	2.46	Eq. 1
Mortality			
$m_{0^{\circ}}^{Z_j}$ (d ⁻¹)	0.12	0.02	Eq. 1
c_{Z_j}	1.20	3.00	Eq. 1
K^{Z_j} (μmol C L ⁻¹)	20.0e-6	20.0e-6	Eq. 1
GGE	0.29	0.30	Eq. 4
Grazing half saturation constant $K_{1/2}^{Z_j}$ (μmol C L ⁻¹)	10.0e-6	9.0e-6	Eq. 5



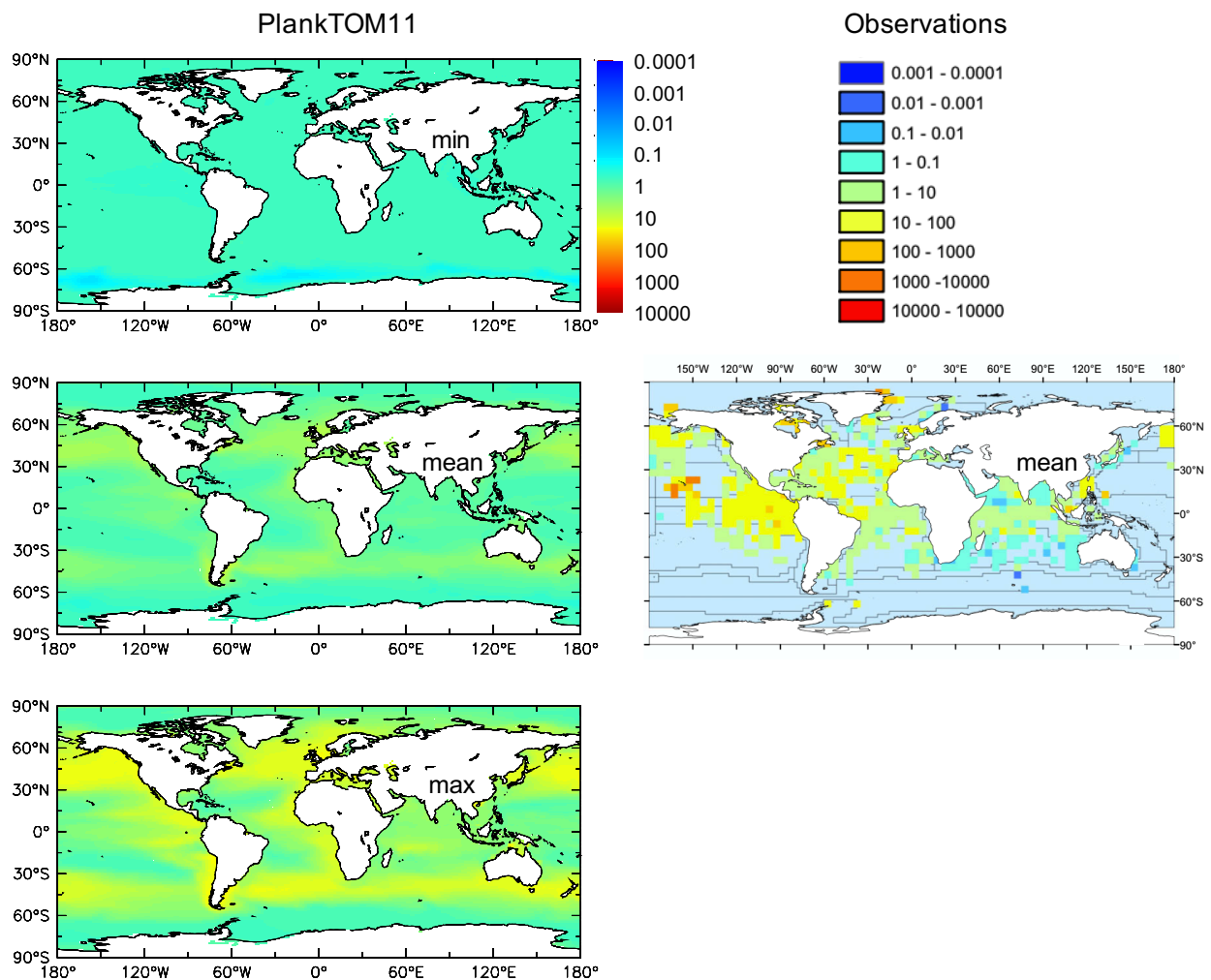
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798 **Figure 4.** Results from sensitivity tests on jellyfish mortality rates. The adjusted fit simulation used
 799 for PlankTOM11 is shown by the black filled circle and the fit to the data simulation is shown by the
 800 grey filled circle; global mean PFT biomass ($\mu\text{mol C L}^{-1}$) for 0-200m depth (top - middle), regional
 801 mean surface chlorophyll concentration ($\mu\text{g chl L}^{-1}$; bottom). For the regional mean chlorophyll the
 802 observations are calculated from SeaWiFS. All data are averaged for 1985-2015, and between 30° and
 803 55° latitude in both hemispheres: $140\text{-}240^\circ\text{E}$ in the north and $140\text{-}290^\circ\text{E}$ in the south (see Fig. 8).
 804 Phyto is the sum of all the phytoplankton PFTs.

Table 5. Changes to non-jellyfish PFT parameters across the PlankTOM simulations. PlankTOM10^{LQ16} is the latest published version of PlankTOM with 10 PFTs (Le Quéré et al., 2016), while PlankTOM10 is the simulation from this study.

Parameters	PlankTOM10 ^{LQ16}	PlankTOM10	PlankTOM10.5	PlankTOM11
MAC mortality	0.020	0.012	0.005	0.005
MES respiration	0.014	0.014	0.001	0.001

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Figure 6. Jellyfish carbon biomass (mg C m^3) in PlankTOM11 and the observed jellyfish carbon biomass (mg C m^3) from JeDI (panel reproduced from Lucas et al., 2014) on a logarithmic scale. PlankTOM11 results (left) are the mapped monthly minimum, mean and maximum biomass from monthly climatologies. Observations (right) are the mean biomass (with no observations in pale blue). All data is for 0-200m. Only the mean values are available for the observations (Lucas et al. 2014), while for the model the min, mean and max are given. Due to the patchy nature of the observations in depth and time, the mean may be skewed high or low, while the model is sampled across the full time and depth.

Table 6. Global mean values for rates and biomass from observations and the PlankTOM11 and PlankTOM10 models averaged over 1985–2015. In parenthesis is the percentage share of the plankton type of the total phytoplankton or zooplankton biomass. The percentage share of mixed-phytoplankton is not included, as there are no mixed-phytoplankton observations, therefore, the phytoplankton percentages are of total phytoplankton minus mixed-phytoplankton. References for observations are given in Appendix Table A5.

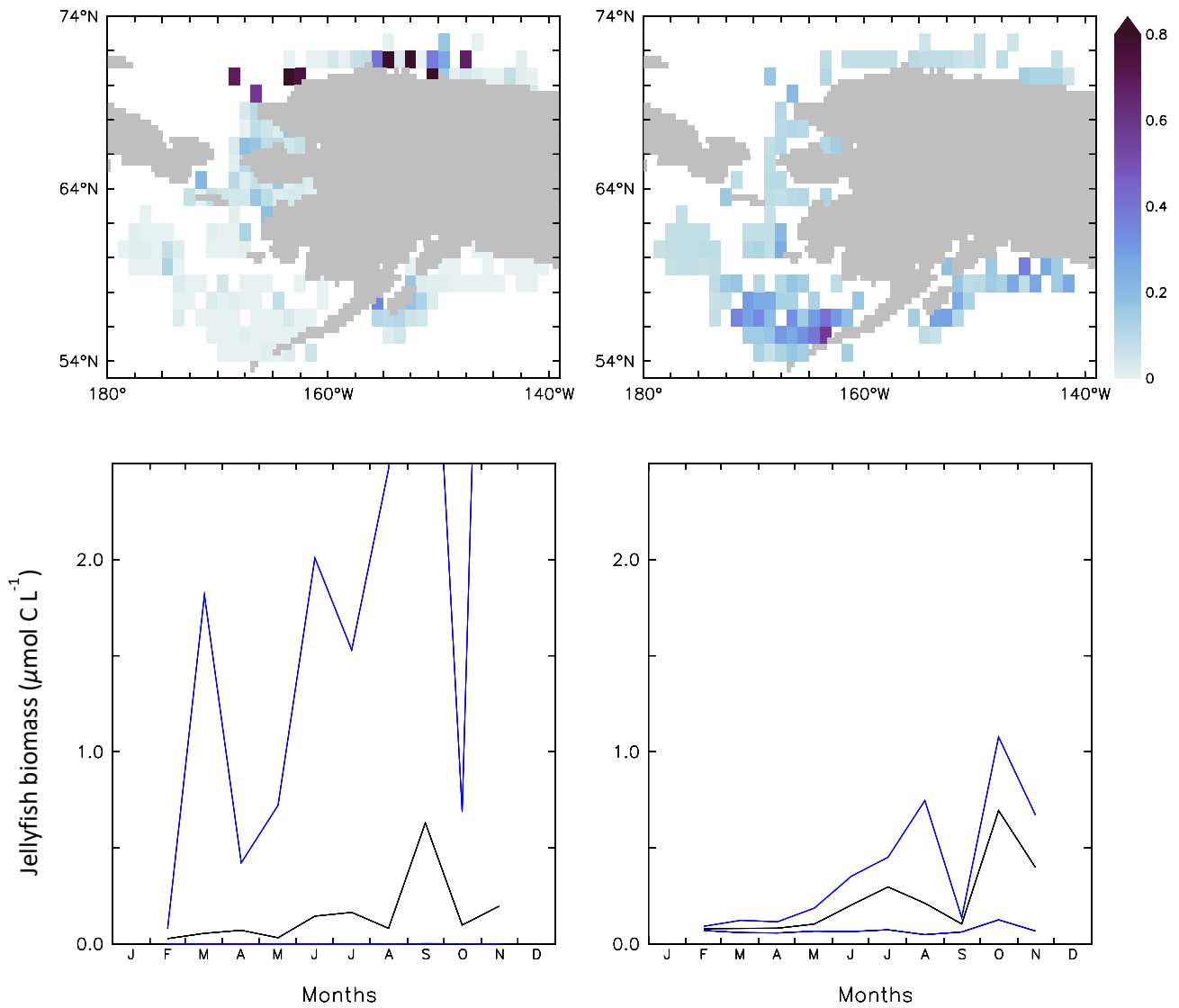
	PlankTOM11	PlankTOM10	Observations
Rates			
Primary production (PgC y ⁻¹)	41.6	43.4	51-65
Export production at 100m (PgC y ⁻¹)	7.1	7.0	5-13
CaCO ₃ export at 100m (PgC y ⁻¹)	1.3	1.2	0.6-1.1
N ₂ fixation (TgN y ⁻¹)	97.2	95.9	60-200
Phytoplankton biomass 0-200m (PgC)			
N ₂ -fixers	0.065 (8%)	0.075 (10%)	0.008-0.12 (2-8%)
Picophytoplankton	0.141 (17%)	0.153 (20%)	0.28-0.52 (35-68%)
Coccolithophores	0.248 (30%)	0.212 (27%)	0.001-0.032 (0.2-2%)
Mixed-phytoplankton	0.263	0.268	-
Phaeocystis	0.177 (22%)	0.170 (22%)	0.11-0.69 (27-46%)
Diatoms	0.183 (22%)	0.167 (21%)	0.013-0.75 (3-50%)
Total phytoplankton biomass	1.077	1.046	0.412 – 2.112
Heterotrophs biomass 0-200m (PgC)			
Bacteria	0.041	0.046	0.25-0.26
Protozooplankton	0.295 (36%)	0.330 (32.7%)	0.10-0.37 (27-31%)
Mesozooplankton	0.193 (23%)	0.218 (21.6%)	0.21-0.34 (25-66%)
Macrozooplankton	0.205 (25%)	0.460 (45.6%)	0.01-0.64 (3-47%)
Jellyfish zooplankton	0.129 (16%)	-	0.10-3.11
Total zooplankton biomass	0.823	1.008	0.42 – 4.46

Table 7. Jellyfish biomass globally from observations (MAREDAT) and PlankTOM11. Three types of mean are given for the observations; Med is the median, AM is the arithmetic mean and GM is the geometric mean. The ratios are all scaled to mean = 1. All units are $\mu\text{g C L}^{-1}$.

		Mean	Max	Ratio
Observations	AM	3.61	156.0	1 : 43
	GM	0.95	156.0	1 : 165
	Med	0.29	156.0	1 : 538
PlankTOM11	AM	1.18	98.9	1 : 84

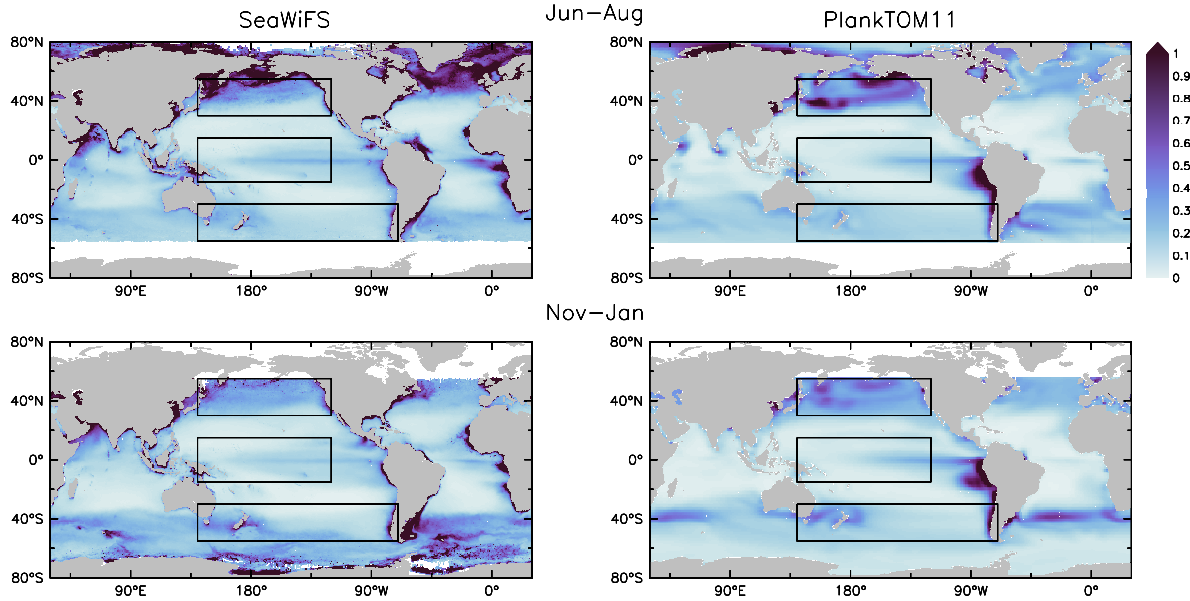
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824 **Figure 7.** Carbon biomass of jellyfish in $\mu\text{mol C L}^{-1}$ from observations (left) and PlankTOM11
 825 (right) for the coast of Alaska (the region with the highest density of observations). The top panels
 826 show the mean jellyfish biomass and the bottom panels show the seasonal jellyfish biomass, with the
 827 monthly mean in black and the monthly minimum and maximum in blue. Observations and
 828 PlankTOM11 results are for 0-150m, as the depth range where >90% of the observations occur. No
 829 observations were available for January or December.

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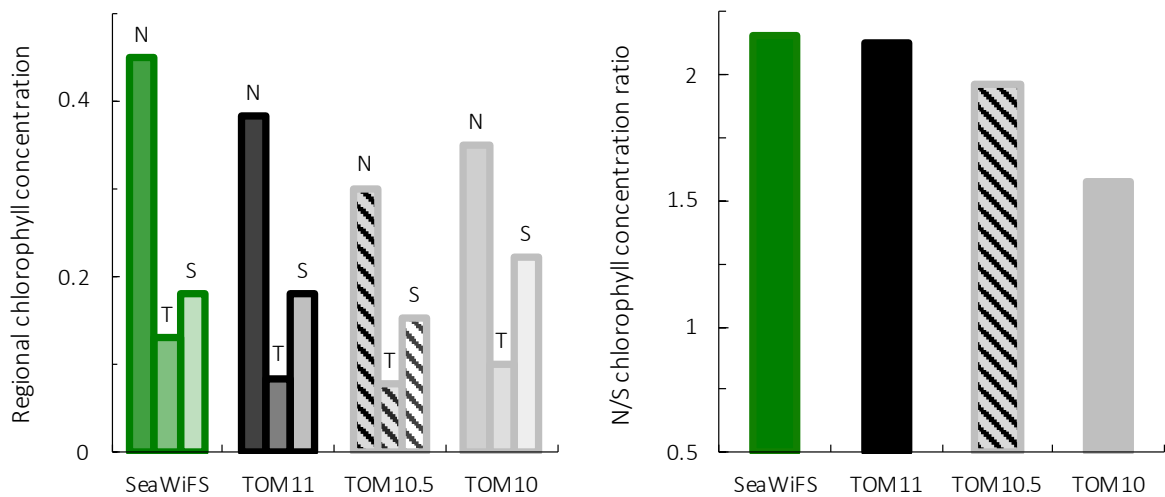
832 **Figure 8.** Surface chlorophyll ($\mu\text{g chl L}^{-1}$) averaged for June to August (top) and November to
 833 January (bottom). Panels show observations from SeaWiFS (left) satellite and results from
 834 PlankTOM11 (right). Observations and model are averaged for 1997-2006. The black boxes show the
 835 Pacific north, tropic and south regions used in Fig. 4 and Fig. 9.

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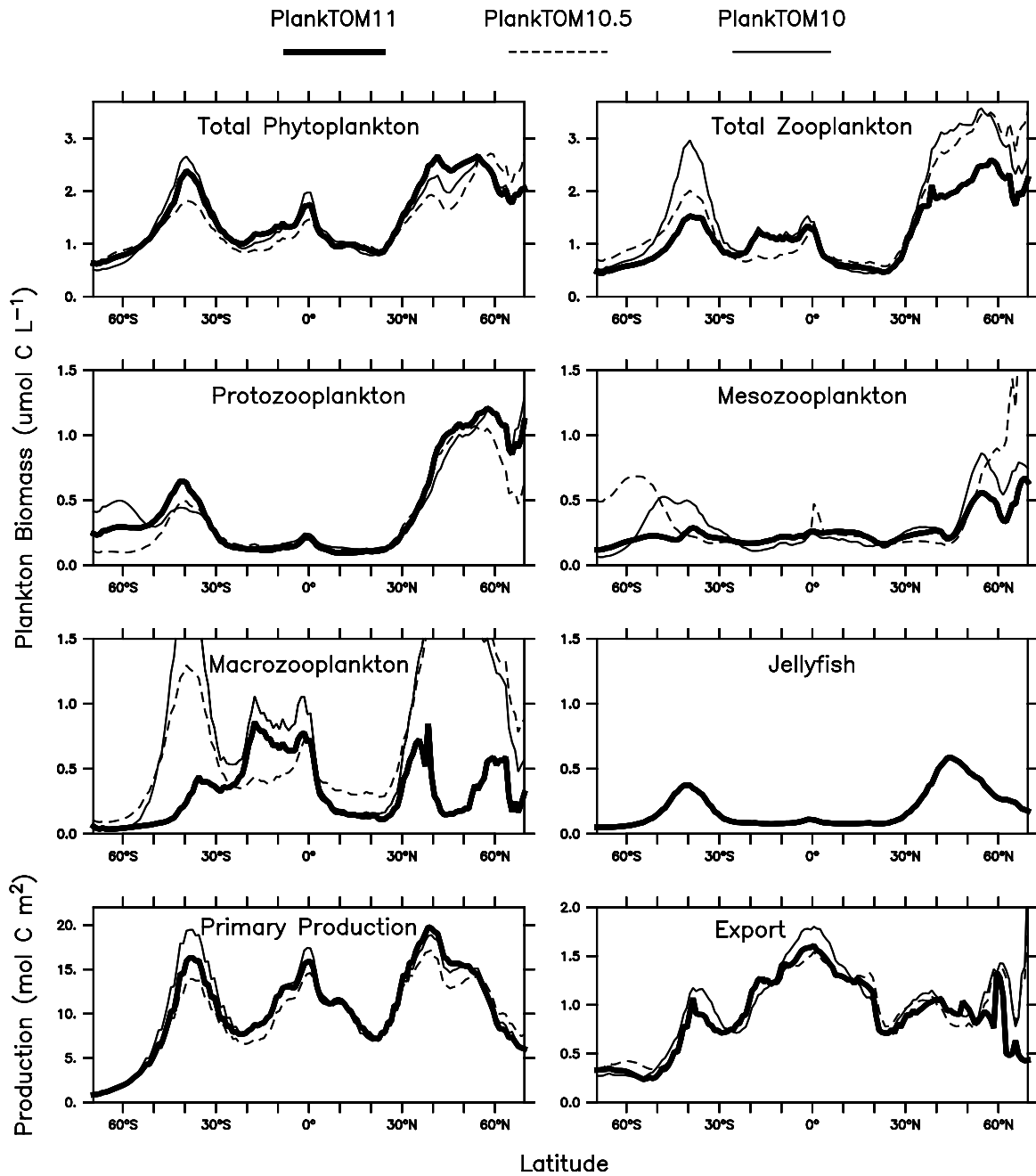
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841 **Figure 9.** Surface chlorophyll for observations from SeaWiFS satellite, PlankTOM11,
 842 PlankTOM10.5 and PlankTOM10. Regional chlorophyll concentration in $\mu\text{g chl L}^{-1}$ (right) for the
 843 north (N), tropic (T) and south (S) Pacific Ocean regions shown in Fig. 8 and the N/S chlorophyll
 844 concentration ratio (left). Observations and model are averaged for 1997-2006.



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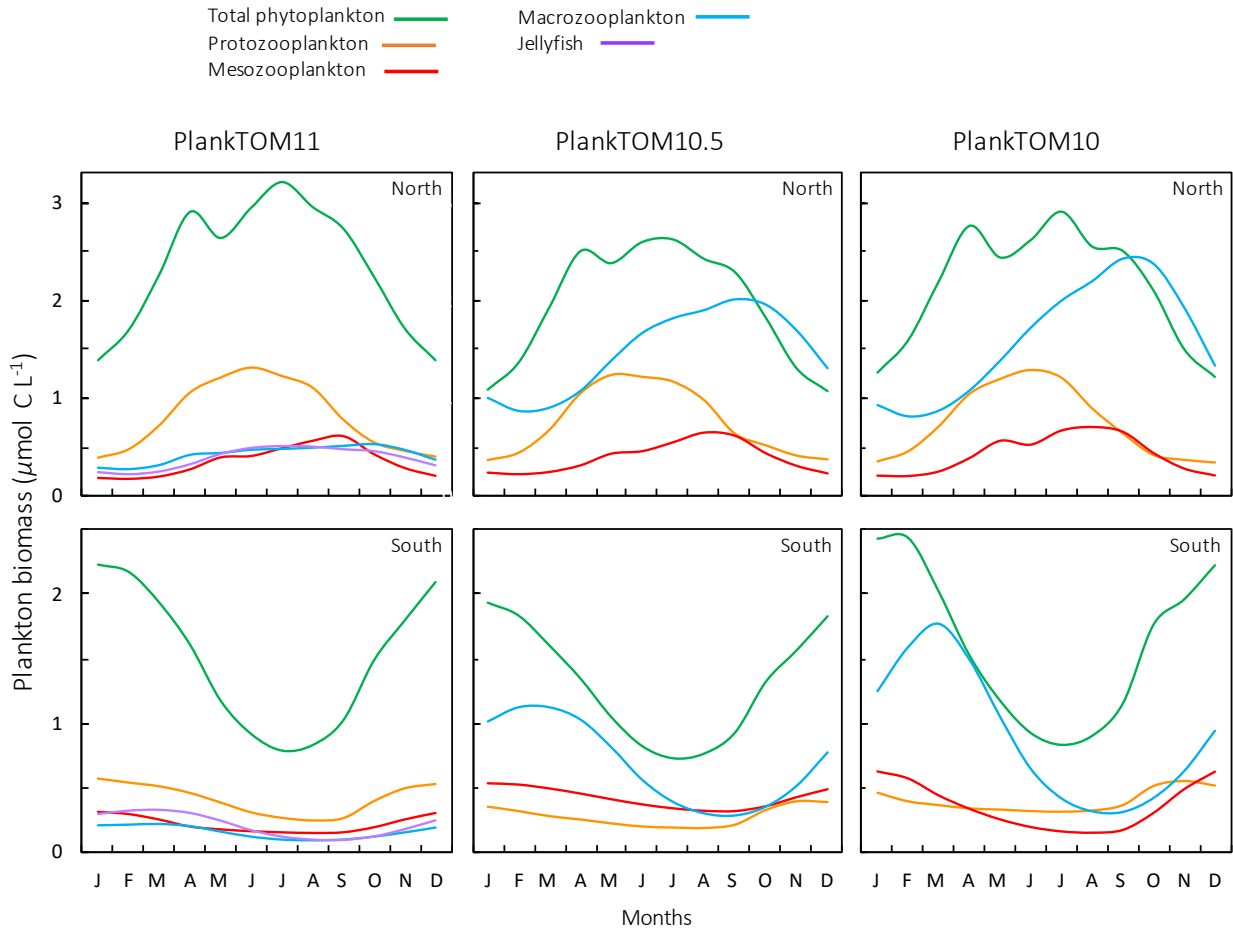
846 **Figure 10.** Zonal mean distribution for the PlankTOM11, PlankTOM10.5 and PlankTOM10
 847 simulations. All plankton biomass data are for the surface box (0-10m). For PlankTOM10.5 the MAC
 848 PFT has been summed with the 11th PFT that duplicates MAC. The bottom panels are the zonal mean
 849 distribution of primary production, integrated over the top 100m, and export production at 100m. All
 850 data are averaged for 1985-2015.

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856 **Figure 11.** Seasonal surface carbon biomass ($\mu\text{mol C L}^{-1}$) of total phytoplankton PFTs,
 857 protozooplankton, mesozooplankton, macrozooplankton and jellyfish For PlankTOM10.5 the MAC
 858 PFT has been summed with the 11th PFT that duplicates MAC. Panels shown PFT biomass for
 859 PlankTOM11 (left), PlankTOM10.5 (middle) and PlankTOM10 (right), for two regions; the north
 860 30°N - 70°N (top) and the south 30°S - 70°S (bottom) across all longitudes. All data are averaged for
 861 1985-2015.

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Table A1: Sources and metadata for jellyfish growth rates, including references with associated number of data, species and life stage used to inform the growth parameter of jellyfish in PlankTOM11.

Reference	<i>n</i>	Species	Life Stage
Båmstedt et al., (1997)	3	<i>Cynea capillata</i>	Ephyrae
Daan (1986)	8	<i>Sarsia tubulosa</i>	Medusae
Frandsen & Riisgård (1997)	5	<i>Aurelia aurita</i>	Medusae
Hansson (1997)	20	<i>Aurelia aurita</i>	Medusae
Møller & Riisgård (2007a)	34	<i>Sarsia tubulosa</i> , <i>Aurelia aurita</i> , <i>Aequorea vitrina</i>	Medusae, ephyrae
Møller & Riisgård (2007b)	10	<i>Aurelia aurita</i>	Medusae, ephyrae
Olesen (1994)	8	<i>Aurelia aurita</i> , <i>Chrysaora</i> <i>quinquecirrha</i>	Medusae, ephyrae
Widmer (2005)	10	<i>Aurelia labiata</i>	Ephyrae

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Table A2: The fit to the growth data for PFT's for the new three-parameter fit used in this study (see Eq. 3 and Fig. 2) and the two-parameter fit (see Eq. 2 and Fig. 2).

PFT	R ²		<i>n</i>
	Two-parameter	Three-parameter	
CNI	9.58	11.36	98
MAC	36.57	36.76	253
MES	0.32	0.34	2742
PRO	0.00	7.81	1300
BAC	1.66	1.66	1429
DIA	9.59	9.58	439
PHA	6.29	37.07	67
MIX	21.25	19.17	95
COC	33.91	36.01	322
PIC	20.17	20.29	150
FIX	2.67	10.62	32

Table A3: Sources and metadata for jellyfish grazing preferences, including references with associated species, life stage and preference for prey (categorised into PFTs) with any notable phrases used to inform the grazing of jellyfish in PlankTOM11.

Reference	Species/Class/Genera	Life Stage	PFT preference
Båmstedt et al. (2001)	<i>Aurelia aurita</i>	Ephyrae	Mixed-phytoplankton, mesozooplankton and particulate organic material
Colin et al. (2005)	<i>Aglaura hemistoma</i>	Medusa	“microplanktonic omnivores”; protozooplankton and some phytoplankton
Flynn and Gibbons (2007)	<i>Chrysaora hysoscella</i>	Medusa	Wide variety ranging in size from protozooplankton to macrozooplankton, with the “numerically dominant” prey as mesozooplankton
Malej et al. (2007)	<i>Aurelia</i> sp.	Medusa	Mesozooplankton and protozooplankton
Morais et al. (2015)	<i>Blackfordia virginica</i>	Medusa	Mesozooplankton and diatoms
Purcell (1992)	<i>Chrysaora quinquecirrha</i>	Medusa	Mesozooplankton (upto 71% of diet)
Purcell (1997)	Hydromedusa		“mostly generalist feeders”, mesozooplankton as a preference
Purcell (2003)	<i>Aurelia labiata</i> , <i>Cyanea capillata</i> , <i>Aequorea aequorea</i>		Mainly mesozooplankton
Stoecker et al. (1987)	<i>Aurelia aurita</i>	Medusa	Protozooplankton and mesozooplankton preferentially removed from “natural mircozooplankton” assemblage. In cultured prey assemblage, larger protozooplankton were selected.
Uye and Shimauchi (2005b)	<i>Aurelia aurita</i>	Medusa	Mostly mesozooplankton, some protozooplankton
Costello and Colin (2002)	<i>Aglantha digitale</i> , <i>Sarsia tubulosa</i> , <i>Proboscoidactyla flavicirrata</i> , <i>Aequorea victoria</i> , <i>Mitrocoma cellularia</i> , <i>Phialidium gregarium</i>	Medusa	Mesozooplankton (crustacean) and protozooplankton (ciliates)

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Table A4: Additional tuning parameter values for PlankTOM11 (see section 2.1.5) following the change to the growth rate formulation. ‘Before growth change’ values are those used in PlankTOM10^{LQ16} and ‘after growth change’ values are used in simulations for this study (PlankTOM11, PlankTOM10.5 and PlankTOM10).

Parameter	Before growth change	After growth change
Grazing preference ratio of mesozooplankton for <i>Phaeocystis</i>	0.75	1
Grazing preference ratio of protozooplankton for picophytoplankton	2	3
Half saturation constant of phytoplankton grazing on iron		
Diatoms	40.0e-9	80.0e-9
Picophytoplankton	10.0e-9	25.0e-9
<i>Phaeocystis</i>	25.0e-9	80.0e-9
Half saturation constant of bacteria for dissolved organic carbon	10.0e-6	8.0e-7
Maximum bacteria uptake rate	3.15	1.90
Diatom respiration	0.012	0.12

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Table A5. Global mean values for rates and biomass from observations with the associated references. In parenthesis is the percentage share of the plankton type of the total Phytoplankton or Zooplankton biomass.

	Observations	Reference for the data
Rates		
Primary production (PgC y ⁻¹)	51-65	Buitenhuis et al. (2013b)
Export production at 100m (PgC y ⁻¹)	5-13	Henson et al. (2011), Palevsky et al. (2018)
CaCO ₃ export at 100m (PgC y ⁻¹)	0.6-1.1	Lee (2001), Sarmiento et al. (2002)
N ₂ fixation (TgN y ⁻¹)	60-200	Gruber (2008)
Phytoplankton biomass 0-200m (PgC)		
N ₂ -fixers	0.008-0.12 (2-8%)	Luo et al. (2012)
Picophytoplankton	0.28-0.52 (35-68%)	Buitenhuis et al. (2012b)
Coccolithophores	0.001-0.032 (0.2-2%)	O'Brien et al. (2013)
Mixed-phytoplankton	-	-
<i>Phaeocystis</i>	0.11-0.69 (27-46%)	Vogt et al. (2012)
Diatoms	0.013-0.75 (3-50%)	Leblanc et al. (2012)
Heterotrophs biomass 0-200m (PgC)		
Bacteria	0.25-0.26	Buitenhuis et al. (2012a)
Protozooplankton	0.10-0.37 (27-31%)	Buitenhuis et al. (2010)
Mesozooplankton	0.21-0.34 (25-66%)	Moriarty and O'Brien (2013)
Macrozooplankton	0.01-0.64 (3-47%)	Moriarty et al. (2013)
Jellyfish zooplankton	0.10-3.11	Bar-On et al. (2018), Lucas et al. (2014), Buitenhuis et al. (2013b)

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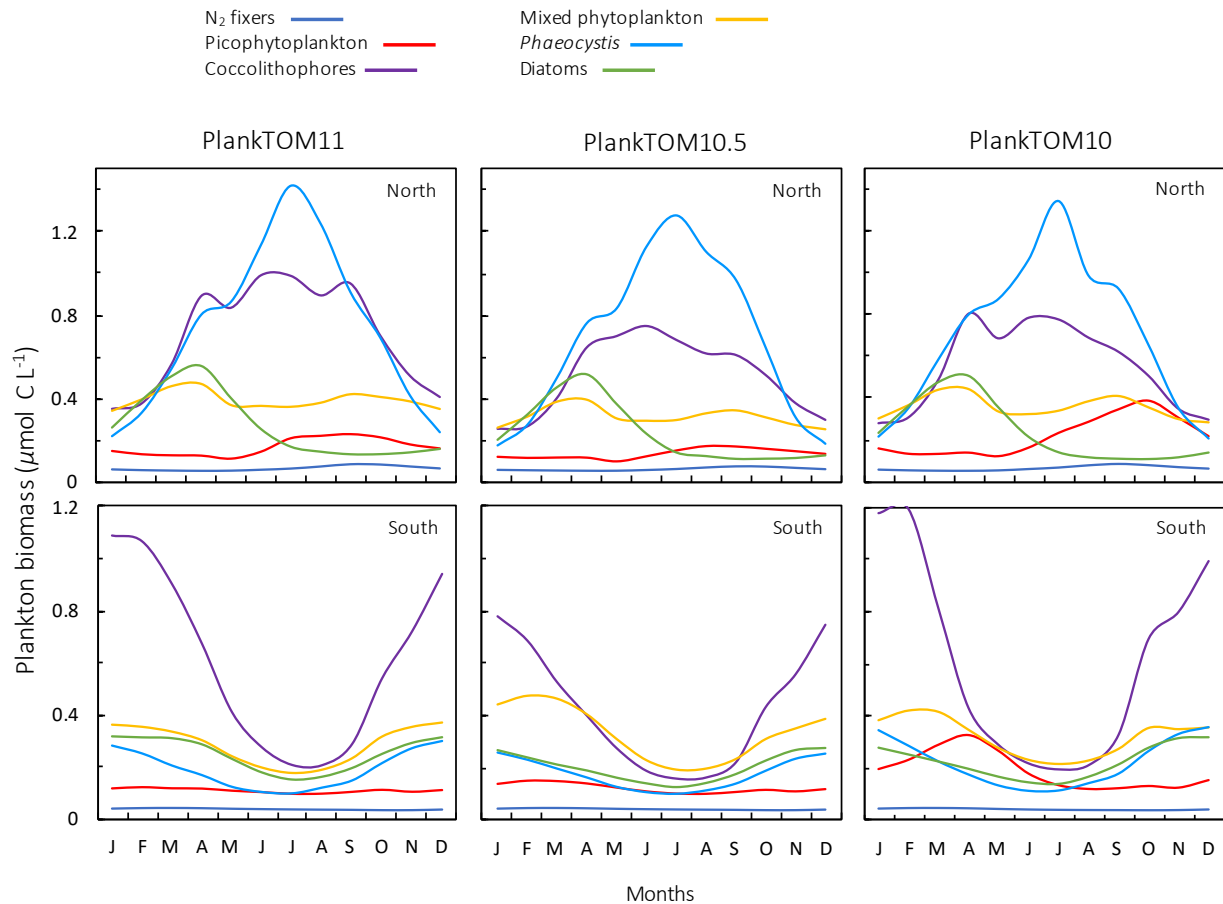
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Table A6: Total phytoplankton biomass ($\mu\text{mol C L}^{-1}$) for $30^\circ\text{N} - 70^\circ\text{N}$ across all longitudes. Observations are from gridded MAREDAT, all data are for the surface ocean (0-10 meters). Phytoplankton types include picophytoplankton, *Phaeocystis*, diatoms, nitrogen-fixers and coccolithophores. The seasonal amplitude is the amplitude for the full seasonal cycle (January – December) and the non-winter amplitude is the amplitude for March – October.

	Seasonal Amplitude	Non-winter Amplitude
Observations (median – mean)	0.78 – 2.67	0.70 – 2.12
PlankTOM11	1.82	0.97
PlankTOM10.5	1.54	0.80
PlankTOM10	1.69	0.81
PlankTOM10 ^{LQ16}	1.68	1.02

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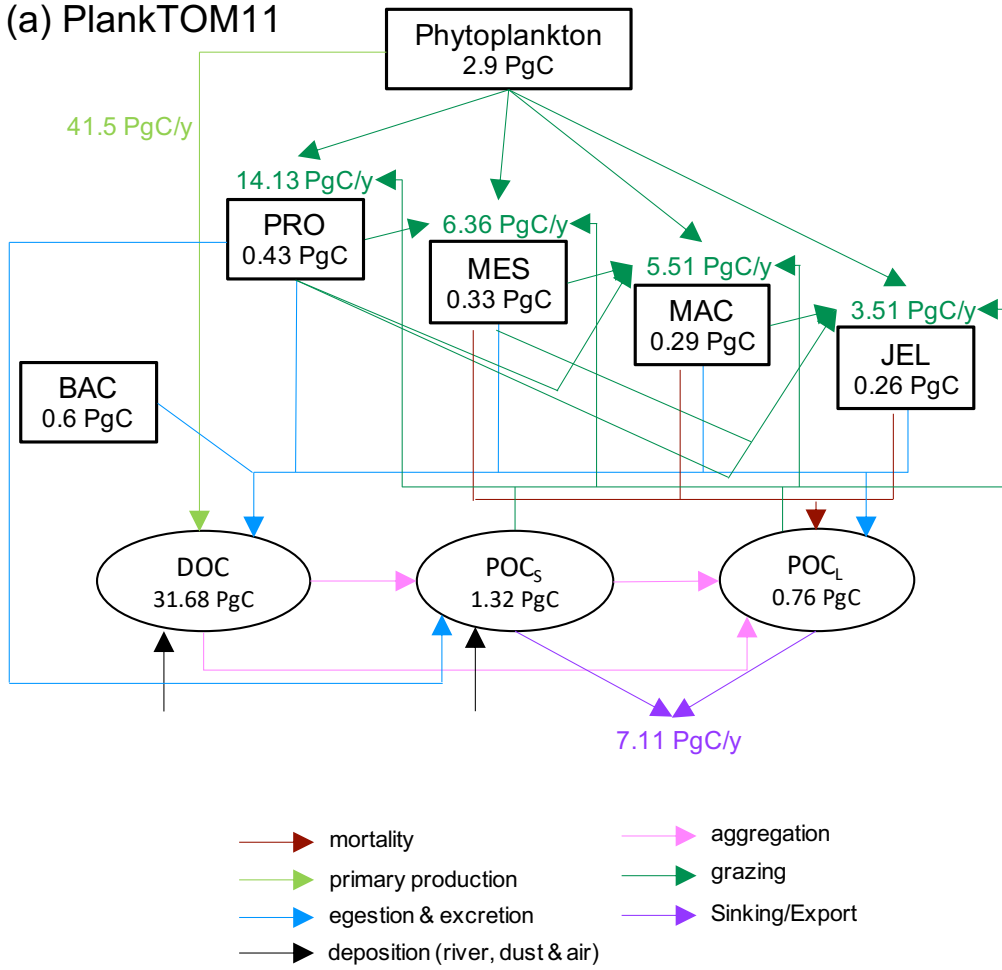
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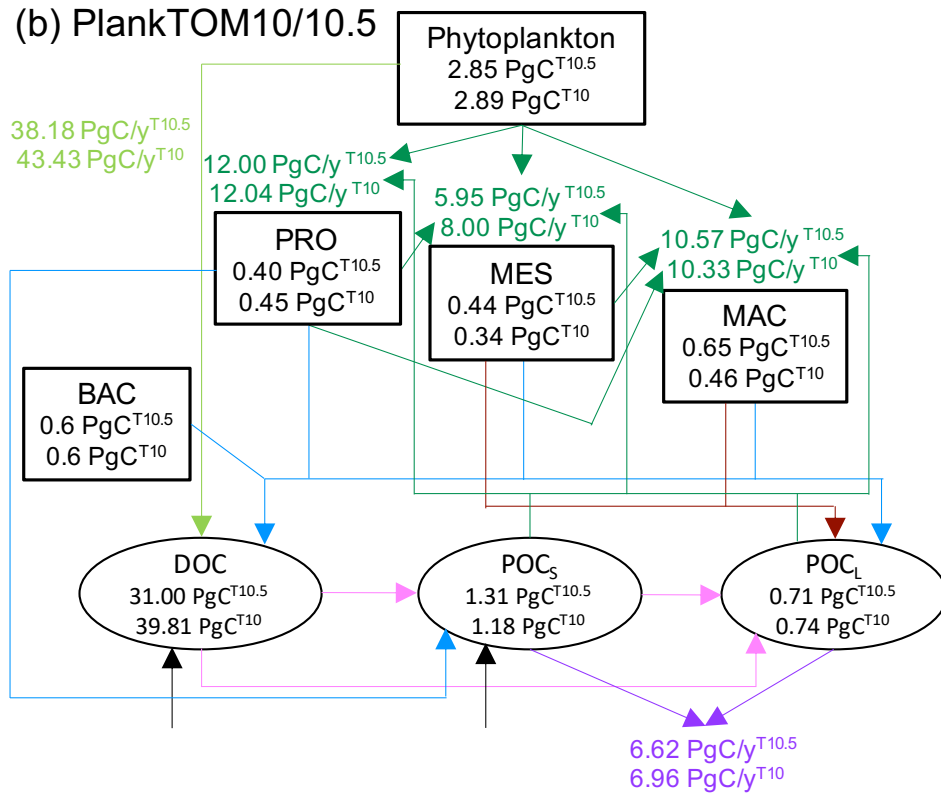
894 **Figure A1.** Seasonal surface carbon biomass ($\mu\text{mol C L}^{-1}$) of phytoplankton PFTs; N_2 fixers,
 895 picophytoplankton, coccolithophores, mixed phytoplankton, *Phaeocystis* and diatoms. Panels shown
 896 PFT biomass for PlankTOM11 (left), PlankTOM10.5 (middle) and PlankTOM10 (right), for two
 897 regions; the north $30^\circ\text{N} - 70^\circ\text{N}$ (top) and the south $30^\circ\text{S} - 70^\circ\text{S}$ (bottom) across all longitudes. All data
 898 are averaged for 1985-2015.

(a) PlankTOM11



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(b) PlankTOM10/10.5



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901 **Figure A2.** Schematic representation of global carbon biomass and rates in the PlankTOM marine
902 ecosystem model including sources and sinks for dissolved organic carbon (DOC) and small (POC_s)
903 and large (POC_L) particulate organic carbon. (a) PlankTOM11 and (b) PlankTOM10 and
904 PlankTOM10.5. Carbon biomass (PgC) of PFT's and organic carbon pools are given within boxes and
905 ovals, carbon rates (PgC/y) of primary production (light green), grazing (dark green) and export
906 production (purple) are given next to the corresponding arrows. All data are averaged for 1985 to
907 2015.

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