Supplementary Material

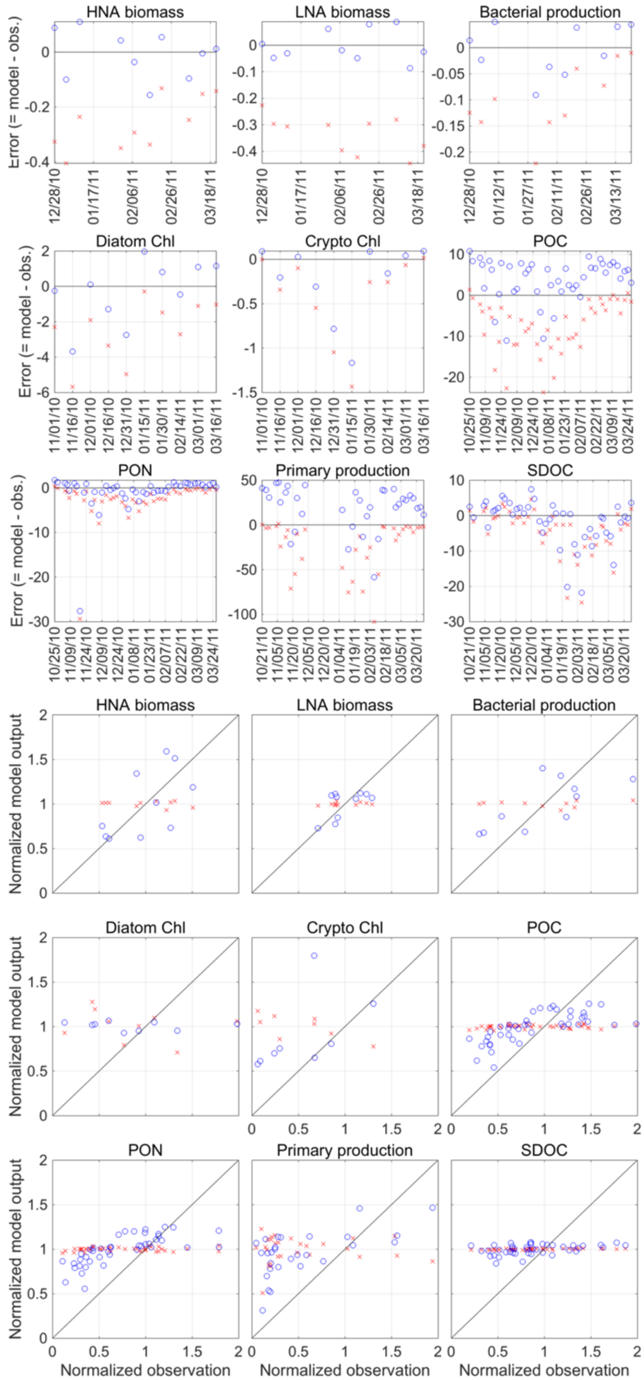

Figure S1: Agreement between observations and model output before and after optimization for 2010-11. Error as the difference and 1:1 agreement between optimized model outputs (blue dots) and model outputs before optimization (red dots) for each data type for 2010-11.

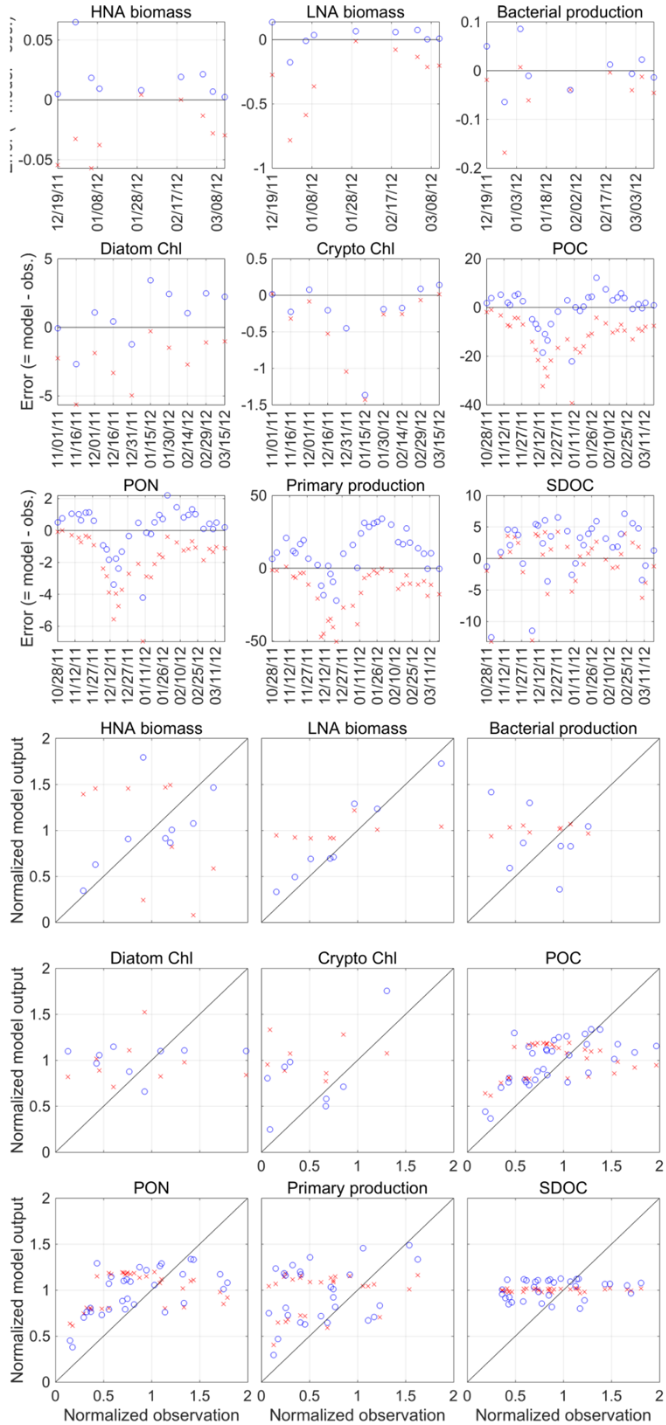

Figure S2: Agreement between observations and model output before and after optimization for 2011-12. Error as the difference and 1:1 agreement between optimized model outputs (blue dots) and model outputs before optimization (red dots) for each data type for 2011-12.

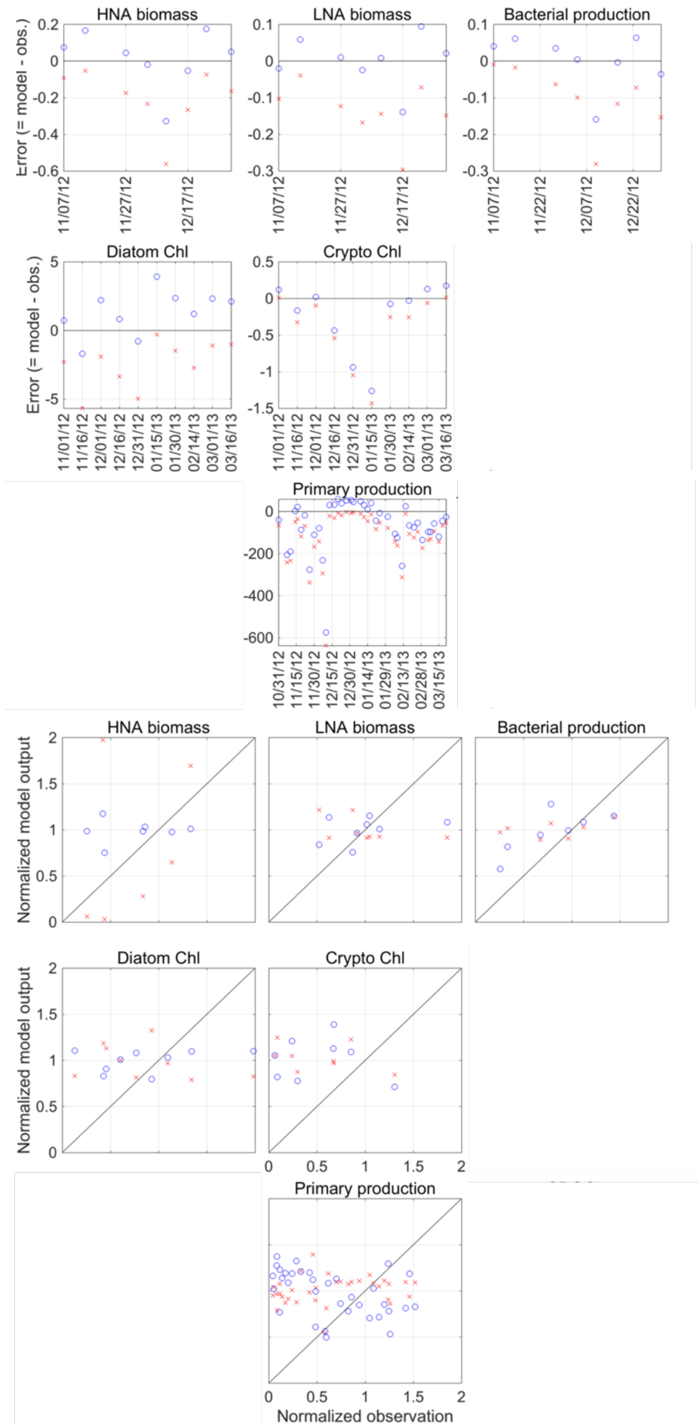

Figure S3: Agreement between observations and model output before and after optimization for 2012-13. Error as the difference and 1:1 agreement between optimized model outputs (blue dots) and model outputs before optimization (red dots) for each data type for 2012-13.

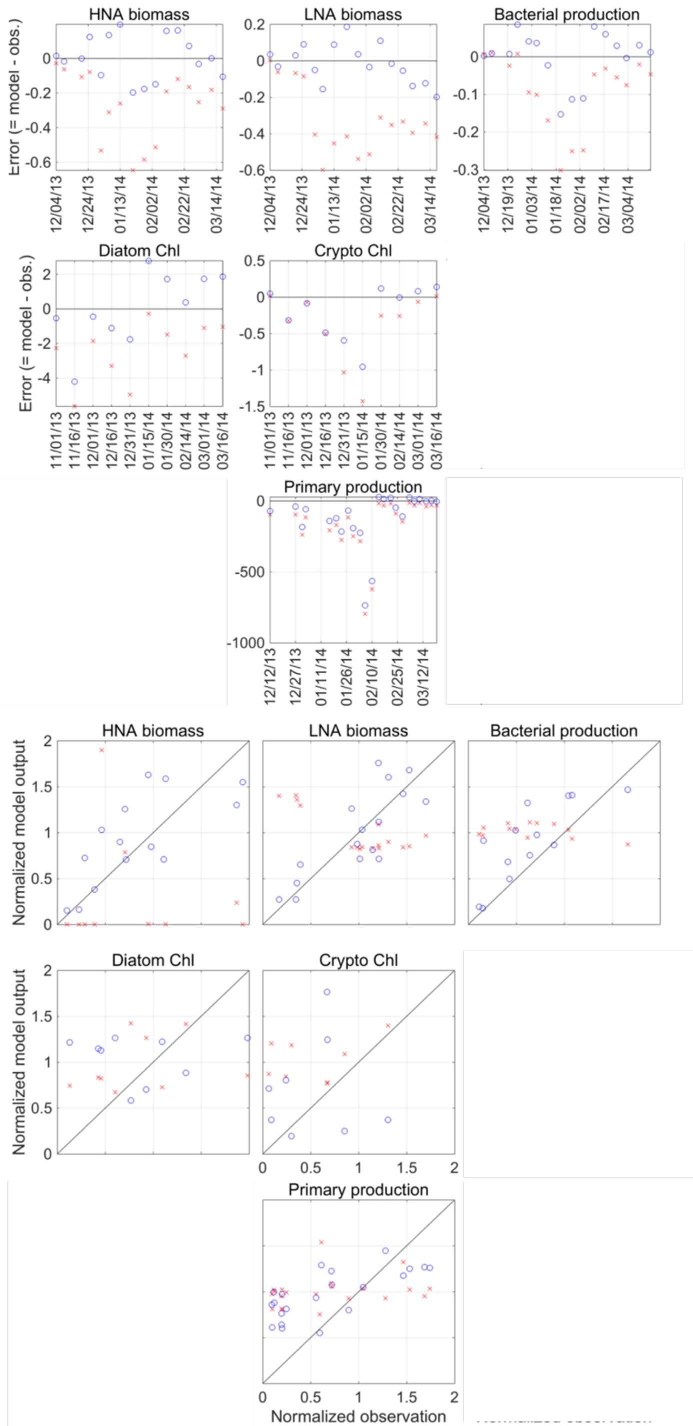

Figure S4: Agreement between observations and model output before and after optimization for 2013-14. Error as the difference and 1:1 agreement between optimized model outputs (blue dots) and model outputs before optimization (red dots) for each data type for 2013-14.

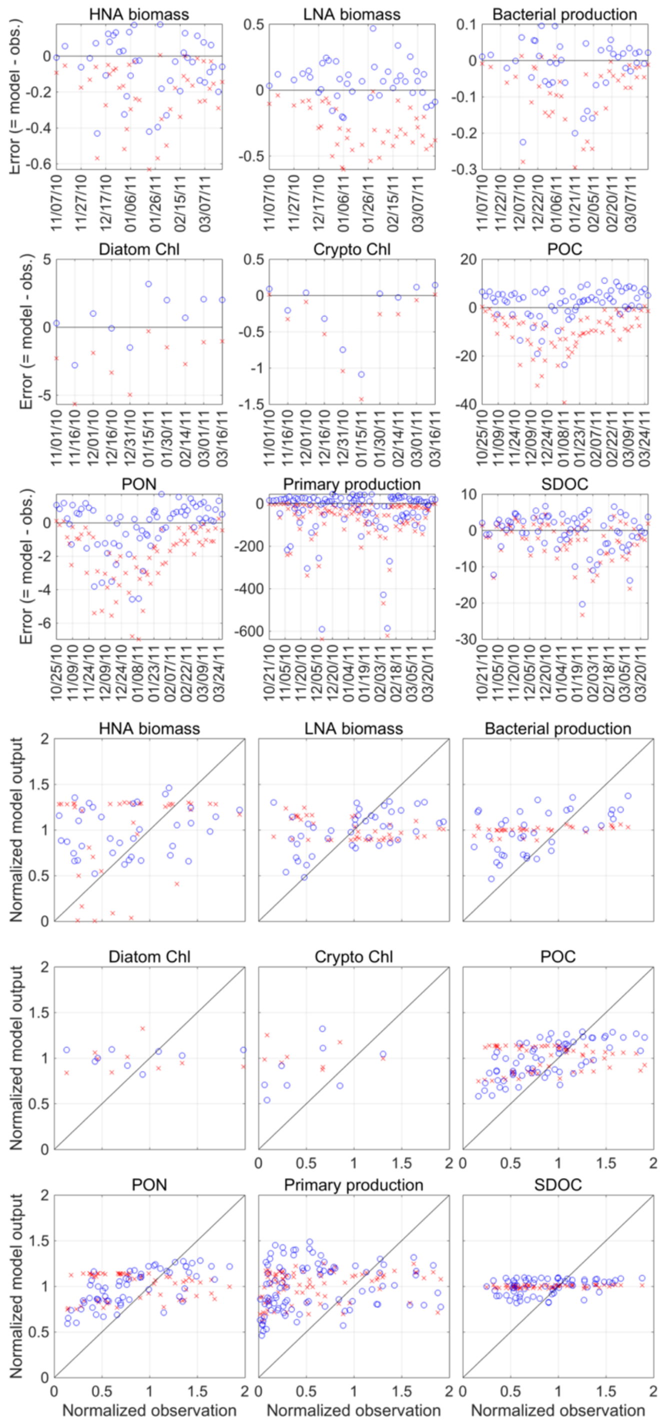

Figure S5: Agreement between observations and model output before and after optimization for the climatological year. Error as the difference and 1:1 agreement between optimized model outputs (blue dots) and model outputs before optimization (red dots) for each data type for the climatological year (i.e., climatological model).

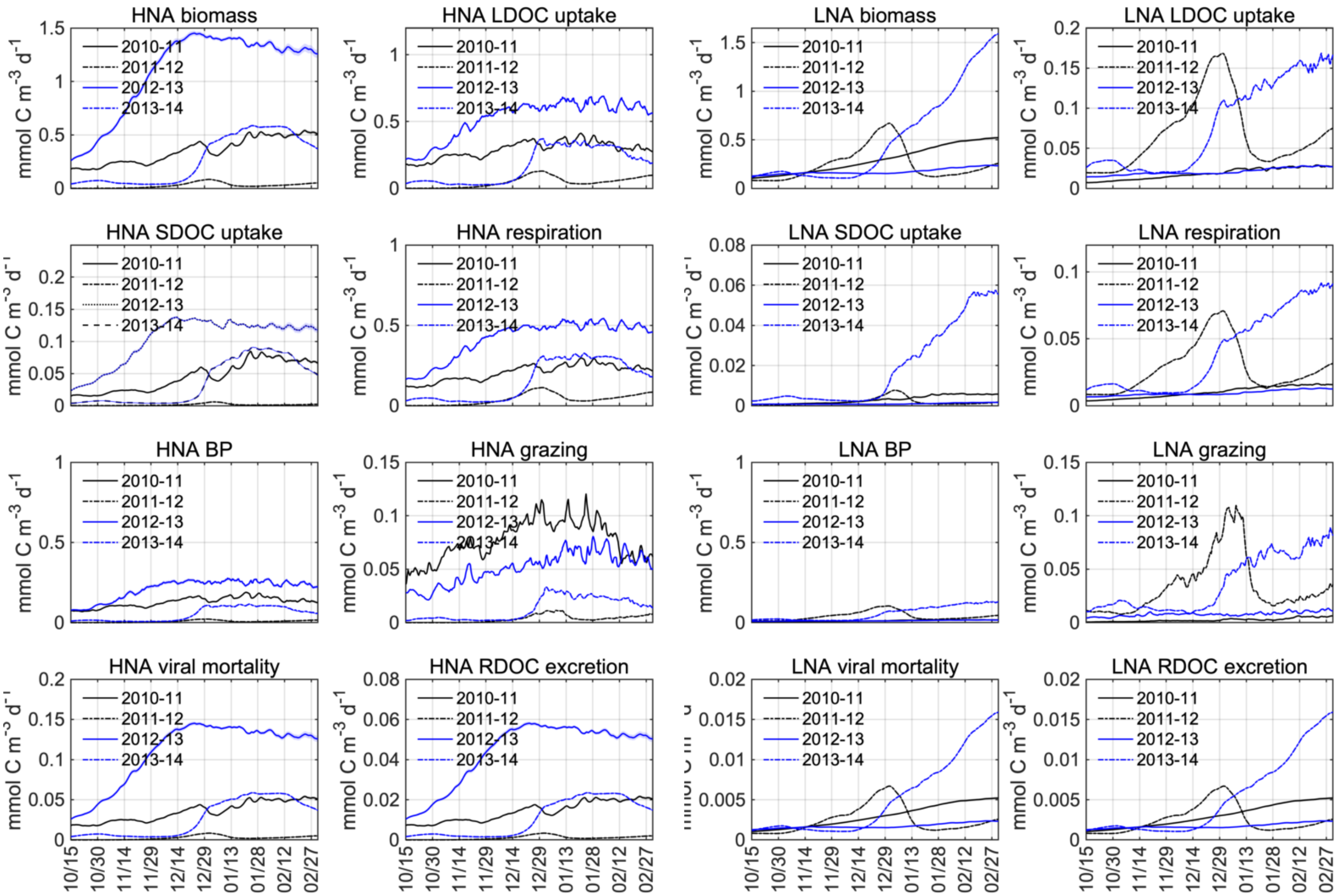

Figure S6: Seasonal patterns of modelled bacterial C stocks and flows. Error spreads as the Monte Carlo experiment-derived standard deviation (typically very small and only obviously shown at the end of the season of 2012-13).

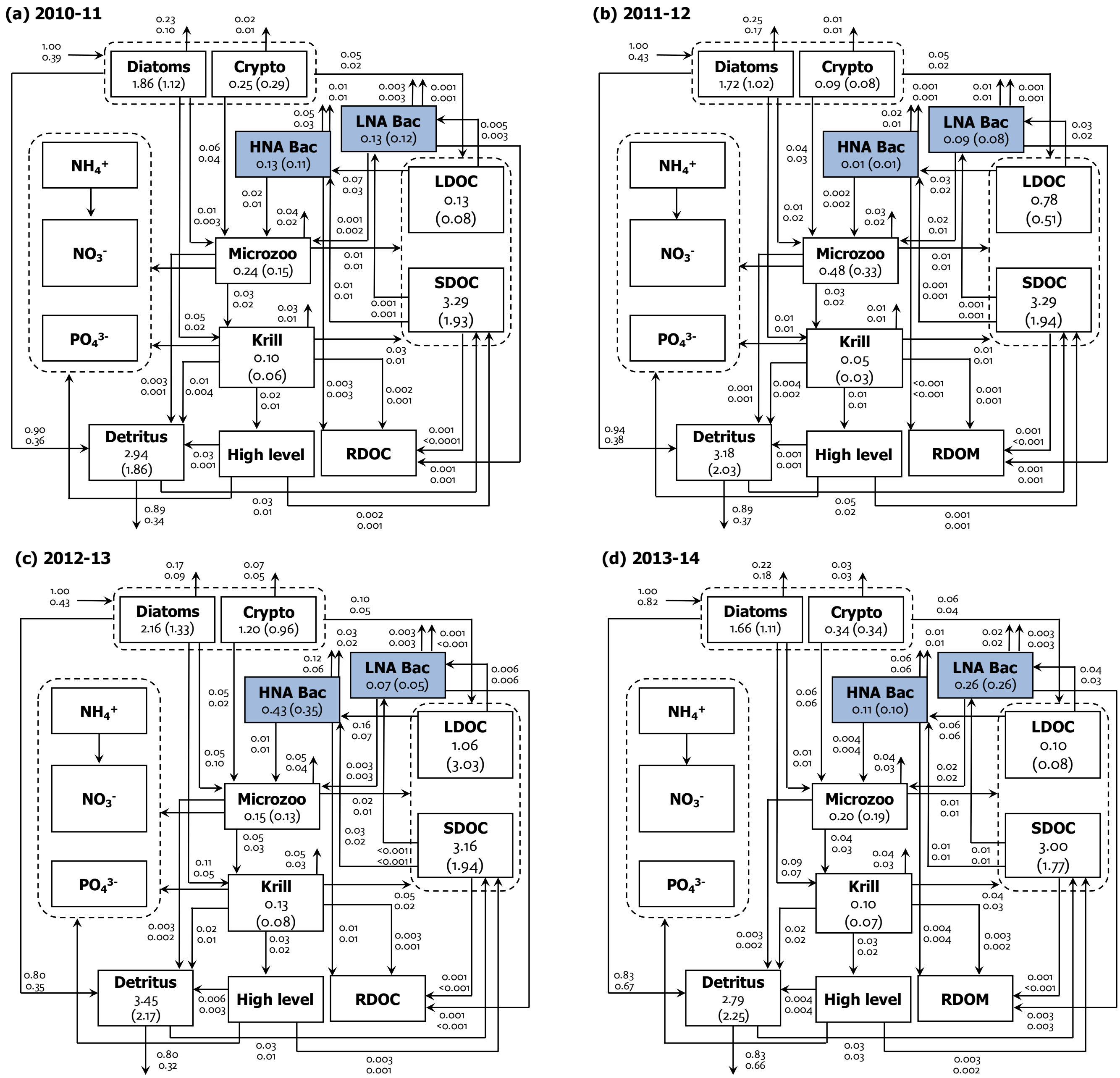

Figure S7: Annual mean carbon stocks and flows normalized by NPP. Carbon stocks (mmol C m^{-3}) and flows (mmol C m^{-3} d^{-1}) averaged over the growth season in each year that are normalized by NPP (for C flows) and NPP in 1-day (for C stocks) are denoted as the numbers on the first row, while the numbers on the second row or in the parentheses are the standard deviation propagated from averaging over the growth season and the Monte Carlo experiment-derived uncertainties. Flows do not necessarily balance to zero due to the build-up or loss in a compartment over the growth season. N and P flows are omitted. The original unit of POC export fluxes is mmol m^{-2} d^{-1}, but normalized by depth to facilitate comparisons with other C flows and stocks in this diagram.

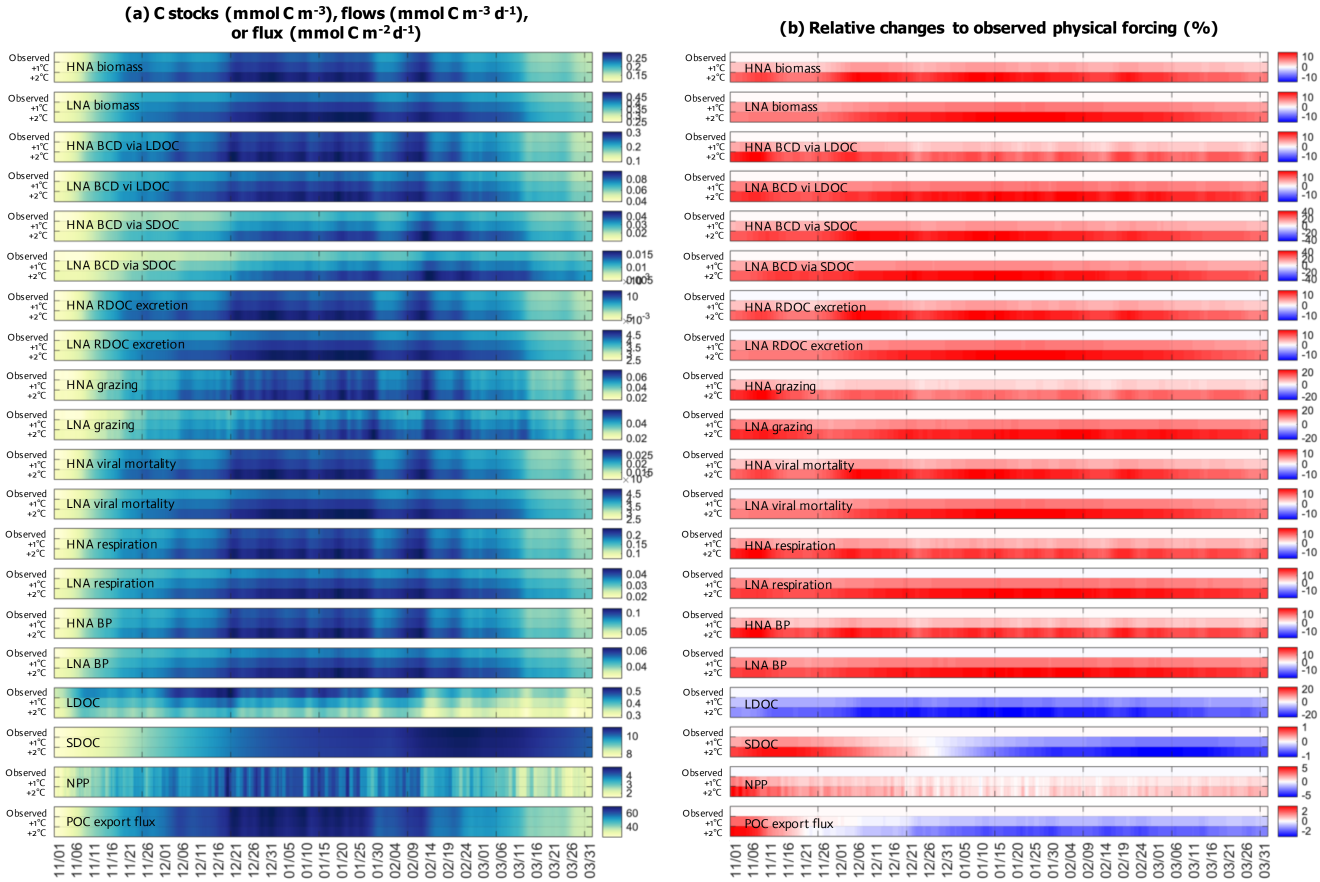

Figure S8: Warming alone scenarios. Seasonal progression of simulated HNA and LNA bacterial stocks and processes and key ecosystem functions over the growth season under observed physical forcing and warming alone scenarios (a) and the percent change of the corresponding variable under climate change scenarios compared to observed temperature fields (b).

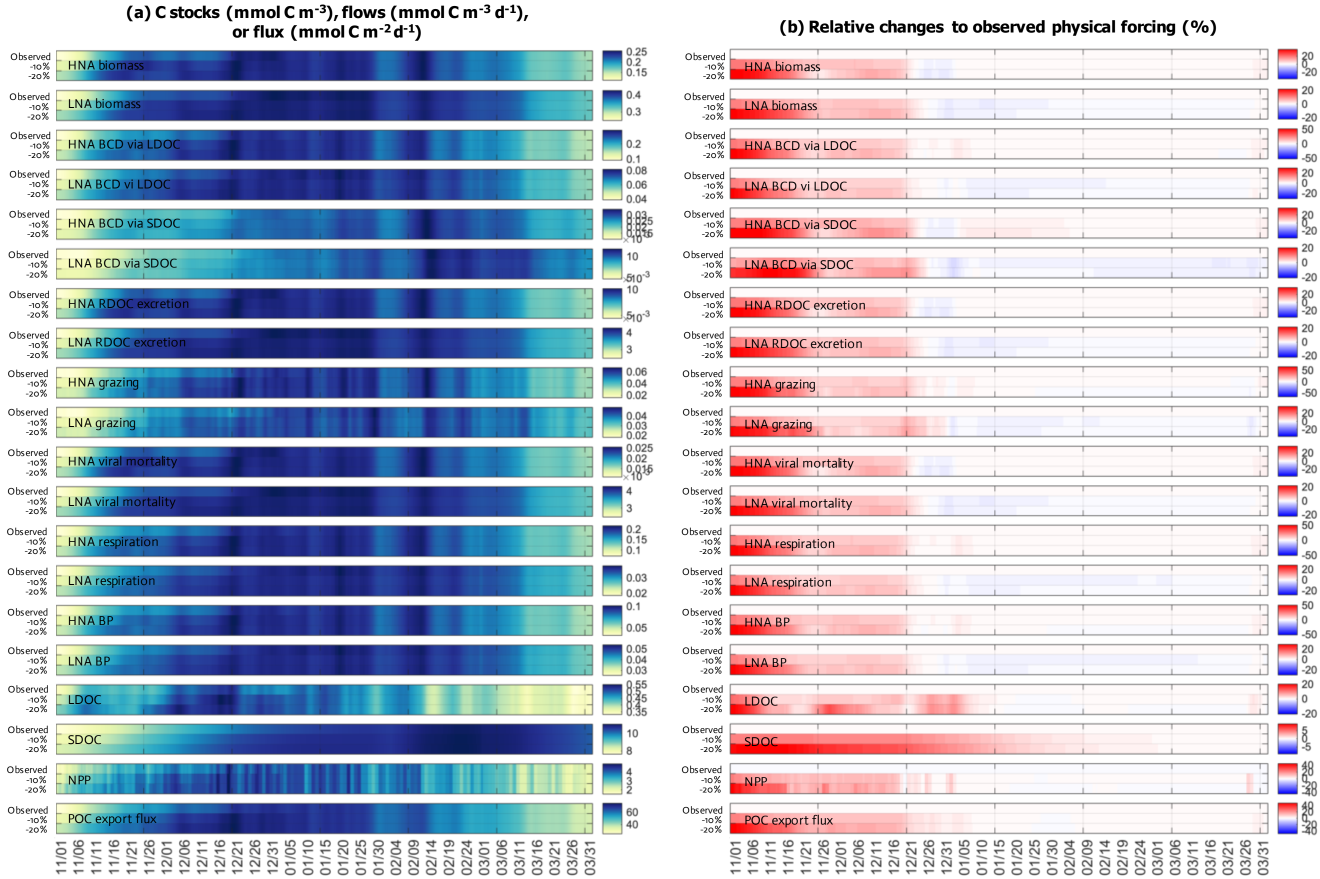

Figure S9: Melting alone scenarios. Seasonal progression of simulated HNA and LNA bacterial stocks and processes and key ecosystem functions over the growth season under observed physical forcing and melting alone scenarios (a) and the percent change of the corresponding variable under climate change scenarios compared to observed sea-ice fields (b).

Number of assimilated observations for each data type				
Data type	2010-11	2011-12	2012-13	2013-14
NO_3^-	0	32	35	20
PO_4^{3-}	38	31	37	21
Microzoo biomass	6	6	6	6
$\log_{10}(Chl_{DIATOM})$	10	10	10	10
$\log_{10}(Chl_{CRYPTO})$	10	10	10	10
$\log_{10}(PP)$	35	34	40	23
HNA biomass	10	9	8	16
LNA biomass	10	9	8	16
Total BP	10	9	8	16
SDOC	45	34	0	0
POC	46	34	0	0
PON	46	34	0	0

Table S1: The number of assimilated observations for each data type. SDOC, POC, and PON data types are not assimilated for 2012-13 and 2013-14 due to lack of observations.

2010-11					
Model parameter		Initial guess	Optimized value	Gradient	Mark
A_E	Arrhenius parameter for temperature function	4000		6.5	
μ_{DIATOM}	C-specific maximum for diatom growth rate	3.5		-7.82	
μ_{CRYPTO}	C-specific maximum for crypto growth rate	3.0		1.4	
α_{DIATOM}	Initial slope of Photosynthesis vs. irradiance (PI) curve of diatoms	0.24	0.20	3.30E-04	CS
α_{CRYPTO}	Initial slope of Photosynthesis vs. irradiance (PI) curve of crypto	0.12	0.10	8.93E-04	CS
β_{DIATOM}	Light inhibition parameter for photosynthesis of diatoms	0.005		2.17	
β_{CRYPTO}	Light inhibition parameter for photosynthesis of crypto	0.005		-1.05	
$v^N_{REF,DIATOM}$	Maximum nitrogen assimilation rate per diatom carbon biomass	0.5		-1.37	
$v^N_{REF,CRYPTO}$	Maximum nitrogen assimilation rate per crypto carbon biomass	0.3		-0.254	
k^{NH4}_{DIATOM}	Ammonium half-saturation concentration for diatom growth	0.1		5.54E-02	
k^{NH4}_{CRYPTO}	Ammonium half-saturation concentration for crypto growth	0.1		-6.83E-03	
k^{NO3}_{DIATOM}	Nitrate half-saturation concentration for diatom growth	0.9		5.79E-03	
k^{NO3}_{CRYPTO}	Nitrate half-saturation concentration for crypto growth	0.6		1.65E-02	
$v^P_{REF,DIATOM}$	Maximum phosphorus assimilation rate per diatom carbon biomass	0.03	0.10	-1.35	OP
$v^P_{REF,CRYPTO}$	Maximum phosphorus assimilation rate per crypto carbon biomass	0.03		-2.09E-02	
k^{PO4}_{DIATOM}	Phosphate half-saturation concentration for diatom growth	0.05		5.85E-02	
k^{PO4}_{CRYPTO}	Phosphate half-saturation concentration for crypto growth	0.04		9.35E-04	
ζ^{NO3}	Carbon requirement (respiration) to assimilate nitrate	2.0	1.68	1.25	OP
Θ	Maximum chlorophyll a to nitrogen ratio	2.9	4.07	8.14E-05	CS
$ex_{PSV,DIATOM}$	Diatom passive excretion rate (per biomass)	0.05	0.002	-1.13E-02	OP
$ex_{PSV,CRYPTO}$	Crypto passive excretion rate (per biomass)	0.05		0.149	
$ex_{CHO,DIATOM}$	Diatom carbon hydrate excretion rate (per growth rate)	0.05	0.03	0.419	OP
$ex_{CHO,CRYPTO}$	Crypto carbon hydrate excretion rate (per growth rate)	0.05		0.105	
pom_{DIATOM}	POM production rate by diatom aggregation	0.04	0.13	4.73	OP
pom_{CRYPTO}	POM production rate by crypto aggregation	0.03		0.156	
$k_{DOM,HNA}$	Half-saturation concentration of available DOC for heterotrophic HNA bacteria uptake	0.5		0.279	
$k_{DOM,LNA}$	Half-saturation concentration of available DOC for heterotrophic LNA bacteria uptake	0.2		-6.40E-02	
r_{SDOM}	parameter for SDOM's lability	0.005		0.723	
μ_{HNA}	Maximum HNA bacterial growth rate	5.0	4.88	-0.852	OP
μ_{LNA}	Maximum LNA bacterial growth rate	2.0	0.24	7.70E-05	CS
$b_{RESP,HNA}$	Parameter control HNA bacterial active respiration rate versus production	0.08		0.223	
$b_{RESP,LNA}$	Parameter control LNA bacterial active respiration rate versus production	0.2		8.70E-03	

$ex_{ADJ,HNA}$	HNA bacteria extra semilabile DOC excretion rate	2.0		0	
$ex_{ADJ,LNA}$	LNA bacteria extra semilabile DOC excretion rate	2.0		0	
$remi_{HNA}$	HNA bacteria inorganic nutrients regeneration rate	8.0		4.12E-02	
$remi_{LNA}$	LNA bacteria inorganic nutrients regeneration rate	2.0		1.62E-03	
$ex_{REFR,HNA}$	HNA bacteria refractory DOC production rate	0.04		-0.291	
$ex_{REFR,LNA}$	LNA bacteria refractory DOC production rate	0.01		0.167	
$f_{SLCT,HNA}$	HNA BA selection strength on SDOM	0.1		1.54E-04	
$f_{SLCT,LNA}$	LNA BA selection strength on SDOM	0.7		7.65E-04	
$resp^{B}_{HNA}$	HNA bacterial basal respiration rate	0.04		3.23E-02	
$resp^{B}_{LNA}$	LNA bacterial basal respiration rate	0.01		6.18E-02	
$r^{A}_{min,HNA}$	HNA bacteria minimum active respiration rate	0.08		-3.49E-02	
$r^{A}_{min,LNA}$	LNA bacteria minimum active respiration rate	0.04		-9.71E-04	
$r^{A}_{max,HNA}$	HNA bacteria maximum active respiration rate	0.8	0.61	-6.10E-04	CS
$r^{A}_{max,LNA}$	LNA bacteria maximum active respiration rate	0.4		0.31	
$mort_{HNA}$	HNA bacteria mortality rate	0.1		-0.676	
$mort_{LNA}$	LNA bacteria mortality rate	0.01		9.70E-02	
$\mu_{MICROZOO}$	Microzoo maximum growth rate	2.5	1.34	3.3	OP
g_{DIATOM}	Half-saturate density of diatoms in microzoo grazing function	1.0	4.70	1.22	OP
g'_{DIATOM}	Half-saturate density of diatoms in krill) grazing function	1.0	6.79	1.8	OP
g_{CRYPTO}	Half-saturate density of crypto in microzoo grazing function	1.0	0.22	-3.94	OP
g_{HNA}	Half-saturate density of HNA bacteria in microzoo grazing function	0.55	0.23	2.48E-05	CS
g_{LNA}	Half-saturate density of LNA bacteria in microzoo grazing function	0.55	1.18	1.22E-04	CS
$ex_{MICROZOO}$	Total DOM excretion rate per microzoo gross growth	0.15		-0.431	
$f_{ex,MICROZOO}$	Fraction of labile DOC of total microzoo DOC excretion	0.75		0.789	
$resp^{B}_{MICROZOO}$	Microzoo basal respiration rate	0.01		-2.49E-02	
$resp^{A}_{MICROZOO}$	Microzoo active respiration rate	0.42		-0.609	
$ex_{ADJ,MICROZOO}$	Microzoo extra SDOM excretion rate	2.0		0	
$remi_{MICROZOO}$	Microzoo inorganic nutrients regeneration rate	4.68		5.74E-02	
$pom_{MICROZOO}$	POM production rate per Microzoo gross growth	0.03		-4.49E-02	
μ_{KRILL}	Maximum krill growth rate	1.2	4.69	-7.57E-02	OP
$g_{MICROZOO}$	Half-saturate density of microzoo in krill grazing function	1.0	1.08	1.1	OP
ex_{KRILL}	Total DOM excretion rate per krill gross growth	0.3		-0.291	
$f_{ex,KRILL}$	Fraction of labile DOC of total krill DOC excretion	0.75		1.39	
$resp^{B}_{KRILL}$	Krill basal respiration	0.03		7.99E-02	
$resp^{A}_{KRILL}$	Krill active respiration	0.30	0.32	0.214	OP
$ex_{ADJ,KRILL}$	Krill extra semilabile DOM excretion rate	2.0		0	
$remi_{KRILL}$	Krill inorganic nutrients regeneration rate	4.0		3.97E-02	
pom_{KRILL}	POM production rate per krill gross growth	0.15		0.109	
$ex_{REFR,KRILL}$	Krill refractory DOM production rate	0.02		1.35E-02	
$remv_{KRILL}$	Krill removal rate by higher-trophic levels	0.78		3.47E-02	
$f_{SDOM,HZ}$	Fraction of SDOM production by higher-trophic level ingestion	0.1		-0.114	
$f_{POM,HZ}$	Fraction of POM production by higher-trophic level ingestion	0.2		-3.52E-02	
$ex_{REFR,SDOM}$	Conversion rate of SDOM to refractory DOM	0.0009		2.73E-02	
$q^{C}_{N,REFR}$	Refractory DOM N/C ratio	0.05		6.73E-02	

$q^C_{P,REFR}$	Refractory DOM P/C ratio	0.00065		-2.12E-03	
$q^C_{N,POM}$	N/C ratio for POM generation by microzoo and krill	0.12		-0.137	
$q^C_{P,POM}$	P/C ratio for POM generation by microzoo and krill	0.00045		-4.11E-02	
r_{ntrf}	Nitrification rate (NH4 to NO3)	0.076		2.14E-02	
prf_N	Preference parameter for dissolving N content in POM	1.1		0.393	
prf_P	Preference parameter for dissolving P content in POM	4.0		6.45E-02	
wnsv	Detritus sinking velocity	5.0	8.62	6.07E-05	OP
diss	POM dissolution rate	0.14	0.01	-1.26	OP

Table S2: List of model parameters for the year 2010-11. Summary of the values of model parameters (the initial guess and optimized values), gradient changes, and uncertainties after data assimilation for 2010-11. 'OP' indicates optimized but with high errors (>0.5) and 'CS' indicates optimized with well-constrained errors (<0.5). The uncertainties of the optimized parameters are calculated as the square roots of diagonal elements of the inverse of the Hessian matrix. The gradient changes of each parameter with respect to the cost function after data assimilation are defined as: when a parameter multiplied by $e^{\Delta a}$ (Δa is infinitely small), the change of the total cost function divided by Δa, given that $e^{\Delta a} \approx \Delta a$ when Δa is small enough. For example, a 10% change of a parameter (Δa = 10%) will approximately result in a total cost change of 10% of the corresponding gradient.

2011-12					
Model parameter		Initial guess	Optimized value	Gradient	Mark
A_E	Arrhenius parameter for temperature function	4000		11.7	
μ_{DIATOM}	C-specific maximum for diatom growth rate	3.5		-12.9	
μ_{CRYPTO}	C-specific maximum for crypto growth rate	3.0		-0.957	
α_{DIATOM}	Initial slope of Photosynthesis vs. irradiance (PI) curve of diatoms	0.24	0.13	-5.94E-06	CS
α_{CRYPTO}	Initial slope of Photosynthesis vs. irradiance (PI) curve of crypto	0.12	0.10	-1.2	OP
β_{DIATOM}	Light inhibition parameter for photosynthesis of diatoms	0.005		2.69	
β_{CRYPTO}	Light inhibition parameter for photosynthesis of crypto	0.005		-7.82E-02	
$v^N_{REF,DIATOM}$	Maximum nitrogen assimilation rate per diatom carbon biomass	0.5		-0.743	
$v^N_{REF,CRYPTO}$	Maximum nitrogen assimilation rate per crypto carbon biomass	0.3		-0.376	
k^{NH4}_{DIATOM}	Ammonium half-saturation concentration for diatom growth	0.1		5.13E-03	
k^{NH4}_{CRYPTO}	Ammonium half-saturation concentration for crypto growth	0.1		-1.94E-02	
k^{NO3}_{DIATOM}	Nitrate half-saturation concentration for diatom growth	0.9		3.20E-02	
k^{NO3}_{CRYPTO}	Nitrate half-saturation concentration for crypto growth	0.6		3.05E-02	
$v^P_{REF,DIATOM}$	Maximum phosphorus assimilation rate per diatom carbon biomass	0.03	0.10	1.75	OP
$v^P_{REF,CRYPTO}$	Maximum phosphorus assimilation rate per crypto carbon biomass	0.03		-9.79E-02	
k^{PO4}_{DIATOM}	Phosphate half-saturation concentration for diatom growth	0.05		-9.40E-02	
k^{PO4}_{CRYPTO}	Phosphate half-saturation concentration for crypto growth	0.04		2.10E-03	
ζ^{NO3}	Carbon requirement (respiration) to assimilate nitrate	2.0	1.68	3.85	OP
Θ	Maximum chlorophyll a to nitrogen ratio	2.9	5.64	-1.35E-05	CS
$ex_{PSV,DIATOM}$	Diatom passive excretion rate (per biomass)	0.05	0.002	0.794	OP
$ex_{PSV,CRYPTO}$	Crypto passive excretion rate (per biomass)	0.05		0.184	
$ex_{CHO,DIATOM}$	Diatom carbon hydrate excretion rate (per growth rate)	0.05	0.03	2.53	OP
$ex_{CHO,CRYPTO}$	Crypto carbon hydrate excretion rate (per growth rate)	0.05		0.444	
pom_{DIATOM}	POM production rate by diatom aggregation	0.04	0.09	4.89	OP
pom_{CRYPTO}	POM production rate by crypto aggregation	0.03		-1.26E-02	
$k_{DOM,HNA}$	Half-saturation concentration of available DOC for heterotrophic HNA bacteria uptake	0.5		0.666	
$k_{DOM,LNA}$	Half-saturation concentration of available DOC for heterotrophic LNA bacteria uptake	0.2		-0.18	
r_{SDOM}	parameter for SDOM's lability	0.005		0.718	
μ_{HNA}	Maximum HNA bacterial growth rate	5.0	4.88	-3.42	OP
μ_{LNA}	Maximum LNA bacterial growth rate	2.0	0.65	-3.59E-06	CS
$b_{RESP,HNA}$	Parameter control HNA bacterial active respiration rate versus production	0.08		9.55E-03	
$b_{RESP,LNA}$	Parameter control LNA bacterial active respiration rate versus production	0.2		-0.324	

$ex_{ADJ,HNA}$	HNA bacteria extra semilabile DOC excretion rate	2.0		0	
$ex_{ADJ,LNA}$	LNA bacteria extra semilabile DOC excretion rate	2.0		0	
$remi_{HNA}$	HNA bacteria inorganic nutrients regeneration rate	8.0		8.57E-02	
$remi_{LNA}$	LNA bacteria inorganic nutrients regeneration rate	2.0		0.579	
$ex_{REFR,HNA}$	HNA bacteria refractory DOC production rate	0.04		-0.135	
$ex_{REFR,LNA}$	LNA bacteria refractory DOC production rate	0.01		-0.323	
$f_{SLCT,HNA}$	HNA BA selection strength on SDOM	0.1		7.96E-04	
$f_{SLCT,LNA}$	LNA BA selection strength on SDOM	0.7		1.24E-02	
$resp^{B}_{HNA}$	HNA bacterial basal respiration rate	0.04		-8.37E-02	
$resp^{B}_{LNA}$	LNA bacterial basal respiration rate	0.01		-0.196	
$r^{A}_{min,HNA}$	HNA bacteria minimum active respiration rate	0.08		-1.02E-03	
$r^{A}_{min,LNA}$	LNA bacteria minimum active respiration rate	0.04		3.68E-02	
$r^{A}_{max,HNA}$	HNA bacteria maximum active respiration rate	0.8	0.84	5.96E-05	CS
$r^{A}_{max,LNA}$	LNA bacteria maximum active respiration rate	0.4		-3.25	
$mort_{HNA}$	HNA bacteria mortality rate	0.1		-7.91E-02	
$mort_{LNA}$	LNA bacteria mortality rate	0.01		-0.105	
$\mu_{MICROZOO}$	Microzoo maximum growth rate	2.5	0.49	30.4	OP
g_{DIATOM}	Half-saturate density of diatoms in microzoo grazing function	1.0	3.56	9.53	OP
g'_{DIATOM}	Half-saturate density of diatoms in krill) grazing function	1.0	5.84	-3.07	OP
g_{CRYPTO}	Half-saturate density of crypto in microzoo grazing function	1.0	0.19	2.96E-06	CS
g_{HNA}	Half-saturate density of HNA bacteria in microzoo grazing function	0.55	0.12	-2.39E-06	CS
g_{LNA}	Half-saturate density of LNA bacteria in microzoo grazing function	0.55	0.30	8.86E-07	CS
$ex_{MICROZOO}$	Total DOM excretion rate per microzoo gross growth	0.15		-11.7	
$f_{ex,MICROZOO}$	Fraction of labile DOC of total microzoo DOC excretion	0.75		1.02	
$resp^{B}_{MICROZOO}$	Microzoo basal respiration rate	0.01		-2.75	
$resp^{A}_{MICROZOO}$	Microzoo active respiration rate	0.42		-35.9	
$ex_{ADJ,MICROZOO}$	Microzoo extra SDOM excretion rate	2.0		0	
$remi_{MICROZOO}$	Microzoo inorganic nutrients regeneration rate	4.68		5.73E-02	
$pom_{MICROZOO}$	POM production rate per Microzoo gross growth	0.03		-2.62	
μ_{KRILL}	Maximum krill growth rate	1.2	1.77	-22.8	OP
$g_{MICROZOO}$	Half-saturate density of microzoo in krill grazing function	1.0	0.96	18.6	OP
ex_{KRILL}	Total DOM excretion rate per krill gross growth	0.3		14.9	
$f_{ex,KRILL}$	Fraction of labile DOC of total krill DOC excretion	0.75		0.304	
$resp^{B}_{KRILL}$	Krill basal respiration	0.03		0.236	
$resp^{A}_{KRILL}$	Krill active respiration	0.30	0.32	14.7	OP
$ex_{ADJ,KRILL}$	Krill extra semilabile DOM excretion rate	2.0		0	
$remi_{KRILL}$	Krill inorganic nutrients regeneration rate	4.0		-3.98E-02	
pom_{KRILL}	POM production rate per krill gross growth	0.15		6.89	
$ex_{REFR,KRILL}$	Krill refractory DOM production rate	0.02		0.917	
$remv_{KRILL}$	Krill removal rate by higher-trophic levels	0.78		13.1	
$f_{SDOM,HZ}$	Fraction of SDOM production by higher-trophic level ingestion	0.1		2.56E-02	
$f_{POM,HZ}$	Fraction of POM production by higher-trophic level ingestion	0.2		1.26E-02	
$ex_{REFR,SDOM}$	Conversion rate of SDOM to refractory DOM	0.0009		-3.48E-02	
$q^{C}_{N,REFR}$	Refractory DOM N/C ratio	0.05		-9.79E-02	

$q^{C}_{P,REFR}$	Refractory DOM P/C ratio	0.00065		3.02E-04	
$q^{C}_{N,POM}$	N/C ratio for POM generation by microzoo and krill	0.12		-0.123	
$q^{C}_{P,POM}$	P/C ratio for POM generation by microzoo and krill	0.00045		5.17E-02	
r_{ntrf}	Nitrification rate (NH4 to NO3)	0.076		5.33E-02	
prf_{N}	Preference parameter for dissolving N content in POM	1.1		2.41E-02	
prf_{P}	Preference parameter for dissolving P content in POM	4.0		-3.10E-02	
wnsv	Detritus sinking velocity	5.0	4.65	0.631	OP
diss	POM dissolution rate	0.14	0.01	1.66	OP

Table S3: List of model parameters for the year 2011-12. Summary of the values of model parameters (the initial guess and optimized values), gradient changes, and uncertainties after data assimilation for 2011-12. ‘OP’ indicates optimized but with high errors (>0.5) and ‘CS’ indicates optimized with well-constrained errors (<0.5). The uncertainties of the optimized parameters are calculated as the square roots of diagonal elements of the inverse of the Hessian matrix. The gradient changes of each parameter with respect to the cost function after data assimilation are defined as: when a parameter multiplied by $e^{\Delta a}$ (Δa is infinitely small), the change of the total cost function divided by Δa, given that $e^{\Delta a} \approx \Delta a$ when Δa is small enough. For example, a 10% change of a parameter (Δa = 10%) will approximately result in a total cost change of 10% of the corresponding gradient.

2012-13					
Model parameter		Initial guess	Optimized value	Gradient	Mark
A_E	Arrhenius parameter for temperature function	4000		17.7	
μ_{DIATOM}	C-specific maximum for diatom growth rate	3.5		-2.54	
μ_{CRYPTO}	C-specific maximum for crypto growth rate	3.0		-1.28	
α_{DIATOM}	Initial slope of Photosynthesis vs. irradiance (PI) curve of diatoms	0.24	0.19	-9.49E-02	CS
α_{CRYPTO}	Initial slope of Photosynthesis vs. irradiance (PI) curve of crypto	0.12	0.28	5.4	OP
β_{DIATOM}	Light inhibition parameter for photosynthesis of diatoms	0.005		-0.122	
β_{CRYPTO}	Light inhibition parameter for photosynthesis of crypto	0.005		0.133	
$v^N_{REF,DIATOM}$	Maximum nitrogen assimilation rate per diatom carbon biomass	0.5		1.85	
$v^N_{REF,CRYPTO}$	Maximum nitrogen assimilation rate per crypto carbon biomass	0.3		-0.219	
k^{NH4}_{DIATOM}	Ammonium half-saturation concentration for diatom growth	0.1		0.325	
k^{NH4}_{CRYPTO}	Ammonium half-saturation concentration for crypto growth	0.1		-0.1	
k^{NO3}_{DIATOM}	Nitrate half-saturation concentration for diatom growth	0.9		-0.408	
k^{NO3}_{CRYPTO}	Nitrate half-saturation concentration for crypto growth	0.6		0.114	
$v^P_{REF,DIATOM}$	Maximum phosphorus assimilation rate per diatom carbon biomass	0.03	0.10	-13.9	OP
$v^P_{REF,CRYPTO}$	Maximum phosphorus assimilation rate per crypto carbon biomass	0.03		-0.124	
k^{PO4}_{DIATOM}	Phosphate half-saturation concentration for diatom growth	0.05		0.466	
k^{PO4}_{CRYPTO}	Phosphate half-saturation concentration for crypto growth	0.04		3.03E-03	
ζ^{NO3}	Carbon requirement (respiration) to assimilate nitrate	2.0	1.68	-8.94E-02	OP
Θ	Maximum chlorophyll a to nitrogen ratio	2.9	3.69	5.13E-02	CS
$ex_{PSV,DIATOM}$	Diatom passive excretion rate (per biomass)	0.05	0.002	0.542	OP
$ex_{PSV,CRYPTO}$	Crypto passive excretion rate (per biomass)	0.05		0.341	
$ex_{CHO,DIATOM}$	Diatom carbon hydrate excretion rate (per growth rate)	0.05	0.03	0.539	OP
$ex_{CHO,CRYPTO}$	Crypto carbon hydrate excretion rate (per growth rate)	0.05		2.76E-02	
pom_{DIATOM}	POM production rate by diatom aggregation	0.04	0.05	-10.6	OP
pom_{CRYPTO}	POM production rate by crypto aggregation	0.03		-0.452	
$k_{DOM,HNA}$	Half-saturation concentration of available DOC for heterotrophic HNA bacteria uptake	0.5		2.27E-02	
$k_{DOM,LNA}$	Half-saturation concentration of available DOC for heterotrophic LNA bacteria uptake	0.2		-0.107	
r_{SDOM}	parameter for SDOM's lability	0.005		1.15	
μ_{HNA}	Maximum HNA bacterial growth rate	5.0	4.88	-5.46	OP
μ_{LNA}	Maximum LNA bacterial growth rate	2.0	0.29	5.81E-02	CS
$b_{RESP,HNA}$	Parameter control HNA bacterial active respiration rate versus production	0.08		-0.429	
$b_{RESP,LNA}$	Parameter control LNA bacterial active respiration rate versus production	0.2		2.88E-04	

$ex_{ADJ,HNA}$	HNA bacteria extra semilabile DOC excretion rate	2.0		0	
$ex_{ADJ,LNA}$	LNA bacteria extra semilabile DOC excretion rate	2.0		0	
$remi_{HNA}$	HNA bacteria inorganic nutrients regeneration rate	8.0		0.431	
$remi_{LNA}$	LNA bacteria inorganic nutrients regeneration rate	2.0		0.114	
$ex_{REFR,HNA}$	HNA bacteria refractory DOC production rate	0.04		-0.482	
$ex_{REFR,LNA}$	LNA bacteria refractory DOC production rate	0.01		-0.116	
$f_{SLCT,HNA}$	HNA BA selection strength on SDOM	0.1		-4.94E-03	
$f_{SLCT,LNA}$	LNA BA selection strength on SDOM	0.7		-2.10E-03	
$resp^{B}_{HNA}$	HNA bacterial basal respiration rate	0.04		-0.175	
$resp^{B}_{LNA}$	LNA bacterial basal respiration rate	0.01		-5.01E-02	
$r^{A}_{min,HNA}$	HNA bacteria minimum active respiration rate	0.08		5.79E-02	
$r^{A}_{min,LNA}$	LNA bacteria minimum active respiration rate	0.04		-3.23E-05	
$r^{A}_{max,HNA}$	HNA bacteria maximum active respiration rate	0.8	0.69	-0.208	CS
$r^{A}_{max,LNA}$	LNA bacteria maximum active respiration rate	0.4		-0.313	
$mort_{HNA}$	HNA bacteria mortality rate	0.1		-0.684	
$mort_{LNA}$	LNA bacteria mortality rate	0.01		-7.77E-02	
$\mu_{MICROZOO}$	Microzoo maximum growth rate	2.5	2.40	-0.207	CS
g_{DIATOM}	Half-saturate density of diatoms in microzoo grazing function	1.0	3.56	1.04	OP
g'_{DIATOM}	Half-saturate density of diatoms in krill) grazing function	1.0	4.18	-33	OP
g_{CRYPTO}	Half-saturate density of crypto in microzoo grazing function	1.0	0.17	0.103	CS
g_{HNA}	Half-saturate density of HNA bacteria in microzoo grazing function	0.55	0.16	-2.15E-02	CS
g_{LNA}	Half-saturate density of LNA bacteria in microzoo grazing function	0.55	0.46	3.36E-02	CS
$ex_{MICROZOO}$	Total DOM excretion rate per microzoo gross growth	0.15		-2	
$f_{ex,MICROZOO}$	Fraction of labile DOC of total microzoo DOC excretion	0.75		1.8	
$resp^{B}_{MICROZOO}$	Microzoo basal respiration rate	0.01		-5.35E-02	
$resp^{A}_{MICROZOO}$	Microzoo active respiration rate	0.42		-4.43	
$ex_{ADJ,MICROZOO}$	Microzoo extra SDOM excretion rate	2.0		0	
$remi_{MICROZOO}$	Microzoo inorganic nutrients regeneration rate	4.68		0.181	
$pom_{MICROZOO}$	POM production rate per Microzoo gross growth	0.03		-0.262	
μ_{KRILL}	Maximum krill growth rate	1.2	4.07	0.273	CS
$g_{MICROZOO}$	Half-saturate density of microzoo in krill grazing function	1.0	0.42	-0.205	CS
ex_{KRILL}	Total DOM excretion rate per krill gross growth	0.3		1.32E-02	
$f_{ex,KRILL}$	Fraction of labile DOC of total krill DOC excretion	0.75		4.79	
$resp^{B}_{KRILL}$	Krill basal respiration	0.03		-0.53	
$resp^{A}_{KRILL}$	Krill active respiration	0.30	0.32	-1.23	OP
$ex_{ADJ,KRILL}$	Krill extra semilabile DOM excretion rate	2.0		0	
$remi_{KRILL}$	Krill inorganic nutrients regeneration rate	4.0		0.497	
pom_{KRILL}	POM production rate per krill gross growth	0.15		-0.243	
$ex_{REFR,KRILL}$	Krill refractory DOM production rate	0.02		-3.05E-02	
$remv_{KRILL}$	Krill removal rate by higher-trophic levels	0.78		-5.66E-02	
$f_{SDOM,HZ}$	Fraction of SDOM production by higher-trophic level ingestion	0.1		3.26E-02	
$f_{POM,HZ}$	Fraction of POM production by higher-trophic level ingestion	0.2		4.35E-02	
$ex_{REFR,SDOM}$	Conversion rate of SDOM to refractory DOM	0.0009		-3.14E-03	
$q^{C}_{N,REFR}$	Refractory DOM N/C ratio	0.05		0.112	

$q^{C}_{P,REFR}$	Refractory DOM P/C ratio	0.00065		-3.11E-02	
$q^{C}_{N,POM}$	N/C ratio for POM generation by microzoo and krill	0.12		1.25	
$q^{C}_{P,POM}$	P/C ratio for POM generation by microzoo and krill	0.00045		-0.86	
r_{ntrf}	Nitrification rate (NH4 to NO3)	0.076		3.70E-02	
prf_N	Preference parameter for dissolving N content in POM	1.1		-9.45E-02	
prf_P	Preference parameter for dissolving P content in POM	4.0		0.466	
wnsv	Detritus sinking velocity	5.0	5.87	-0.441	OP
diss	POM dissolution rate	0.14	0.01	0.437	OP

Table S4: List of model parameters for the year 2012-13. Summary of the values of model parameters (the initial guess and optimized values), gradient changes, and uncertainties after data assimilation for 2012-13. ‘OP’ indicates optimized but with high errors (>0.5) and ‘CS’ indicates optimized with well-constrained errors (<0.5). The uncertainties of the optimized parameters are calculated as the square roots of diagonal elements of the inverse of the Hessian matrix. The gradient changes of each parameter with respect to the cost function after data assimilation are defined as: when a parameter multiplied by $e^{\Delta a}$ (Δa is infinitely small), the change of the total cost function divided by Δa, given that $e^{\Delta a} \approx \Delta a$ when Δa is small enough. For example, a 10% change of a parameter (Δa = 10%) will approximately result in a total cost change of 10% of the corresponding gradient.

2013-14					
Model parameter		Initial guess	Optimized value	Gradient	Mark
A_E	Arrhenius parameter for temperature function	4000		5.42	
μ_{DIATOM}	C-specific maximum for diatom growth rate	3.5		-0.202	
μ_{CRYPTO}	C-specific maximum for crypto growth rate	3.0		-7.25	
α_{DIATOM}	Initial slope of Photosynthesis vs. irradiance (PI) curve of diatoms	0.24	0.22	2.70E-04	CS
α_{CRYPTO}	Initial slope of Photosynthesis vs. irradiance (PI) curve of crypto	0.12	0.10	-10.3	OP
β_{DIATOM}	Light inhibition parameter for photosynthesis of diatoms	0.005		1.71	
β_{CRYPTO}	Light inhibition parameter for photosynthesis of crypto	0.005		1.2	
$v^{N}_{REF,DIATOM}$	Maximum nitrogen assimilation rate per diatom carbon biomass	0.5		-4.3	
$v^{N}_{REF,CRYPTO}$	Maximum nitrogen assimilation rate per crypto carbon biomass	0.3		-0.398	
k^{NH4}_{DIATOM}	Ammonium half-saturation concentration for diatom growth	0.1		-0.697	
k^{NH4}_{CRYPTO}	Ammonium half-saturation concentration for crypto growth	0.1		0.286	
k^{NO3}_{DIATOM}	Nitrate half-saturation concentration for diatom growth	0.9		0.876	
k^{NO3}_{CRYPTO}	Nitrate half-saturation concentration for crypto growth	0.6		-0.276	
$v^{P}_{REF,DIATOM}$	Maximum phosphorus assimilation rate per diatom carbon biomass	0.03	0.10	9.31	OP
$v^{P}_{REF,CRYPTO}$	Maximum phosphorus assimilation rate per crypto carbon biomass	0.03		4.40E-02	
k^{PO4}_{DIATOM}	Phosphate half-saturation concentration for diatom growth	0.05		-0.403	
k^{PO4}_{CRYPTO}	Phosphate half-saturation concentration for crypto growth	0.04		-2.08E-03	
ζ^{NO3}	Carbon requirement (respiration) to assimilate nitrate	2.0	1.68	4.23	OP
Θ	Maximum chlorophyll a to nitrogen ratio	2.9	4.36	8.60E-04	CS
$ex_{PSV,DIATOM}$	Diatom passive excretion rate (per biomass)	0.05	0.002	0.316	OP
$ex_{PSV,CRYPTO}$	Crypto passive excretion rate (per biomass)	0.05		-0.826	
$ex_{CHO,DIATOM}$	Diatom carbon hydrate excretion rate (per growth rate)	0.05	0.03	0.88	OP
$ex_{CHO,CRYPTO}$	Crypto carbon hydrate excretion rate (per growth rate)	0.05		0.52	
pom_{DIATOM}	POM production rate by diatom aggregation	0.04	0.09	-9.3	OP
pom_{CRYPTO}	POM production rate by crypto aggregation	0.03		1.65	
$k_{DOM,HNA}$	Half-saturation concentration of available DOC for heterotrophic HNA bacteria uptake	0.5		2.88	
$k_{DOM,LNA}$	Half-saturation concentration of available DOC for heterotrophic LNA bacteria uptake	0.2		-1.52	
r_{SDOM}	parameter for SDOM's lability	0.005		-2.63	
μ_{HNA}	Maximum HNA bacterial growth rate	5.0	4.88	-0.193	OP
μ_{LNA}	Maximum LNA bacterial growth rate	2.0	0.73	-3.96E-04	CS
$b_{RESP,HNA}$	Parameter control HNA bacterial active respiration rate versus production	0.08		-0.725	
$b_{RESP,LNA}$	Parameter control LNA bacterial active respiration rate versus production	0.2		0.117	

$ex_{ADJ,HNA}$	HNA bacteria extra semilabile DOC excretion rate	2.0		0	
$ex_{ADJ,LNA}$	LNA bacteria extra semilabile DOC excretion rate	2.0		0	
$remi_{HNA}$	HNA bacteria inorganic nutrients regeneration rate	8.0		0.257	
$remi_{LNA}$	LNA bacteria inorganic nutrients regeneration rate	2.0		0.132	
$ex_{REFR,HNA}$	HNA bacteria refractory DOC production rate	0.04		0.628	
$ex_{REFR,LNA}$	LNA bacteria refractory DOC production rate	0.01		-0.291	
$f_{SLCT,HNA}$	HNA BA selection strength on SDOM	0.1		2.96E-02	
$f_{SLCT,LNA}$	LNA BA selection strength on SDOM	0.7		6.75E-02	
$resp^{B}_{HNA}$	HNA bacterial basal respiration rate	0.04		0.583	
$resp^{B}_{LNA}$	LNA bacterial basal respiration rate	0.01		-5.76E-03	
$r^{A}_{min,HNA}$	HNA bacteria minimum active respiration rate	0.08		8.89E-02	
$r^{A}_{min,LNA}$	LNA bacteria minimum active respiration rate	0.04		-1.33E-02	
$r^{A}_{max,HNA}$	HNA bacteria maximum active respiration rate	0.8	0.75	6.33E-05	CS
$r^{A}_{max,LNA}$	LNA bacteria maximum active respiration rate	0.4		1.19	
$mort_{HNA}$	HNA bacteria mortality rate	0.1		1.07	
$mort_{LNA}$	LNA bacteria mortality rate	0.01		-0.391	
$\mu_{MICROZOO}$	Microzoo maximum growth rate	2.5	1.21	33.9	OP
g_{DIATOM}	Half-saturate density of diatoms in microzoo grazing function	1.0	4.40	8.81E-04	CS
g'_{DIATOM}	Half-saturate density of diatoms in krill) grazing function	1.0	5.28	-1.73E-04	CS
g_{CRYPTO}	Half-saturate density of crypto in microzoo grazing function	1.0	0.22	-19.5	OP
g_{HNA}	Half-saturate density of HNA bacteria in microzoo grazing function	0.55	0.34	1.89E-04	CS
g_{LNA}	Half-saturate density of LNA bacteria in microzoo grazing function	0.55	0.37	-2.36E-04	CS
$ex_{MICROZOO}$	Total DOM excretion rate per microzoo gross growth	0.15		-7.32	
$f_{ex,MICROZOO}$	Fraction of labile DOC of total microzoo DOC excretion	0.75		-2.17	
$resp^{B}_{MICROZOO}$	Microzoo basal respiration rate	0.01		-0.657	
$resp^{A}_{MICROZOO}$	Microzoo active respiration rate	0.42		-19.1	
$ex_{ADJ,MICROZOO}$	Microzoo extra SDOM excretion rate	2.0		0	
$remi_{MICROZOO}$	Microzoo inorganic nutrients regeneration rate	4.68		-0.118	
$pom_{MICROZOO}$	POM production rate per Microzoo gross growth	0.03		-1.47	
μ_{KRILL}	Maximum krill growth rate	1.2	4.70	-39.5	OP
$g_{MICROZOO}$	Half-saturate density of microzoo in krill grazing function	1.0	1.08	31.6	OP
ex_{KRILL}	Total DOM excretion rate per krill gross growth	0.3		27.3	
$f_{ex,KRILL}$	Fraction of labile DOC of total krill DOC excretion	0.75		-1.73	
$resp^{B}_{KRILL}$	Krill basal respiration	0.03		0.978	
$resp^{A}_{KRILL}$	Krill active respiration	0.30	0.32	29.5	OP
$ex_{ADJ,KRILL}$	Krill extra semilabile DOM excretion rate	2.0		0	
$remi_{KRILL}$	Krill inorganic nutrients regeneration rate	4.0		-0.413	
pom_{KRILL}	POM production rate per krill gross growth	0.15		13.1	
$ex_{REFR,KRILL}$	Krill refractory DOM production rate	0.02		1.78	
$remv_{KRILL}$	Krill removal rate by higher-trophic levels	0.78		21	
$f_{SDOM,HZ}$	Fraction of SDOM production by higher-trophic level ingestion	0.1		-0.168	
$f_{POM,HZ}$	Fraction of POM production by higher-trophic level ingestion	0.2		-0.246	
$ex_{REFR,SDOM}$	Conversion rate of SDOM to refractory DOM	0.0009		8.25E-03	
$q^{C}_{N,REFR}$	Refractory DOM N/C ratio	0.05		-0.2	

$q^{C}_{P,REFR}$	Refractory DOM P/C ratio	0.00065		3.33E-02	
$q^{C}_{N,POM}$	N/C ratio for POM generation by microzoo and krill	0.12		-1.55	
$q^{C}_{P,POM}$	P/C ratio for POM generation by microzoo and krill	0.00045		0.677	
r_{ntrf}	Nitrification rate (NH4 to NO3)	0.076		1.38E-02	
prf_{N}	Preference parameter for dissolving N content in POM	1.1		0.315	
prf_{P}	Preference parameter for dissolving P content in POM	4.0		-0.871	
wnsv	Detritus sinking velocity	5.0	5.87	1.35	OP
diss	POM dissolution rate	0.14	0.01	-1.36	OP

Table S5: List of model parameters for the year 2013-14. Summary of the values of model parameters (the initial guess and optimized values), gradient changes, and uncertainties after data assimilation for 2013-14. 'OP' indicates optimized but with high errors (>0.5) and 'CS' indicates optimized with well-constrained errors (<0.5). The uncertainties of the optimized parameters are calculated as the square roots of diagonal elements of the inverse of the Hessian matrix. The gradient changes of each parameter with respect to the cost function after data assimilation are defined as: when a parameter multiplied by $e^{\Delta a}$ (Δa is infinitely small), the change of the total cost function divided by Δa, given that $e^{\Delta a} \approx \Delta a$ when Δa is small enough. For example, a 10% change of a parameter (Δa = 10%) will approximately result in a total cost change of 10% of the corresponding gradient.

Climatological model					
Model parameter		Initial guess	Optimized value	Gradient	Mark
A_E	Arrhenius parameter for temperature function	4000		8.29	
μ_{DIATOM}	C-specific maximum for diatom growth rate	3.5		-8.11	
μ_{CRYPTO}	C-specific maximum for crypto growth rate	3.0		-0.533	
α_{DIATOM}	Initial slope of Photosynthesis vs. irradiance (PI) curve of diatoms	0.24	0.18	4.26	OP
α_{CRYPTO}	Initial slope of Photosynthesis vs. irradiance (PI) curve of crypto	0.12	0.10	1.40	OP
β_{DIATOM}	Light inhibition parameter for photosynthesis of diatoms	0.005		1.35	
β_{CRYPTO}	Light inhibition parameter for photosynthesis of crypto	0.005		7.91E-02	
$v^{N}_{REF,DIATOM}$	Maximum nitrogen assimilation rate per diatom carbon biomass	0.5		-0.625	
$v^{N}_{REF,CRYPTO}$	Maximum nitrogen assimilation rate per crypto carbon biomass	0.3		-7.89E-02	
k^{NH4}_{DIATOM}	Ammonium half-saturation concentration for diatom growth	0.1		-0.107	
k^{NH4}_{CRYPTO}	Ammonium half-saturation concentration for crypto growth	0.1		-3.34E-03	
k^{NO3}_{DIATOM}	Nitrate half-saturation concentration for diatom growth	0.9		0.135	
k^{NO3}_{CRYPTO}	Nitrate half-saturation concentration for crypto growth	0.6		6.82E-03	
$v^{P}_{REF,DIATOM}$	Maximum phosphorus assimilation rate per diatom carbon biomass	0.03	0.10	0.177	OP
$v^{P}_{REF,CRYPTO}$	Maximum phosphorus assimilation rate per crypto carbon biomass	0.03		-2.74E-02	
k^{PO4}_{DIATOM}	Phosphate half-saturation concentration for diatom growth	0.05		-4.52E-02	
k^{PO4}_{CRYPTO}	Phosphate half-saturation concentration for crypto growth	0.04		4.99E-04	
ζ^{NO3}	Carbon requirement (respiration) to assimilate nitrate	2.0	1.68	1.09	OP
Θ	Maximum chlorophyll a to nitrogen ratio	2.9	4.97	2.97E-02	CS
$ex_{PSV,DIATOM}$	Diatom passive excretion rate (per biomass)	0.05	0.002	4.71E-02	OP
$ex_{PSV,CRYPTO}$	Crypto passive excretion rate (per biomass)	0.05		-2.35E-02	
$ex_{CHO,DIATOM}$	Diatom carbon hydrate excretion rate (per growth rate)	0.05	0.03	0.440	OP
$ex_{CHO,CRYPTO}$	Crypto carbon hydrate excretion rate (per growth rate)	0.05		-7.74E-03	
pom_{DIATOM}	POM production rate by diatom aggregation	0.04	0.09	4.01	OP
pom_{CRYPTO}	POM production rate by crypto aggregation	0.03		-3.4E-02	
$k_{DOM,HNA}$	Half-saturation concentration of available DOC for heterotrophic HNA bacteria uptake	0.5		0.349	
$k_{DOM,LNA}$	Half-saturation concentration of available DOC for heterotrophic LNA bacteria uptake	0.2		0.235	
r_{SDOM}	parameter for SDOM's lability	0.005		4.86E-02	
μ_{HNA}	Maximum HNA bacterial growth rate	5.0	4.88	-1.54	OP
μ_{LNA}	Maximum LNA bacterial growth rate	2.0	0.54	-7.15E-03	CS
$b_{RESP,HNA}$	Parameter control HNA bacterial active respiration rate versus production	0.08		0.113	
$b_{RESP,LNA}$	Parameter control LNA bacterial active respiration rate versus production	0.2		1.6E-02	

$ex_{ADJ,HNA}$	HNA bacteria extra semilabile DOC excretion rate	2.0		0.00	
$ex_{ADJ,LNA}$	LNA bacteria extra semilabile DOC excretion rate	2.0		0.00	
$remi_{HNA}$	HNA bacteria inorganic nutrients regeneration rate	8.0		0.155	
$remi_{LNA}$	LNA bacteria inorganic nutrients regeneration rate	2.0		0.112	
$ex_{REFR,HNA}$	HNA bacteria refractory DOC production rate	0.04		-6.91E-03	
$ex_{REFR,LNA}$	LNA bacteria refractory DOC production rate	0.01		5.69E-02	
$f_{SLCT,HNA}$	HNA BA selection strength on SDOM	0.1		1.53E-03	
$f_{SLCT,LNA}$	LNA BA selection strength on SDOM	0.7		3.91E-03	
$resp^{B}_{HNA}$	HNA bacterial basal respiration rate	0.04		-4.3E-02	
$resp^{B}_{LNA}$	LNA bacterial basal respiration rate	0.01		8.29E-03	
$r^{A}_{min,HNA}$	HNA bacteria minimum active respiration rate	0.08		-1.51E-02	
$r^{A}_{min,LNA}$	LNA bacteria minimum active respiration rate	0.04		-1.81E-03	
$r^{A}_{max,HNA}$	HNA bacteria maximum active respiration rate	0.8	0.69	-2.44E-02	CS
$r^{A}_{max,LNA}$	LNA bacteria maximum active respiration rate	0.4		-0.115	
$mort_{HNA}$	HNA bacteria mortality rate	0.1		4.15E-02	
$mort_{LNA}$	LNA bacteria mortality rate	0.01		5.36E-02	
$\mu_{MICROZOO}$	Microzoo maximum growth rate	2.5	1.19	-1.8E-02	CS
g_{DIATOM}	Half-saturate density of diatoms in microzoo grazing function	1.0	3.56	0.915	OP
g'_{DIATOM}	Half-saturate density of diatoms in krill) grazing function	1.0	4.15	2.32E-02	CS
g_{CRYPTO}	Half-saturate density of crypto in microzoo grazing function	1.0	0.22	-1.45	OP
g_{HNA}	Half-saturate density of HNA bacteria in microzoo grazing function	0.55	0.23	2.93E-02	CS
g_{LNA}	Half-saturate density of LNA bacteria in microzoo grazing function	0.55	0.44	6.2E-03	CS
$ex_{MICROZOO}$	Total DOM excretion rate per microzoo gross growth	0.15		0.122	
$f_{ex,MICROZOO}$	Fraction of labile DOC of total microzoo DOC excretion	0.75		-0.156	
$resp^{B}_{MICROZOO}$	Microzoo basal respiration rate	0.01		1.03E-03	
$resp^{A}_{MICROZOO}$	Microzoo active respiration rate	0.42		-0.234	
$ex_{ADJ,MICROZOO}$	Microzoo extra SDOM excretion rate	2.0		0.00	
$remi_{MICROZOO}$	Microzoo inorganic nutrients regeneration rate	4.68		2.46E-02	
$pom_{MICROZOO}$	POM production rate per Microzoo gross growth	0.03		-3.58E-03	
μ_{KRILL}	Maximum krill growth rate	1.2	4.44	2.70	OP
$g_{MICROZOO}$	Half-saturate density of microzoo in krill grazing function	1.0	1.08	-1.81	OP
ex_{KRILL}	Total DOM excretion rate per krill gross growth	0.3		-0.985	
$f_{ex,KRILL}$	Fraction of labile DOC of total krill DOC excretion	0.75		-0.329	
$resp^{B}_{KRILL}$	Krill basal respiration	0.03		-0.103	
$resp^{A}_{KRILL}$	Krill active respiration	0.30	0.32	-2.08	OP
$ex_{ADJ,KRILL}$	Krill extra semilabile DOM excretion rate	2.0		0.00	
$remi_{KRILL}$	Krill inorganic nutrients regeneration rate	4.0		-7.41E-02	
pom_{KRILL}	POM production rate per krill gross growth	0.15		-0.797	
$ex_{REFR,KRILL}$	Krill refractory DOM production rate	0.02		-0.125	
$remv_{KRILL}$	Krill removal rate by higher-trophic levels	0.78		-1.31	
$f_{SDOM,HZ}$	Fraction of SDOM production by higher-trophic level ingestion	0.1		8.05E-02	
$f_{POM,HZ}$	Fraction of POM production by higher-trophic level ingestion	0.2		8.05E-02	
$ex_{REFR,SDOM}$	Conversion rate of SDOM to refractory DOM	0.0009		-6.75E-03	
$q^{C}_{N,REFR}$	Refractory DOM N/C ratio	0.05		-1.02E-02	

$q^{C}_{P,REFR}$	Refractory DOM P/C ratio	0.00065		2.82E-04	
$q^{C}_{N,POM}$	N/C ratio for POM generation by microzoo and krill	0.12		-8.56E-02	
$q^{C}_{P,POM}$	P/C ratio for POM generation by microzoo and krill	0.00045		4.6E-02	
r_{ntrf}	Nitrification rate (NH4 to NO3)	0.076		-3.62E-02	
prf_{N}	Preference parameter for dissolving N content in POM	1.1		0.281	
prf_{P}	Preference parameter for dissolving P content in POM	4.0		-0.181	
wnsv	Detritus sinking velocity	5.0	6.22	6.77E-03	CS
diss	POM dissolution rate	0.14	0.01	0.351	OP

Table S6: List of model parameters for the climatological year. Summary of the values of model parameters (the initial guess and optimized values), gradient changes, and uncertainties after data assimilation for the climatological year. ‘OP’ indicates optimized but with high errors (>0.5) and ‘CS’ indicates optimized with well-constrained errors (<0.5). The uncertainties of the optimized parameters are calculated as the square roots of diagonal elements of the inverse of the Hessian matrix. The gradient changes of each parameter with respect to the cost function after data assimilation are defined as: when a parameter multiplied by $e^{\Delta a}$ (Δa is infinitely small), the change of the total cost function divided by Δa, given that $e^{\Delta a} \approx \Delta a$ when Δa is small enough. For example, a 10% change of a parameter (Δa = 10%) will approximately result in a total cost change of 10% of the corresponding gradient.

Text S1. Bacteria-oriented ecosystem model. Our bacteria-oriented ecosystem model is modified from the WAP data-assimilative model (Kim et al. In Review) that is originally adapted from regional test-bed models of the Arabian Sea, the Equatorial Pacific, and the Hawaii Ocean Time-series Station ALOHA (Friedrichs 2002, Friedrichs et al. 2006, Friedrichs et al. 2007, Luo et al. 2010). The structure of our bacteria-oriented ecosystem model is presented in Figure 1 in the main text. The model has 12 prognostic state variables, simulating the flows and stocks of C, N, and P through each of the state variables except inorganic nutrients (ammonium, nitrate, and phosphorus). Chlorophyll a (Chl) is simulated for two size-fractionated phytoplankton compartments, diatoms and cryptophytes. The model equations require specification of a total of 84 model parameters. Among the model compartments, refractory dissolved organic matter (DOM) is not explicitly represented due to its much longer turnover time than labile and semi-labile DOM pools, but some mass flows are included between refractory DOM and prognostic model compartments to account for loss terms for those state variables. Detritus represents an average particulate organic carbon (POC) pool after removing living phytoplankton and bacterial biomasses. Model formulates that particle export is determined by the amount of water-column detritus times an optimizable vertical sinking velocity. Here, we only present the bacterial model equations. Detail of other model schemes is found in Supplementary Material of Kim et al. ni prep and Luo et al. (2010).

Text S2. Bacterial equations. The model allows bacteria (same equations with different initial guess values assigned to each parameter for HNA and LNA bacteria hereafter; Table 1, Tables S2-4) to utilize both labile and semi-labile DOM as the sources for biomass synthesis and growth. The amount of labile DOM (LDOM) available for bacterial uptake is simply the concentration of LDOM (all of LDOM is available for bacterial utilization during a time unit), while the amount of semi-labile DOM available (SDOM) for bacterial uptake is determined by the parameter controlling SDOM lability (r_{SDOM}). Broadly, our model represents bacterial processes in three unique ways: (1) nutrient contents let the lability of semi-labile DOM continuously variable for bacterial utilization, (2) selective SDOM uptake by bacteria, and (3) variable bacterial growth efficiency as a function of bacterial production rate.

First, the amount of LDOM (ALC, mmol m^{-3}) and SDOM (ASC, mmol m^{-3}) available for bacterial uptake are calculated as follows:

- $ALC = C_{LDOM}$ (S1)
- $ASC = r_{SDOM} * C_{SDOM}$ (S2)

where r_{SDOM} is the parameter controlling semi-labile DOM lability.

Bacteria C growth ($Nfun_{BA}$) is determined by bacterial cellular quota, ALC, and ASC above. The cellular quota limitation term in the case of nitrate (the same form is used for phosphate) is defined as:

- $Nfun_{BA} = Q^{C}_{N,BA}/q^{C}_{N,BA}$,
  set as $0 \le Nfun_{BA} \le 1$ (S3)

Bacteria C growth is limited if the cellular N or P quota is less than the corresponding reference quota. Bacterial LDOC consumption ($GROW^{LDOC}_{BA}$, mmol C m^{-3} d^{-1}) and SDOC consumption ($GROW^{SDOC}_{BA}$, mmol C m^{-3} d^{-1}) are calculated as follows:

- $GROW^{LDOC}_{BA} = \mu_{BA}*Tfun*C_{BA}*\min(Nfun_{BA}, Pfun_{BA})*\{ALC/(ALC+k_{DOM}+ASC)\}$ (S4)
- $GROW^{SDOC}_{BA} = \mu_{BA}*Tfun*C_{BA}*\min(Nfun_{BA}, Pfun_{BA})*\{ASC/(ASC+k_{DOM}+ALC)\}$ (S5)

where μ_{BA} is the C-specific maximum bacterial growth rate and k_{DOM} is the half-saturation concentration of available DOC for bacterial growth. The equations S4-S5 demonstrate that bacterial uptake of LDOC and SDOC would influence each other but would not allow bacteria grow faster than μ_{BA}. Thus, r_{SDOM} represents the relative lability between LDOM and SDOM. Bacterial carbon demand (BCD; total bacterial carbon consumption) is the sum of $GROW^{LDOC}_{BA}$ and $GROW^{SDOC}_{BA}$.

Bacteria take up LDOM such that the ratio of LDON (LDOP) to LDOC consumption is the same as the bulk N(P):C ratio of LDOM. However, bacteria can also uptake SDOM with higher N:P ratios because SDOM with higher N:P ratios is more labile. Bacteria SDON consumption ($GROW^{SDON}_{BA}$, mmol N m^{-3} d^{-1}) is calculated as:

- $GROW^{SDON}_{BA} = GROW^{SDOC}_{BA}$
  $*\min\{q^{C}_{N,BA}, Q^{C}_{N,SDOM} + f_{SLCT,BA}/N\mathit{fun}_{BA}*(q^{C}_{N,BA} - Q^{C}_{N,SDOM})\}$ (S6)

where $f_{SLCT,BA}$ is the parameter of selection strength (between 0 and 1). The equation S6 demonstrates that the ratio of SDON to SDOC consumption varies between the bulk N:C of SDOM ($Q^{C}_{N,SDOM}$) and the bacterial reference cellular quota ($q^{C}_{N,BA}$). The higher selection strength ($f_{SLCT,BA}$) and lower limitation of bacterial cellular quota ($Nfun_{BA}$) will make the ratio closer to the bacterial reference cellular quota ($q^{C}_{N,BA}$) (therefore lower $Q^{C}_{N,BA}$).

Bacteria take up both DOM and dissolved inorganic nutrients simultaneously. This scheme is adopted to present rather stable and consistent stoichiometry of bacterial cells (Kirchman, 2000) by taking up or releasing inorganic nutrients. As the reduced form of the nutrients, ammonium and phosphate are readily available for bacterial uptake (Kirchman 1994). The model assumes the same activity (lability) of ammonium and phosphate as labile DOM. Using ammonium (or phosphate) as an example, the ratio of ammonium (or phosphate) to LDON (or LDOP) consumption ($GROW^{NH4}_{BA}/GROW^{LDON}_{BA}$) equals to the ratio of their concentration before bacterial cellular quota limitation:

- $GROW^{NH4}_{BA} = GROW^{LDON}_{BA}*NH_4/N_{LDOM}/Nfun_{BA}$ (S7)

In contrast, bacteria nitrate consumption occurs only when the bacterial cellular N:C ratio is less than its reference ratio (i.e., when bacteria are in short of nitrogen). This is to reflect higher energetic cost of bacterial nitrate uptake processes.

Bacterial nitrate consumption rate ($GROW^{NO3}_{BA}$, mmol N m^{-3} d^{-1}) is calculated as:

- $GROW^{NO3}_{BA} = \min\{0.1*NO3*1/Nfun_{BA}*(GROW^{LDON}_{BA}+GROW^{SDON}_{BA})/(N_{LDOM}+N_{SDOM}),$
  $(NO3+NH4)*(GROW^{LDON}_{BA}+GROW^{SDON}_{BA})/(N_{LDOM}+N_{SDOM}) - GROW^{NH4}_{BA}\}$ (S8)

The equation S8 demonstrates that: (1) bacteria nitrate consumption is no more than 10% of N-specific bulk LDOM and SDOM consumption rate and (2) the nitrate plus ammonium consumption rate is no more than N-specific bulk labile and SDOM consumption rate. These limit the maximum nitrate consumption rate and set the inhibition of ammonium consumption on nitrate consumption, respectively.

Bacterial growth efficiency (BGE) is defined as the ratio of BP to BCD (BGE = BP/BCD where BCD = BP + bacterial respiration). This relationship sets that bacterial respiration = BCD∗(1-BGE) and represents a positive relationship between BGE and BCD and a negative correlation between bacterial active respiration and BCD (del Giorgio and Cole 1998). Bacterial respiration ($RESP_{BA}$, d^{-1}) is the sum of basal respiration, active respiration, and the respiration required to reduce assimilated nitrate and calculated as follows:

- $RESP_{BA} = \zeta^{NO3} * GROW^{NO3}_{BA} + resp^{B}_{BA} * T\mathit{fun} * C_{BA}$
  $+\{resp^{A}_{min,BA} + (resp^{A}_{max,BA} - resp^{A}_{min,BA}) * \exp(-b_{RESP} * GROW^{C}_{BA})\} * GROW^{C}_{BA}$ (S9)

where $RESP_{BA}$ is the basal respiration rate (d^{-1}), $GROW^{NO3}_{BA}$ is the BCD or bacterial total DOC uptake, $resp^{A}_{min,BA}$ and $resp^{A}_{max,BA}$ are the minimum and maximum portions of gross production actively respired with inversed unit to $GROW^{C}_{BA}$, and b_{RESP} is the positive parameter with inversed unit to $GROW^{C}_{BA}$. The equation S9 demonstrates that BGE can increase with BP.

Bacteria contribute refractory DOM (RDOM) pool either by directly releasing RDOM or transforming LDOM to RDOM. Bacteria adjust their elemental composition by either excreting ammonium or phosphate, or excreting SDOM if C is in excess, similar to phytoplankton excretion for adjusting their stoichiometry. Compared to phytoplankton, higher values are assigned to bacterial SDOM excretion rate ($ex_{ADJ,BA}$) to represent that bacteria have higher ability to control their stoichiometry. Lastly, a certain percentage of bacteria gets lost to LDOM pool as a mortality term due to viral attack. Another loss term by bacterial grazing is discussed in the zooplankton equations below (Equation S10).

The bacterial grazing equation represents a density-dependent grazing function and a preferential selection of a predator on different food (prey) sources. N and P components are grazed relative to C at the same ratios as those of prey composition. C-specific grazed amount of HNA bacteria by microzooplankton (mmol C m^{-3}) is defined as:

- $GRAZ^{C}_{HNA} = Tfun * \mu_{MICROZOO} * C_{MICROZOO}$
  $* [C_{HNA}^{2} / \{C_{HNA}^{2} + g_{HNA}^{2} + (C_{DIATOM} * g_{HNA}/g_{DIATOM})^{2} + (C_{CRYPTO} * g_{HNA}/g_{CRYPTO})^{2} + (C_{LNA} * g_{HNA}/g_{LNA})^{2}\}]$
  (S10)

where $\mu_{MICROZOO}$ is the maximum growth rate of microzooplankton and g_{HNA} is the half-saturation density of HNA bacteria in microzooplankton grazing function. The same equation applies to C-specific grazed amount of LNA bacteria by microzooplankton.

Text S3. Model initialization and spin-up. The model is initialized by prescribing initial conditions 150 days (June 1) prior to the model start date of the growth season (November 1). This 150-day spin up is conducted in order to minimize the impact of initial conditions on the model output over the Austral growth season (November - March). Initial conditions are prepared by first generating an optimized model simulation of the full annual cycle forced by climatological physics and assimilated with climatological observations (i.e., climatological year or climatological model hereafter; 2010-11, 2011-12, 2012-13, and 2013-14). The climatological model is constructed using four years (2010-11 to 2013-14), not the whole Palmer LTER multi-decadal record (since 1991), due to the availability of HNA and LNA biomass data only in those years. To capture a non-linear aspect of the WAP system (e.g., strong interannual variability in the phytoplankton bloom phenology), we construct the climatological year by applying a single time shift to all variables so that a seasonal PP peak of each year lined up with an average date of seasonal PP peaks from all years. Next, the output from the climatological simulation for June 1 conditions following the end of the seasonal growth season is used as the Austral winter initial condition for 2010-11. The resulting simulated conditions for June 1, 2011 from the optimized 2011-12 model is then used as the initial conditions for the 2012-13 simulation, and so on. Boundary conditions are set to zero at the bottom boundary of the model for most variables as low light and presence of sea ice during winter ceased most biological processes. The boundary conditions of nitrate, phosphate, SDOC, SDON, and SDOP are set to 30.9 mmol m^{-3}, 2.4 mmol m^{-3}, 6.5 mmol m^{-3}, 0.6 mmol m^{-3}, and 0.03 mmol m^{-3}, respectively, based on climatological observations at Palmer Station B.

Text S4. Uncertainty analysis. When computed at the minimum of the cost function value, the inverse of the Hessian matrix provides the uncertainties of optimized parameters, cross-correlations among parameters and sensitivities of the total cost to each parameter (Matear 1996; Tziperman and Thacker 1989). High off-diagonal values in the inversed Hessian matrix indicate highly cross-correlated model parameters, and one of the highly cross-correlated parameters should be and is removed from the optimization. The square root of a diagonal element in the inversed Hessian matrix is the logarithm of the relative uncertainty of the corresponding optimized parameter (σ_i). An optimized parameter with σ_i larger than 50% is updated but removed from the next optimization cycle, while the optimized parameter with σ_i smaller than 50% is updated and kept for the next optimization cycle. We denote the optimized parameters with σ_i larger than 50% as 'optimized parameters' and the optimized parameters with σ_i smaller than 50% as 'constrained' parameters throughout this article (Tables S2-6).

References

del Giorgio PA, Cole JJ (1998) Bacterial growth efficiency in natural aquatic systems. *Annu Rev Ecol Syst* 29:503–541.

Friedrichs MAM (2002) Assimilation of JGOFS EqPac and SeaWiFS data into a marine ecosystem model of the central equatorial Pacific Ocean. *Deep-Sea Res II* 49:289–319.

Friedrichs MAM, Hood RR, Wiggert JD (2006) Ecosystem model complexity versus physical forcing: quantification of their relative impact with assimilated Arabian Sea data. *Deep-Sea Res II* 53:576–600.

Friedrichs MAM, Dusenberry JA, Anderson LA, Armstrong RA and others (2007) Assessment of skill and portability in regional marine biogeochemical models: role of multiple planktonic groups. *J Geophys Res* 112:C08001. doi:10. 1029/2006jc003852

Kirchman DL (1994) The uptake of inorganic nutrients by heterotrophic bacteria. *Microb Ecol* 28:255–271

Kirchman DL (2000) Uptake and regeneration of inorganic nutrients by marine heterotrophic bacteria. In: Kirchman DL (ed)

Luo YW, Friedrichs MA, Doney SC, Church MJ, Ducklow HW (2010) Oceanic heterotrophic bacterial nutrition by semilabile DOM as revealed by data assimilative modeling. *Aquat Microb Ecol* 60(3):273-287.