Constraining carbon cycle parameters in the North Atlantic through independent measurements of bacterial production, respiration, and particulate carbon export

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Introduction: Pairing direct observations and flux attenuation model simulations to constrain key carbon export parameters

Using independent observations in the North Atlantic of particulate carbon flux, bacterial production (BP), and respiration by both free-living and particle-attached bacterial communities, we attempt to constrain several other unmeasured parameters associated with particle export. In a series of sensitivity analyses, we model particle flux attenuation as a function of observed respiration and bacterial production rates, using a range of values where required for unknown parameters. By comparing these model results to direct observations of particle flux made at the same stations using sediment traps, we are able to constrain bacterial growth efficiency and the average particle sinking speed.

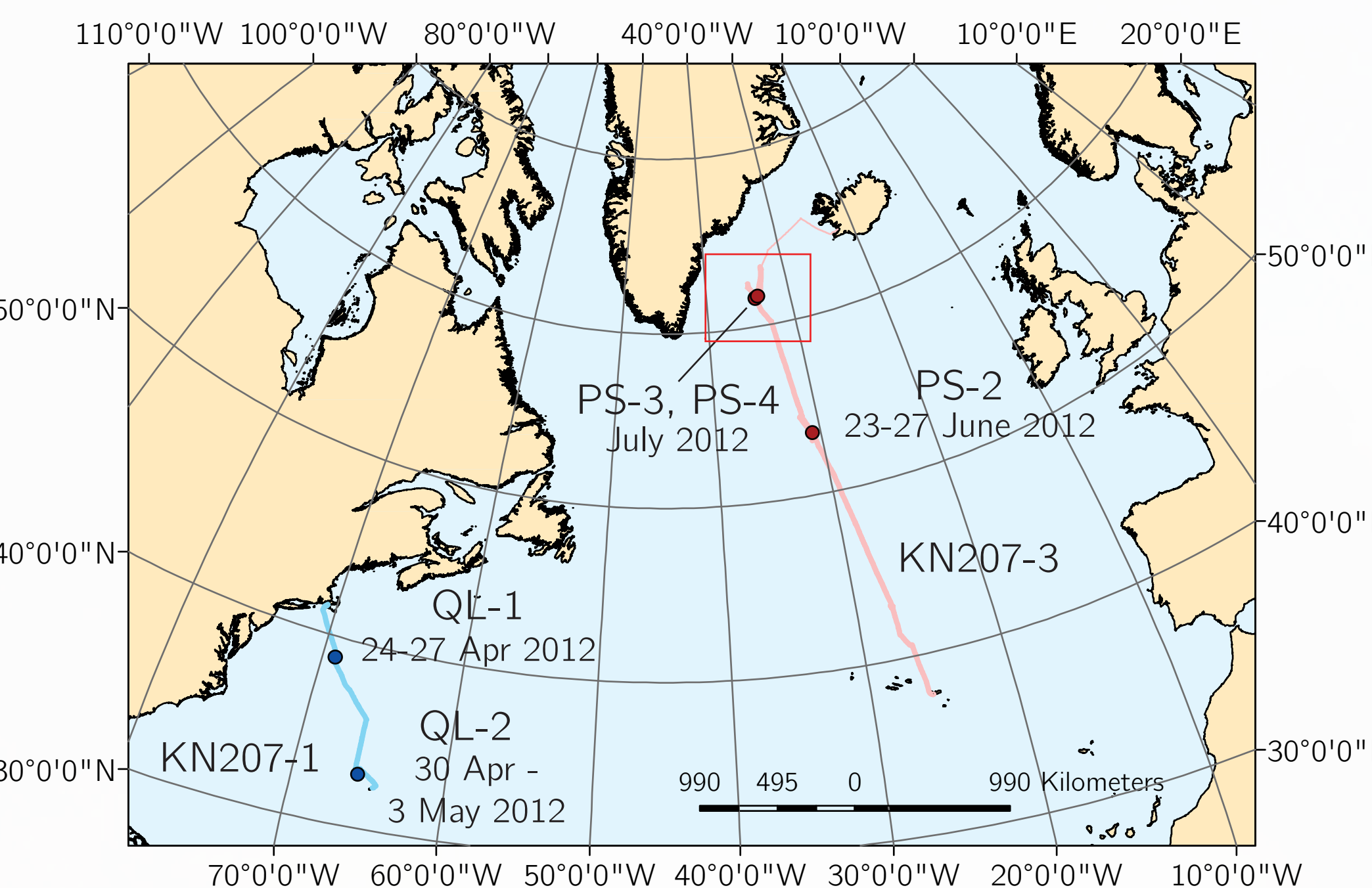## Deployment locations and cruise tracks

Figure 1. *Upper panel:* Quasi-lagrangian stations in the North Atlantic at which we conducted 3-5 day deployments of surface-tethered sediment traps (50, 150, and 300 m). *Lower panel:* Locations of stations PS-3 and PS-4, superimposed over 8-day-average MODIS Aqua surface reflectance at 555 nm, an indicator of biological PIC precipitation. The high export fluxes and very low POC : PIC rain ratios observed at these stations suggest export was driven by coccolithophorids.
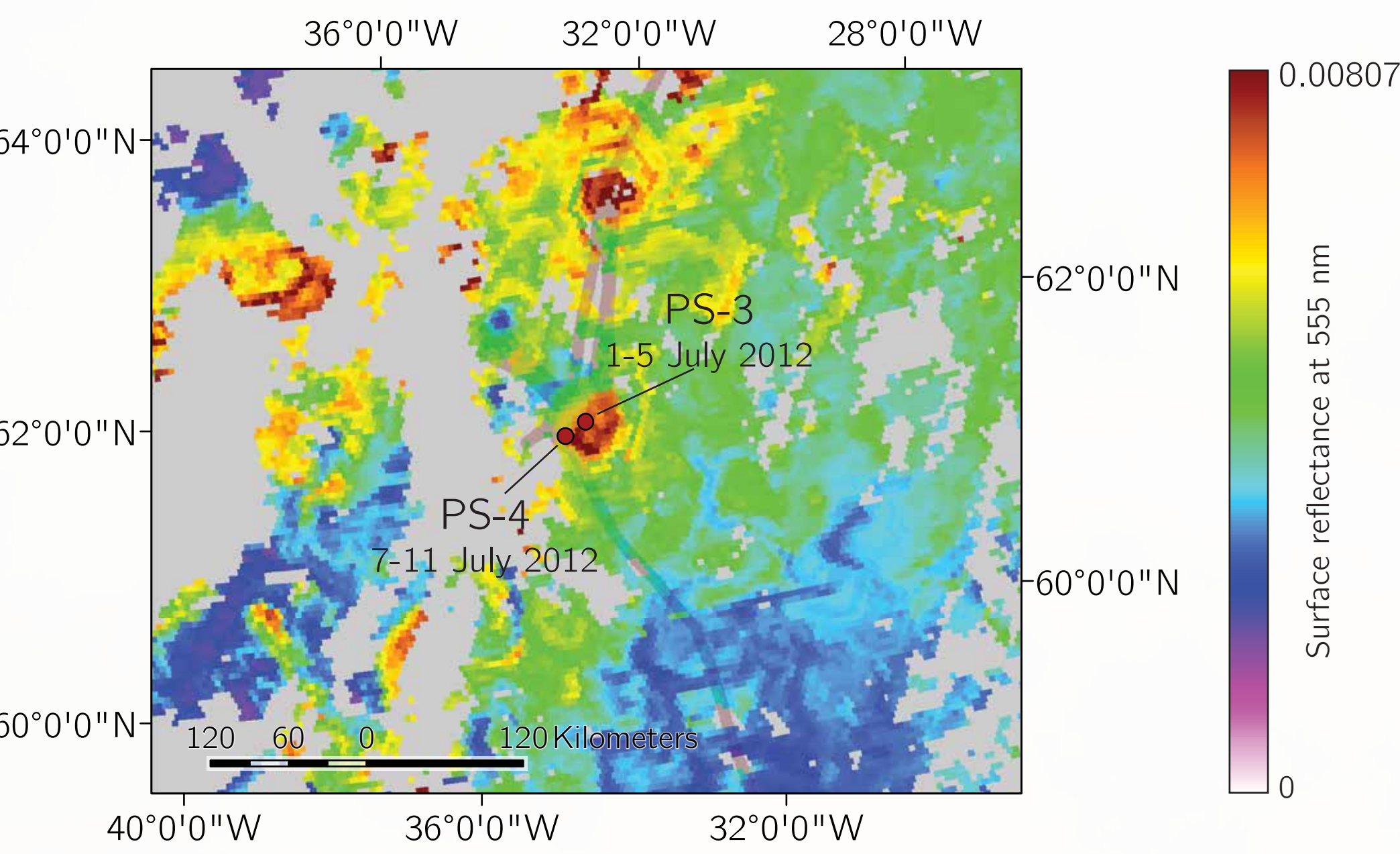
Model methodology

We first attempted to constrain the average particle sinking speed (W_{avg}; m d^{-1}) at each station assuming the flux at depth z can be predicted by

$$F_z = F_0 \left(1 - \frac{R_{spec}(z - z_0)}{W_{avg}} \right)$$

where F_0 is the flux observed at the overlying depth (Table 1). R_{spec} (d^{-1}) is a specific respiration rate calculated from incubation of sinking particle material according to

$$R_{spec} = \frac{(r_{pa} - r_{col})V_{inc}\nu_{C:O_2}}{POC_{trap}}$$

where r_{col} and r_{pa} are volumetric respiration rates measured in the water column and on sinking particle material, respectively, $\nu_{C:O_2}$ is the respiratory quotient (1.2), and V_{inc} and POC_{trap} are the vessel volume and quantity of POC used for particle material incubation. To constrain W_{avg}, we used this model to calculate the predicted flux at 150 and 300 m for a range of average sinking speeds (1 to 300 m d^{-1}), then compared the results to observed fluxes. In each exercise, we considered uncertainties in both observations and in the model.

We next attempted to constrain the bacterial growth efficiency (*BGE*) at each station, assuming the flux at depth z can be modeled according to

$$F_z = F_0 - BCD_{pa}$$

where F_0 is the flux observed at the overlying depth and BCD_{pa} is the integrated carbon demand incurred by particle-attached bacteria over the intervening depth interval. BCD_{pa} was calculated from bacterial production rates for a range of isotope dilutions (*ID*; 1 to 2) and values of *BGE* (0.01 to 0.6) according to

$$BCD_{pa} = \frac{BP_{int}}{BGE} f_{pa}$$

and

$$BP_{int} = \int_{z=50}^{150} BP_{leu}\,\nu_{C:protein}\,\nu_{BPAA:leu}\,ID\,dz$$

where BP_{int} is the depth-integrated bacterial production estimated from discrete samples (Fig. 2) and f_{pa} is the estimated fraction of total BP attributable to particle-attached bacteria (0.25).

Application of export flux models to constrain BGE and sinking speed

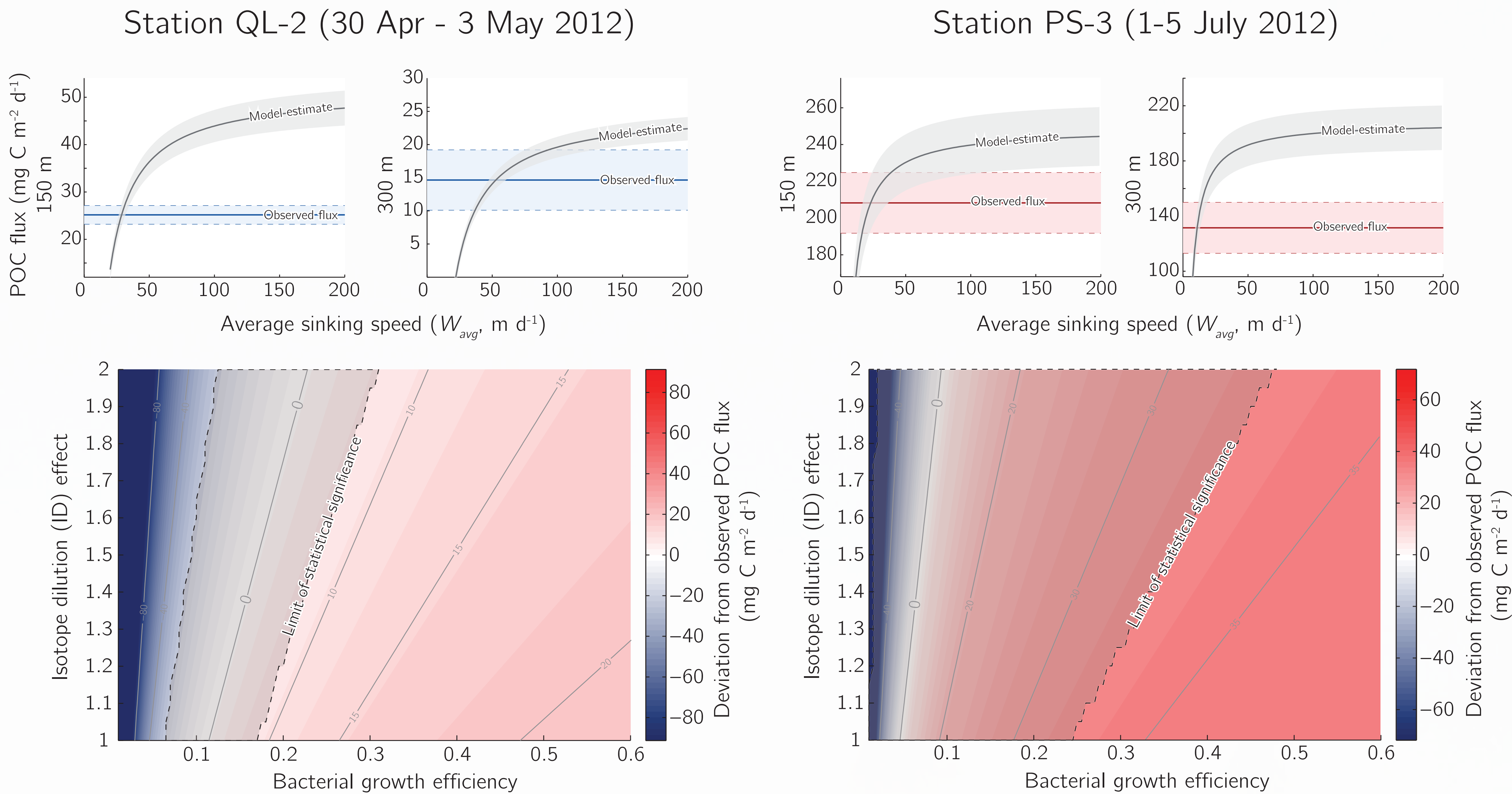### Typical model results from two stations

Figure 3. Comparison of model results to observed POC fluxes for two representative stations. *Upper panels:* Flux estimates at 150 and 300 m for a range of assumed average sinking speeds. Shaded uncertainties: Around observed fluxes, ± 1 SD; surrounding model estimates, propagated uncertainties largely derived from calculation of R_{spec}. *Lower panels:* Model deviation from observed flux at 150 m over a range of values for *BGE* and *ID*. Pairs of values along the "0" isoline are best-fit solutions. The shaded region represents the combined uncertainty associated with observed fluxes and model results.

At each station, W_{avg} and *BGE* can be predicted by minimization of model-observed deviation
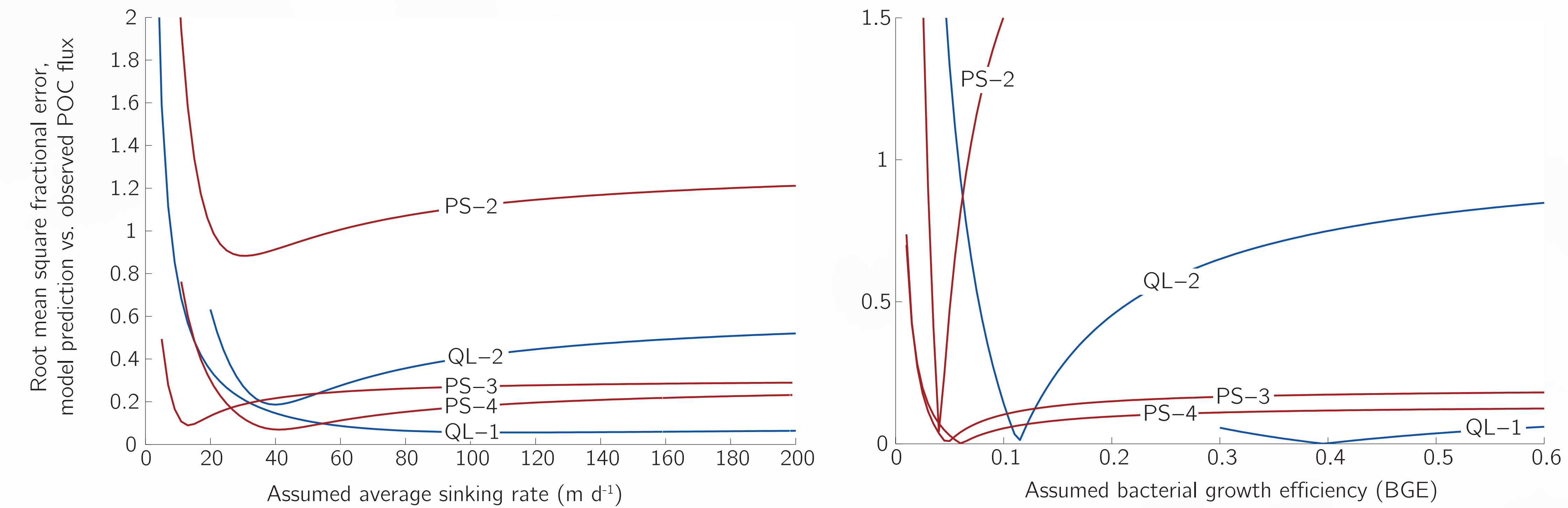

Figure 4. Root mean square fractional error of model simulations versus observed POC fluxes for a range of values of W_{avg} (*left-hand panel*) and *BGE* (*right-hand panel*). The average sinking speed and bacterial growth efficiency for each station can be predicted by minimizing this measure of error. *Left-hand panel:* Pooled errors from estimates at both depth intervals (50-150 and 150-300 m) yield a single optimal value of W_{avg} for each station. *Right-hand panel:* An optimal value of BGE is predicted for the 50 to 150 m interval at each station, assuming *ID*=1.

Observational results: Bacterial production rates and particulate carbon fluxes

Table 1. Particulate carbon fluxes from sediment traps.

Cruise	Station	Depth m	POC flux mg C m^{-3} d^{-1}	PIC flux mg C m^{-3} d^{-1}	Rain ratio POC : PIC
KN207-1	QL-1	50	47.9 ± 16.5	2.9 ± 1.6	16.6
		150	40.7 ± 7.9	2.1 ± 0.9	19.3
		300	38.8 ± 27.1	1.2 ± 0.2	33.6
	QL-2	50	51.5 ± 4.0	3.8 ± 1.1	13.4
		150	25.2 ± 2.0	8.6 ± 0.5	2.9
		300	14.7 ± 4.6	3.3 ± 0.3	4.5
KN207-3	PS-2	50	58.6 ± 13.5	7.4 ± 0.3	7.9
		150	16.6 ± 8.2	6.2 ± 0.7	2.7
		300	9.6 ± 0.9	2.9 ± 0.9	3.3
	PS-3	50	249 ± 16.3	109 ± 16.3	2.3
		150	208 ± 16.5	81.8 ± 12.7	2.5
		300	131 ± 18.5	75.1 ± 14.3	1.8
	PS-4	50	179 ± 33.7	42 ± 6.1	4.3
		150	158 ± 21.1	62.2 ± 5.7	2.5
		300	101 ± 12.3	48.1 ± 8.3	2.1

Figure 2. Contour plots of bacterial production rates measured using the ³H-leucine incorporation method. Data are presented in units of leucine uptake and in mg C m^{-3} d^{-1}. For conversion to units of C, an isotope dilution of 1 was assumed, making the rates a minimum estimate of bacterial carbon turnover.
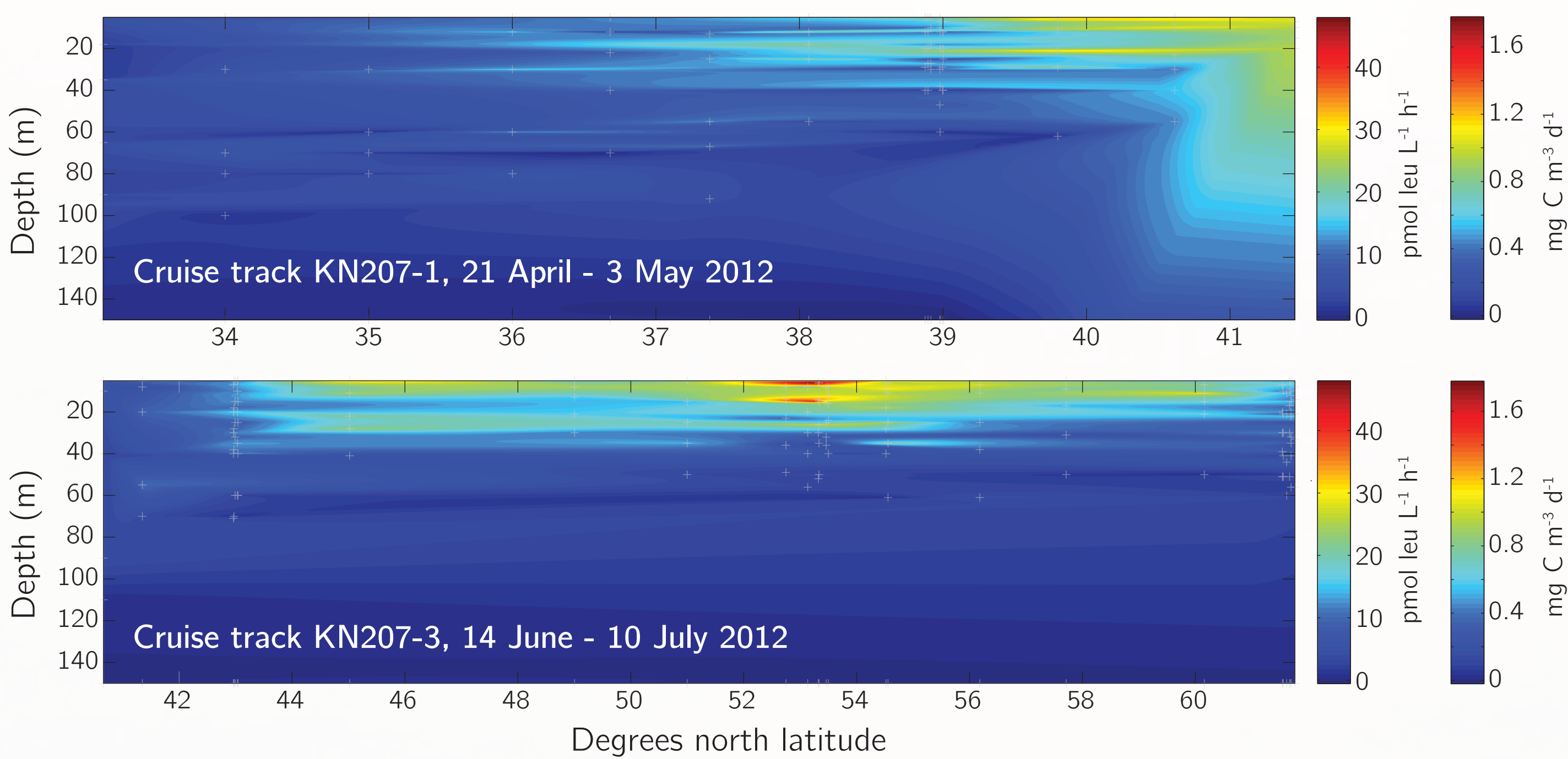
Model results: Bounded estimates of BGE & sinking speed

Cruise	Station	Average particle sinking speed (m d^{-1})			Bacterial growth efficiency (BGE)		
		Estimate	Lower bound	Upper bound	Estimate	Lower bound	Upper bound
KN207-1	QL-1	103	13	n/c	0.40	0.10	n/c
	QL-2	38	26	130	0.12	0.06	0.31
KN207-3	PS-2	25	9	n/c	0.04	0.02	0.17
	PS-3	15	10	107	0.05	0	0.48
	PS-4	45	22	n/c	0.06	0	n/c

Table 2. Summary of estimates and model-imposed constraints on key parameters. "n/c": Bound could not be constrained given uncertainties.

Acknowledgments

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