Ideas and Perspectives:

Climate-Relevant Marine Biologically-Driven Mechanisms in Earth System Models

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Abstract. Marine biota drives a number of climate-relevant mechanisms not all of which are included in current Earth system models (ESMs). We identify three classes of mechanisms and distinguish (1) those related to matter cycling via "biogeochemical pumps", (2) those affecting the atmospheric composition via the "biological gas and particle shuttles" and (3) those changing the thermal, optical and mechanical properties of the ocean via the "biogeophysical mechanisms". We argue that to adequately resolve these mechanisms, ESMs need to account for five functional groups, including bulk phyto- and zooplankton, calcifiers as well as coastal gas and surface mat producers. Thereby links to other Earth system components are ensured and a larger number of relevant feedbacks are enabled to take place.

1 Introduction

The description of the marine ecosystem in Earth system models (ESMs) used for climate projections has been significantly refined during the past years. Plankton has been split into functional groups and physiological details such as light or nutrient acclimation have been added, to name only a few of the recent modifications (Vichi et al., 2011; Aumont and Bopp, 2006; Aumont et al., 2015). As a direct consequence, today's models better represent biological and biogeochemical variables like chlorophyll or nutrient fields. Particularly nutrients strongly regulate the carbon fluxes in the ocean; improving the representation of the marine nutrient cycle in ESMs will therefore also improve the carbon cycle. Clearly, the goal to "perfectly" reproduce sources and sinks of carbon in the ocean is understandable in the first place. From a climate perspective, however, the strategy to increase "only" the complexity of one climate relevant aspect is questionable.

An alternative approach is to identify the links between marine biota and different Earth system components and to increase the number of climate relevant mechanisms in ESMs. These mechanisms are defined

here as a series of intertwined processes that can trigger climate feedbacks; they are fundamentally influencing the response of the climate system to external forcing in general and to anthropogenically induced perturbations in particular. Instead of improving a single mechanism, the idea is to account for "mechanism diversity", without going into too much detail of one specific process at the expense of others. Thereby,

5 more emphasis is placed on the relative importance of the different feedbacks which may vary under climate change due to altered marine ecosystem functioning. To follow this approach, we present a necessary evaluation of the role of ocean biota in the climate system.

So far, ESMs distinguish plankton functional groups mainly because of their role for biogeochemical cycles. For example, the phytoplankton group "diatoms", the main contributor to the marine silicon cy-

10 cle is distinguished from the phytoplankton group "coccolithophores", responsible for calcification (e.g. Le Quéré et al., 2005). Even if these organisms are not named as such and mathematically described in the model *a priori* like in the so called trait-based approach, their role is assigned in hindcast based on the combination of species characteristics that turn out to be successful in specific geographical regions (e.g. Follows et al., 2007).

15 Here, we will present in more detail biologically-driven mechanisms that are most important in the climate context as well as functional groups that regulate them. In addition, we will show the links between the marine biota, the mechanisms and the larger feedback loops in the climate system. Finally, we critically evaluate the current state of these aspects in climate modeling.

What is needed

20 To account for the "mechanism diversity" and thus the generation of climate feedbacks (see Fig. 1), we introduce three classes of mechanisms (M1-M3) and five functional groups that are mainly involved (Table 1). For each class, the main mechanisms are briefly explained, the key organisms involved are presented, the climate relevance is highlighted and the functional groups that are needed in ESMs to capture this mechanism are concretely described.

25 **M1 - biogeochemical pumps**

The first class of mechanisms comprise the marine part of the carbon cycle, the *biological carbon pump* and the *alkalinity pump*.

The *biological carbon pump* includes the processes related to the uptake of carbon dioxide in the upper ocean and the sinking of organically bound carbon to deeper waters. Two organism groups are mainly

30 involved – phyto- and zooplankton. The former drives the carbon cycle, because inorganic is transferred to organic carbon via photosynthesis, and the latter decisively contributes to carbon export to the deeper ocean via fecal pellet production. Without the biological carbon pump ocean uptake of CO_2 would be strongly reduced. Rough estimates suggest that atmospheric CO_2 levels would rise by approximately 200 ppmv after shutdown of the biological carbon pump (Volk and Hoffert, 1985; Broecker and Peng, 1986). As part of the

35 climate-carbon cycle feedback (Friedlingstein et al., 2006), this mechanism is well known and regarded as

the most important marine biologically-driven mechanism. To capture it in ESMs, a bulk phytoplankton and a bulk zooplankton group are in principle sufficient to describe the transformation process from inorganic to organic matter and sinking of the latter. However, all additional functional groups that are needed for other mechanisms will also contribute (see Table 1).

5   The *alkalinity pump* is the other essential part of the marine carbon cycle, because this mechanism alters the carbonate chemistry in the ocean. Organisms that affect the carbonate equilibrium are calcifying species, specifically coccolithophores. They live and build up their calcareous shells in the upper ocean, where alkalinity is consumed and CO_2 is released during the calcification process, causing a decrease in alkalinity. When coccolithophores die, they sink down to the deeper part of the ocean, where the calcareous

10   shells dissolve and the alkalinity increases. Since alkalinity is the capacity of the ocean to buffer acids and sets the limit how much CO_2 can be stored, the vertical gradient in alkalinity has consequences for the CO_2-storage: it is reduced in the upper ocean where calcification takes place but increased deeper down. While the quantitative impact of the alkalinity pump on climate is currently unclear, its role via the "calcification feedback" on atmospheric CO_2-concentrations is assumed to be large (Zhang and Cao, 2016). To correctly

15   simulate alkalinity and adequately represent the carbonate chemistry in ESMs one additional key group, the calcifiers, is required.

M2 - biological gas and particle shuttles

The second class of mechanisms, the "*biological gas and particle shuttles*" addresses the impact of the marine biosphere on the atmosphere due to emission of gases and particles. These substances belong to the

20   group of "short-lived climate-relevant air contaminants" (SCC), a subset of short-lived health- and climate-relevant air contaminants (SHCC), sensu Pöschl and Shiraiwa (2015). They may act as aerosols, being involved in cloud formation; they may affect the atmospheric chemistry or influence the thermodynamics as greenhouse gases.

Particulate SCCs of marine biogenic origin with direct effects on cloud formation are so-called "marine

25   biogenic primary aerosols". These include entire organisms, like phytoplankton cells or organisms' remnants, or "exudates", which are substances secreted by organisms (e.g. Knopf et al., 2011; Burrows et al., 2013; Wilson et al., 2015). Although this research area is relatively new, recent studies suggest that at least on a regional scale, ocean biota strongly influences the concentrations of cloud droplets with significant consequences for the reflected shortwave radiation (McCoy et al., 2015). Thus, ocean biota as a source for

30   primary aerosols can directly contribute to the cloud-albedo feedback. As a first approximation, no additional functional group needs to be added in ESMs; a fraction of those organisms in the surface layer that are implemented in ESMs anyway may serve as a source for primary aerosols.

Gaseous SCCs may be involved in aerosol formation or participate in ozone reactions. The most important ones produced by marine organisms are dimethyl sulfide (DMS) and short-lived halocarbons. For

35   both it is meaningful to distinguish open and coastal ocean sources since the efficiency in gas release is highly dissimilar and different organism groups are involved. DMS (or its precursors) is produced by "open ocean" (coccolithophores) and "coastal" phytoplankton (*Phaeocystis*) groups (e.g. Barnard et al., 1984;

Malin et al., 1993). Short-lived bromine halocarbons are associated with "open ocean" phytoplankton and "coastal" macroalgae (e.g. Moore et al., 1996; Nightingale et al., 1995; Carpenter and Liss, 2000).

Dimethyl sulfide (DMS) is a precursor of sulfate aerosols and plays a role in the climate system via the cloud-albedo feedback (e.g. Charlson et al., 1987; Ayers and Cainey, 2008; Von Glasow, 2008). Local
5 effects on shortwave radiation of DMS emission by a phytoplankton bloom can induce cooling up to -15 W m^{-2} at the top of the atmosphere; such a high value is usually associated with heavily air-polluted regions (Meskhidze and Nenes, 2006). The global direct radiative effect of DMS has been estimated to be -0.23 W m^{-2}, the indirect as -0.76 W m^{-2}. The contribution of primary producers via DMS production to sources of natural aerosols is therefore larger than for example those from sea salt or volcanoes (Rap et al., 2013).

10 Short-lived halocarbons, particularly brominated substances are important SCCs, because they destroy ozone and thereby significantly change the radiative forcing (Sturges et al., 2000; Saiz-Lopez et al., 2012; Laube et al., 2008). The radiative effect is estimated to be about -0.2 W m^{-2} and thus larger than the one by the widely known anthropogenically produced long-lived halocarbons such as CFCs (Hossaini et al., 2015).

15 For both DMS and short-lived halocarbons, it is crucial to correctly represent the spatial patterns of marine primary production and corresponding SCCs. To capture the gradient between coastal and open ocean, an additional model compartment, the "coastal gas producers", has to be included in ESMs. A relatively easy way to describe them in the model is by allowing the sediment or deepest model layer being an additional nutrient pool and by taking into account relatively high emissions per unit biomass. Even if
20 different types of organisms are involved in the coastal production of DMS and shortlived halocarbons, one functional group is sufficient, because coastal patterns of the two SCCs do not clearly differ. The group of open ocean organisms can be represented either by coccolithophores in case of DMS, or a "bulk phytoplankton" group in case of halocarbons (although parametrizations are necessary, because not the entire bulk phytoplankton produces halocarbons).

25 Last but not least, there are a number of greenhouse gases of marine biogenic origin, notably CO_2. This gas is respired by all organisms and is more or less automatically captured in ESMs through the loss rate of all functional groups. Marine sources of other biogenic greenhouse gases like N_2O or CH_4 are related to marine microorganisms such as bacteria and archaea (e.g. Bange et al., 2010; Valentine, 2011). The effect of CH_4 and N_2O of marine biogenic origin on the climate system might be rather small, because the main
30 sources are restricted to oxygen deficient waters near the coast. Thus it is not justifiable currently to add more model compartments.

M3 - biogeophysical mechanisms

The third class includes all the *biogeophysical mechanisms*. These mechanisms comprise changes of thermal, optical and mechanical properties of the ocean, predominantly caused by phytoplankton species.
35 Among them, positively buoyant cyanobacteria are particularly important, because they can produce surface mats of up to several millions of square kilometers (e.g. Capone et al., 1998). Such surface mats significantly change light absorption with consequences on the surface mixed layer heat balance (e.g.
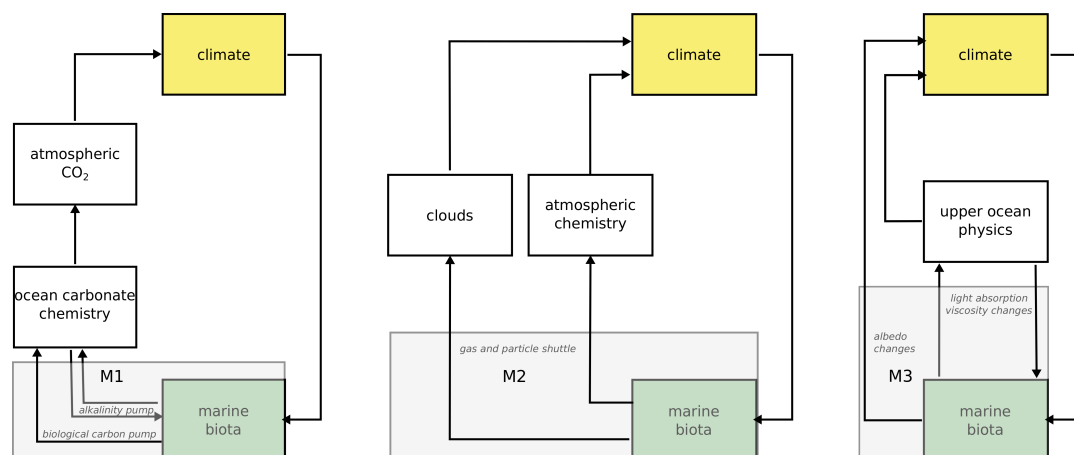
Figure 1. Major globally acting climate feedback loops, based on the three classes of mechanisms (light grey-shaded boxes), driven by marine biota (green-shaded boxes). Only links originating from the marine biota are shown; additional inter- and cross-links between the different boxes are ignored for a clarity. a) the two mechanisms (the biological carbon pump and the alkalinity pump) affect the CO_2 inventory in the ocean, which in turn leads to changes in atmospheric CO_2 and thus in climate. An altered global climate influences the marine biota (through e.g. changes in SST, near surface stratification and circulation patterns), closing the marine part of the climate-carbon cycle feedback loop which also includes the CO_2-calcification feedback. b) the gas and particle shuttle alter cloud formation rates and distribution as well as atmospheric chemistry. There is a complex interplay between different atmospheric components that ultimately lead to climate change, again with consequences on the marine biota. A number of atmospheric feedbacks (e.g. the cloud-albedo feedback, the longwave radiation feedback, the chemistry feedbacks) are involved in this loop. Note that the influence of marine biota by changes in *local* cloud cover is not illustrated here. c) two biogeophysical mechanisms (based on light absorption and viscosity changes) directly affect the upper ocean physics such as heat distribution and circulation and hence the biota. The third one (albedo changes) has a more direct effect on the climate which influences in turn the marine biota.

Sathyendranath et al., 1991; Kahru et al., 1993). In addition, they increase the albedo (e.g. Kahru et al., 1993), alter the viscosity and reduce the vertical mixing (e.g. Jöhnk et al., 2008). Surface mats may also reduce the air-sea gas exchange, if we assume similar effects as for surface microlayers (e.g. Liss and Duce, 2005).

5   The climate impact of the light absorption mechanism has been only assessed for *neutrally buoyant* phytoplankton so far. Even their impact is significant with pronounced effects on atmosphere and ocean temperature, circulation patterns, cloudiness, humidity, precipitation and evaporation, as well as sea ice cover (Patara et al., 2012); also ENSO dynamics is shown to be influenced through light absorption (e.g. Jochum et al., 2010). The strong response triggered by this mechanism results from multiple feedback
10   loops that involve different Earth system components.

      A rough estimate indicates that changes of albedo through phytoplankton, specifically coccolithophores can result in a cooling by roughly 0.2 W m^{-2} globally (Tyrrell et al., 1999). A more sophisticated evaluation, however, points towards a negligible impact on the albedo, at least on a basin-wide scale (Gondwe et al., 2001). In any case there is a direct link to the albedo-temperature feedback (Watson and Lovelock, 1983).

15   Unfortunately, the climate effect through biotic induced changes of ocean's viscosity has not been addressed, yet. However, idealized model studies (Sonntag, 2013) suggest that biologically induced increase or decrease of viscosity by surface mats can affect ocean circulation patterns on a basin-wide scale.

organism groups	M1	M2	M3
bulk phytoplankton	✓	✓	✓
bulk zooplankton	✓	-	-
calcifier	✓	✓	✓
coastal gas producer	✓	✓	✓
surface mat producer	✓	✓	✓

Table 1. Organism groups that drive climate mechanisms 1: biogeochemical pumps; 2: gas and particle shuttle and 3: biogeophysical mechanisms

To account for biogeophysical aspects in ESMs one additional key group, the "surface mat producers" is needed. To represent this group, cyanobacteria can be implemented. They possess the trait "positive buoyancy" which they do not share with other phytoplankton and should therefore be considered separately. In addition, they need higher temperature for growth and are expected to benefit from global warming (Hense et al., 2013). Clearly, all other groups of marine primary producers that are explicitly described in ESMs have an impact on light absorption, too but by distinguishing neutrally or negatively from positively buoyant phytoplankton a more realistic representation of the light absorption feedback will be achieved.

To summarize, including the above mentioned 5 functional groups (Table 1) will cover the requirements for an adequate representation of biologically-driven mechanisms in ESMs.

What has been done

Today's ESMs represent the marine biogeochemical part related to the carbon cycle reasonably well (Table 2). Most of these models explicitly consider phyto- and zooplankton. Both organism groups are described in such a way that the model results give reasonable values for export production (see e.g. Ilyina et al., 2013; Palmer and Totterdell, 2001). Also, the carbonate chemistry is relatively well represented, even though calcifiers are not explicitly included but parametrized by assuming that they constitute a certain proportion of phytoplankton. This parametrization may work out for today's ocean but might become problematic if climate projections are conducted. Under future acidified conditions, the composition of calcifying and non-calcifying species of the phytoplankton as well as the growth behavior of calcifiers may significantly change due to competing selection pressures. To allow for such shifts in community composition, calcifiers should be explicitly implemented as a separate state variable.

The second class of mechanisms, which affect the atmospheric composition, has received less attention. Some of the ESMs do consider DMS (Table 2) and the results support the earlier hypothesis about the importance of this SCC (Six et al., 2013). Other marine biologically produced SCCs (except CO_2) and aerosols are usually not included; but there are a number of recent model activities in which the processes involved have been implemented, and the climate impact of these substances has been evaluated at least partly (e.g. Kirkevåg et al., 2013; Stemmler et al., 2014, 2015; Hossaini et al., 2015). The largest problem of ESMs in this respect is that primary production is still not sufficiently well represented, in particular in coastal regions (e.g. Schneider et al., 2008; Anav et al., 2013). Although the respective ESMs as well

ESMs	MBMs	1	2	3	P	Z	C	cG	S
BCC_CSM1.1	OCMIP	$\checkmark$[bcp]	–	–	–	–	–	–	–
CanESM1	CMOC	$\checkmark$	–	–	$\checkmark$[1]	$\checkmark$[1]	–	–	–
CESM1	BEC	$\checkmark$	–	$\checkmark$[LA−nbp]	$\checkmark$[3]	$\checkmark$[1]	($\checkmark$)	–	–
ESM2M/ESM2G	TOPAZ2	$\checkmark$	–	$\checkmark$[LA−nbp]	$\checkmark$[3]	–	($\checkmark$)	–	–
HadGEM2-ES	Diat-HadOCC	$\checkmark$	$\checkmark$[DMS]	–	$\checkmark$[2]	$\checkmark$[1]	–	–	–
INGV-CMCC-CE	PELAGOS	$\checkmark$[bcp]	–	$\checkmark$[LA−nbp]	$\checkmark$[3]	$\checkmark$[4*]	–	–	–
IPSL-CM5A	PISCES	$\checkmark$	$\checkmark$[DMS]	$\checkmark$[LA−nbp]	$\checkmark$[2]	$\checkmark$[2]	($\checkmark$)	–	–
MIROC-ESM	NPZD	$\checkmark$[bcp]	–	–	$\checkmark$[1]	$\checkmark$[1]	–	–	–
MPI-ESM	HAMOCC	$\checkmark$	$\checkmark$[DMS]	–	$\checkmark$[1]	$\checkmark$[1]	($\checkmark$)	–	–

Table 2. Different marine biosphere modules (MBMs) in Earth System Models (ESMs) that are used also for climate projections: OCMIP: Wu et al. (2013); CMOC: Christian et al. (2010); BEC: Moore et al. (2013); TOPAZ2: Dunne et al. (2010, 2013); Diat-HadOCC: Palmer and Totterdell (2001); Martin et al. (2011), PELAGOS: (Vichi et al., 2007, 2011, *bacterioplankton is included in zooplankton); PISCES: Aumont and Bopp (2006); Lengaigne et al. (2009); Aumont et al. (2015), NPZD: Watanabe et al. (2011); Kawamiya et al. (2000); HAMOCC: Maier-Reimer et al. (2005); Ilyina et al. (2013). The Roman numerals refer to the biologically-driven mechanisms while P, Z, C, cG, S denote the organism groups phytoplankton, zooplankton, calcifiers, coastal gas producers, and surface mat producers. Organism groups that are not explicitly described but parametrized are in parenthesis. Checkmarks with additions refer to the biogeochemical carbon pump (bcp), DMS (a specific SCC), light absorption by neutrally/negatively buoyant phytoplankton (LA-nbp) or to the numbers of explicitly described functional groups. The MBMs represented here reflect the variety of those that participated in CMIP5 (Arora et al., 2013); the most recent peer-reviewed reference of each MBM is used. MBMs are only listed once, albeit some of them are used in more than one ESM. For comparison, we additionally included a more complex MBM of an ESM (PELAGOS) that was not employed in any of the CMIP5 experiments.

as global marine biogeochemical models have become more and more complex in recent years (see e.g. Aumont et al., 2003; Le Quéré et al., 2005; Dunne et al., 2013; Buitenhuis et al., 2013), the situation has only marginally improved. Not surprisingly, models generally fail to simulate SCC concentrations and air-sea fluxes on the shelf (see e.g. Halloran et al., 2010; Stemmler et al., 2015); much could be gained if

5   coastal primary production is better represented.

Finally, marine biogeophysical aspects are only partly taken into account by today's ESMs. So far, only the light absorption mechanism with the feedback on temperature is included in some ESMs (Table 2). Recent studies indicate that consequences for the upper ocean heat balance and the climate system are profound (e.g. Patara et al., 2012; Lengaigne et al., 2009), although only neutrally or negatively buoy-

10 ant phytoplankton are considered in these models. Thus, the effects might be even stronger if also positively buoyant organisms are included; whether organisms stay at the surface or whether they are homogeneously distributed in the surface mixed layer makes a big difference for the upper ocean heat budget (e.g. Sonntag and Hense, 2011). None of the ESMs or even coupled global biogeochemical ocean circulation models account for other biogeophysical effects, i.e. changes in albedo and viscosity.

2 Summary and Conclusions

We conclude that it is reasonable to distinguish three main classes of *climate relevant* mechanisms, driven by marine biota. To adequately describe them in ESMs, at least five functional groups are needed, including bulk phyto- and zooplankton, calcifiers as well as coastal gas and surface mat producers. Our suggested
5   marine biosphere module for ESMs is less complex than those modules currently used for climate projections. But in contrast to these state-of-the-art concepts, we consider important links between the marine biosphere and other Earth system components and allow in that way more important feedback loops to take place.

     We believe that our framework is better suited to account for possible changes in the strength of feed-
10   backs. Such changes can be expected, because with global warming and ocean acidification the marine ecosystem and consequently links to other Earth system components will be altered. For instance, if it is true that surface buoyant cyanobacteria will rise in future (Hense et al., 2013), there will be a trend in the effects through the biogeophysical mechanisms. The feedback loops associated with these mechanisms will change accordingly. Thus, the different pathways that amplify or diminish the effects in the different Earth
15   system components must be considered to evaluate the response of the climate system.

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