There and back again, ~~an organic carbon~~ a journey ~~: mapping~~ of many pathways~~and loops~~: conceptualising the marine organic carbon cycle

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Abstract. Understanding and determining ~~where~~ the pathways that organic carbon (OC) ~~ends up~~ takes in the ocean ~~and how long it remains there~~ is one of the most pressing tasks of our time, as the fate of OC in the ocean ~~links~~ is linked to the climate system ~~. To provide an additional tool to accomplish this and other related tasks, we map and conceptualize OC pathways in a qualitative model. The model is complementary to existing concepts of OC processes and pathways based mainly on quantifications and observations of current states and dominant processes. Our model, on the contrary, presents general pathway patternsand embedded processes without focusing on dominant processes or pathways or omitting rare ones. By~~ and the functionality of marine ecosystems. The multitude and complexity of these pathways are investigated with sophisticated, mainly quantitative methods focusing on individual pathways to resolve their interactions and processes as realistically as possible. In addition to these approaches to understand and recreate complexity, there is a need to identify commonalities and differences between individual OC pathways and define their overarching and core structures. Such core structures can provide a framework for the increasing number of sub-concepts, some of which overlap, and promote more structured comparisons and consistent communication, especially between different disciplines. In response, we propose a (visual) concept that defines these structures as higher-level ’pathway patterns’. These pathway patterns are defined by mapping, comparing, and condensing ~~pathways and involved spatial scales , we define three remineralization and two refractory~~ the sequences of processes and spatial scales of the marine OC pathways. The result includes the definition of closed-loop patterns, three remineralisation and two recalcitrant dissolved organic carbon loops that close ~~within the marine systems. Pathways that exit~~ in marine systems, and ’open’ loops, condensing pathways leaving the marine system ~~comprise inorganic atmospheric, OC atmospheric, and long-term sediment loops. With the defined loops and the embedded process options, the model is flexible and~~ to the atmosphere or deeper sediment layers. In addition, we extend these basic structures (loops) with a synthesis of the underlying processes, pools, and agents. By translating a definition of the biological carbon pump into our pathway patterns, we show how the application and discussion of these patterns facilitate a consistent visualisation, a structured comparison of differently resolved concepts and studies, and integration of these in the larger picture of the OC cycle. As a complement to quantitative studies and descriptions of individual pathways, our concept defines new core structures of all OC pathways by decomposing their complexity into basic patterns. These basic patterns provide a skeleton that can be adapted to different systems ~~, changing understanding or~~

~~changing mechanisms. As such, it can help tracking pathway changes and assessing the impact of human interventions on pathways, marine ecosystems, and the oceanic organic carbon cycle.~~ and filled with life by the users.

1 Introduction

~~We present a qualitative conceptual model of marine~~ The pathways along which organic carbon (OC) ~~pathways. The model shows general patterns of potential OC pathways that loop within the marine system or exit the system into the deeper sediment or atmosphere. It is the first concept to explicitly resolve pathways and processes alike, without focusing on single dominant processes and fluxes such as the carbon export flux. The congruent and flexible concept facilitates 1) comparing carbon pathways of different marine systems and 2) identifying pathways of OC that close within or leave the marine system. Furthermore, it allows a congruent integration of new findings or changes in OC pathways and processes. In this way,~~ moves through oceanic systems affect not only the climate system (Barange et al., 2017) and ecosystem functioning (Griffiths et al., 2017), but also human well-being and socio-ecological systems (Ullah et al., 2018). Therefore, understanding marine OC pathways and the current and future marine OC dynamics resulting from the multiplicity of these pathways and the human influence on them is an essential and very productive focus of ocean research (Jiao et al., 2018). Studies on marine OC pathways are continuously expanding our understanding of the ~~model can help research and society identifying options and limits of human actions to address the climate emergency and deterioration of nature.~~ OC cycle through comprehensive observations and sophisticated numerical models, e.g. by the Joint Global Ocean Flux Study (JGOFS) (Doney and Ducklow, 2006), improved carbon budgets (e.g. by Giering et al. (2014)) and quantitative estimates of the contribution of individual organisms (e.g. in Bianchi et al. (2021)), to name but a few.

~~Each OC particle moves along a pathway through marine ecosystems and the OC cycle. An OC particle in the surface ocean can end up in the surface or the deep oceans, be decomposed, or become refractory, to name just a fewoptions. Each pathway is unique in its~~ Complementing the often-quantitative results, these studies sometimes provide (visual) concepts that abstractly describe and generalise OC pathways as a sequence of processes~~like sinking and decomposition. There is thus a myriad of pathway options. An all-encompassing description and study of all the different pathway options are therefore neither possible nor meaningful. However, there is a need to understand and model the current and future marine OC dynamics that result from the multitude of these pathways and the human impact on them. Identifying and conceptualizing pathway patterns - the condensed structure of pathways- and involved processes can facilitate this.However, pathway options have not yet been mapped systematically and congruently, nor have general pathway patterns been identified.~~ , higher-level structures or a core mechanism. Due to the multitude of disciplines involved, the heterogeneity of marine systems and the complexity of the OC cycle, these concepts have a relatively narrow focus and consider a selection of pathways. For example, some studies conceptualise and generalise pathway structures for specific carbon pools e.g. dissolved OC in the microbial pump (Jiao et al., 2010; Jiao and Zheng, 2011), a selection of species such as bacteria in the microbial loop (Azam et al., 1994) or physical processes of different scales e.g. large-scale or eddy-subduction export (Levy et al., 2013; Omand et al., 2015).

~~Most concepts of marine OC dynamics and pathways focus on~~ The different foci and the limited spectrum of the pathways considered lead to concepts that complement each other through different resolutions (focusing on different processes or pools), but also promote partly overlapping sub-concepts. An example is the generalisation of pathways leading to the biota-induced vertical gradient of dissolved inorganic carbon in the oceans, described by the concept of the ~~OC export to the deep sea and marine sediments through different pumping concepts that describe inter alia the physical transport of OC derived from biota (like the biological gravitational pump (Boyd et al., 2019)),~~ biological carbon pump (BCP). Several sub-concepts of the BCP have emerged, describing, among other things, the transport of carbon into and out of specific water layers~~(e.g.~~ , such as the mixed layer pump (Gardner et al., 1995)~~)~~ , or carbon export ~~via~~ by species-specific behaviour~~(~~, such as the lipid pump (Jónasdóttir et al., 2015)~~). Commonly, the main research objective is to understand and quantify the efficiency and capacity of these carbon pumps (De La Rocha and Passow, 2007) and the processes (e.g. sinking (De La Rocha and Passow, 2007)), system conditions (like temperature (Cael et al., 2017)) and particle types (seperated by~~ . Recent approaches to further generalise the pump concept by defining its main functions, e.g. particle ~~size (Fender et al., 2019)) that influence the C export flux to the sediment~~injection by Boyd et al. (2019), show the need to define structural patterns to make concept such as the BCP more comparable, comprehensive, systematic and adaptable.

~~By focusing on C export/ C pumps, the final destination of carbon pathways of interest is predefined as the sediment or deep-sea, and the loss/attenuation of the pump, which is a deviation from this destination, is only implicitly considered, e. g. by changing the density of sinking particles with depth in some concepts (Turner, 2015). The fate of carbon whose pathway does not end in the sediment or deep ocean, and the return pathways of this carbon to the surface and the involved processes are often~~ It is plausible that studies on individual OC pathways or systems produce specific and small-scale sub-concepts. However, in science, there is an additional need to identify commonalities and to find and define basic unifying structures (Scheiner and Willig, 2011). So far, there has been no attempt to summarise and generalise OC pathways and conceptual ideas into an overarching general concept of the core structures of the marine part of the OC cycle.

Existing concepts, especially those aiming at a more comprehensive representation of the OC cycle, are often not visually congruent within the respective graphics or graphics in other publications. Processes and pathways are not represented with the same level of detail ~~, resolution, or congruence. For instance, Steinberg and Landry (2017)and Cavan et al. (2019)include physical mixing and movements of migrating species as upward transport mechanisms of possible return pathways, by displaying upwards pointing arrows in their graphic concepts, but it remains unclear what is transported upwards. Other studies include loss processes , such as respiration (Anderson and Ducklow, 2001) or remineralization (Boscolo-Galazzo et al., 2018), but without resolving what happens to the productsof these processes. Some concepts of carbon pumps and dynamics~~or resolution. For example, Steinberg and Landry (2017), Cavan et al. (2019), Anderson and Ducklow (2001) and Boscolo-Galazzo et al. (2018) visually detach some products from the processes that produce them or do not mention the products, such as ~~Sigman and Haug (2004) and Zhang et al. (2018), acknowledge return pathways forming cycles and show them in their graphical representations. However, even these concepts usually address only a selection of possible processes, like upward mixing of DOC and particles (Siegel et al., 2016), or consider these pathways mainly to differentiate how long OC remains in the ocean when comparing different water depths (Sigman and Haug, 2004; Zhang et al., 2018) for example.~~ DIC, in the figures at all. Such illustrations usually work despite these (small) inconsistencies because the aim of such studies is not to create congruent conceptual representations of the OC cycle, and their visualisations are rather tools to highlight their research focus in an overarching picture. However, we would like to emphasise that graphics are a visualisation of the mapper's mental concepts. By deciding what to visualise and at what resolution, and by omitting information, parts of this mental concept are obscured, which can make it difficult to understand and use the concepts for studies other than the one for which it was created. Graphics are powerful tools for disseminating information, generalising structures and promoting discussion (Margoluis et al., 2009). Non-congruent graphics do not exploit that full potential.

The lack of an overarching (and congruently visualised) concept of the OC cycle can reduce the transparency of the scientific process and make comparisons and discussions as well as the adaptation of concepts and ideas more difficult (Scheiner and Willig, 2011). Different resolutions and definitions of pathways and pathway structures risk misunderstanding and miscommunication in education (Fortuin et al., 2011), among young but also more experienced researchers or in interdisciplinary communities (Heemskerk et al., 2003) and may foster a growing number of sub-concepts with different resolutions (Scheiner and Willig, 20
, some of which may overlap.

~~Besides the focus on carbon export and pumping, other studies dealing with marine OC focus on the processes and pathways of specific carbon species (e.g. dissolved OC in the microbial pump (Jiao et al., 2010)) and systems (e.g. the twilight zone (Giering et al., 2014)), a selection of species (such as bacteria in the microbial loop (Azam et al., 1994)), and / or individual processes (e. g. up-mixing (Shen and Benner, 2018)). The current understanding of the significance or dominance of single processes in the respective system drives these foci.~~

~~All the above-described conceptsare based on quantifications and interpretations and represent our current understanding of carbon dynamics bound to the system state today and somewhat static. Static in the sense that the concepts represent one manifestation of, for example, the loss/attenuation in the pump that implies that this manifestation is generally valid and will continue to be so. The current state and our understanding of it shine through by the implicit inclusion of concentrations and quantities in the graphical representation. For instance, in Passow and Carlson (2012)) , the export arrow becomes thinner with increasing depth. The thickness carries secondary information about the path. The decreased thickness of the export arrow implies that the amount of carbon reaching the sediment is very small. While this is true, it is not a conceptual representation as it already comprises quantification and is not showing unweighted conceptual mechanisms. In addition, the current state is manifested by focusing on carbon export (as described above) and the (resulting) exclusion of pathways or of trophic interactions that are considered unimportant and /or rare (see e.g. few interactions of higher trophic levels in the concept of Steinberg and Landry (2017). Thus, our description of carbon pathways mimics our present viewpoint. However, a conceptual model that congruently represents the various possible pathways a particle can take without interpretations or quantifications of present-day systems is missing.~~

To ~~fill this gap~~reduce this risk, we propose ~~an additional conceptual model~~ to step back from quantitative, specific, and numerically advanced research and to summarise and generalise what is known about the carbon cycle and OC pathways. The result of this step is a general concept that does not represent specific carbon processes or a single pathway ~~of the OC cycle but general pathway patternswith pathway and process options. Our conceptual model distinguishes~~ but defines the basic and common structures of all pathways as pathway patterns. We define these generalised pathway patterns in linguistic and visual units by comparing and condensing core similarities of possible OC pathways in the marine system. The result is the definition of several pathway patterns of ~~closed and '~~'closed and open' OC loops that ~~are generally applicable. We define these general loops by comparing and condensing similarities of possible pathways of OC in the marine system~~summarise the structure of all pathways that close within the marine system or leave the system into the deeper sediment or atmosphere.

The resulting concept facilitates 1) comparing models and concepts of different resolutions, 2) synthesizing concepts, definitions and scientific languages, 3) adding new scientific knowledge in a congruent and structured way, 4) identifying research gaps and inconsistencies, and 5) placing finite pathways into an overarching framework of the OC cycle. In this way, the concept can help researchers from different disciplines to facilitate research design, discuss individual concepts, and improve interdisciplinary communication, collaboration, and scientific education.

In the following, we describe ~~the qualitative model framework of our concept and how we develop it by asking:~~ how we developed our concept based on the questions 1) ~~what~~ What are the different pathways for an OC ~~particle~~ compounds in marine systems? 2) ~~what are the general~~ What are the core pathway patterns that can be ~~condensed~~summarised? 3) ~~what process options do the general pathway patternsinclude? Answering~~ Which processes, pools and agents are included in the core pathway patterns? By answering the first two questions, we obtain an OC pathway ~~model in its most general state~~concept with core structure of marine OC pathways. The last question allows us to ~~specify process options embedded in the pathways, which enhance the relatability and adaptability of the model to specific ecosystems. We finish by highlighting how our model complements existing concepts and could benefit research and society~~identify the processes, pools and agents embedded in these structures, which allow defining smaller-scale pathway patterns that can be adapted to specific research questions and marine systems. In the discussion, we describe as an application example how a definition of BCP can be translated into our concept, and discuss the add-ons of this representation.

2 ~~A general conceptual model of the marine organic carbon cycle~~Concept specifications

2.1 ~~Qualitative model framework~~

Given that we ~~conceptualize~~ conceptualise only the OC pathways ~~, inorganic carbon (IC) is only an intermediate step within our concept. Therefore,~~ (for a definition of relevant terms of the concept, see Table 1), we do not resolve carbonate and alkalinity interactions, and ~~we~~ do not display marine carbonate systems ~~such as coral reefs within our model~~within our concept.

~~We subdivide OC if the processes or pathways considered are specific to different OC species. In such cases, we distinguish particulate organic carbon (POC), living and non-living OC with sizes larger than 0.7 mm comprising aggregates and marine snow; dissolved organic carbon (DOC), defined as non-living carbon larger 0.22 mm; and volatile organic compounds (VOCs), such as dimethyl sulphate and methane. In~~ In addition, we ~~separately consider recalcitrant DOC (rDOC), defined here as DOC that is remineralized on time scales between 1.5 and 40,000 years, as opposed to DOC with a turnover time of minutes to weeks (Hansell 2013). We consider rDOC separately from DOC because rDOC is associated with a different set of processes than more labile forms of DOC and is considered the only form of OC that accumulates in the water column in quantities relevant to~~

~~the climate system (Jiao et al., 2010, 2011). We also include dissolved inorganic carbon (DIC). Whilst this DIC pool consists of various IC species, we do not distinguish them within our model.~~

~~In addition, we~~ focus on OC that remains within the marine system~~—~~, i.e. ~~,~~ the water column plus upper sediment that still interacts with the water column. Therefore, we only consider pathways that start as OC within the surface waters, acknowledging that this initial position (Table 1) is an artificial construct since cycles do not start somewhere and marine carbon may originate from terrestrial ~~runoff~~run-off, atmospheric deposition, or photosynthesis. As soon as an OC pathway leaves ~~this~~ the marine system, either into the atmosphere or into deeper sediment layers that do not interact with the water column, we ~~no longer consider~~ not detailed describe them within this ~~model~~ concept and assign them to ~~“open”~~ ’open’ loops. These ~~“open”~~ loops close too, but outside our focal marine system.

~~As long as the particle does not leave the marine system, it~~ It is irrelevant for our ~~model~~ concept how much time ~~the particle~~ an organic compound spends on the ~~path~~pathway. As such we are not interested in resolving the time scales of ~~these pathways and do not resolve~~ pathways and the accumulation of OC, standing stocks, in the system. ~~For example, we consider carbon that~~ Thus, it is the same pathway when OC remains in the standing stock of a whale throughout its life and is ~~remineralized at the water surface after~~ respired at the surface right before its death and ~~carbon that~~ when OC is respired by a whale at the water surface immediately after being consumed~~as the same pathway~~. However, we do implicitly include time scales of pathways, since we consider different spatial scales closely connected to temporal scales (Dickey, 1990).

~~Since this is a qualitative model, we are also~~ We provide a qualitative concept and are not interested in the amount of carbon that passes through the different pathways or ~~their probabilities~~ the probabilities of OC to do so. We consider all pathways to being equally possible by assuming that each ~~particle~~ carbon compound finds the conditions for each ~~different~~ pathway at the same time. ~~That is, our system can provide the necessary processes and conditions for each path, i.e. our~~ For instance, the system provides suitable consumers that reduce sinking of material and at the same time a ~~delay of consumers that favour~~ spatio-temporal mismatch with consumers that favours sinking.

2.0.1 ~~What are the different pathways for an organic carbon particle in marine systems?~~

~~Our conceptual model~~ For identifications of pathway patterns on a higher resolution (Sect. 3.2), we operationally subdivide OC into different pools, if the pathways involve OC of different size, volatility and lability. In such cases, we distinguish particulate organic carbon (POC), embedding living and non-living OC with sizes larger 0.2 μm (Kharbush et al., 2020), aggregates and marine snow; dissolved organic carbon (DOC), defined as non-living carbon smaller 0.2 μm (Kharbush et al., 2020); and volatile organic compounds (VOCs), such as dimethyl sulphate and CH_4. In addition, we separately consider recalcitrant (or refractory) DOC (rDOC), defined here as DOC that is remineralised on time scales between 1.5 and 40,000 years for semi-labile to ultra-refractory (Hansell, 2013), as opposed to 0.001 years for labile DOC (Hansell, 2013). We consider rDOC separately from DOC because rDOC is considered the only form of OC that accumulates in the water column in quantities relevant to the climate system (Jiao et al., 2010, 2011). We also include dissolved inorganic carbon (DIC) as an intermediate pool. Whilst this DIC pool consists of various inorganic (IC) molecules, we do not distinguish them within our concept.

3 A (visual) concept of the marine organic carbon cycle

3.1 Main patterns of the marine organic carbon cycle

Our concept is based on the comparison and condensation of possible OC pathways using state-of-the-art knowledge. To this end, we ~~have established~~ generate a base pathway ~~model~~ concept (see Supplement A) based on a ~~non-exclusive~~ non-systematic literature review. In this base pathway ~~model~~concept, we collect and map the different pathways that an OC ~~particle~~ compound can "go" within the marine carbon cycle. The different pathways in this ~~model~~ concept are defined by *sequences of processes* (Table 1), such as sinking and ~~remineralization, and lead either outside the marine system,~~ remineralisation, and head into the sediment~~or~~, the atmosphere, or back to the initial position in the surface ~~waters. The base pathway model is accessible (will be uploaded on Pangaea and is now added as supplement) and allows the identification and comparison of different pathways. We use this model in the next step to condense the identified pathways and define the general pattern~~ water. We use the base pathway concept to compare the mapped pathways and condense their core structures into generally applicable core patterns of OC pathways.

3.1.1 ~~What are the general pathway patterns that can be condensed?~~

~~As a result of condensing pathways, we obtain a general OC cycling model showing different general~~ The core pathway patterns, e.g. closed loops, ~~without showing any processes~~are stripped of any processes, pools or involved agents (organisms, ~~OC species,~~ etc.). We add this information in the next step (Sect. ~~??).~~ 3.2) allowing a higher resolution of pathway patterns.

Table 1. Definitions and examples of relevant terms based on three individual pathways.

Mapped example pathways in the base pathway concept	**Pathway 1**: Phytoplankton DOC exudation → Bacterial remineralisation → DIC uptake by phytoplankton **Pathway 2**: Zooplankton grazing on phytoplankton → Zooplankton respiration → DIC uptake by macrophytes **Pathway 3**: Phytoplankton respiration → DIC outgassing

Term	**Definition**	**Example**
Space	Spatially bounded volumes with different environmental conditions.	Surface layer space (SLS), Atmosphere space (AS)
Initial position	Abstract start position of the OC pathways.	OC in the surface space
Process	A self-contained change in the properties or position of carbon. A process is embedded in a path segment.	Phytoplankton DOC exudation, Zooplankton grazing on phytoplankton, Bacterial remineralisation, Zooplankton respiration, Phytoplankton respiration, DIC uptake by phytoplankton, DIC uptake by macrophytes, DIC outgassing
Path segment	The condensed function of processes that have the same general functionality. They are defined by the abstracted result of the processes, independent of species involved, etc. Path segment comprise all globally applicable processes having the same general functionality.	OC size change, POC consumption, OC remineralisation, DIC uptake by primary producers, DIC exit
Pathway	A sequence of processes or path segments. Each pathway is embedded in a pathway pattern. Although pathways can be described by sequences of general path segments, they always represent individual structures and not condensed ones.	Pathway 1: OC size change → OC remineralisation → DIC uptake by primary producers Pathway 2: POC consumption → OC remineralisation → DIC uptake by primary producers Pathway 3: OC remineralisation → DIC exit
Pathway patterns	Pathway patterns are superordinate structures of pathways. They are defined by the sequence of critical path segments and the involved spaces. Sequences of critical path segments describing a pathway pattern must be true for all pathways within the pathway pattern. Syntax: Path segment [Space]	Pathway pattern 1: OC remineralisation [SLS] → DIC uptake by primary producers [SLS] Pathway pattern 2: OC remineralisation [SLS] → DIC exit [AS]
Closed loops	Closed loops are a subordinate classification of pathway patterns (sub-pattern), comprising all pathways returning to the initial position. Each closed loop can be described by the sequence of critical path segments and the involved spaces. Sequences of critical path segments describing a loop must be true for all pathways of that loop.	Surface layer remineralisation loop (SLRL): OC remineralisation [SLS] → DIC uptake by primary producers [SLS]

Marine OC cycle	The marine OC cycle consists of all closed loops.

To explain how to compare ~~pathways and condense~~ and ~~define general~~ condense pathways and define core patterns of the OC cycle, we use ~~a city~~ as an analogy a town with a sandbank ~~beach~~ separated by a lagoon~~as an example. People~~. The inhabitants of the town regularly visit the sandbank to spend their evenings ~~on the beach(under the given hygiene conditions, of course). A street map of the city~~at the beach. A route planner, comparable to ~~a base pathway model~~our basic pathway concept, shows 100 ~~different pathways that all~~ individual pathways that end at the beach. ~~The pathways differ or resemble each other to some extent, but are all different comparing the whole sequence of processes, the streets used.~~ These pathways are similar, but all differ in the overall sequence of routes and vehicles used.

However, there is ~~one denominatorthat all the pathways have in common. It is essential to cross the lagoon to reach the beach.~~ a common denominator. To reach the beach, the lagoon must be crossed. This condition is independent of the method of crossing. People get to the sandbank via different processes, such as taking the public ferry or a private boat. The outcome 'people reach the sandbank' and the general functionality 'crossing the lagoon' of these processes coincide. Therefore, we define 'crossing the lagoon' as a path segment (*summarised function of the involved processes with the same general functionality*, Table 1). This path segment is critical to all pathways. If the crossing is not possible, no one will ~~arrive at~~ reach the beach. All pathways ~~depend on this part, being also the minimum (simplest) path~~ can thus be generally described by this critical path segment, the bottleneck.

~~Analogous to this example, we use the base pathway model to identify critical parts of the mapped pathways. We start by identifying all pathways that form a loop and end in the initial position in the surface layer. By comparing their sequences of processes, we identify critical parts,~~ However, this very general description does not capture higher resolution structures. At higher resolution, some pathways to the beach have not one but several critical path segments. We describe these by a sequence of critical path segments. To stay with the lagoon analogy: People who do not live on the harbour front have to use one of three routes to reach the harbour (functionality: 'reach the harbour'). Their pathways can be described minimally by the sequence of 'reaching the harbour' and 'crossing the lagoon', while the pathways of people living at the harbour front can be minimally condensed to and described by the smallest pathway, the critical path segment 'crossing the lagoon'.

From these two distinct sequences of critical path segments, ~~of these pathways. We define a path segment as the *condensed function of the involved processes, which have the same general functionality*, although they may differ e. g. in their spatiotemporal scales (Table 1). In our lagoonexample, "~~different pathway patterns can be defined. The most general and superior pattern is the 'entire city-beach route' pattern defined by the path segment 'crossing the lagoon', which is common to all pathways. That sequence is the minimum sequence shared by all pathways and the highest-level pattern. For the subordinate patterns, a distinction is made between a 'harbour front-beach route' pattern (crossing the lagoon) and a 'behind the harbour-beach route' pattern (reaching the harbour and crossing the lagoon~~", with the outcome "people reach the sandbank", which includes processes such as taking a public ferry or a private boat, is the condensed function and hence critical path segment of pathways leading to the sandbank. Most pathways have not one but several critical path segments. We, therefore, describe them by a~~

~~sequence of~~). The resolution is a matter of choice. One could even increase the resolution, find commonalities between the routes in the rest of the city and define subordinate route patterns. However, if one assumes that the rest of the city has a very diverse and complicated road network, the description of the two subordinate patterns may be sufficient as a resolution to define pressure points and bottlenecks when, for example, construction works block some of the three routes to the harbour.

Similarly, we identify critical path segments ~~. To stay with the example of the lagoon: The pathways people take to get to the sandbank and from there back home can be minimally described as~~ of the mapped OC pathways in the basic pathway concept (see Supplement B for a schematic of the methodological steps). One pathway pattern that immediately catches the eye are pathways that loop inside or outside the marine system. We define these patterns as closed and ’open’ loops. We focus on the closed patterns and identify all pathways that loop and end at the starting position in the surface layer. We compare their process sequences and the ~~sequence of two path segments - crossing the lagoon in one direction and crossing the lagoon in the other direction.~~ general functionality of the processes involved. Based on these comparisons, we define critical path segments and minimum sequences of critical path segments to condense all pathways that belong to closed loops.

For the OC cycle, we identify six critical path segments necessary to define the minimal sequences of all ~~closed OC pathways in our general pattern model (Figure ??): OC position change (A), Formation of rDOC (B), rDOC conversion to more labile DOC (C), OC remineralization (D), DIC upward position change (E) and DIC uptake by primary producers (F).~~ OC pathways that belong to closed loops (Figure 1): *OC position change (A), Formation of rDOC (B), rDOC conversion to DOC (C), OC remineralisation (D), DIC upward position change (E) and DIC uptake by primary producers (F)*. We recognise that not including the rDOC-related path segments would further reduce the number of path segments and loops. However, as described earlier, rDOC is relevant to the climate system and is related to very different phenomena and processes. So although it may not technically be the minimum solution, it is the minimum solution that still captures relevant differences.

~~——Table 1——~~

The path segments do not contain any temporal or spatial information. However, the spatial extent of ~~some path segments changes the properties of the pathway and the pathway pattern. To stay~~ path segments can change the pathway pattern. Staying with the lagoon ~~example~~analogy: The public ferry has two anchor points on the sandbank. It takes twice as long to get to the second stop. After work, during the week, people will use the closer anchor point, while at the weekend ~~,~~ both anchor points will be used, ~~following~~ depending on personal preferences. Since people do not regularly ~~go to~~ visit the second anchor point during the week, ~~bars at the second anchor point~~ the bars there only open at the weekend. Thus, the ~~way peopledistribute~~distribution of people, the opening hours of ~~local restaurants, and what governs the decision, temporal considerations~~ the local restaurants and the considerations that determine the decision, time constraints during the week versus preferences at the weekend, change. The ~~path segment "~~’crossing the lagoon~~" or the process "taking~~’ path segment or the ’use of the public ferry~~"~~’ process do not allow this differentiation. The same applies to the carbon path segments. For example, ~~whether the OC ends up in the sediment or the water column changes its ecosystem function~~ the function of carbon in the ecosystem (e.g. as a food source for benthic organisms), the environmental conditions that determine its pathway (e.g. bioturbation) ~~,~~ and the time it takes for ~~the~~ carbon to return to the surface layer (e.g. years ~~versus decades)~~ or decades) change depending on whether it ends up in the sediment or in the water column. However, the OC position change segment (A) does not ~~resolve~~ provide information on whether the transport ends up in the water column or in the sediment.

~~**Term Definition Example Initial position** Abstract start position of the OC pathways. OC in the surface **Process** A self-contained change in the properties or position of carbon. A process is embedded in a path segment. Bacterial remineralization **Path segment** The condensed function of processes that have the same general functionality. Processes: Bacterial remineralization, Fish respiration They are defined by the outcome of the processes, independent of species involved, etc. Path segment: OC remineralization (transformation from OC to IC) **Pathway** A sequence of processes or path segments returning OC to its initial position or leading outside the marine system. Sequence of processes: Phytoplankton DOC exudation, Bacterial remineralization, Mixing by autumn storm, Uptake by phytoplankton A pathway is embedded in a loop. Sequence of path segments: OC size change, OC remineralization, DIC position change, DIC uptake by primary producers **Space** Spatially bounded volumes with very different environmental conditions. Surface layer space (SLS) **Closed loop** A closed loop comprises all pathways returning to the initial position. It can be described by the sequence of critical (and optional) path segments and the involved spaces. Pathway 1: Phytoplankton DOC exudation, Bacterial remineralization, Mixing by autumn storm, Uptake by phytoplankton for photosynthesisSequences of critical path segments describing a loop must be true for all pathways of that loop. Pathway 2: Zooplankton grazing on phytoplankton, Fish feeding on zooplankton, Fish respiration providing IC, Uptake by macrophytes for photosynthesisOptional path segments comprise processes that are not required to produce a certain outcome.*Sequence of critical path segments plus space*: OC remineralization (SLS), DIC uptake by primary producers (SLS) A closed loop is a pathway pattern and is embedded in the OC cycle.Closed loop: Surface remineralization loop **Open loop** An open loop comprises all pathways that lead outside the marine system. Open loop: Atmospheric IC loop **Process options** All globally applicable processes embedded in a path segment. Path segment: OC remineralization Process options: Respiration by primary producers, Bacterial remineralization, POC consumer remineralization, Photoremineralization **Pathway pattern** Pathway patterns are open and closed loops that can be defined based on differences and commonalities of involved pathways. Closed and "open" loops, e.g. remineralization and rDOC loops **Marine OC cycle** The marine OC cycle consists of all loops (pathway patterns) that close within the marine system. The combination of closed remineralization and rDOC loops.~~

~~Therefore, we add spatial informationby defining four spaces, spatially bounded~~ Hence, pathway patterns cannot be unambiguously defined without spatial information. To systematically add this information, we define five spaces, volumes with distinctly different environmental conditions and processes~~(Table 1). Following~~ . After general considerations of the ocean layers, the ~~surface space (SLS)~~ *surface layer space (SLS)* encounters sufficient light to support ~~photosynthesizing~~ photosynthesising organisms and primary production. Seasonal and continuous mixing counteract material loss and keep matter ~~near remineralisers.The water column space (WCS),~~ close to remineralisers.In the *water column space (WCS)* below the well-mixed layer, ~~encounters less frequent, slower, or very rare mixing, depending beside~~ mixing occurs less frequently, more slowly or very infrequently, depending among other things on the water depth (DeVries et al., 2012). Matter ~~needs~~ takes more time to ~~reach the surface again and can~~ resurface and may escape remineralisers due to changing positions or its ~~refractory~~ recalcitrant or degraded character (Baker et al., 2017). In the ~~upper sedimentary space (USS), remineralisers remineralize even highly degraded matter~~ *upper* *sedimentation space (USS)*, remineralisers also remineralise highly degraded material as it remains in their vicinity longer than in the water column (Middelburg, 2019). The ~~lower sedimentation space (LSS) is mostly~~ *lower sedimentary space (LSS)* is largely abiotic and undisturbed and allows lithification processes. In addition, we define the *atmospheric space (AS)* above the marine system. Users of the ~~model can modify~~ concept can change the spaces, e.g. by partitioning the water column space, resulting in a different number of closed loops. However, ~~any~~ if the minimum number of closed loops is to be conceptually described, each coastal system must be represented by at least two spaces (SLS and USS) ~~,~~ and pelagic marine systems by at least three spaces (SLS, WCS and USS). In the following we represent path segments with the corresponding letters and in square brackets behind them the spaces in which the associated processes end or take place (syntax example: A [WCS], OC position change ending in the WCS).

We ~~now~~ define five closed OC loops (Figure ~~??~~ 1 and Table 2) by their unique combinations of 1) their sequences of critical path segments and 2) the involved spaces. The pathway patterns ’closed loops’ can be divided into two sub-pattern: *closed remineralisation and rDOC loops.*

We define three ~~remineralization~~ remineralisation loops: a ~~surface remineralization loop (SRL), a water column remineralization loop (WCRL)~~*surface layer remineralisation loop (SLRL)*, a *water column remineralisation loop (WCRL)*, and an ~~upper sediment remineralization loop (USRL) (~~*upper sediment remineralisation loop (USRL)* (Table 2). All three loops include pathways on which OC is ~~remineralized~~ remineralised to DIC (~~path segment~~ D), which is taken up by primary producers in the SLS (F [SLS]). The path segments ~~"~~’OC position change~~"~~’ (A) and ~~"~~’DIC upward position change~~"~~’ (E) as well as the space in which the OC is ~~remineralized distinguish the remineralization~~ remineralised distinguish the remineralisation loops. The WCRL includes pathways that lead to a downward position change of OC into the WCS, ~~remineralization~~ remineralisation in the WCS, and an upward position change of DIC into the SLS, where it is taken up (WCRL: A [WCS] → D [WCS] → E [SLS] → F [SLS]). An exemplary WCRL pathway involves OC uptake by zooplankton in the SLS, its migration into and respiration in the WCS, and the upward mixing of the resulting DIC into the SLS where it is taken up by primary producers (WCRL: A [WCS] → D [WCS] → E [SLS] → F [SLS]). If zooplankton respiration occurs in the SLS, the pathway belongs to the ~~SRL~~SLRL (SLRL: D [SLS] → F [SLS]). We define the USRL analogous to the WCRL, but with ~~remineralization~~ remineralisation taking place in the USS (USRL: A [USS] → D [USS] → E [SLS] → F [SLS]).

~~—Figure 1—~~

The two path segments ~~"~~’Formation of rDOC~~"~~’ (B) and ~~"~~’rDOC conversion to ~~more labile DOC"~~ DOC’ (C) in the SLS are part of the second ~~set~~ sub-patterns of closed loops, the rDOC loops (Figure ~~??~~ 1 and Table 2). The rDOC loops describe the change of labile OC to more recalcitrant forms, its persistence in the system, and its return to bioavailable forms in the SLS. We differentiate a ~~short rDOC loop (SrDOCL)~~*short rDOC loop (SrDOCL)*, rDOC that accumulates in the surface waters on time scales of human life, and a ~~long-term rDOC loop (LrDOCL)~~*long-term rDOC loop (LrDOCL)*, rDOC that persists in the entire water column on geological time scales. The short-term rDOC loop is defined by the ~~“~~’Formation of rDOC~~”~~’ (B) and ~~“~~’rDOC conversion to ~~more labile DOC”~~ DOC’ (C) in the SLS (SrDOCL: B [SLS] → C [SLS]), while the rDOC long-term loop additionally comprises the path segment ~~“~~’OC position change~~”~~’ (A), with accumulation mostly or even entirely in the WCS (~~Figure ??~~LrDOCL: B [SLS] → A [WCS/USS] → A [SLS] → C [SLS] or A [WCS/USS] → B [WCS/USS] → A

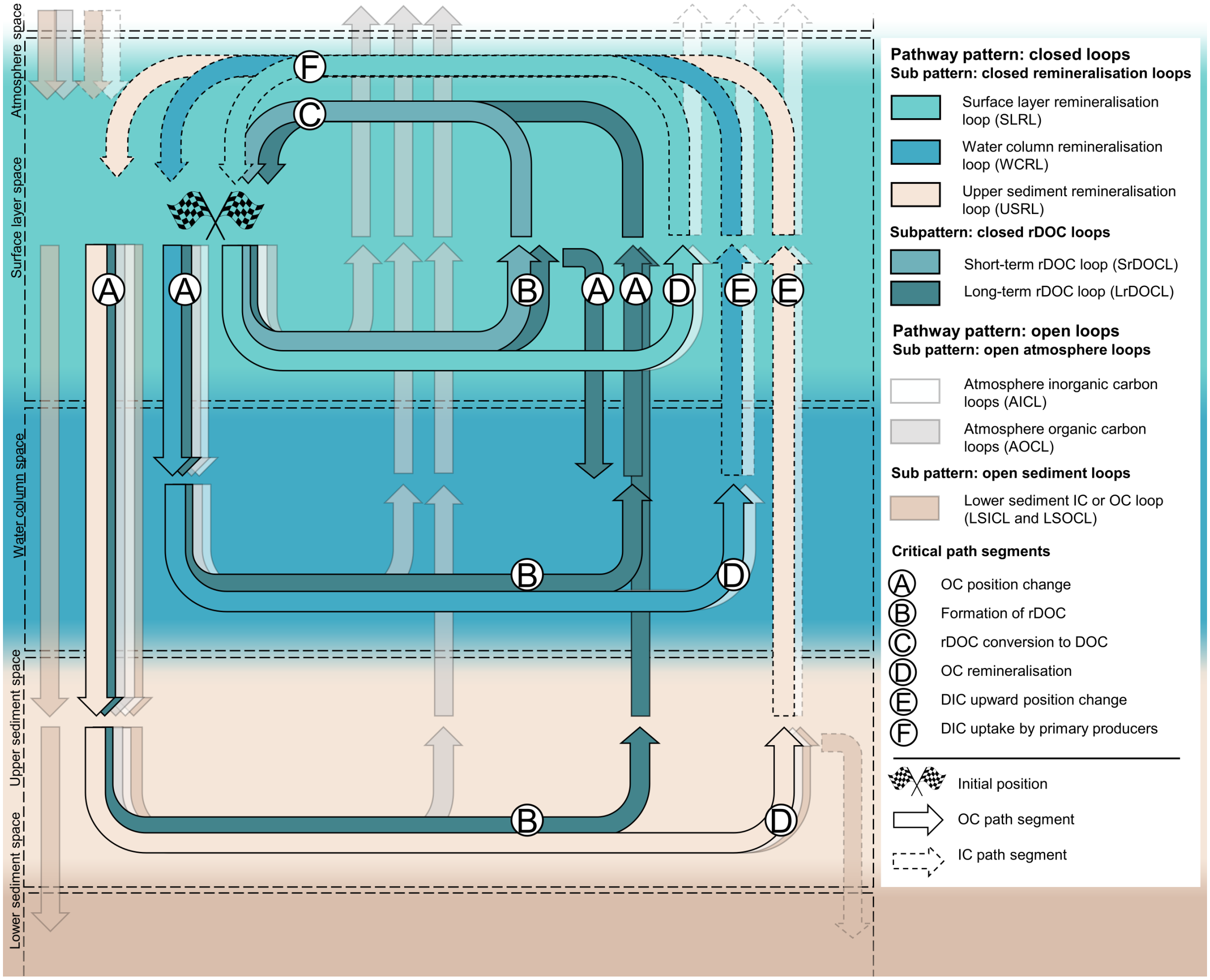


Figure 1. General pathway patterns of OC cycling with three closed ~~remineralization~~ remineralisation and two closed rDOC loops, the spaces and the involved critical path segments. ~~“~~’Open~~”~~’ loops are only displayed with transparent colours as they are not our focus.

[SLS] → C [SLS]). In contrast to the ~~remineralization pathways~~remineralisation loops, we do not explicitly consider a rDOC loop in the upper sediment, as the temporal scales of rDOC produced there or in the water column overlap to our knowledge. Therefore, the long-term rDOC loop includes rDOC production in the USS alongside its transport to the WCS.

All loops ~~include~~ comprise a continuum of processes ~~that are optional and thus belong~~ belonging to non-critical (optional) path segments. ~~Optional path segments do not change the outcome but can still alter the spatiotemporal scales of the pattern.~~ For example, the ~~SRL includes carbon that is remineralized and taken up by primary producers in the SLS. This definition ultimately means that OC, which is~~ SLRL includes OC that is transported and processed below the SLS but ~~returned~~ returns to the SLS as OC to be ~~remineralized and taken up, is also part of the surface remineralization loop~~remineralised and used by primary producers (SLRL: A [WCS] → A [SLS] → D [SLS] → F [SLS]). Another example is rDOC, which is part of the ~~WCS remineralization loop if remineralized in the WCS~~ WCRL when remineralised in WCS (WCRL: B [SLS] → A [WCS] → D [WCS] → E [SLS] → F [SLS]). Only rDOC that reaches the surface and is converted back ~~to~~ into more bioavailable forms in the SLS belongs to the LrDOCL ~~.~~ (LrDOCL: ... A [SLS] → C [SLS]). Because of the climatic importance of rDOC, we distinguish rDOC from DOC as described ~~in the model framework~~before. Technically, however, rDOC represents ~~an intermediate~~ a "storage" ~~step of remineralization~~ intermediate step of remineralisation or open loops. ~~Users of the model can freely combine optional~~ For the minimal description of the loops, the sequence of critical path segments is sufficient and unambiguous. However, users of the concept can combine additional (optional) path segments along the sequence of critical path segments to define individual pathways or sub-pathway patterns.

~~Two~~ In this case, two separation rules apply to avoid ~~double-counting~~double counting when assigning pathways with optional path segments to one of the parent loops. The first rule states that the space of the ~~last remineralization~~ ultimate remineralisation before entry and reuse in the SLS defines the ~~remineralization~~ remineralisation loop. OC that is ~~remineralized~~ remineralised several times in different spaces is part of the ~~SRL if remineralized~~ SLRL if it is last remineralised in the SLS ~~the last time~~ before uptake by primary producers in the SLS. ~~Analogous~~Similarly, OC belongs to the WCRL or USRL if it is ultimately ~~remineralized~~ remineralised in the WCS or USS. The second rule states that rDOC leaving the surface or produced below the SLS always belongs to the LrDOCL (Table 2).

~~—Table 2—~~

Although we focus on the closed loops, it is noteworthy that there are parallel ~~“open”~~ ’open’ loops of carbon that close outside the marine systems, e.g. in the atmosphere. ~~There are three open-loop patterns. The openIC atmosphere loops~~We define four sub-patterns of ’open’ loops. The *atmosphere IC loops (AICLs)* describe the outgassing of DIC, produced in different spaces, to the atmosphere. The ~~open OC atmospheric loops~~ *atmospheric OC loops (AOCLs)* comprise the exit of marine OC, marine aerosols, volatile organic compounds (VOCs), and ~~methane~~ CH_4 through the surface to AS, e.g. via fish predation by birds or outgassing. The ~~open long-term sediment loop describes~~ *lower sediment IC and OC loops (LSOCL and LSICL)* describe the burial and lithification of carbon in the LSS, entering geological cycling.

3.1.1 ~~What process options do general pathway patterns comprise?~~

~~After defining general pathway patternsbefore~~

3.2 Embedded processes, pools and agents

Having defined the superordinate pathway patterns, we now add and describe global ~~process options~~ processes, pools and agents embedded in each path segment (Figure ~~??~~ 2 and Table 3). This addition allows ~~applying the model to smaller-scale ecosystems, relating existing concepts to our concept, and demonstrates how to add different processes and agents to the model~~to define pathway patterns with higher resolution and to link and complement our concept with existing ones. Global in this context means that the process mechanisms are globally valid, but that the frequency, extent, ~~initialization, and agents~~

Table 2. Summary of sequences of critical path segments and spaces defining the closed loops. The separation rule only comes to play, if additional (at this resolution level optional) path segments are added ~~, see description of~~ to describe a sub-pattern or individual pathways. Spaces in square brackets indicate the ~~separation rules~~spaces where the processes happen or end. Bold spaces are the ~~major~~ naming spaces of this loop. Non-bold spaces are intermediate or "walk-through" spaces. Loops: Surface ~~remineralization~~ layer remineralisation loop (~~SRL~~SLRL), Water column ~~remineralization~~ remineralisation loop (WCRL), Upper sediment ~~remineralization~~ remineralisation loop (USRL), short and long-term rDOC loop (SrDOCL, LrDOCL). Spaces: Surface layer space (SLS), Water column space (WCS) and Upper sediment space (USS). Path segments: OC position change (A), Formation of rDOC (B), rDOC conversion to ~~more labile~~ DOC (C), OC ~~remineralization~~ remineralisation (D), DIC upward position change (E) and DIC uptake by primary producers (F).

Closed Loops	Sequence of critical path segments plus spaces	~~Involved spaces~~Separation rule
~~SRL~~ SLRL	D ~~, F~~ [**SLS**] → F [**SLS**]	Ultimate ~~remineralization~~ remineralisation in SLS before F
WCRL	A ~~, D , E , F SLS,~~ [**WCS**] → D [**WCS**] → E [SLS] → F [SLS]	Ultimate ~~remineralization~~ remineralisation in WCS before E and F
USRL	A ~~, D , E , F SLS, WCS,~~ [**USS**] → D [**USS**] → E [SLS] → F [SLS]	Ultimate ~~remineralization~~ remineralisation in USS before E and F
SrDOCL	B ~~, C~~ [**SLS**]→ C [**SLS**]	Formation of rDOC in SLS and no A
LrDOCL	B ~~, A , A , C or A, B, A, C~~[SLS] → A [**WCS/USS**]→ A [SLS] → C [SLS] or A [**WCS/USS**]→ B [**WCS/USS**]→ A [SLS] → C [SLS]	~~SLS, WCS, USS~~Formation of rDOC in SLS with A or Formation of rDOC in WCS or USS

~~driving~~ initialisation and triggers of these processes differ. We focus on non-anthropogenic processes and the previously defined critical path segments. This means that, for example, upward position changes of POC or DOC are not resolved.

Two of ~~three remineralization loops include~~ the three remineralisation loops include the path segments OC position change (A) and DIC upward position change (E). Processes belonging to path segments ~~related to the position change of OC or IC. Processes that belong to the path segments~~ A and E ~~are either biotic or abiotic and comprise~~ include sinking, diffusion ~~, and advectionas well as~~ and advection, and direct and indirect biota-induced ~~position change (Figure ?? and Table 3)~~transport.

~~Particulate matter that sinks~~ Organic compounds that sink from one space in the water column ~~into another is mostly~~ to another are usually either large or dense~~and/ or escapes~~ , or escape consumption or dissolution in the upper space (De La Rocha, 2006). ~~Burial~~ Sedimentation and compaction by subsequent matter is the analogous process within the sediment-water interface and ~~the~~ sediment. Matter is ~~buried and compacted by weight deposited above it and "sinks"~~ compacted by the weight deposited over it and "sinks" as it loses volume. Sinking ~~is always downward directed (Boyd et al., 2019) and restricted~~ and sedimentation always act downwards and are confined to POC. ~~Gravitational induced~~ Gravity-induced sinking (and ~~burial~~sedimentation) is thus part of ~~each downward-pointing~~ any path segment A of POC (Figure ~~?? and Table 3~~2).

~~DOC can diffuse in every direction following large~~

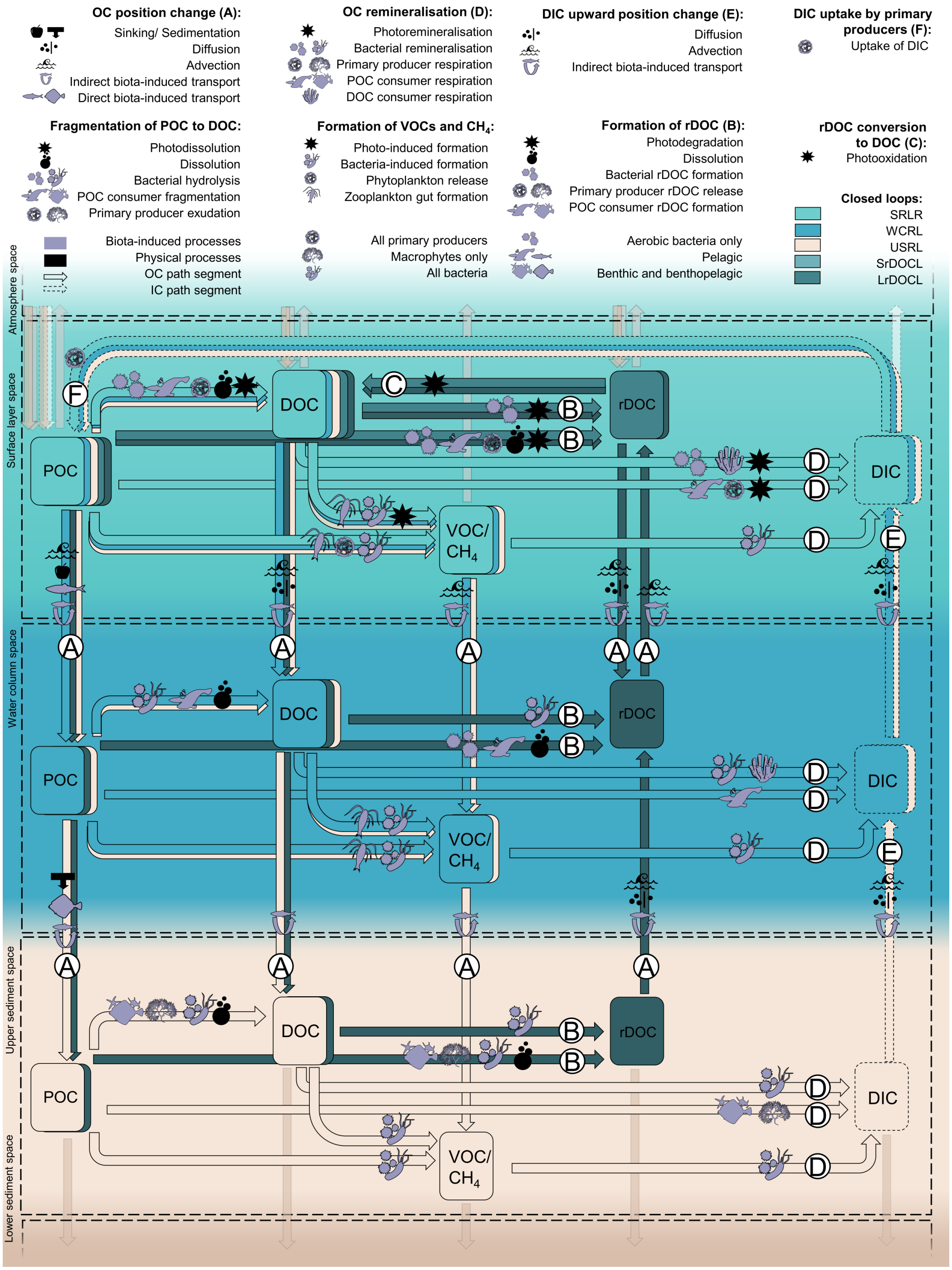


Figure 2. OC pathway patterns with critical path segments (A-F), spaces and embedded processes, C pools and involved organisms. 'Open' loops are indicated by transparent colours. Organisms can be agents (producing DOC by sloppy feeding) and part of the carbon pool (consumers as part of POC respire DIC) at the same time. Optional fragmentation processes and pathways for DOC and VOCs/ CH_4 are included. As such these pathways are not marked with capital letters.

(R)DOC and DIC potentially diffuse in all directions, following large- or small-scale gradients in the water column, at the water-sediment ~~boundary layer, and pore-waters in the~~ interface and in the pore water of the sediment. We ~~use present-day decreasing DOC concentrations with water depth (Hansell, 2013) , higher sedimentary DOC concentrations compared to overlying waters (Burdige et al., 1999), and higher DIC concentrations at the surface compared to the deep sea (Oka, 2020) . Hence,~~ assume that (r)DOC concentrations decrease with depth (Hansell, 2013) but are higher in the sediment than in the overlying water (Burdige et al., 1999; Rowe and Deming, 2011) and that DIC concentrations increase with depth (Oka, 2020) . Following these gradients, (r)DOC diffuses downwards in the water column and upwards ~~within and from the sediment since consumption cannot cope with production (Rowe and Deming, 2011) (path segments A , E in Figure ??) . DIC diffuses upwards in A and E (Figure ??).~~ in and out of the sediment (A of (r)DOC in 2) and DIC always diffuses upwards (E). The upward diffusion of non-refractory DOC from the sediment is not considered as it is part of a non-critical path segment.

Other physically induced position changes are related to water or sediment mass movements based on advection. These include large-scale upwelling and downwelling ~~patterns~~water movements, seasonal mixing, wind-induced turbulence and eddies, and storm-induced resuspension. Advection is globally applicable although its direction, magnitude, and frequency vary. The advection-induced position change occurs in all path segments A and E~~(Figure ??)~~. Advection does not act downwards into the sediment but upwards in the form of resuspension. Resuspension is only included for rDOC and is limited to the upper part of the sediment, as physical perturbation do not commonly reach below 10 cm (Boudreau, 1998; Bunke et al., 2019).

Biota-induced ~~position changes involve~~ transport involves the direct transport of OC in the living tissue of migrating organisms (e.g. a fish feeds in the SLS, migrates down, and dies in the WCS) as well as the internal flux of OC in organisms that span different spaces (e.g. macrophytes ~~(Middelburg, 2019)~~ living in the SLS and the USS (Middelburg, 2019)). Organisms change their position in the water column (e.g. via diel vertical migration (Steinberg et al., 2002)) or in the sediment (e.g. via burrowing (Middelburg, 2019)) and produce faecal pellets or die after the position change. The result of direct biota-induced position change is POC of all sizes, e.g. living organisms and roots, faeces, and carcasses. Direct biota-induced position change works in all directions and is involved in all ~~critical path segments of~~ path segments A of POC~~(Figure ??)~~.

Indirect biota-induced ~~position change~~ transport comprises biogenic turbulence (Kunze et al., 2006; Huntley and Zhou, 2004), and induced drift, which describes the transport of substances that adhere to the bodies of swimming organisms (Katija and Dabiri, 2009). Indirect biota-induced position change in the sediment is related to ~~inter alia~~ among others bioturbation (Berke, 2010), associated with sediment reworking and resuspension, and bioirrigation (Kristensen et al., 2012), which leads to inflows of ocean water into the sediment. Indirect biota-induced position change works in all directions and is involved in all ~~critical~~ path segments of A ~~and E~~ for (r)DOC and POC and E in the water column and the sediment~~(Figure ??)~~.

The next ~~group of processes belongs~~ processes belong to the path segment ~~remineralization of OC~~ OC remineralisation (D). We define ~~remineralization~~ remineralisation as the provision of DIC based on OC and restrict it to the spaces above the LSS, assuming that ~~remineralization~~ remineralisation in the LSS is negligible.

~~Bacteria and archaea remineralize DOC in~~ Light-induced photoremineralisation, the only physically induced remineralisation, directly oxidises DOC and POC to IC (Mopper and Kieber, 2002; Mayer et al., 2009) and works only in the SLS. We include this process in D in the SLS.

Table 3. Processes embedded in the critical path segments. Italic C forms are products of the processes. Processes end or take place in the spaces in square brackets in the loop syntax.

OC position change (A)

Process	**Loop syntax**	**Process description**	**Pools**	**Organisms**	**Directions**
Sinking	WCRL: A [WCS] LrDOCL: A [WCS]	Gravitational sinking	POC		Downwards
Sedimentation	USRL: A [USS] LrDOCL: A [USS]	Sedimentation of sinking matter	POC		Downwards
Diffusion	WCRL: A [WCS]	Diffusion in the water column and pore waters	DOC		Downwards
	LrDOCL: A [WCS]		rDOC		Downwards, upwards
Advection	WCRL: A [WCS]	Up- and downwelling, mixing, turbulence, eddies	POC, DOC, VOCs, CH_4		Downwards
	LrDOCL: A [WCS]		POC, DOC, rDOC		Downwards, upwards
Indirect biota-induced transport	WCRL: A [WCS] USRL: A [USS]	Biota-induced turbulence, induced drift, digging, burrowing, bioirrigation, sediment reworking	POC, DOC, VOCs, CH_4	Swimming and moving species (pelagic, bentho-pelagic and benthic)	Downwards
	LrDOCL: A [WCS] LrDOCL: A [USS]		POC, DOC, rDOC		Downwards, upwards
Direct biota-induced transport	WCRL: A [WCS] USRL: A [USS]	Transport in living tissue or OC distribution in organisms spanning several spaces	POC	Swimming and moving species (pelagic, bentho-pelagic and benthic), organisms spanning several spaces (e.g. kelp)	Downwards
	LrDOCL: A [WCS] LrDOCL: A [USS]				Downwards, upwards

Formation of rDOC (B)

Process	**Loop syntax**	**Process description**	**Pools**	**Organisms**	**Directions**
Photo-degradation	SrDOCL: B [SLS] LrDOCL: B [SLS]	Degradation of labile to recalcitrant OC by UV light	DOC, POC, *rDOC*		

Dissolution	SrDOCL: B [SLS] LrDOCL: B [SLS] LrDOCL: B [WCS] LrDOCL: B [USS]	Dissolution due to sinking (enhanced by bacteria) or pore-water interactions	POC, *rDOC*		
Bacterial rDOC formation	SrDOCL: B [SLS] LrDOCL: B [SLS] LrDOCL: B [WCS] LrDOCL: B [USS]	Release of capsular material and rDOC under e.g. stress conditions	DOC, POC, *rDOC*	Bacteria, viruses	
Primary producer rDOC release	SrDOCL: B [SLS] LrDOCL: B [SLS] LrDOCL: B [WCS] LrDOCL: B [USS]	Release of rDOC	POC, *rDOC*	Phytoplankton and e.g. macrophytes	
POC consumer rDOC formation	SrDOCL: B [SLS] LrDOCL: B [SLS] LrDOCL: B [WCS] LrDOCL: B [USS]	Direct (excretion) or indirect release (e.g. via sloppy feeding) of rDOC	POC, *rDOC*	POC consumers (pelagic, bentho-pelagic and benthic)	

Conversion of rDOC to DOC (C)

Process	**Loop syntax**	**Process description**	**Pools**	**Organisms**	**Directions**
Photooxidation	SrDOCL: C [SLS] LrDOCL: C [SLS]	Photochemical conversion rDOC to DOC	rDOC, *DOC*		

OC remineralisation (D)

Process	**Loop syntax**	**Process description**	**Pools**	**Organisms**	**Directions**
Photo-remineralisation	SLRL: D [SLS]	Direct UV remineralisation	POC, DOC, *DIC*		
Bacterial remineralisation	SLRL: D [SLS] WCRL: D [WCS] USRL: D [USS]	Bacterial DOC (VOCs)-based respiration	DOC, VOCs, CH_4, *DIC*	Bacteria and archaea	
Primary producer respiration	SLRL: D [SLS] USRL: D [USS]	Respiration of primary producers	POC, *DIC*	Phytoplankton and e.g. macrophytes	
POC consumer respiration	SLRL: D [SLS] WCRL: D [WCS] USRL: D [USS]	Respiration of POC consumers	POC, *DIC*	POC consumers (pelagic, bentho-pelagic and benthic)	
DOC consumer respiration	SLRL: D [SLS] WCRL: D [WCS]	Respiration of DOC consumers	DOC, *DIC*	DOC consumers (filter feeders) excluding bacteria	

DIC upward position change (E)

Process	Loop syntax	Process description	Pools	Organisms	Directions
Diffusion	WCRL: E [SLS] USRL: E [SLS]	Diffusion in the water column and pore waters	DIC		Upwards
Advection	WCRL: E [SLS] USRL: E [SLS]	Down- and upwelling, mixing, turbulence and eddies, physical induced resuspension	DIC		Upwards
Indirect biota-induced transport	WCRL: E [SLS] USRL: E [SLS]	Biota-induced turbulence, induced drift, digging, burrowing, bioirrigation, sediment reworking and related processes	DIC	Swimming and moving species (pelagic, bentho-pelagic and benthic)	Upwards

DIC uptake by primary producers (F)

Process	Loop syntax	Process description	Pools	Organisms	Directions
Uptake of DIC	SLRL: F [SLS] WCRL: F [SLS] USRL: F [SLS]	Photosynthesis	DIC, *POC*	Phytoplankton and e.g. macrophytes	

Bacteria and archaea remineralise DOC in path segment D in every space above LSS~~(all path segments D of DOC, Figure ??),~~ , also under different oxygen conditions. The DOC is either of allochthonous origin (e.g. entering via riverine input (Dai et al., 2012)), or of autochthonous origin based on living or non-living POC. For instance, POC dissolves while sinking (Carlson and Hansell, 2015)~~)~~, is fragmented by turbulence (Ruiz, 1997; Briggs et al., 2020), or photodissolved (Mayer et al., 2006). Consumers directly reduce the size of organic POC by sloppy feeding on living and non-living POC (e.g. zooplankton coprorhexy (Lampitt et al., 1990)), by producing small metabolites ~~, and/~~either or by excreting DOC (Lampert, 1978). Indirectly, consumers fragment non-living POC by swimming or moving (Dilling and Alldredge, 2000). Further, primary ~~producer~~ producers exudate DOC in the water column (e.g. under nutrient-limited conditions or viral lysis (Azam and Malfatti, 2007)) and in the sediment (by macrophytes (Duarte and Cebrián, 1996)). Bacteria, for their part, hydrolyse POC to DOC (Smith et al., 1992) and additionally release DOC by viral lysis (Middelboe et al., 1996). ~~The conversion~~

The transformation from POC to DOC (arrows from POC to DOC, Figure ~~??) that occur before bacterial remineralization are optional path segmentssince not all OC~~ 2) that takes place before bacterial remineralisation are not part of the previously defined critical path segments, as not every OC compound needs to undergo one of these changes to be ~~remineralized.~~ remineralised.

However, considering only DOC-based pathways, the change in OC size from POC to DOC can be defined as a critical path segment for sub-patterns such as POC-DOC remineralisation loops.

~~—Figure 2—~~

In addition, bacteria can ~~oxidize VOCs and methane~~ oxidise VOCs and CH_4 (e.g. shown in Halsey et al. (2017)) (~~path segment~~ D of VOCs/ ~~methane in Figure ??~~CH_4 in Figure 1), produced via abiotic processes (photochemical degradation of DOC (Kieber et al., 1989)) and biogenic processes (production by phytoplankton (Lenhart et al., 2016) and zooplankton in anaerobic areas of their guts (Weber et al., 2019; Schmale et al., 2018)).

Another form of ~~remineralization~~ remineralisation is respiration by living organisms other than bacteria. Primary producers respire in the photic SLS. ~~Macrophytes additionally respire with their roots~~ The roots of macrophytes additionally produce DIC in the USS at night (Pedersen et al., 1995). Higher trophic levels, ~~POC-consumers~~ POC consumers (e.g. zooplankton and fish) and non-bacterial DOC consumers (e.g. suspension-feeding sponges at the sediment-water interface (Wooster et al., 2019)), also ~~remineralize by respiring. We, therefore, include remineralization~~ remineralise by respiration. Therefore, we include remineralisation by primary producers in path segments D in the SLS and USS~~and~~, respiration by DOC consumers in the SLS and WCS, and respiration by POC ~~(DOC)-consumers~~ consumers in all spaces with aerobic conditions above the LSS~~(Figure ??)~~.

~~OC carbon pathways with critical path segments (A-F), spaces and embedded processes, C species and involved organisms. Open loops are indicated by transparent colours. Organisms can be agents (producing DOC by sloppy feeding) and part of the carbon pool (consumers as part of POC respire DIC) at the same time. Optional fragmentation processes and pathways for DOC and VOCs/methane are included. As such these pathways are not marked with capital letters.~~

~~Light-induced photoremineralization, the only physically induced remineralization, directly oxidizes DOC and POC to IC (Mopper and Kieber, 2002; Mayer et al., 2009) and works only in the SLS. We include this process into path segment D in the SLS.~~

Once OC is ~~remineralized~~ remineralised to DIC, this DIC is transported by the above-described processes of position change to the SLS (~~path segment E~~ E [SLS]). Subsequently, primary producers take up the DIC for photosynthesis (~~path segment C~~F [SLS]) and close the ~~remineralization~~ remineralisation loops.

The rDOC loops include the formation of rDOC (B), the reconversion to DOC in the SLS (C), and, in case of the long-term loop, position change of OC (A). We present some of the involved abiotic and biotic processes, which have been reviewed e.g. in ~~Legendre et al. (2015)~~Legendre et al. (2015).

UV light can change the lability and increase ~~refractory~~ recalcitrant components of the DOC pool ~~(Benner and Biddanda, 1998; Hansell, 2~~ ~~(path segment B in the SLS~~via photodegradation (Benner and Biddanda, 1998; Hansell, 2013)(B [SLS]). Biota supply rDOC via successive microbial processing of DOC (Jiao et al., 2010, 2011), the release of capsular material by bacteria (Stoderegger and Herndl, 1998), bacterial hydrolysis of POC (Jiao et al., 2011), bacterial stress responses to low-labile DOC and unfortunate nutrient conditions (Stoderegger and Herndl, 1998), and successive consumption by higher trophic levels (Jiao et al., 2011). In addition, some phytoplankton directly exudates rDOC (Jiao et al., 2011). Both microbes and phytoplankton also release rDOC due to viral lysis of host cells (Jiao et al., 2011)~~(Figure ?? and Table 3)~~. In addition, processes from living and non-living

POC to DOC, e.g. dissolution, can lead to very diluted DOC that is not available for consumption and therefore ~~refractory~~ recalcitrant (Arrieta et al., 2015) (Figure ~~??~~2, arrow from POC to rDOC).

rDOC that stays in or returns to the SLS, via the position change processes described above (~~path segment A~~ A [SLS]), can be converted back to more bioavailable forms by ~~photodegradation/ photooxidation (path segment C in the SLS~~photooxidation (C [SLS]) (Kieber et al., 1989). We consider ~~other~~ pathways with other rDOC removal processes, such as direct ~~photooxidation~~ light-induced oxidation from rDOC to DIC (Shen and Benner, 2018), sorption of rDOC into POC (Hansell et al., 2009) and hydrothermal removal mechanisms in hydrothermal vents or the Earth's crust (Lang et al., 2006), as ~~optional path segments of either one of the open or the closed remineralization~~ parts of the closed remineralisation or 'open' loops. Once the rDOC is converted to DOC in the SLS, the rDOC loops are closed.

~~—Table 3—~~ ~~**Process Loops and(spaces Process description Involved C forms Involved organisms DirectionSinking/Burial**~~ ~~WCRL, USRL, LrDOCL (SLS, WCS) Gravitational sinking USRL, LrDOCL (WCS, USS)Burial by sinking matter~~ ~~**Diffusion**~~ ~~LrDOCL (SLS, WCS, USS) Diffusion in the water column and pore waters rDOC (DOC)Downwards, upwards (lateral)~~ ~~**Advection**~~ ~~WCRL, USRL(SLS, WCS)Large-scale downwelling, seasonal mixing, small-scale turbulence and eddies POC, DOC, VOCs, methane Downwards (upwards, lateral) LrDOCL (SLS, WCS)POC, DOCLrDOCL (SLS, WCS, USS) Large-scale down- and upwelling, seasonal mixing, small-scale turbulence and eddies, physical induced resuspension rDOC Downwards upwards, (lateral)~~~~**Indirect biota-induced transport**~~ ~~WCRL, USRL (SLS, WCS) Biota-induced turbulence, induced drift DOC, VOCs, methane Swimming and moving species Downwards (upwards, lateral) LrDOCL (SLS, WCS)DOCUSRL (WCS, USS) Digging, burrowing, bioirrigation, sediment reworking POC, DOC, VOCs, methane Moving benthic (-pelagic) and bioturbating species, mammals feeding on benthic species LrDOCL (SLS, WCS) POC, DOC, rDOCDownwards, upwards (lateral)~~~~**Process Loops and(spaces Process description Involved C forms Involved organisms DirectionPhoto-degradation**~~ ~~SRL (SLS) Degradation of labile to refractory OC by UV light DOC, POC,~~ ~~*rDOC*~~ ~~**Dissolution**~~ ~~SRL (SLS~~Based on these embedded processes, pools, and agents, we can now define pathway patterns of higher resolution. For example, for SLRL, six sub-patterns can be defined based on the carbon pools involved: a POC-SLRL, a POC-DOC-SLRL, a POC-DOC-VOC/CH_4-SLRL and a POC-VOC/CH_4-SLRL, as well as a DOC-SLRL and a DOC-VOC/CH_4-SLRL. Depending on the research question or desired level of detail, multiple sub-patterns can be defined based on the processes and agents involved. The higher the resolution of the pathway pattern, the more the patterns resemble descriptions of individual pathways. In the following discussion, we use the example of the biological carbon pump to show how such sub-patterns can look like and which insights e.g. a comparison of such different patterns can provide.

4 Discussion

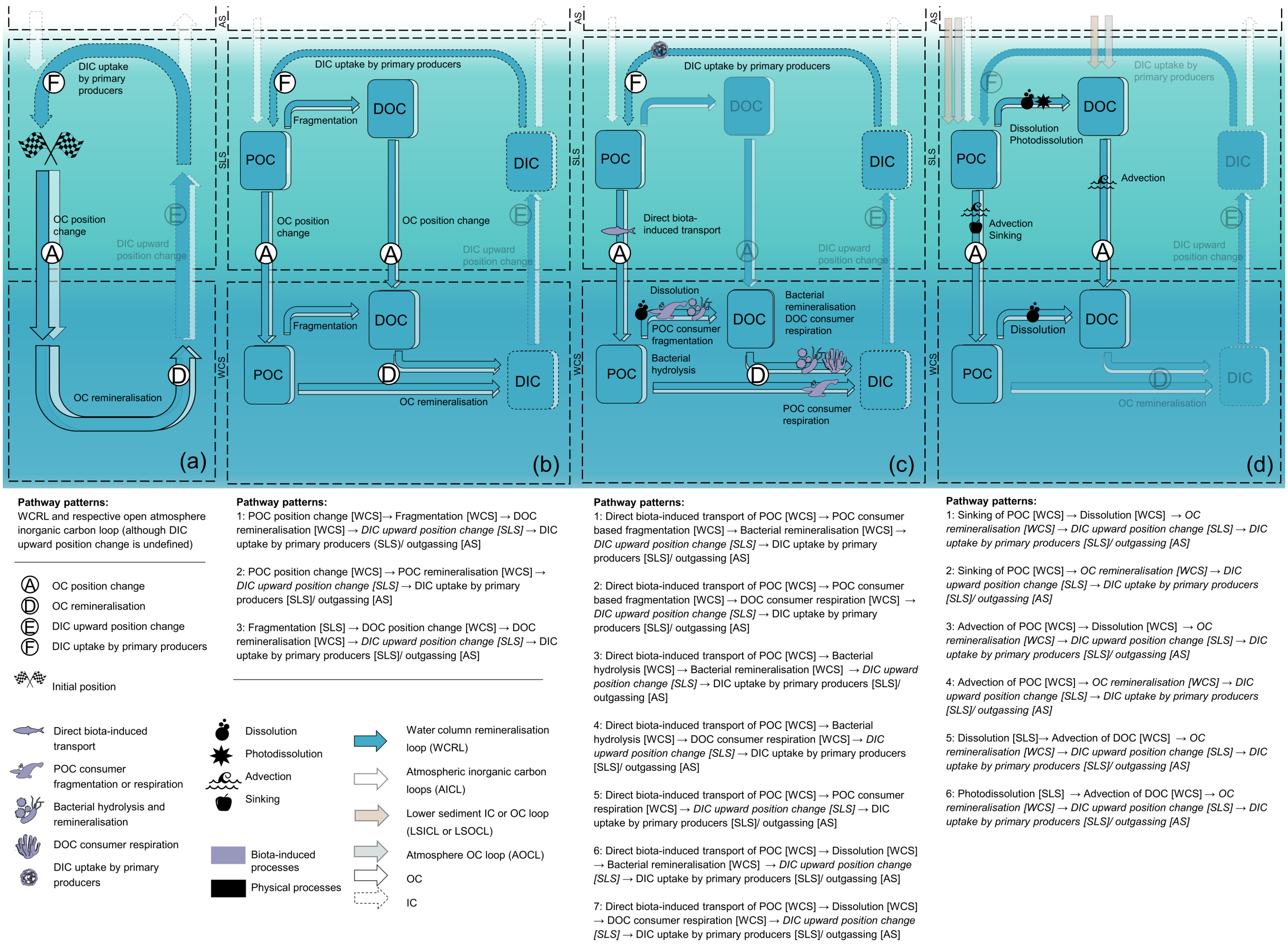
Our concept of the OC cycle condenses pathways to superordinate pathway patterns and provides an overview of embedded processes, pools, and agents, which allows resolving patterns of smaller scale and higher resolution. Our overarching structure complements existing concepts of OC pathways and processes in the ocean, providing a basis for using a consistent terminology.

As such, the concept facilitates comparing different definitions of pathway structures, integrating new findings and placing, for example, pathways of finite length scale in a broader framework.

To discuss some of these aspects in an application example, we translate pathways of the biological carbon pump (BCP) into our concept (Figure 3). Based on the definition of Giering and Humphreys (2020), who define the BCP as "the collection of marine biogeochemical processes that convert dissolved inorganic matter in the surface ocean into biomass and transport this to the ocean interior, where the biomass is returned to its original dissolved inorganic forms", we illustrate different pathway patterns with different resolutions and choices of pathways.

As defined by Giering and Humphreys (2020), all pathways of the BCP involve the uptake of inorganic carbon into biomass in the surface waters (F [SLS]). This biomass is transported to the interior of the ocean (A [Ocean Interior]), where it is remineralised to DIC (D [Ocean interior]). In Figure 3 panel (a), we fit this information into our concept. For simplicity, we disregard the rDOC loops and VOCs/ CH_4 production and start again with the previously introduced initial position. Missing further information, we assume that the ocean interior does not contain the USS and define it as WCS. Based on the definition of Giering and Humphreys (2020) and the restriction of "ocean interior" we classify the BCP as part of the WCRL or the corresponding atmospheric inorganic carbon cycle (AICL). To close the loop, we need to add path segment E not included in the defined BCP.

If we now resolve involved OC pools (here POC and DOC) ~~WCRL (WCS) USRL (USS) Dissolution due to sinking (enhanced by bacteria)or pore-water interactions POC,~~ ~~*rDOC*~~ ~~**Bacterial rDOC formation**~~ ~~SRL (SLS)WCRL (WCS)USRL (USS) Release of capsular material and rDOC under stress conditionsDOC, POC,~~ ~~*rDOC*~~~~Bacteria, viruses~~~~**Primary producer rDOC formation**~~~~SRL (SLS)Release of rDOC (either due to molecule characteristics or dilution)POC,~~ ~~*rDOC*~~~~Phytoplankton and macrophytesUSRL (USS~~ in the BCP of Giering and Humphreys (2020), we can define three sub-patterns (sub-loops, when adding path segment E) that still describe all pathways of the defined BCP, but at a higher resolution (panel b). Restricting the sub-patterns to pathways with a specific set of processes changes the inclusivity of the sub-pattern. For example, if the focus lies on the general structure of pathways involving direct biota-induced transport (A), the result is a subset of seven loops (with path segment E). These loops serve only two of the superordinate loops of panels (a) and (b) (Figure 3) and thus represent a subset of the defined BCP. This subset resembles patterns condensed in other concepts of BCP such as the mesopelagic-migrant pump and the seasonal lipid pump (Boyd et al., 2019). A focus on the purely physical induced pathways of the BCP leads to six different sub-patterns, which do not resolve remineralisation and DIC uptake, as these are non-physical processes (Figure 3, panel (d)). These six sub-patterns could potentially serve all the higher-level loops in panels (a) and (b) but do not resolve some parts of the definition of the BCP by Giering and Humphreys (2020). Thereby these sub-patterns resemble some other, often more traditional, concepts of the BCP, e.g. by Hansell and Carlson (2001) and De La Rocha (2006), that do not consider DIC uptake and remineralisation explicitly. Interestingly, in this subset of the BCP (panel (d))~~Macrophytes' roots~~~~**POC-consumer rDOC formation**~~~~SRL (SLS) WCRL (WCS) Direct (excretion) or indirect release (sloppy feeding) of rDOC (either due to molecule characteristics or dilution) POC,~~ ~~*rDOC*~~ ~~POC consumers USRL (USS)Benthic POC consumers~~ ~~**Process Loops and(spaces Process description Involved C forms Involved organisms Direction**~~~~**Photooxidation**~~ ~~SRL (SLS) Photochemical conversion rDOC to DOC rDOC,~~ ~~*DOC*~~ ~~**Process Loops and(spaces Process description Involved C forms**~~



Pathway patterns:
WCRL and respective open atmosphere inorganic carbon loop (although DIC upward position change is undefined)

Pathway patterns:
1: POC position change [WCS]→ Fragmentation [WCS] → DOC remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers (SLS)/ outgassing [AS]

2: POC position change [WCS] → POC remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

3: Fragmentation [SLS] → DOC position change [WCS] → DOC remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

Pathway patterns:
1: Direct biota-induced transport of POC [WCS] → POC consumer based fragmentation [WCS] → Bacterial remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

2: Direct biota-induced transport of POC [WCS] → POC consumer based fragmentation [WCS] → DOC consumer respiration [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

3: Direct biota-induced transport of POC [WCS] → Bacterial hydrolysis [WCS] → Bacterial remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

4: Direct biota-induced transport of POC [WCS] → Bacterial hydrolysis [WCS] → DOC consumer respiration [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

5: Direct biota-induced transport of POC [WCS] → POC consumer respiration [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

6: Direct biota-induced transport of POC [WCS] → Dissolution [WCS] → Bacterial remineralisation [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

7: Direct biota-induced transport of POC [WCS] → Dissolution [WCS] → DOC consumer respiration [WCS] → *DIC upward position change [SLS]* → DIC uptake by primary producers [SLS]/ outgassing [AS]

Pathway patterns:
1: Sinking of POC [WCS] → Dissolution [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

2: Sinking of POC [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

3: Advection of POC [WCS] → Dissolution [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

4: Advection of POC [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

5: Dissolution [SLS]→ Advection of DOC [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

6: Photodissolution [SLS] → Advection of DOC [WCS] → *OC remineralisation [WCS] → DIC upward position change [SLS] → DIC uptake by primary producers [SLS]/ outgassing [AS]*

Figure 3. Different pathway patterns of the BCP defined by Giering and Humphreys (2020). Panel (a) shows the superordinate BCP pathway patterns. Panel (b) resolves involved pools. Panel (c) and (d) resolve choices of processes: (c) pathways with direct biota-induced transport and (d) pathways with only physical processes. Transparent or italic path segments are not explicitly included in the definition of the BCP or the selected pathways.

~~**Involved organisms DirectionPhoto-remineralization**SRL (SLS) Direct UV remineralization POC , DOC~~, ~~*DIC* **Bacterial remineralization** SRL (SLS) WCRL (WCS) USRL (USS) Bacterial DOC (VOCs)-based respirationDOC, VOCs, methane, *DIC* Bacteria and archaea**Primary producer remineralization** SRL (SLS) Respiration of phytoplankton and macrophytes POC, *DIC* Phytoplankton and macrophytes USRL (USS)Respiration of macrophytesMacrophytes**POC-consumer remineralization** SRL (SLS)WCRL (WCS) Respiration of POC consumers POC, *DIC* POC consumers USRL (USS)Respiration of benthic POC consumers Benthic POC consumers **DIC upwards position change (E)** WCRL (WCS) DOC-consumer respiration DOC, *DIC*~~

~~DOC consumers excluding bacteria **Process Loops and(spaces Process description Involved C forms Involved organisms DirectionDiffusion** WCRL (SLS, WCS) USRL (SLS, WCS, USS) Diffusion in~~ the input of POC and DOC from outside the marine system may also be part of the BCP, as the biota-induced uptake of DIC is not critical for this set of pathways.

Integrating the BCP definition of Giering and Humphreys (2020) into our concept illustrates where the BCP concept shows ambiguity and may need to be refined to concretise which pathways belong to the BCP and which do not. Giering and Humphreys (2020) give "ocean interior" as the spatial constraints of the pathways of the BCP. We translate "ocean interior" as WCS, as no further depth constraints are given. Other BCP definitions constrain depth more concretely, for example describing the BCP as export (Buchan et al., 2014; Hansell and Carlson, 2001) and sequestration fluxes (Sigman and Haug, 2004) acting at depths below 100 m and 1000 m (Passow and Carlson, 2012). Because of the ambiguity of the space, we might include pathways in our concept, which are not part of the BCP. On the other hand, we exclude the sediment and pathways leading to POC sedimentation from the BCP by using the WCS only, although it is still debated whether or not POC sedimentation belongs to the BCP. Steinberg and Landry (2017) for instance considers POC sedimentation as part of the BCP, while Sigman and Haug (2004) claim that it is not sensu stricto. Anyhow, these examples show that the spaces in which the BCP operates need to be more clearly defined. Based on the BCP definition of Giering and Humphreys (2020), we may include pathways that do not belong to the BCP, while excluding some that do. Subdividing the WCS into several spaces, e.g. a space below a sequestration depth, may thus be more appropriate for the representation of the ~~water column and pore waters DIC Upwards**Advection** WCRL, USRL (SLS, WCS) Large-scale down- and upwelling, seasonal mixing, wind-induced turbulence and eddies DIC UpwardsUSRL (WCS, USS)Physical induced resuspension **Indirect biota-induced transport** WCRL, USRL (SLS, WCS) Biota-induced turbulence, induced drift DIC Swimming and moving speciesUpwardsUSRL (WCS, USS) Digging, burrowing, bioirrigation, sediment reworking and related processes Moving benthic (-pelagic) species **Process Loops and(spaces Process description Involved C forms Involved organisms DirectionUptake of DIC** SRL (SLS)WCRL (WCS)USRL (USS) Photosynthesis DIC, *POC* Phytoplankton and macrophytes~~ BCP, as the definition of spaces allows a refinement of the pathways that belong to a pathway pattern.

5 ~~Discussion and Conclusions~~

~~Our qualitative concept of OC cycling is complementary to existing models of OC dynamics and processes in the ocean and resolves general pathway patterns and different process options without assessing the importance or rarity of these.~~

~~By not stopping at one process, such as respiration, but showing complete pathways to their end, we illustrate and emphasize the cycling nature of OC dynamics in~~ A similar vagueness as with the spaces applies to the OC pools involved. Does the BCP include pathways based on DOC in the SLS, e.g. as defined by Honjo et al. (2014), or not as defined by De La Rocha (2006) ? DOC is one of the ~~ocean. The decoupling of carbon pumping from return pathways in some previous concepts and their graphical representa-tions seems to imply that increased transport of OC into the ocean interior always leads to increased sequestration and storage of atmospheric carbon in the ocean. However, increased export of OC is not necessarily associated with increased carbon storage, which depends, among other things, on the ratio of regenerated and preformed nutrients and~~

~~on the carbon that escapes the deep ocean (Gnanadesikan and Marinov, 2008). The export of carbon to the sediment and the deep oceans is~~ relevant carbon fluxes to the deep sea, especially in oligotrophic areas (Roshan and DeVries, 2017). Therefore, and because the definition of Giering and Humphreys (2020) does not explicitly exclude the DOC pool, we add DOC to our illustration of BCP in panel (b). However, the presentation would also work without DOC. In such a case, our concept shows which pathways are missing by dispensing DOC.

Illustrating what is missing also allows placing individual pathways and concepts such as the BCP in a broader framework. For example, mentioning pathway section E is a must to place the BCP in the carbon cycle, as there is no dead end in nature. Furthermore, our approach helps to identify how different sub-concepts fit into more general definitions (panel (b)-(c) compared to panel (a)), but also where some inconsistencies might occur, e.g. external sources of OC are not part of the ~~carbon processing, but not the whole story. Research on and the communication of the potential oceanic carbon sinks necessarily need to consider the return and exit pathways. Our model can help to communicate and acknowledge the cycling nature of OC pathways~~biological carbon pump contrary to what is suggested in panel (d). In addition, it facilitates identifying which pathways are not resolved and the potential informative value of studies based on a limited number of pathways. In panel (c), for example, the DOC in the WCS comes only from fragmentation of POC. If fragmentation processes decrease significantly, this does not necessarily mean a decrease in remineralisation of DOC (D [WCS]), as DOC can also come from the SLS. A study based on the pathways as in panel (d) does not consider DOC from the SLS and therefore has limited informative value about changes in remineralisation of DOC. All mentioned considerations are already part of most studies and publications. But we provide a new tool to structure these considerations and make them more comparable.

~~Another add-on of our model is that we refrain from quantification or interpretation and do not indicate dominant pathways or omit rare ones, as our understanding of OC dynamics is constantly changing. Higher trophic levelswere previously neglectedand are now recognized~~ The example also shows how new concepts and processes can be integrated into our concept. Panel (d) resembles more traditional definitions of the BCP, which focus mainly on physically driven processes. The role of organisms, particularly higher trophic levels, has been neglected. Now, however, the contribution of this biota is recognised as relevant to the carbon cycle. For example, large migratory species link to nutrient distribution and overall mixing (Roman and McCarthy, 2010), zooplankton ~~significantly influence the~~ have a significant influence on carbon export (Steinberg and Landry, 2017), reptile falls provides an alternative carbon pathway to the sediment (McClain et al., 2019), and fish and ~~fishes and~~ mammals contribute to the carbon cycle through various processes (Martin et al., 2021). ~~In addition, some studies suggest that current models overestimate particle export by underestimating processesthat lead to shifts in carbon pools, such as fragmentation (Baker et al., 2017). These ongoing new findings show how short-living and dynamic our understanding of processes and OC pathways is.~~

~~To account for these changes in understanding, our model provides a conceptual skeleton, an overarching concept that can be brought to life by users~~With these processes, many new pathway patterns emerge, some of which we resolve in panel (c). Our concept provides overarching structures that users can bring to life to integrate new insights. Processes, organisms, pathways, and loops can easily be added, changed, or deleted to ~~accommodate new insights~~ incorporate new findings or specific systems ~~. At the same time, existing concepts of OC cycling also fit into our model, e.g. the microbial carbon pump finds its reference~~

~~in the rDOC loops and the lipid pump in pathways of the WCRL. Overall, this gives our model a high degree of flexibility.~~ into the general structures.

~~This flexibility is necessary since not just our understanding but ocean systems around the globe are changing (Doney et al., 2012). Today's dominant pathway or process may not be dominant tomorrow. For example, the assumption that dense particles predominately sink (~~By generalizing must-pass structures and providing a congruent visual representation, our concept may reduce the potential for misunderstandings of the OC cycle potentially and unintentionally caused by visual concepts of finite length scale. An example of such a potential misunderstanding is the decoupling pathways transporting DIC to depths and return pathways in some earlier visual OC concepts (as e.g. ~~by Le Quere et al. (2005))is only correct as long as their density-induced sinking is not prevented by default or to a large extent, e. g. by aggregation with microplastics that reduces density and thus sedimentation (Long et al., 2015). Concepts that implicitly or explicitly state that most dense particles sink and only or mainly consider pathways of OC sinking cannot resolve what might happen to the particle instead, for example, when microplastics reduce the sinking of these particles.~~

~~In our model, density-induced sinking is only one option among many others. Dense particles can end up in different loops, e. g. in the SRL, staying in the SLS, or the WCRL if transported to deeper water layers by processes other than sinking. Besides these changes in sinking, there are numerous other examples of process changes that have the potential to alter OC cycle pathways, e. g. changes in the phytoplankton community (Vernet et al., 2017), changes in the DOC pool (Lønborg et al., 2020), and depletion of higher trophic levels (Wilmers et al., 2012),~~ discussed for Boscolo-Galazzo et al. (2018) in the introduction). While these representations are justified for finite length scale studies, this visual decoupling can lead to the false impression that increased transport of OC to ~~name~~ the deep ocean always leads to increased sequestration and storage of atmospheric carbon. However, increased OC export is not necessarily accompanied by increased carbon storage, which depends, among other things, on the ratio of regenerated to pre-formed nutrients and on the carbon that escapes from the deep ocean (Gnanadesikan and Mari . The export of carbon to the deep sea is part of carbon processing, but not the whole story, as we can also see from the example of the definition of the BCP. We propose to use a concept like ours as a reference concept to account for the increasingly interdisciplinary scientific community, to increase consistency of (visual) concepts and to bring structure into the larger framework of the OC cycle.

Our concept brings structure to the marine OC cycle but does not capture its complexity. Each OC compound travels its pathway through the OC cycle. An OC compound in the surface ocean may end up on the surface or in the deep sea, be decomposed, or become recalcitrant, to name just a few possibilities. Each pathway is unique in its sequence of processes. So, there is a ~~few~~multitude of possible pathways. An all-encompassing description of these possibilities is, therefore, neither possible nor meaningful. Accordingly, our concept does not want to and cannot resolve individual pathways. On the contrary, it focuses on critical path segments and overarching structures. Hence, our concept reduces many pathways to a sequence that does not capture their full extent, biological relevance, complexity, and temporal dimension. ~~All of these changes might deconstruct and modify the pathways of particles. Therefore, the fate of a carbon particle in our model is open. And we present pathway options instead of a selection of dominant ones with a fixed destiny.~~

~~How OC moves through the system and where it ends affects the climate system (e.g. via alteration of the biological pump (Barange et al., 2017)), the ecosystem functioning (e. g. via changes in the benthic-pelagic coupling (Griffiths et al., 2017)) but also human well-being and socio-ecological systems (via alterations of the trophic energy flows leading to less productive coastal systems (Ullah et al., 2018)) at all scales. Therefore, there is a societal need to understand today's systems and their possible changes due to anthropogenic interventions under different scenarios.~~

~~Our model can serve as a basis for such scenario considerations and assessments of interventions and management strategies in marine ecosystems. Deliberate interventions in OC pathways, like geoengineering, and interventions that incidentally change OC pathways, e. g. fish management strategies, should both be tested for their impact on the different pathways in different systems. For illustration, changes in the food web through fisheries likely alter OC cycling. Our model helps to identify all pathways with involved fishes and invites us to ask: Do changes in fish stocks dry up carbon pathways? Are others taking over? Are there changes in loops? Do these changes differ in different ecosystems? What are~~ Moreover, our concept is purely abstract and not capable of quantification or forecasting expected changes. It is a skeleton that needs to be filled with life. Further, it proved difficult to find an unambiguous language and visualisation for the ~~implications for the food web and carbon storage?~~

~~Science and society need to find answers to these and many other questions to adapt system-tailored management options, assess the impacts of these options on OC pathways, and identify and evaluate nature-based solutions that are efficient and preserve ocean resources and health for future generations. While our model helps to address these questions and adjust our understanding of the mechanisms of the OC cycle, it needs complementation and extensions~~concept. For example, we depict organisms that are a pool and organisms that are agents with the same symbol. Adjustments of terms and symbols appear reasonable as soon as users identify problems. We hope that the concept will grow, improve and become more complete with use.

~~Quantifications of the magnitudes of carbon moving through different pathways in individual ecosystems and qualitative modelling of scenario-based changes in loopsand processes need to follow. In particular, to understand whether and how much pathwayschange due to anthropogenic interventions, our qualitative conceptual model is only a first step. In addition to these methodological next steps, advanced conceptual pathway models need to consider the interactions of alkalinity and solubility with the OC cycle to understand and predict how the OC cycle might change, also in terms of possible consequences for the climate system and the options and barriers that exist for society to alter carbon pathwaysand adapt to unintended or irreparable changes. Marine ecosystems and the carbon cycle are changing. Just as important, our perception and approaches to address these changes are changing and must adapt even further. We offer a new conceptual model to accommodate these changes, structure them, and make themuseful for further research.~~

5 Conclusion

We propose a general (visual) concept for the marine part of the organic carbon cycle. It complements and integrates existing concepts and defines overarching structure of OC pathway patterns (loops) and the processes, pools and agents involved. Building on concepts that focus on the structure of individual or a subset of marine OC pathways, our concept identifies the general structure of all pathways. Details and complexity are disregarded in favour of a systematic structure that can facilitate the identification and comparison of concepts, pathways, pools and studies. The concept can be adapted to a wide range of questions, pathway choices, resolutions and thus serve as a basis for discussion and reference to understand the current and future marine OC dynamics arising from the multiplicity of OC pathways and the human influence on them.

Data availability. The base pathway concept is attached as supplement A.

Author contributions. M.I.E.S. designed the study, conducted the research and prepared the manuscript. I.H. designed the study and contributed to the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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