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Supplementary Information for

Metrics that matter for assessing the ocean biological carbon pump

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Consideration of non-gravitational BCP pathways and increasing POC flux vs. depth

Our analyses are primarily focused on the gravitational settling of sinking POC, but the assessment of BCP efficiencies will also demand a common reference depth when considering the physically- or biologically-mediated injection pumps (PIPs) including the physical subduction of OM to depth, such as occurs with the mixed-layer pump and the subduction pump (see review by Boyd et al. (1)). For physical PIPs and questions related to longer term C sequestration, depths below the winter ML are appropriate upper boundaries (2), (3). For transport related to diel vertical migration (DVM) of zooplankton and larger organisms, as well as transport associated with their seasonal hibernation at depth, resulting in a C-rich “lipid” pump (4), the depth of DVM needs to be considered.

Several of the studies compiled here, show an increase in POC flux vs. depth (T_{100} >1 in Figure 2a). Could these PIPs cause this increase in particle flux with depth, or are there other possible explinations? In one model (5), a sensitivity analysis showed that if DVM accounted for more than 40% of the POC flux out of the Ez, a maximum, or bump in POC flux curve would be expected below the DVM reference depth, but this was not observed. This model assumed that POC consumed in the surface would be released as sinking POC flux (i.e. fecal pellets) at the depth of maximum daily DVM. However, the impact of DVM on POC flux, will also be set by the fraction of surface OM that is respired back in to inorganic C or released in dissolved or suspended organic C forms at depth, relative to new fecal material. Global models that consider DVM such as that by Archibald et al. (6), are sensitive to the fraction of zooplankton that participate in DVM. These authors found that while DVM accounts for 14% of global POC export from the base of the Ez, DVM has little impact on the magnitude of POC flux due to the large respiration terms, and dissolved OM losses below the Ez due to rapid migrations in their model.

Increases in POC flux with depth may also be due to transient changes in surface POC flux (7). For example, it would take 3-6 days for a particle exiting the surface to reach 300 m with sinking speeds of 50-100 m d^{-1}, and so a rapidly declining surface flux over several days could result in a remnant higher POC flux peak at depth on this time scale. Another way to account for an increase in POC flux vs. depth is due to horizontal inputs of particles, for example from ocean margins (8), (9). Though more often reported for deep moored times-series traps, horizontal sources of POC need not be restricted to deeper depths. For example, Lam et al. (10) postulate a <200 m margin-derived lateral source of iron rich particles in the NE Pacific. Ollie et al. (11)

also postulate a shelf source for particles in their study of shallow trap fluxes, but this source did not lead to a POC flux increase with depth. Finally, a subsurface flux peak can also arise as an artifact when moored conical traps are used at depths <1000 m, where trap collection efficiencies are systematically too low (12), (13). Thus, the finding of POC flux increasing with depth can be attributed to several possible causes and is not uncommon in the upper TZ; however, it is impossible to fit a Martin curve to such POC flux data.

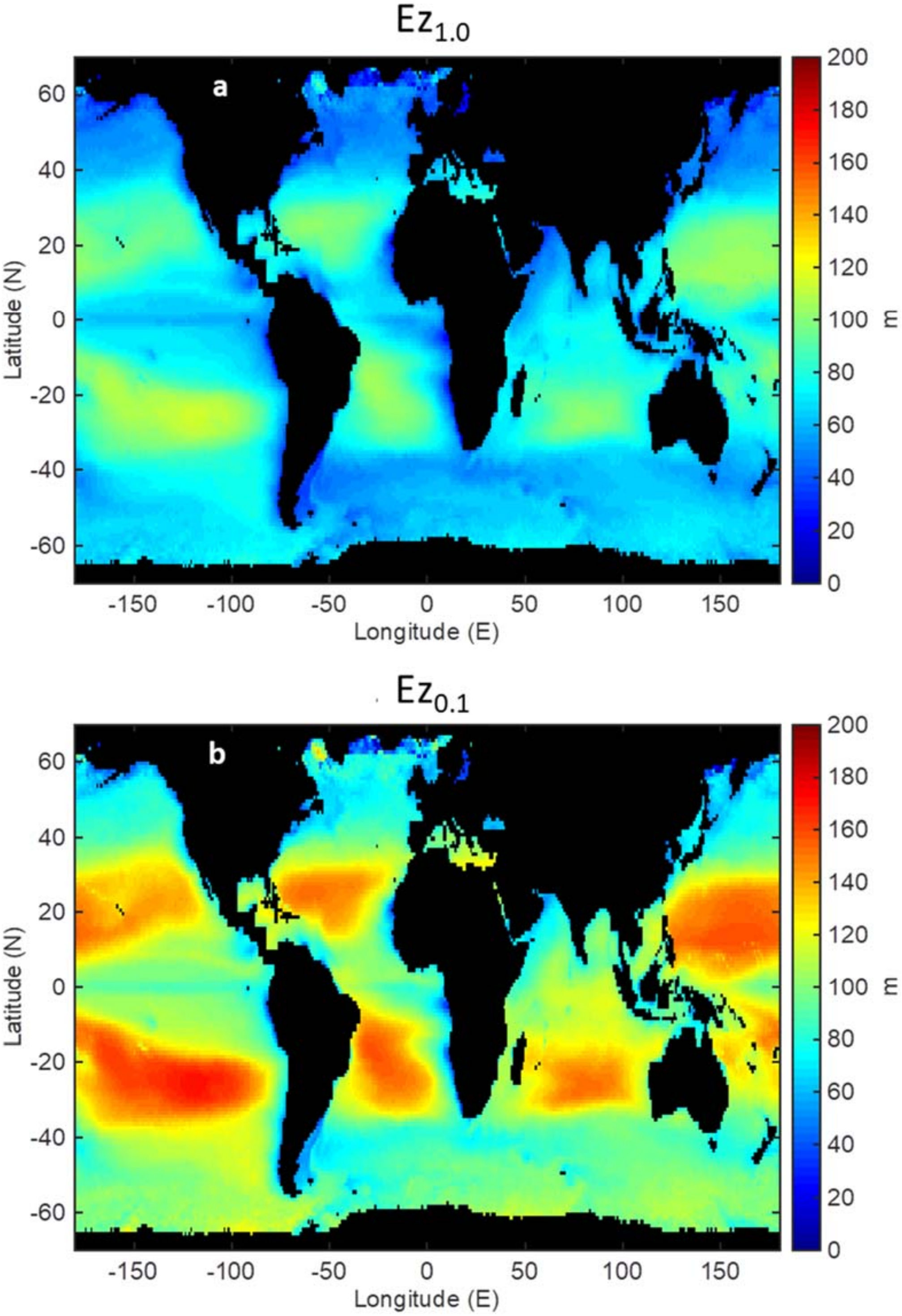

Fig. S1. Depth of 1% (a. upper) and 0.1% (b. lower) PAR (photosynthetically available radiation). Derived from Siegel et al. (14).

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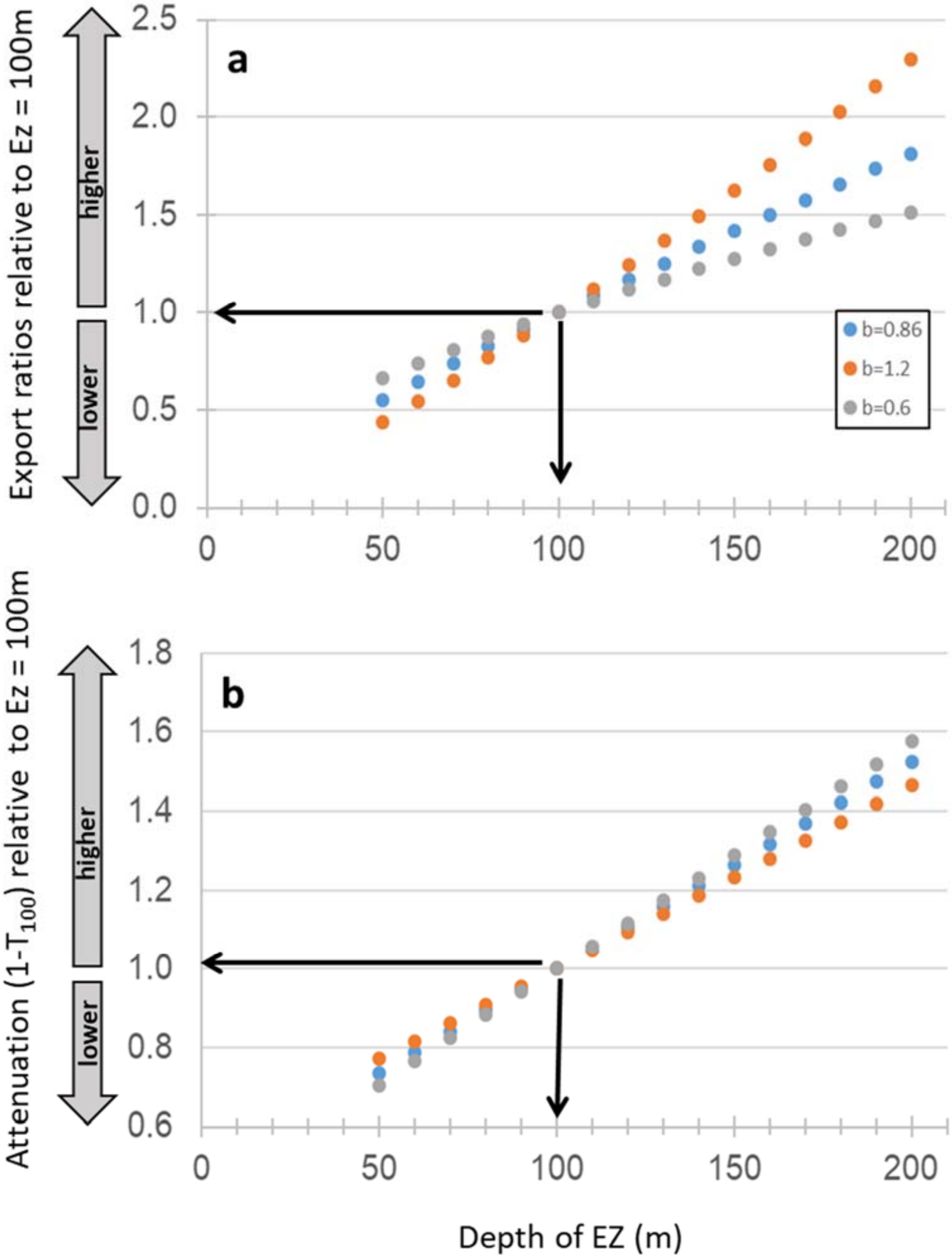

Fig. S2a. Sensitivity of the 100 m export ratio (100 m flux/NPP) for differing euphotic zone depths (x-axis) and attenuation ranges (b = 0.6 to 1.2). For example, if flux were measured 100 m, the apparent Ez ratio would be lower by a factor of two, if the Ez was actually 50 m and b=0.86. If flux were measured at 100 m and the Ez was 200 m, the apparent Ez ratio would be more than two times higher. The sensitivity changes with different attenuation rates (i.e. with steeper POC flux attenuation, i.e. with a higher b, the impacts are greater). **Fig. S2b**. Same but for the change in attenuation (defined as 1-T_{100}) so that higher attenuation is a larger positive number. Differences are 25-30% lower 50% higher for attenuation if the flux were measured at 100 m, yet the Ez was actually 50 or 200 m, respectively.

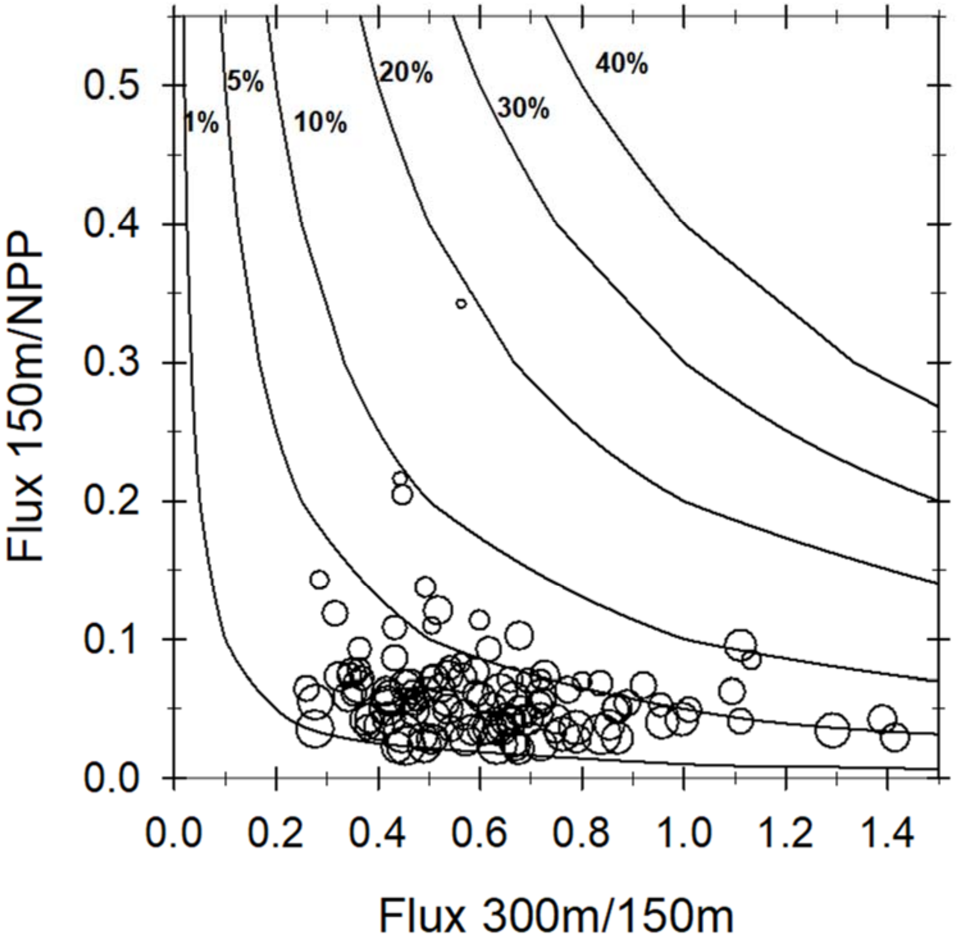

Fig. S3. Export ratio (y-axis) vs. flux transmission (x-axis) for 1990-2006 Bermuda Atlantic Time-Series sediment trap data from April-November when the 150 m traps are always deeper than the mixed layer. Here the export ratio is defined by the trap POC flux at 150 m/NPP and flux transmission by the measured flux at 300 m/150 m, with values >1.0 indicating an increasing flux vs. depth. The size of the circles is proportional to NPP as measured at BATS during the deployment. Data compiled from BATS web site (http://bats.bios.edu/bats-data/).

S1. Table of common terms used to describe the biological carbon pump

Nomenclature	**Meaning**
BCP efficiency	General term for the sum of processes that determine magnitude of POC flux out of Ez and its attenuation in the upper twilight zone
Strength of the BCP	Magnitude of POC flux out of the Ez
Export ratio	POC flux at reference depth/NPP
Ez-ratio	POC flux at Ez/NPP
Transfer efficiency	Fraction of POC flux transported to some reference depth
T_{100}	POC flux 100m below Ez/POC flux at Ez T_{100} = 1.0 = 100% transfer = zero POC flux loss
$EZ_{1.0}$	Euphotic zone with base defined by 1% PAR
$EZ_{0.1}$	Euphotic zone with base defined by 0.1% PAR
PPZ	Primary production zone = depth at which the signal from in-situ fluorescence sensors drops to 10% of the maximum above that depth
TZ	Twilight Zone = base of Ez to 500 m (note other studies use 1000 m)

Table S2. Compilation of POC flux data

									^{234}Th				Martin curve					
ID#	**Dates**	**# sta's**	**ML (m)**	**Ez (m)**	**Type**[1]	**NPP**[2] **(mg m^{-2} d^{-1})**	**# depths**	**Depth range (m)**	**F at Ez (mg m^{-2} d^{-1})**	**F at Ez +100m (mg m^{-2} d^{-1})**	**Ez ratio**[3]	**T_{100}**[4]	**F_{100} (mg m^{-2} d^{-1})**	**b**	**Ez-ratio**[5]	**T_{100}**[6]	**Original site name**	**SI Ref. #**
^{234}Th Based Studies																		
	NW Pacific, 47˚N 160˚E																	
1	Jul/Aug-05	13	25	50	0.1%	530	8 to 20	surf to 400	133	68	0.25	0.51	77	-0.79	0.15	0.58	K2-D1	(5)
2	Jul/Aug-05	13	25	50	0.1%	365	8 to 24	surf to 400	39	25	0.11	0.64	26	-0.61	0.07	0.66	K2-D2	(5)
	North Pacific Subtropical Gyre, 22˚N 158˚W																	
3	Jun/Jul-04	19	50	125	0.1%	200	4 to 10	surf to 200	15	10	0.07	0.69	23	-1.17	0.12	0.44	ALOHA	(5)
	NE Atlantic, 47˚N 20˚W																	
4	Apr/May-89	4	20	50	1.0%	1104	8	surf to 300	493	600	0.45	1.22	no fit		no fit		JGOFS NABE	(5)
	Equatorial Pacific, 0˚N 140˚W																	
5	Mar & Oct-92	2	40	120	0.1%	1300	10	surf to 375	26	17	0.02	0.65	32	-1.03	0.02	0.49	EQPAC- spring/fall avg	(5)
	S. Ocean polar frontal zone, 61.5-65.5˚S, 170˚W																	
6	Dec-97	4	22	30	1.0%	984	7	surf to 300	284	78	0.29	0.27	116	-1.29	0.12	0.41	KIWI-7	(5)
7	Jan-98	4	45	60	1.0%	1428	7	surf to 300	488	345	0.34	0.71	394	-0.27	0.28	0.83	KIWI-8	(5)
8	Feb-98	3	70	90	1.0%	300	7	surf to 300	127	105	0.42	0.83	no fit		no fit[7]		KIWI-9	(5)
	NE Pacific subpolar, 50˚N 145˚W																	
9	May-96	1	60	60	0.1%	1020	8	surf to 400	31	8	0.03	0.26	15	-1.05	0.01	0.48	OSP-May	(5)
10	Aug-96	2	40	40	0.1%	700	8	surf to 400	97	29	0.14	0.30	43	-1.16	0.06	0.45	OSP-Aug	(5)
	S. Ocean polar frontal zone[8], 60˚S 172˚W																	
11	Jan/Feb-02	1	35	51	1.0%	600	8	surf to 150	36	10	0.06	0.27	21	-0.31	0.04	0.81	SOFex-start	(15)
12	Jan/Feb-02	2	35	37	1.0%	900	8	surf to 150	77	107	0.09	1.39	no fit		no fit		SOFex-day 10	(15)
13	Jan/Feb-02	3	35	29	1.0%	1620	8	surf to 150	72	130	0.04	1.80	no fit		no fit		SOFex-day 20	(15)
	North Atlantic Subtropical Gyre, 31˚N 66˚W																	
14	Jun-04	17	40	140	1.0%	403	10	surf to 300	71	87	0.17	1.23	no fit		no fit		EDDIES- I Cyclone C1	(16)
15	Aug-04	11	45	140	1.0%	594	10	surf to 300	23	25	0.04	1.07	no fit		no fit		EDDIES- II Cyclone C1	(16)
16	Jul-05	18	20	140	1.0%	273	10	surf to 300	14	5	0.05	0.34	17	-1.03	0.06	0.49	EDDIES- IIII MWE A4	(16)
17	Aug-05	18	30	140	1.0%	426	10	surf to 300	27	30	0.06	1.08	29	-0.24[9]	0.07	0.85	EDDIES- IV MWE A4	(16)
	Equatorial Pacific zonal transect, 15˚S 77-78˚W																	
18	Nov/Dec-13	4	21	37	PPZ	1524	8 to 12	surf to 200	589	103	0.39	0.21	135	-1.53	0.10	0.35	EZPT shelf avg	(17)
	Equatorial Pacific zonal transect, 15˚S 79-105˚W																	
19	Nov/Dec-13	11	59	118	PPZ	614	8 to 12	surf to 200	48	25	0.08	0.62	41	-0.77	0.07	0.60	EZPT offshore avg	(17)
	Equatorial Pacific zonal transect, 15˚S 105-155˚W																	
20	Nov/Dec-13	20	60	169	PPZ	561	8 to 12	surf to 200	13	11	0.02	0.82	20	-0.58	0.04	0.67	EZPT gyre avg.	(17)

Table S2 cont.

SEDIMENT TRAPS

	North Pacific Subtropical Gyre, 22˚N 158˚W																	
21	Sep-13	1	50	175	0.1%	750	12	100 to 500	23	16	0.03	0.69	42.66	-0.89	0.06	0.54	ALOHA Sept 2013	(18)
	Barents Sea, 74-76˚N 31-32.5˚E																	
22	May-93	1	36	35	0.1%	814	14	20 to 200	647	265	0.79	0.41	226	-0.95	0.28	0.52	Barents I	(19)
23	May-93	1	14	40	0.1%	913	14	20 to 200	425	330	0.47	0.78	328	-0.32	0.36	0.80	Barents II	(19)
24	May-93	1	64	40	0.1%	804	14	20 to 200	576	320	0.72	0.56	383	-0.51	0.48	0.70	Barents III	(19)
25	May-93	1	61	60	0.1%	314	14	20 to 200	303	215	0.96	0.71	216	-0.39	0.69	0.76	Barents IV	(19)
	NW Spanish coast, 40˚N 9.5˚W																	
26	Aug-98	3	35	60	0.1%	316	8	40 to 200	114	62.7	0.36	0.55	44.1	0.56	0.14	1.47	OMEX- Leg	(11)

Footnotes

1 *Ez depths determined by different methods, including 1% and 0.1% PAR and PPZ (see text for details)*
2 *Net Primary Production determined via model or incubation methods per original reference*
3 *POC flux using ^{234}Th at Ez/NPP*
4 *POC flux using ^{234}Th 100m below Ez/POC flux at Ez*
5 *F_{100} from Martin fit/NPP*
6 *F_{200} from Martin fit/F_{100}*
7 *No Martin fit as flux decreases than increases within upper 300m*
8 *Ocean Iron Fertilization (OIF) experiment*
9 *Martin fit 80-200m only as flux at 300m increases*

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