Supplementary Information

Uncertain response of ocean carbon export in a changing world

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Contents:

Supplementary Table 1: Full model analysis of whether export flux processes are excluded/included. We surveyed the IPCC CMIP6 archive for global climate models which incorporate explicit marine biogeochemistry (total of 19; Supplementary Table 4). The model structure was examined to determine whether the processes we identify as important to export flux are included, and the particle sinking rate and model resolution were also assessed.

Model & *ecosystem module*	Fragmentation	Zooplankton vertical migration	Phytoplankton size effect on sinking (*1)	Temperature dependent remineralization	Oxygen dependent remineralization	Viscosity of seawater	Mineral ballasting	Mineral protection	Fish migration	TEP production /stickiness	Variable stoichiometry (*2)	Sinking rate (small & large POC) (*3)	Model resolution (*4)
Can ESM5	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	8 m d^{-1}	(*5)
CanESM5-CanOE	✗	✗	✓	✓	✗ (*6)	✗	✗	✗	✗	✗	✗	2 & 30 m d^{-1}	(*5)
CESM & CESM-WACCM *MARBL* (*7)	✗	✗	✗ (*12)	✗	✓	✗	✓	✓	✗	✗	✗	No explicit sinking	1°
CMCC-ESM2 *BFM5.2*	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✓	1 m d^{-1}	1°
CNRM, EC-Earth-CC & IPSL *PISCES2* (*7)	✓ (*9)	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	2 & 30-200 m d^{-1}, depth dependent	1°
CSIRO *WOMBAT*	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	24 m d^{-1}	1°
GFDL-CM4 *BLING*	✗	✗	✗	✓	✓	✗	✓	✓	✗	✗	✗	50-180 m d^{-1}, depth dependent	¼°
GFDL-ESM4 *COBALT*	✗	✗	✗ (*12)	✓	✓	✗	✓	✓	✗	✗	✗	100 m d^{-1}	½°
MIROC	✗	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗	5 m d^{-1} from 0-200 m	1°
MPI HR & MPI LR *Hamocc6* (*7,*8)	✗	✗	✗	✗	✗ (*6)	✗	✗	✗	✗	✗	✗	3.5-80 m d^{-1}, depth dependent	½°
MRI	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	2 m d^{-1}	(*10)
NASA-GISS	✗ (*11)	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	Varies with viscosity	1°
NorESM LM & NorESM MM *Hamocc5.1* (*7)	✗	✗	✗	✗	✗ (*6)	✗	✗	✗	✗	✗	✗	5 m d^{-1}	1°
UK-ESM *Medusa*	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✗	2.5 m d^{-1}	1°
Summary (19 models total)	✗ 18 ✓ 1	✗ 19 ✓ 0	✗ 13 ✓ 6	✗ 8 ✓ 11	✗ 9 ✓ 10	✗ 18 ✓ 1	✗ 14 ✓ 5	✗ 14 ✓ 5	✗ 19 ✓ 0	✗ 19 ✓ 0	✗ 18 ✓ 1	1-200 m d^{-1}	¼ - 1°

(*1) We consider whether more than one size of sinking detritus is modelled, i.e. whether large plankton generates large, fast sinking particles and small plankton generate small, slow sinking particles. Sometimes models have different phytoplankton size classes, and large phytoplankton generates a higher fraction of sinking particles than small phytoplankton, so that a change in phytoplankton community composition will result in more/less particles being generated. However, with only one type of sinking particle, the sinking speed will not change with phytoplankton community composition. These models are classed as a “No” for the category of ‘phytoplankton size effect on sinking’.

(*2) A model is classed as “Yes” for variable stoichiometry if C:N:P is allowed to vary in the detritus. A "No" can mean that it does vary in phytoplankton, or that C:Fe varies, or only C:N.
(*3) Small and large POC sinking rates are reported separately for models which include two size classes of particles.
(*4) Model resolution is included as an indication of whether the eddy pump could potentially be simulated.
(*5) ORCA1 tripolar grid, 1° with refinement to 1/3° within 20° of the equator.
(*6) Hamocc6 and CanESM-CanOE switch to denitrification at very low oxygen concentrations, but there is otherwise no oxygen dependence of remineralization.
(*7) ‘Sister’ versions of a model, which are run with different physical models but the same marine biogeochemistry model.
(*8) HAMOCC now includes a more comprehensive aggregation, remineralization, and sinking scheme (Maerz et al., 2020), but not in the CMIP6 archive output used here.
(*9) Large POC decays to small POC, although it is parameterized as a remineralization rate, so the model is classed as a “Yes” for the category of ‘fragmentation’.
(*10) Tripolar grid, primarily 0.5° latitude/1° longitude with meridional refinement down to 0.3° within 10° of the equator.
(*11) POC can decay to DOC, but here we consider fragmentation as the decay from large into small particles so the model is classed as a “No” for the category of ‘fragmentation’.
(*12) CESM-MARBL and COBALT have different phytoplankton types, but only one detritus type, so there is no size effect (i.e. smaller/larger phytoplankton do not result in slow/fast sinking detritus). However, there is a ballasting effect, so via generating ballasting material different phytoplankton do result in slow/fast sinking detritus.

Supplementary Table 2: Detailed rationale for our prioritisation of export flux processes. Details of the evidence in the literature for the baseline and future effects of various processes on export flux are provided. Published studies are classified as baseline (B), future (F), observational (O), experimental (E), model (M) or review (R). Acronyms: OMZ = Oxygen Minimum Zone, POC = particulate organic carbon, DVM = diel vertical migration, IPCC = Intergovernmental Panel on Climate Change, BCP = biological carbon pump.

Process	Baseline effect size and direction	Future effect size and direction	Evidence
Fragmentation	LARGE: Including fragmentation would substantially reduce export.	UNKNOWN: Direction of change unknown. Changes in environmental conditions could lead to changes in zooplankton biomass or distributions, and hence grazing-caused fragmentation, resulting in changes in export. Potentially larger OMZs could result in less zooplankton grazing and fragmentation, and thus increased export.	- Giering et al. (2014) (B, O+M): "Zooplankton fragment and ingest half of the fast-sinking particles, of which more than 30 percent may be released as suspended and slowly sinking matter…" [between 50 - 1000 m]. - Briggs et al. (2020) (B, O): "Fragmentation accounted for 49 ± 22% of the observed flux loss" [between 100 - 1000 m]. - Cavan et al. (2017) (B+F, O): "Here we show in the Eastern Tropical North Pacific OMZ 70% of POC remineralization is due to microbial respiration...Microbial remineralization rates in the OMZ are comparable to those in fully oxic waters but not high enough to offset the decrease in particle disaggregation and consumption by zooplankton, resulting in higher transfer efficiency in the offshore region of the OMZ."
Zooplankton vertical migration	MODERATE-LARGE: Including vertical migration would increase export significantly.	UNKNOWN: No literature on future effect found. Theoretically, changes in environmental conditions lead to changes in zooplankton biomass or migration depth, which changes export. Potentially, expanded OMZs may result in shallower migration and hence reduced export.	- Archibald et al. (2019) (B, M): "The modeled global export flux from the base of the euphotic zone was 6.5 PgC/year, which represents a 14% increase over the export flux in model runs without DVM...The model results were most sensitive to the assumptions for the fraction of individuals participating in DVM, the fraction of fecal pellets produced in the euphotic zone, and the fraction of grazed carbon that is metabolized." - Gorgues et al. (2019) (B, M): "...two relative biomasses of migrating zooplankton (30% and 60%) have been tested. It leads to an active to passive export ratio in agreement with published estimations and to an increase in the carbon export efficiency at 1,000 m between 20% and 40%. However, this effect is partially canceled out by a simulated primary production decrease." - Aumont et al. (2018) (B, M): "About one third of the epipelagic biomass is predicted to perform DVM. The flux of carbon driven by DVM is estimated to be 1.05 ± 0.15 PgC/year, about 18% of the passive flux of carbon due to sinking particles at 150 m." - Hansen & Visser (2016) (B, M): "We estimate that the amount of carbon transported below the mixed layer by migrating zooplankton in the North Atlantic Ocean constitutes 27% (16–30%) of the total export flux associated with the biological pump in that region." - Stukel et al. (2013) (B, O): "We assessed these contributions of mesozooplankton to vertical flux in the California Current Ecosystem. Across

			the range of 9 ecosystem conditions encountered on the cruises, recognizable fecal pellet mass flux varied from 3.5 to 135 mg C m^{-2} d^{-1} (3 to 94% of total passive flux) at the 100 m depth horizon. The active transport of carbon by migratory mesozooplankton taxa contributed an additional 2.4 to 47.1 mg C m^{-2} d^{-1} (1.9 to 40.5% of total passive flux)."
Phytoplankton size effect on sinking	UNKNOWN: Direction of effect is unknown, as it depends on the parameterisation of sinking rate in each model, which then drives whether adding variability would result in a net increase or decrease in export. For example, compared to a model with uniform particle sizes, resolving spatial variability in phytoplankton and particle sizes may result in higher export rates in areas with large phytoplankton and smaller export rates in areas with small phytoplankton; however, it is unknown whether global mean export relative to the uniform case would increase, decrease, or remain the same.	SMALL-LARGE: Decreased phytoplankton and particle size results in slower sinking speeds and hence decreased export. Effect may be modulated by a negative feedback between particle size and remineralisation depth, which boosts surface nutrients as phytoplankton size structure becomes smaller.	- Boyd (2015) (F, M): "Model simulations reveal that in the surface ocean, changes to algal community structure (i.e., a shift toward small cells) has the greatest individual influence (decreased flux) on downward POC flux in the coming decades." - Leung et al. (2021) (F, M): "This negative feedback mechanism (termed the particle-size–remineralization feedback) slows export decline over the next century by ∼14 % globally (from −0.29 to −0.25 GtC yr^{-1}) and by ∼20 % in the tropical and subtropical oceans, where export decreases are currently predicted to be greatest." - Laufkötter et al. (2016) (F, M): "The removal of the sinking particles by remineralisation is simulated to increase in the low and intermediate latitudes in three models, driven by either warming-induced increases in remineralisation or slower particle sinking, and show insignificant changes in the remaining model. Changes in ecosystem structure, particularly the relative role of diatoms matters as well, as diatoms produce larger and denser particles that sink faster and are partly protected from remineralisation. Also this controlling factor is afflicted with high uncertainties, particularly since the models differ already substantially with regard to both the initial (present-day) distribution of diatoms (between 11–94 % in the Southern Ocean) and the diatom contribution to particle formation (0.6–3.8 times higher than their contribution to biomass). As a consequence, changes in diatom concentration are a strong driver for export production changes in some models but of low significance in others." - Bopp et al. (2005) (F, M): "Our global warming simulation shows a large decrease of the export ratio (export production divided by the primary production) with global warming, by as much as 25% at 4xCO_2 (from 10 PgC/yr to 7.5 PgC/yr) whereas primary production decreases by only 15%. This change in the export ratio is explained by the modifications the ecosystem undergoes with global warming: diatoms are replaced by small phytoplankton and recycling of nutrients and carbon in the surface ocean is increased (i.e., the export ratio decreases)."
Temperature dependent remineralisation	UNKNOWN: Including temperature dependent remineralisation rates would change export differently in different regions, but the global mean effect is unclear.	SMALL-LARGE: Warming results in increased remineralisation and hence decreased export. Papers by Cavan et al. suggest the effect is moderate – large (although feedback of changing export not incorporated); those by Laufkötter et al. suggest the	- Marsay et al. (2015) (B, O): "We show that the observed variability in attenuation of vertical POC flux can largely be explained by temperature, with shallower remineralization occurring in warmer waters." - Cael et al. (2017) (B+F, M): "Temperature changes are suggested to have caused a statistically significant decrease in export efficiency of 1.5% ± 0.4% over the past 33 years. Larger changes are suggested in the midlatitudes and Arctic." - Laufkötter et al. (2017) (B+F, M): "The new [temperature] remineralization parameterization results in shallower remineralization in the low latitudes but

		effect is small (feedback of changing export is incorporated).	deeper remineralization in the high latitudes, redistributing POC flux toward the poles. It also decreases the volume of the oxygen minimum zones...While projections of NPP appear to be rather sensitive to assumptions about temperature dependence, all our model projections of POC flux as well as the model studies by Taucher and Oschlies [2011] and Segschneider and Bendtsen [2013] indicate that the POC flux at 100 m depth does not react strongly to increases in temperature, even despite simulated increases in net primary production." - Cavan & Boyd (2018) (F, O): "Our results showed that POC-normalised respiration increased with warming. We estimate that POC export (scaled to primary production) could decrease by 17 ± 7% (SE) by 2100, using projected regional warming (+1.9°C) from the IPCC RCP 8.5 ('business-as-usual' scenario) for our sub-Antarctic site." - Cavan et al. (2019) (F, M): "POC export is projected to decline by 12% by the end of the century according to fundamental metabolic theory and Earth System Models. The inclusion of spatially variable temperature sensitivity terms...resulted in more pronounced projected declines in POC export; applying high sensitivity globally resulted in a decline in export of 30% and applying it just to cold regions resulted in a global decline of up to 23%."
Oxygen dependent remineralisation	UNKNOWN: If models assume homogenous, well-oxygenated remineralisation rates, then including reduced remineralisation rates in OMZs would decrease remineralisation and so increase export, but the magnitude of the effect is unclear.	UNKNOWN: Theoretically, decreased remineralisation occurs in decreased oxygen concentrations, and hence leads to increased export; however, there are no studies examining export changes modulated by oxygen-dependent respiration (or grazing rates) alone.	- Weber & Bianchi (2020) (B, O+M): "...Both OMZs exhibit slow flux attenuation between 100 and 1000 m where suboxic waters reside, and sequester carbon beneath 1000 m more than twice as efficiently...three different mechanisms might explain the shape of the OMZ flux profiles: (i) a significant slow-down of remineralization ...(ii) the exclusion of zooplankton that mediate disaggregation of large particles from suboxic waters, and (iii) the limitation of remineralization by the diffusive supply of oxidants (oxygen and nitrate) into large particles." * - Devol & Hartnett (2001) (B, O): "The generally smaller rain rates off Mexico are probably due to the lower primary production, hence lower initial supply. The lower attenuation rate, however, is hypothesized to result from a decreased oxidation rate of the sinking flux within the oxygen-deficient zone relative to a more typical oxic water column." * * Note that for both of the above studies, the results are not as relevant to export flux, as the upper boundary of OMZs generally are not sufficiently shallow to intercept the export depth.
Viscosity of seawater	SMALL: Including viscosity decreased export by ~3%.	SMALL-MODERATE: Warmer water is less viscous, and thus enables particles to sink more quickly, which increases future export.	- Taucher et al. (2014) (B+F, M): "In our global warming simulation, the viscosity effect accelerates particle sinking by up to 25%..." [But these biggest effects are 2000 years in the future. Export at 130 m in 2000 AD: without viscosity = 6.56, with viscosity = 6.37 GtC yr^{-1}, equivalent to a baseline decrease of <3% with viscosity.]
Mineral ballasting	UNKNOWN: The assumption is that ballasting increases particle sinking speed and thus export, although there is	SMALL-MODERATE: A 50% decrease in calcium carbonate export would equate to only a ~10% decrease in total export from 100 m depth.	- Heinze (2004) (F, M): "For an A1B IPCC emission scenario and constant emission rates after year 2100, the simulation predicts a global decrease of biological $CaCO_3$ export production by about 50% in year 2250." - Hofmann & Schellnhuber (2009) (F, M): [From Fig 1b, $CaCO_3$ export at the bottom of the euphotic zone is reduced by ~0.1 molC m^{-2} yr^{-1} (from a baseline

	weak evidence for this occurring. Including calcite, silicate and lithogenic ballasting could increase export, but the magnitude of change is unclear.		of ~0.2 molC m^{-2} yr^{-1}) by 2200; this ~ 50% reduction in $CaCO_3$ export = ~10% reduction in total export] - Wilson et al. (2012) (B, O): “The absence of a strong globally uniform relationship between $CaCO_3$ and POC in our spatial analysis calls into question whether a simple ballasting mechanism exists...Our findings present a challenge to ocean carbon cycle modelers who to date have applied a single statistical global relationship in their carbon flux parameterizations when considering mineral ballasting...” - Le Moigne et al. (2014) (B, O): “...no globally uniform relationship between export of one type of mineral and POC, contrary to earlier suggestions by Klaas and Archer [2002] and Sanders et al. [2010]...” “Mineral ballasting is of greatest importance in the high-latitude North Atlantic, where 60% of the POC flux is associated with ballast minerals. This fraction drops to around 40% in the Southern Ocean. The remainder of the export flux is not associated with minerals, and this unballasted fraction thus often dominates the export flux. The proportion of mineral-associated POC flux often scales with regional variation in export efficiency (the proportion of primary production that is exported). However, local discrepancies suggest that regional differences in ecology also impact the magnitude of surface export. We propose that POC export will not respond equally across all high-latitude regions to possible future changes in ballast availability.”
Mineral protection	ZERO-SMALL: Scant observational evidence showing effects of mineral protection.	ZERO-SMALL: Scant observational evidence showing effects of mineral protection.	- Iversen & Ploug (2013) (B, E+R): “Our results show that ballasting of aggregates in the upper ocean appears to have a large influence on sinking velocities, while the similar average carbon-specific respiration rates between the treatments indicate no protective mechanisms against remineralization of labile organic matter as also found in copepod fecal pellets (Ploug et al., 2008b).” - Iversen & Robert (2015) (B, E): “This study shows that the inclusion of smectite offers no protection against degradation of organic matter in freshly produced or aged marine snow aggregates.”
Eddy pump	SMALL: Including eddy-driven subduction increases export by 2-5% globally.	SMALL: No studies on future effect; however future eddy characteristics are unlikely to change substantially, and the effect is anyway small. Therefore the eddy pump is not likely to have a large effect on projected global export changes.	- Resplandy et al. (2019) (B, M): “These eddy-driven subduction events are able to transfer carbon below the mixed-layer, down to 500- to 1,000-m depth. However, they contribute <5% to the annual flux at the scale of the basin, due to strong compensation between upward and downward fluxes.” - Harrison et al. (2018) (B, M): “The role of mesoscale circulation in modulating export is evaluated by comparing global ocean simulations conducted at 1° and 0.1° horizontal resolution. Mesoscale resolution produces a small reduction in globally integrated export production (<2%); however, the impact on local export production can be large (±50%), with compensating effects in different ocean basins." - Zhou et al. (2020) (B, O): “Scaling these results to the entire South China Sea basin suggests that cyclonic eddies contribute <4% of the net POC flux but >15% of the opal flux.” - Boyd et al. (2019) (B, R) [contribution of −0.09–2.0 Pg C yr^{-1} from the eddy-subduction pumps]

			- Waite et al. (2016) (B, O): [physical concentration of particles] "Here we show the subsurface distribution of eddy particles funneled into a wineglass shape down to 1000 m, leading to a sevenfold increase of vertical carbon flux in the eddy center versus the eddy flanks"
Fish vertical migration	MODERATE-LARGE: Including fish migration would increase export.	UNKNOWN: No studies on future effect.	- Saba et al. (2021) (B, R): "Based on our synthesis of passive (fecal pellet sinking) and active (migratory) flux of fishes, we estimated that fishes contribute an average (± standard deviation) of about 16.1% (± 13%) to total carbon flux out of the euphotic zone. Using the mean value of model-generated global carbon flux estimates, this equates to an annual flux of 1.5 ± 1.2 PgC yr^{-1}."
Particle stickiness, including transparent exopolymers	UNKNOWN: Effect of TEP unclear as multiple studies suggest it is highly situational and dependent on many factors.	UNKNOWN: No studies on future effect.	- Seebah et al. (2014) (F, E): "...in contrast to expectations based on the established relationship between TEP and aggregation, aggregation rates and sinking velocity of aggregates were depressed in warmer treatments, especially under ocean acidification conditions." - Wohlers et al. (2009) (F, E): "The concentration of transparent exopolymer particles (TEP) increased considerably in the warmest treatment T+6 and to a lesser extent also in the T+4 treatment during the postbloom phase of the experiment, whereas it remained low at T+2 and T+0...The extent to which enhanced TEP formation could affect particle sinking in a warming ocean critically depends on the timing of TEP production and the interplay with other biological processes, e.g., microbial degradation and grazing. In our experiment, particulate matter concentrations had decreased to nearly prebloom levels when TEP concentrations increased, hence limiting the potential for TEP-mediated particle export."
Variable stoichiometry in sinking particles	UNKNOWN: Variable stoichiometry could arise from varying levels of nutrient availability, light, and temperature, along with CO_2 sensitivity for phytoplankton growth. Direction of effect is unknown, as it depends on the parameterisation of stoichiometry in each model, which then drives whether adding variability would result in a net increase or decrease in export. For example, compared to a model with constant Redfield stoichiometry, resolving spatial variability in stoichiometry may result in	SMALL: Predicted increasing C:P and C:N in the future would increase carbon export.	- Tanioka & Matsumoto (2017) (F, M): "P:C plasticity could buffer against a generally expected future reduction in global carbon export production by up to 5% under a future warming scenario compared to a fixed, Redfield P:C." - Riebesell et al. (2007) (F, E): "The stoichiometry of carbon to nitrogen drawdown increased from 6.0 at low CO_2 to 8.0 at high CO_2, thus exceeding the Redfield carbon:nitrogen ratio of 6.6 in today's ocean. This excess carbon consumption was associated with higher loss of organic carbon from the upper layer of the stratified mesocosms." - Taucher et al. (2012) (F, E): "The maximum ratio of POC : PON was significantly enhanced at higher temperatures and reached 15.9 at low, 29.0 at intermediate, and 33.7 at high temperatures." "The maximum ratio of DOC : DON was significantly affected by temperature and reached 25.6 at low, 28.1 at intermediate, and 30.8 at high temperatures." - Moreno et al., 2018 (M, B): "environmentally driven shifts in stoichiometry make the biological pump more influential, and may reverse the expected positive relationship between temperature and $pCO_{2,\,atm}$." "Large-scale gradients in stoichiometry can alter the regional efficiency of the biological pump: P supplied to high C:P regions leads to a larger export of carbon than P supplied to low C:P regions."

	higher carbon export rates in warm, oligotrophic areas with higher C:P ratios and lower carbon export rates in cooler, nutrient-rich areas with lower C:P ratios; however, it is unknown whether global mean carbon export relative to the uniform case would increase, decrease, or remain the same.		

Supplementary Table 3: Information needed to inform process understanding-driven model developments of export flux for our priority processes, and current observational capabilities. In all cases, measurements are ideally needed over large space and time scales to match model scales. Additionally, in all cases, simulating a climate change response also requires the drivers of the processes to be understood, otherwise the model assumption will necessarily be that the process does not change with a changing climate. GOOS EOV = Global Ocean Observing System Essential Ocean Variables.

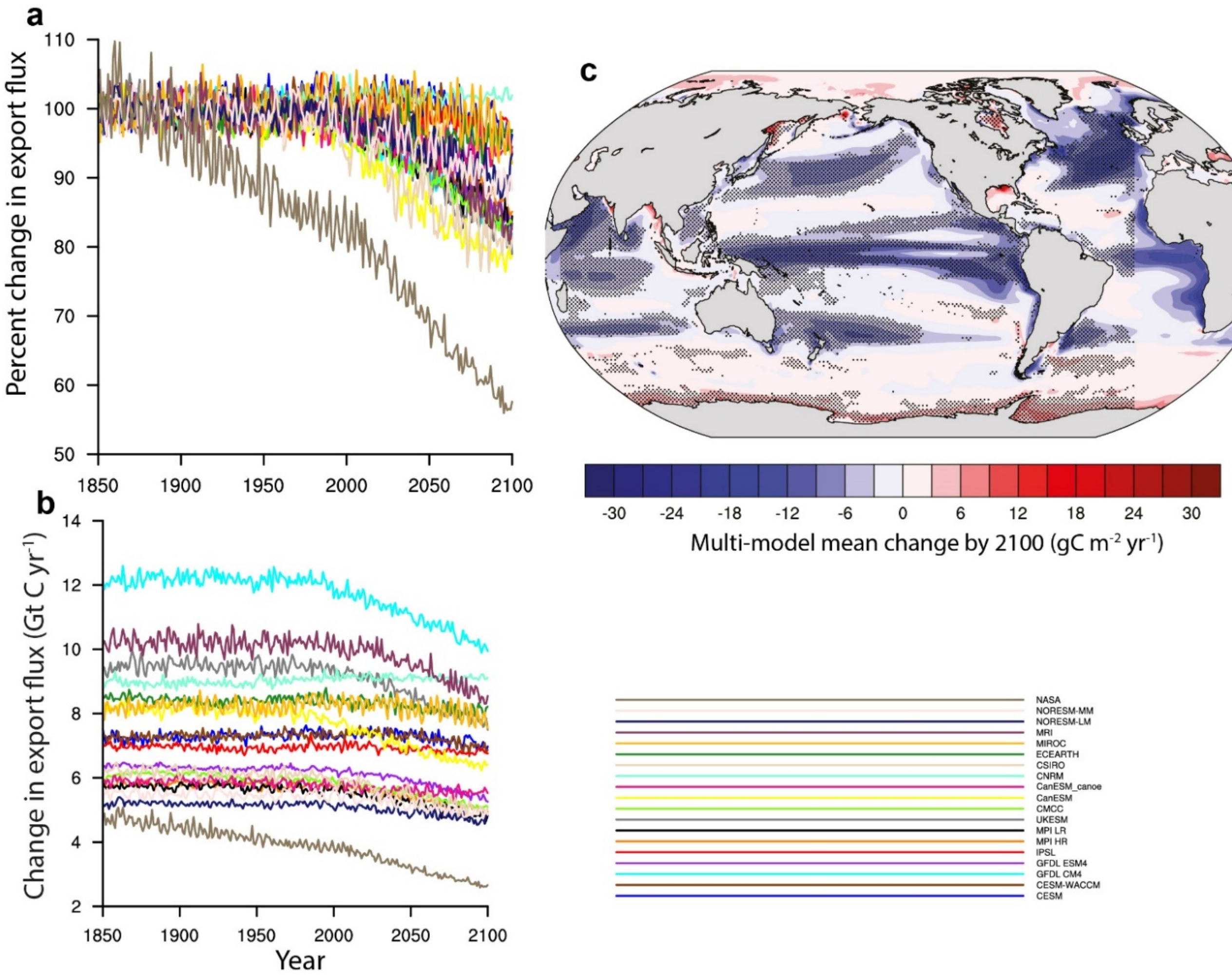
Process	Information needed	Feasibility	GOOS EOV(*1)
Fragmentation	- How does the fragmentation rate vary with depth and in different ocean regions? - What factors drive fragmentation rate? - How does fragmentation rate vary with particle type (e.g. aggregates vs faecal pellets)?	Moderate feasibility. Some knowledge on fragmentation and aggregation rates from lab experiments (O'Brien et al., 2004; Waite et al., 1997), models (Burd & Jackson, 2009; Giering et al., 2014), and indirect observations (Briggs et al., 2020). Most promising methods for large-scale observations are optical measurements on autonomous platforms. For example, bulk rates based on backscatter (Briggs et al., 2020) and *in situ* cameras for particle identification and size spectra (Giering et al., 2020). Rates of detailed driver-specific processes, such as biologically-mediated fragmentation by zooplankton, are difficult to obtain, and there are currently no obvious technological approaches to obtain these data on large scales.	Particulate matter Zooplankton biomass and diversity
Zooplankton vertical migration	- What fraction of zooplankton migrates? - To what depth do they migrate? - What factors drive zooplankton vertical migration and faecal pellet production?	High feasibility. Optical and acoustic measurements allow observations of large-scale patterns (Bianchi & Mislan, 2016). Optical measurements may also provide some taxonomic resolution, although camera avoidance/attraction may cause biases (Hoving et al., 2019; Utne-Palm et al., 2018).	Zooplankton biomass and diversity Oxygen Sea surface temperature/subsurface temperature Phytoplankton biomass and diversity Ocean colour
	- What fraction of faecal pellets are formed above versus below the permanent thermocline/euphotic zone? - How does faecal pellet density and size vary?	Moderate feasibility. Large-scale *in situ* optical data may provide information on particle type, abundance and distribution (and hence particle origin), as well as sinking velocities (Giering et al., 2020).	

	- What are the metabolic rates at depth versus at surface?	Low feasibility. *In situ* metabolic rates are difficult to obtain and require ship-board work. Metabolic markers (e.g. enzyme activity) may prove useful (Yebra et al., 2017), but data are still sparse. Understanding of large-scale, whole population responses to environmental drivers are not yet feasible.	
Phytoplankton size effect on sinking	- What is the size distribution of phytoplankton in the ocean? - How are the size distribution of phytoplankton and the size distribution of particles related?	High feasibility. Information on phytoplankton size and distribution can be obtained from recent developments in satellite-derived products (Mouw et al., 2017), as well as optical devices on autonomous platforms (Lombard et al., 2019).	Phytoplankton biomass and diversity Ocean colour Sea surface temperature/subsurface temperature Nutrients
	- How are particle size and sinking rate related?	Moderate feasibility. Large-scale *in situ* optical data could provide information on particle size and sinking velocities (Giering et al., 2020). Coupled with information on phytoplankton biomass and diversity (e.g. from *in situ* plankton monitoring systems; Lombard et al., 2019), the relationship between particle size and sinking rate could be obtained in the near future.	
Temperature dependent remineralisation	- Does temperature affect different particle types differently? - Does microbial rate temperature sensitivity vary latitudinally?	Moderate to low feasibility. A moderate amount of lab-based data exists (Robinson, 2019), but *in situ* data are still relatively sparse. Large-scale observations of these rates may be obtained indirectly from changes in oxygen and POC concentrations. The acquisition of large-scale information on the sensitivity of these rates remains problematic.	Microbial biomass and diversity (*emerging) Particulate matter Dissolved organic carbon Oxygen Sea surface temperature/subsurface temperature

(*1) To inform process understanding-driven model developments of export flux, we require measurements of key parameters over large space and time scales to match model scales. A useful starting point in assessing feasibility of collating some essential data is through Essential Ocean Variables (EOVs). EOVs have been classified as critical for observing the oceans by the Global Ocean Observing System - an initiative to standardize ocean data collection and promote observing developments (Moltmann et al., 2019). EOVs are assessed for feasibility, capacity and impact, and their maturity rated.

Supplementary Table 4: Table of models assessed and the main marine biogeochemistry module reference.

Climate model & *ecosystem module*	Key references
CanESM5	Swart et al. (2019)
CanESM5-CanOE	Hayashida (2018); Swart et al. (2019)
CESM & CESM-WACCM ***MARBL***	Long et al. (submitted)
CMCC-ESM2 ***BFM5.2***	Vichi et al. (2020)
CNRM, EC-Earth-CC & IPSL ***PISCES2***	Aumont et al. (2015)
CSIRO ***WOMBAT***	Kidston et al. (2011)
GFDL-CM4 ***BLING***	Dunne et al. (2020)
GFDL-ESM4 ***COBALT***	Stock et al. (2020)
MIROC	Hajima et al. (2020)
MPI HR & MPI LR ***Hamocc6***	Ilyina et al. (2013); Mauritsen et al. (2019)
MRI	Nakano et al. (2011); Tsujino et al. (2010)
NASA-GISS	Ito et al. (2020)
NorESM LM & NorESM MM ***Hamocc5.1***	Tjiputra et al. (2020)
UK-ESM ***Medusa***	Sellar et al. (2019); Yool et al. (2021)



Supplementary Figure 1: Uncertain response of export flux to climate change. (a) Percent change and (b) absolute change (Gt C yr^{-1}) in export flux in 19 coupled climate models in the CMIP6 archive, forced with the SSP5-8.5 scenario to year 2100. Percent change is calculated with respect to the mean of years 1850-1900 for each model. (c) Multi-model mean change in export flux (gC m^{-2} yr^{-1}) between the 2080-2100 average and the 1850-1900 average. Hatching indicates where ~ 75% of models (i.e. at least 14 of 19) agree on the sign of the change in export flux.

Supplementary References

Archibald, K. M., Siegel, D. A., & Doney, S. C. (2019). Modeling the Impact of Zooplankton Diel Vertical Migration on the Carbon Export Flux of the Biological Pump. *Global Biogeochemical Cycles*, *33*(2), 181–199. https://doi.org/10.1029/2018GB005983

Aumont, O., Ethé, C., Tagliabue, A., Bopp, L., & Gehlen, M. (2015). PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies. *Geoscientific Model Development*, *8*(8), 2465–2513. https://doi.org/10.5194/gmd-8-2465-2015

Aumont, Olivier, Maury, O., Lefort, S., & Bopp, L. (2018). Evaluating the Potential Impacts of the Diurnal Vertical Migration by Marine Organisms on Marine Biogeochemistry. *Global Biogeochemical Cycles*, *32*(11), 1622–1643. https://doi.org/10.1029/2018GB005886

Bianchi, D., & Mislan, K. A. S. (2016). Global patterns of diel vertical migration times and velocities from acoustic data. *Limnology and Oceanography*, *61*(1), 353–364. https://doi.org/10.1002/lno.10219

Bopp, L., Aumont, O., Cadule, P., Alvain, S., & Gehlen, M. (2005). Response of diatoms distribution to global warming and potential implications: A global model study. *Geophysical Research Letters*, *32*(19), n/a-n/a. https://doi.org/10.1029/2005GL023653

Boyd, P. W. (2015). Toward quantifying the response of the oceans' biological pump to climate change. *Frontiers in Marine Science*, *2*. https://doi.org/10.3389/fmars.2015.00077

Boyd, P. W., Claustre, H., Levy, M., Siegel, D. A., & Weber, T. (2019). Multi-faceted particle pumps drive carbon sequestration in the ocean. *Nature*, *568*(7752), 327–335. https://doi.org/10.1038/s41586-019-1098-2

Briggs, N., Dall'Olmo, G., & Claustre, H. (2020). Major role of particle fragmentation in regulating biological sequestration of CO 2 by the oceans. *Science*, *367*(6479), 791–793. https://doi.org/10.1126/science.aay1790

Burd, A. B., & Jackson, G. A. (2009). Particle Aggregation. *Annual Review of Marine Science*, *1*(1), 65–90. https://doi.org/10.1146/annurev.marine.010908.163904

Cael, B. B., Bisson, K., & Follows, M. J. (2017). How have recent temperature changes affected the efficiency of ocean biological carbon export? *Limnology and Oceanography Letters*, *2*(4), 113–118. https://doi.org/10.1002/lol2.10042

Cavan, E., & Boyd, P. (2018). Effect of anthropogenic warming on microbial respiration and particulate organic carbon export rates in the sub-Antarctic Southern Ocean. *Aquatic Microbial Ecology*, *82*(2), 111–127. https://doi.org/10.3354/ame01889

Cavan, E. L., Trimmer, M., Shelley, F., & Sanders, R. (2017). Remineralization of particulate organic carbon in an ocean oxygen minimum zone. *Nature Communications*, *8*(1), 14847. https://doi.org/10.1038/ncomms14847

Cavan, Emma Louise, Henson, S. A., & Boyd, P. W. (2019). The Sensitivity of Subsurface Microbes to Ocean Warming Accentuates Future Declines in Particulate Carbon Export. *Frontiers in Ecology and Evolution*, *6*. https://doi.org/10.3389/fevo.2018.00230

Devol, A. H., & Hartnett, H. E. (2001). Role of the oxygen-deficient zone in transfer of organic carbon to the deep ocean. *Limnology and Oceanography*, *46*(7), 1684–1690. https://doi.org/10.4319/lo.2001.46.7.1684

Dunne, J. P., Bociu, I., Bronselaer, B., Guo, H., John, J. G., Krasting, J. P., et al. (2020). Simple Global Ocean Biogeochemistry With Light, Iron, Nutrients and Gas Version 2 (BLINGv2): Model Description and Simulation Characteristics in GFDL's CM4.0. *Journal of Advances in Modeling Earth Systems*, *12*(10). https://doi.org/10.1029/2019MS002008

Giering, Sarah L. C., Sanders, R., Lampitt, R. S., Anderson, T. R., Tamburini, C., Boutrif, M., et al. (2014). Reconciliation of the carbon budget in the ocean's twilight zone. *Nature*, *507*(7493), 480–483. https://doi.org/10.1038/nature13123

Giering, Sarah Lou Carolin, Cavan, E. L., Basedow, S. L., Briggs, N., Burd, A. B., Darroch, L. J., et al. (2020). Sinking Organic Particles in the Ocean—Flux Estimates From in situ Optical Devices. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00834

Gorgues, T., Aumont, O., & Memery, L. (2019). Simulated Changes in the Particulate

Carbon Export Efficiency due to Diel Vertical Migration of Zooplankton in the North Atlantic. *Geophysical Research Letters*, *46*(10), 5387–5395. https://doi.org/10.1029/2018GL081748

Hajima, T., Watanabe, M., Yamamoto, A., Tatebe, H., Noguchi, M. A., Abe, M., et al. (2020). Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. *Geoscientific Model Development*, *13*(5), 2197–2244. https://doi.org/10.5194/gmd-13-2197-2020

Hansen, A. N., & Visser, A. W. (2016). Carbon export by vertically migrating zooplankton: an optimal behavior model. *Limnology and Oceanography*, *61*(2), 701–710. https://doi.org/10.1002/lno.10249

Harrison, C. S., Long, M. C., Lovenduski, N. S., & Moore, J. K. (2018). Mesoscale Effects on Carbon Export: A Global Perspective. *Global Biogeochemical Cycles*, *32*(4), 680–703. https://doi.org/10.1002/2017GB005751

Hayashida, H. (2018). *Modelling sea-ice and oceanic dimethylsulfide production and emissions in the Arctic*. University of Victoria. Retrieved from dspace.library.uvic.ca/handle/1828/10486

Heinze, C. (2004). Simulating oceanic CaCO3 export production in the greenhouse. *GEOPHYSICAL RESEARCH LETTERS*, *31*(16). https://doi.org/10.1029/2004GL020613

Hofmann, M., & Schellnhuber, H.-J. (2009). Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA*, *106*(9), 3017–3022. https://doi.org/10.1073/pnas.0813384106

Hoving, H.-J., Christiansen, S., Fabrizius, E., Hauss, H., Kiko, R., Linke, P., et al. (2019). The Pelagic In situ Observation System (PELAGIOS) to reveal biodiversity, behavior, and ecology of elusive oceanic fauna. *Ocean Science*, *15*(5), 1327–1340. https://doi.org/10.5194/os-15-1327-2019

Ilyina, T., Six, K. D., Segschneider, J., Maier-Reimer, E., Li, H., & Núñez-Riboni, I. (2013). Global ocean biogeochemistry model HAMOCC: Model architecture and performance as component of the MPI-Earth system model in different CMIP5 experimental realizations. *Journal of Advances in Modeling Earth Systems*, *5*(2), 287–315. https://doi.org/10.1029/2012MS000178

Ito, G., Romanou, A., Kiang, N. Y., Faluvegi, G., Aleinov, I., Ruedy, R., et al. (2020). Global Carbon Cycle and Climate Feedbacks in the NASA GISS ModelE2.1. *Journal of Advances in Modeling Earth Systems*, *12*(10). https://doi.org/10.1029/2019MS002030

Iversen, M. H., & Ploug, H. (2013). Temperature effects on carbon-specific respiration rate and sinking velocity of diatom aggregates – potential implications for deep ocean export processes. *Biogeosciences*, *10*(6), 4073–4085. https://doi.org/10.5194/bg-10-4073-2013

Iversen, Morten H., & Robert, M. L. (2015). Ballasting effects of smectite on aggregate formation and export from a natural plankton community. *Marine Chemistry*, *175*, 18–27. https://doi.org/10.1016/j.marchem.2015.04.009

Kidston, M., Matear, R., & Baird, M. E. (2011). Parameter optimisation of a marine ecosystem model at two contrasting stations in the Sub-Antarctic Zone. *Deep Sea Research Part II: Topical Studies in Oceanography*, *58*(21–22), 2301–2315. https://doi.org/10.1016/j.dsr2.2011.05.018

Laufkötter, C., Vogt, M., Gruber, N., Aumont, O., Bopp, L., Doney, S. C., et al. (2016). Projected decreases in future marine export production: the role of the carbon flux through the upper ocean ecosystem. *Biogeosciences*, *13*(13), 4023–4047. https://doi.org/10.5194/bg-13-4023-2016

Laufkötter, C., John, J. G., Stock, C. A., & Dunne, J. P. (2017). Temperature and oxygen dependence of the remineralization of organic matter. *Global Biogeochemical Cycles*, *31*(7), 1038–1050. https://doi.org/10.1002/2017GB005643

Leung, S. W., Weber, T., Cram, J. A., & Deutsch, C. (2021). Variable particle size distributions reduce the sensitivity of global export flux to climate change.

Biogeosciences, *18*(1), 229–250. https://doi.org/10.5194/bg-18-229-2021
Lombard, F., Boss, E., Waite, A. M., Vogt, M., Uitz, J., Stemmann, L., et al. (2019). Globally Consistent Quantitative Observations of Planktonic Ecosystems. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00196
Long, M. C., Moore, J. K., Lindsay, K., Levy, M., Doney, S. C., Luo, J. Y., et al. (n.d.). Simulations with the Marine Biogeochemistry Library (MARBL). *Journal of Advances in Modeling Earth Systems*. https://doi.org/10.1002/essoar.10507358.1
Maerz, J., Six, K. D., Stemmler, I., Ahmerkamp, S., & Ilyina, T. (2020). Microstructure and composition of marine aggregates as co-determinants for vertical particulate organic carbon transfer in the global ocean. *Biogeosciences*, *17*(7), 1765–1803. https://doi.org/10.5194/bg-17-1765-2020
Marsay, C. M., Sanders, R. J., Henson, S. A., Pabortsava, K., Achterberg, E. P., & Lampitt, R. S. (2015). Attenuation of sinking particulate organic carbon flux through the mesopelagic ocean. *Proceedings of the National Academy of Sciences*, *112*(4), 1089–1094. https://doi.org/10.1073/pnas.1415311112
Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., et al. (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO 2. *Journal of Advances in Modeling Earth Systems*, *11*(4), 998–1038. https://doi.org/10.1029/2018MS001400
Le Moigne, F. A. C., Pabortsava, K., Marcinko, C. L. J., Martin, P., & Sanders, R. J. (2014). Where is mineral ballast important for surface export of particulate organic carbon in the ocean? *Geophysical Research Letters*, *41*(23), 8460–8468. https://doi.org/10.1002/2014GL061678
Moltmann, T., Turton, J., Zhang, H.-M., Nolan, G., Gouldman, C., Griesbauer, L., et al. (2019). A Global Ocean Observing System (GOOS), Delivered Through Enhanced Collaboration Across Regions, Communities, and New Technologies. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00291
Moreno, A. R., Hagstrom, G. I., Primeau, F. W., Levin, S. A., & Martiny, A. C. (2018). Marine phytoplankton stoichiometry mediates nonlinear interactions between nutrient supply, temperature, and atmospheric CO2. *BIOGEOSCIENCES*, *15*(9), 2761–2779. https://doi.org/10.5194/bg-15-2761-2018
Mouw, C. B., Hardman-Mountford, N. J., Alvain, S., Bracher, A., Brewin, R. J. W., Bricaud, A., et al. (2017). A Consumer's Guide to Satellite Remote Sensing of Multiple Phytoplankton Groups in the Global Ocean. *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00041
Nakano, H., Tsujino, H., Hirabara, M., Yasuda, T., Motoi, T., Ishii, M., & Yamanaka, G. (2011). Uptake mechanism of anthropogenic CO2 in the Kuroshio Extension region in an ocean general circulation model. *Journal of Oceanography*, *67*(6), 765–783. https://doi.org/10.1007/s10872-011-0075-7
O'Brien, K. R., Meyer, D. L., Waite, A. M., Ivey, G. N., & Hamilton, D. P. (2004). Disaggregation of Microcystis aeruginosa colonies under turbulent mixing: laboratory experiments in a grid-stirred tank. *Hydrobiologia*, *519*(1–3), 143–152. https://doi.org/10.1023/B:HYDR.0000026501.02125.cf
Resplandy, L., Lévy, M., & McGillicuddy, D. J. (2019). Effects of Eddy-Driven Subduction on Ocean Biological Carbon Pump. *Global Biogeochemical Cycles*, *33*(8), 1071–1084. https://doi.org/10.1029/2018GB006125
Riebesell, U., Schulz, K. G., Bellerby, R. G. J., Botros, M., Fritsche, P., Meyerhöfer, M., et al. (2007). Enhanced biological carbon consumption in a high CO2 ocean. *Nature*, *450*(7169), 545–548. https://doi.org/10.1038/nature06267
Robinson, C. (2019). Microbial Respiration, the Engine of Ocean Deoxygenation. *Frontiers in Marine Science*, *5*. https://doi.org/10.3389/fmars.2018.00533
Saba, G. K., Burd, A. B., Dunne, J. P., Hernández-León, S., Martin, A. H., Rose, K. A., et al. (2021). Toward a better understanding of fish-based contribution to ocean carbon flux. *Limnology and Oceanography*, lno.11709. https://doi.org/10.1002/lno.11709
Seebah, S., Fairfield, C., Ullrich, M. S., & Passow, U. (2014). Aggregation and

Sedimentation of Thalassiosira weissflogii (diatom) in a Warmer and More Acidified Future Ocean. *PLoS ONE*, *9*(11), e112379. https://doi.org/10.1371/journal.pone.0112379
Sellar, A. A., Jones, C. G., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019). UKESM1: Description and Evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/10.1029/2019MS001739
Stock, C. A., Dunne, J. P., Fan, S., Ginoux, P., John, J., Krasting, J. P., et al. (2020). Ocean Biogeochemistry in GFDL's Earth System Model 4.1 and Its Response to Increasing Atmospheric CO 2. *Journal of Advances in Modeling Earth Systems*, *12*(10). https://doi.org/10.1029/2019MS002043
Stukel, M., Ohman, M., Benitez-Nelson, C., & Landry, M. (2013). Contributions of mesozooplankton to vertical carbon export in a coastal upwelling system. *Marine Ecology Progress Series*, *491*, 47–65. https://doi.org/10.3354/meps10453
Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., et al. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). *Geoscientific Model Development*, *12*(11), 4823–4873. https://doi.org/10.5194/gmd-12-4823-2019
Tanioka, T., & Matsumoto, K. (2017). Buffering of Ocean Export Production by Flexible Elemental Stoichiometry of Particulate Organic Matter. *Global Biogeochemical Cycles*, *31*(10), 1528–1542. https://doi.org/10.1002/2017GB005670
Taucher, J., Schulz, K. G., Dittmar, T., Sommer, U., Oschlies, A., & Riebesell, U. (2012). Enhanced carbon overconsumption in response to increasing temperatures during a mesocosm experiment. *Biogeosciences*, *9*(9), 3531–3545. https://doi.org/10.5194/bg-9-3531-2012
Taucher, J., Bach, L. T., Riebesell, U., & Oschlies, A. (2014). The viscosity effect on marine particle flux: A climate relevant feedback mechanism. *Global Biogeochemical Cycles*, *28*(4), 415–422. https://doi.org/10.1002/2013GB004728
Tjiputra, J. F., Schwinger, J., Bentsen, M., Morée, A. L., Gao, S., Bethke, I., et al. (2020). Ocean biogeochemistry in the Norwegian Earth System Model version 2 (NorESM2). *Geoscientific Model Development*, *13*(5), 2393–2431. https://doi.org/10.5194/gmd-13-2393-2020
Tsujino, H., Motoi, T., Ishikawa, I., Hirabara, M., Nakano, H., Yamanaka, G., et al. (2010). *Reference manual for the Meteorological Research Institute Community Ocean Model (MRICOM) version 3*. Retrieved from https://www.mri-jma.go.jp/Publish/Technical/DATA/VOL_59/tec_rep_mri_59_2.pdf
Utne-Palm, A. C., Breen, M., Løkkeborg, S., & Humborstad, O.-B. (2018). Behavioural responses of krill and cod to artificial light in laboratory experiments. *PLOS ONE*, *13*(1), e0190918. https://doi.org/10.1371/journal.pone.0190918
Vichi, M., Lovato, T., Butenschoen, M., Tedesco, L., Lazzari, P., Cossarini, G., et al. (2020). *The Biogeochemical Flux Model (BFM): Equation Description and User Manual. BFM version 5.2*. Bologna, Italy. Retrieved from https://cmcc-foundation.github.io/www.bfm-community.eu/bfm-documentation/
Waite, A., Gallager, S., & Dam, H. (1997). New measurements of phytoplankton aggregation in a flocculator using videography and image analysis. *Marine Ecology Progress Series*, *155*, 77–88. https://doi.org/10.3354/meps155077
Waite, A. M., Stemmann, L., Guidi, L., Calil, P. H. R., Hogg, A. M. C., Feng, M., et al. (2016). The wineglass effect shapes particle export to the deep ocean in mesoscale eddies. *Geophysical Research Letters*, *43*(18), 9791–9800. https://doi.org/10.1002/2015GL066463
Weber, T., & Bianchi, D. (2020). Efficient Particle Transfer to Depth in Oxygen Minimum Zones of the Pacific and Indian Oceans. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.00376
Wilson, J. D., Barker, S., & Ridgwell, A. (2012). Assessment of the spatial variability in particulate organic matter and mineral sinking fluxes in the ocean interior: Implications for the ballast hypothesis. *Global Biogeochemical Cycles*, *26*(4), n/a-n/a.

https://doi.org/10.1029/2012GB004398
Wohlers, J., Engel, A., Zöllner, E., Breithaupt, P., Jürgens, K., Hoppe, H.-G., et al. (2009). Changes in biogenic carbon flow in response to sea surface warming. *Proceedings of the National Academy of Sciences*, *106*(17), 7067–7072. https://doi.org/10.1073/pnas.0812743106
Yebra, L., Kobari, T., Sastri, A. R., Gusmão, F., & Hernández-León, S. (2017). Advances in Biochemical Indices of Zooplankton Production (pp. 157–240). https://doi.org/10.1016/bs.amb.2016.09.001
Yool, A., Popova, E. E., & Anderson, T. R. (2013). MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. *Geoscientific Model Development*, *6*(5), 1767–1811. https://doi.org/10.5194/gmd-6-1767-2013
Yool, Andrew, Palmiéri, J., Jones, C. G., de Mora, L., Kuhlbrodt, T., Popova, E. E., et al. (2021). Evaluating the physical and biogeochemical state of the global ocean component of UKESM1 in CMIP6 historical simulations. *Geoscientific Model Development*, *14*(6), 3437–3472. https://doi.org/10.5194/gmd-14-3437-2021
Zhou, K., Dai, M., Xiu, P., Wang, L., Hu, J., & Benitez-Nelson, C. R. (2020). Transient Enhancement and Decoupling of Carbon and Opal Export in Cyclonic Eddies. *Journal of Geophysical Research: Oceans*, *125*(9). https://doi.org/10.1029/2020JC016372