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Reviews and Syntheses: Ocean acidification and its potential impacts on marine ecosystems

K. M. G. Mostofa^{1,2,8}, C.-Q. Liu², W. D. Zhai³, M. Minella⁴, D. Vione⁴, K. Gao⁵,
D. Minakata⁶, T. Arakaki⁷, T. Yoshioka^{8,a}, K. Hayakawa⁹, E. Konohira^{8,b},
E. Tanoue^{8,10}, A. Akhand¹¹, A. Chanda¹¹, B. Wang², and H. Sakugawa¹²

¹Institute of Surface Earth System Science, Tianjin University, Tianjin 300072, China

²State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China

³Key Laboratory for Ecological Environment in Coastal Areas (State Oceanic Administration), National Marine Environmental Monitoring Center, Dalian 116023, China

⁴Università degli Studi di Torino, Dipartimento di Chimica, Via P. Giuria 5, 10125 Torino, Italy and Centro Interdipartimentale NatRisk, Via Leonardo da Vinci 44, 10095 Grugliasco (TO), Italy

⁵State Key Laboratory of Marine Environmental Science (B-606), Xiamen University, Daxue Rd 182, Xiamen, Fujian 361005, China

⁶Department of Civil and Environmental Engineering, Michigan Technological University 1400 Townsend Drive, Houghton, MI. 49931, USA

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⁷Department of Chemistry, Biology and Marine Science, Faculty of Science, University of the Ryukyus, Senbaru, Nishihara-cho, Okinawa 903-0213, Japan

⁸Institute for Hydrospheric–Atmospheric Sciences, Nagoya University, Nagoya, Japan

⁹Lake Biwa Environmental Research Institute, Shiga Prefecture, Ohtsu 520-0806, Japan

¹⁰Hydrospheric Atmospheric Research Center, Nagoya University, Nagoya, Japan

¹¹School of Oceanographic Studies, Jadavpur University, Jadavpur, Kolkata 700032, West Bengal, India

¹²Graduate School of Biosphere Science, Department of Environmental Dynamics and Management, Hiroshima University, 1-7-1, Kagamiyama, Higashi-Hiroshima 739-8521, Japan

^aPresent address: Field Science Education and Research Center, Kyoto University, KitashirakawaOiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan

^bPresent address: DLD inc., 2435 kamiyamada, Takatomachi, Ina, Nagagano, 396-0217, Japan

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Correspondence to: K. M. G. Mostofa (mostofa@tju.edu.cn)
and C.-Q. Liu (liucongqiang@vip.skleg.cn)

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Ocean acidification, a complex phenomenon that lowers seawater pH, is the net outcome of several contributions. They include the dissolution of increasing atmospheric CO₂ that adds up with dissolved inorganic carbon (dissolved CO₂, H₂CO₃, HCO₃⁻, and CO₃²⁻) generated upon mineralization of primary producers (PP) and dissolved organic matter (DOM). The aquatic processes leading to inorganic carbon are substantially affected by increased DOM and nutrients via terrestrial runoff, acidic rainfall, increased PP and algal blooms, nitrification, denitrification, sulfate reduction, global warming (GW), and by atmospheric CO₂ itself through enhanced photosynthesis. They are consecutively associated with enhanced ocean acidification, hypoxia in acidified deeper seawater, pathogens, algal toxins, oxidative stress by reactive oxygen species, and thermal stress caused by longer stratification periods as an effect of GW. We discuss the mechanistic insights into the aforementioned processes and pH changes, with particular focus on processes taking place with different time scales (including the diurnal one) in surface and subsurface seawater. This review also discusses these collective influences to assess their potential detrimental effects to marine organisms, and of ecosystem processes and services. Our review of the effects operating in synergy with ocean acidification will provide a broad insight into the potential impact of acidification itself on biological processes. The foreseen danger to marine organisms by acidification is in fact expected to be amplified by several concurrent and interacting phenomena.

1 Introduction

Ocean acidification is typically defined as a process of increasing seawater acidity or lowering seawater pH, as a consequence of the dissolution of elevated atmospheric CO₂. Carbon dioxide from the atmosphere (Orr et al., 2005; Feely et al., 2008) adds to the dissolved inorganic carbon (DIC: dissolved CO₂, H₂CO₃, HCO₃⁻ and CO₃²⁻) origi-

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nated from the degradation of dissolved organic matter (DOM) (Mostofa et al., 2013a), primary producers (PP) (Cai et al., 2011; Mostofa et al., 2013a), anaerobic oxidation of methane (Haroon et al., 2013) and sulphide oxidation coupled to carbonate dissolution (Torres et al., 2014) in seawater. The sources of elevated atmospheric CO₂ include first of all anthropic activities such as fossil fuels combustion (such as coal, petroleum and natural gas (Le Quéré et al., 2009)), enhanced land-use practices (Le Quéré et al., 2009), as well as deforestation (van der Werf et al., 2009; Lapola et al., 2014). Additionally, there could be significant contributions from natural sources such as plant litter decomposition (King et al., 2012), volcanic eruptions (Hall-Spencer et al., 2008), emission of CO₂ from freshwater including the Amazon River basin (Sobek et al., 2005; Abril et al., 2014) and enhanced respiration of soil organic matter (OM) under global warming (GW) conditions (Knorr et al., 2005). Furthermore, while the global oceans are net sinks of atmospheric CO₂, particular locations such as the sub-Antarctic zone during winter and the equatorial oceans are actually net CO₂ sources to the atmosphere (Takahashi et al., 2002, 2009; Cai et al., 2010; Zhai et al., 2014).

The emissions of CO₂ by fossil fuels combustion have increased by 29 % in 2000–2008 (Le Quéré et al., 2009) and, as far as natural-water sources are concerned, the contribution from European estuaries is for instance equivalent to approximately 5 to 10 % of the anthropogenic CO₂ emissions in Western Europe (Frankignoulle et al., 1998). The primary production in the oceans contributes approximately 48.5 petagrams (1 Pg = 10¹⁵ g) of C yr⁻¹ (46.2 % of the total), as estimated using the integrated CASA-VGPM biosphere model (Field et al., 1998). As a consequence, approximately one-third to 50 % of the atmospheric CO₂ is fixed annually worldwide by marine phytoplankton (Sabine et al., 2004; Toseland et al., 2013). However, one should also consider that the photoinduced and biological mineralization of organic matter (OM), including DOM and dead organisms, is an important source of DIC in seawater and liberates again an important fraction of the CO₂ fixed by photosynthesis (Bates and Mathis, 2009; Mostofa et al., 2013a).

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Ocean acidification is responsible for changes in the oceanic carbonate system, with effects on partial pressure of CO_2 (PCO_2), DIC, pH, alkalinity and calcium carbonate saturation state (Feely et al., 2010; Beaufort et al., 2011). In the case of calcifying organisms one observes a marked pattern of decreasing calcification with increasing PCO_2 , which follows the corresponding decreasing concentrations of CO_3^{2-} as a consequence of decreasing pH (Beaufort et al., 2011). Such effects finally cause a decline in calcification and growth rates of shellfish (Talmage and Gobler, 2010; Wittmann and Pörtner 2013), of shell-forming marine plankton and of benthic organisms including corals (Kleypas et al., 1999; Doney et al., 2009; Beaufort et al., 2011; Pandolfi et al., 2011; McCulloch et al., 2012). The latter have already been lost or are highly damaged in coastal areas near many countries including Indonesia, Hawaii, Caribbean, Fiji, Maldives, and Australia (Erez et al., 2011). A 30 % decline or damage of coral reef ecosystems has been estimated worldwide, and it is predicted that as much as 60 % of the world's coral reefs might be lost by 2030 (Hughes et al., 2003).

The extent and effects of ocean acidification can be exacerbated by several complex processes, some of which act as stimulating factors, such as local environmental impacts including terrestrial or riverine runoff (Sunda and Cai, 2012; Bauer et al., 2013), modified land-use practices (Lapola et al., 2014) and atmospheric acid rain (Baker et al., 2007). An additional effect could be represented by the enhanced mineralization of DOM and PP (e.g., phytoplankton) as a consequence of global warming (Mostofa et al., 2013a). Such mineralization could be biological (respiration) or abiotic via different (mainly) photochemical processes. Most of the cited effects are expected to cause eutrophication or algal blooms in coastal seawater, which would in turn affect the carbon cycling and the carbonate chemistry and influence the overall acidification process (Beaufort et al., 2011; Sunda and Cai, 2012; Bauer et al., 2013). Such acidification is responsible for changes in the oceanic carbonate system (Feely et al., 2010; Beaufort et al., 2011), which subsequently impacts on marine living organisms and the related ecosystem processes or services (Cooley et al., 2009; Mora et al., 2013; Mostofa et al., 2013a). Considering the possible devastating consequences on the marine ecosys-

tems, their organisms and the related ecosystem services (Cooley et al., 2009; Doney et al., 2009; Cai, 2011; Doney et al., 2012), it is important to ascertain all the possible causes of ocean acidification and their interlinks.

This review will provide an insight into the mechanisms of the ocean acidification, including the interactions between acidification by CO₂ and other processes that could in turn modify the seawater pH. We shall discuss changes in the pH values in both sea surface and subsurface/deeper water extensively with different time scales, from diurnal to multi-annual. We shall also address potential impacts of ocean acidification on marine organisms, along with possible indirect impact processes from a series of stimulating factors (oxidative stress in surface seawater, hypoxia in subsurface/deeper seawater, stress caused by algal or red-tide toxins and pathogens) for both sea surface and subsurface/deeper water. Our review from point of synergistic effects of ocean acidification with such stimulating factors will broaden to understand the potential impact of acidification on biological processes. Such impact is based on the conceptual model provided for both surface and deeper seawaters.

2 Potential mechanisms behind ocean acidification

Ocean acidification includes several potential phenomena that may be operational at the global and/or local scales (Fig. 1): (i) Increasing dissolution of atmospheric CO₂ to seawater, (ii) input of CO₂ plus DIC upon mineralization of PP influenced by elevated atmospheric CO₂, (iii) enhanced PP and respiration due to the effects of global warming and other processes, and (iv) direct acidification and stimulation of PP by atmospheric acid rain. A pictorial scheme of the main operational processes affecting the ocean acidification is depicted in Fig. 1.

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2.1 Increasing dissolution of atmospheric CO₂ to seawater

Enhanced dissolution of atmospheric CO₂ to seawater lowers pH and modifies the carbonate chemistry, affecting both biogenic and sedimentary CaCO₃. This process has extensively been discussed in earlier reviews (Pearson and Palmer, 2000; Feely et al., 2008; Beaufort et al., 2011). For the given seawater, net CO₂ fluxes (either from atmosphere to water or the reverse) may significantly vary depending mostly on time (day or night) and season. Based on a series of studies, six scenarios can be formulated for the net sea–air fluxes of CO₂. They are: (i) sinking or balance of atmospheric CO₂ to seawater under sunlight, and emission or balance of CO₂ to the atmosphere during the night, (ii) emission or balance of CO₂ to the atmosphere during daytime, and sinking or balance of atmospheric CO₂ to surface water during the night, (iii) emission or balance of seawater CO₂ to the atmosphere during both day and night, (iv) sinking or balance of atmospheric CO₂ to surface water during both day and night, (v) sinking or source or balance of atmospheric CO₂ to surface water during the warm period; and (vi) emission or sinking or balance of seawater CO₂ to the atmosphere during the cold period. These scenarios are described in the Supplement.

2.2 Input of CO₂ plus DIC upon mineralization of PP influenced by elevated atmospheric CO₂

The formation and seawater dissolution of CO₂ and DIC produced from photoinduced and biological mineralization of primary producers (PP) or dissolved organic matter (DOM) also lowers pH and modifies the carbonate chemistry (Fig. 2) (Cai et al., 2006, 2011; Feely et al., 2010; Sunda and Cai, 2012; Bates et al., 2013; Mostofa et al., 2013a). Anticorrelation between pH and CO₂ levels during the diurnal cycle has been observed in surface and sub-surface waters (Fig. 2), where CO₂ is mainly originated from the biological respiration of PP or DOM. Such an issue is further complicated by the fact that enhanced levels of CO₂ are partially responsible for the increase of photosynthesis (Behrenfeld et al., 2006; Kranz et al., 2009), and they may have a deep

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impact on the net primary production (PP) (Hein and Sand-Jensen, 1997; Behrenfeld et al., 2006; Jiao et al., 2010). The upper ocean organisms, mostly the autotrophs, are a massive carbon-processing machine that can uptake atmospheric CO_2 and Sand-Jensen, 1997; Falkowski et al., 1998; Sarmiento et al., 2010) or CO_2 plus DIC regenerated from DOM or PP, particularly during the daytime (Fig. 2a; see also Supplement) (Takahashi et al., 2002, 2009; Yates et al., 2007; Chen and Borges, 2009; Mostofa et al., 2013a). In contrast, during the night seawater can become a source of CO_2 , as shown in Fig. 2 in three different contexts. The ability of water to act as a CO_2 source is shown by the higher values of PCO_2 in seawater compared to that in atmosphere (Zhai et al., 2005, 2014; Yates et al., 2007; Chen and Borges, 2009).

The daytime uptake of CO_2 is the consequence of primary production through photosynthesis, which mostly uses dissolved CO_2 via the enzyme ribulosebiphosphate carboxylase (RUBISCO), which governs the carbon-concentrating mechanisms (CCMs) (Yoshioka, 1997; Behrenfeld et al., 2006; Kranz et al., 2009). Mesocosm experiments using ^{14}C -bottle incubations indicate that elevated CO_2 can increase ^{14}C -primary production or bacterial biomass production, also leading to the formation of dissolved organic carbon (DOC) and to its rapid utilization (Engel et al., 2012).

Photosynthetic carbon fixation by marine phytoplankton leads to the formation of ~ 45 gigatons of organic carbon per annum, of which 16 gigatons (~ 35.6 % of the total) are exported to the ocean depths (Falkowski et al., 1998). Furthermore, all primary producers including the large and small cells can contribute to the carbon export from the surface layer of the ocean, at rates proportional to their production rates (Richardson and Jackson, 2007). The reprocessing of this organic material can cause a decrease in the pH of seawater via the CO_2 produced by respiration (Jiao et al., 2010). If, in addition, organic N and P are biologically transformed into NO_3^- and phosphate (Mostofa et al., 2013a) and if there is also transformation of NH_4^+ to N_2 (Doney et al., 2007), there can be a further decrease of seawater alkalinity. Such processes also increase the buffering capacity of seawater (Thomas et al., 2009), which would become more susceptible to acidification caused by the dissolution of atmospheric CO_2 (Thomas

et al., 2009; Cai et al., 2011). A decrease in alkalinity and accompanying acidification may have negative impacts on shellfish production (Hu et al., 2015).

Heterotrophic bacteria are the main organisms that are responsible for respiration in the ocean (> 95%) (Del Giorgio and Duarte, 2002), and half of the respiration (approximately 37 Gt of C year⁻¹) takes place in the euphotic layer (del Giorgio and Williams, 2005). An interesting issue is that such bacteria are also important sources of the superoxide radical anion (O₂^{•-}) (Diaz et al., 2013), the dismutation of which (2O₂^{•-} + 2H⁺ → H₂O₂ + O₂) consumes H⁺ and could partially buffer at local scale the acidification that is connected to the degradation of OM (Mostofa et al., 2013b).

The biological transformation of DOM and PP is active constantly at the sea surface as well as in the subsurface/deeper water, whilst photoinduced degradation is merely active during daytime in the sea surface layer. Of course, such processes show variations associated with seasonal and annual changes in deep-sea geochemistry and biology, along with phenomena associated with ocean circulation (Asper et al., 1992; Thomas et al., 2004). The entire phytoplankton biomass of the global oceans is consumed every two to six days (Behrenfeld and Falkowski, 1997) and part of the carbon fixed by the autotrophs is actually respired in situ (Sarmiento et al., 2010), also providing nutrients for the microbial food web (Behrenfeld et al., 2006; Sarmiento et al., 2010). In some cases, the reprocessing of nutrients is involved in harmful algal blooms or eutrophication by enhanced photosynthesis in surface seawater (Sunda and Cai, 2012; Mostofa et al., 2013a).

2.3 Enhanced PP and respiration due to the effects of global warming and other processes

The dissolution of CO_{2(g)} and DIC released from PP and its subsequent respiration/degradation can be enhanced by the effects of GW (Behrenfeld et al., 2006; Cai et al., 2006, 2011; Kranz et al., 2009; Sunda and Cai, 2012; Mostofa et al., 2013a). GW is a key factor to increase water temperature (WT), which can affect the extent and the duration of the vertical stratification during the summer season. Furthermore,

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the prolonged exposure of the surface water layer to sunlight may cause photoinduced bleaching of sunlight-absorbing DOM, the so-called Color Dissolved Organic Matter (CDOM), thereby enhancing the water column transparency and modifying the depth of the mixing layer or euphotic zone (Behrenfeld et al., 2006; Huisman et al., 2006).

5 The increased stability of the water column may also enhance the photoinduced and biological mineralization of OM, due to the combination of higher temperature and of the longer exposure of the water surface layer to sunlight (Huisman et al., 2006; Vázquez-Domínguez et al., 2007). A further effect is the reduction of subsurface dissolved O₂ because of the decline of vertical winter mixing, which subsequently reduces the exchange of surface oxygenated water to the deeper layers (Fig. 1). Increasing temperature increases the respiration rates in natural waters (Vázquez-Domínguez et al., 2007), and it affects phytoplankton metabolism nearly as significantly as nutrients and light do (Toseland et al., 2013). Various photoinduced and microbial products/compounds formed from DOM or PP (e.g. CO₂, DIC, H₂O₂, NH₄⁺, NO₃⁻, PO₄³⁻, CH₄, autochthonous DOM), the generation of which can be higher in stratified surface water as a consequence of GW, may enhance photosynthesis and, consequently, primary production as schematized in Fig. S1 (Bates and Mathis, 2009; Cai et al., 2011; Mostofa et al., 2013a). Further details are reported in the Supplement.

3 Diurnal, abrupt and homogeneous pH changes in seawater

20 In some locations, the pH of the sea surface water gradually increases during the period before sunrise to noon and then decreases after sunset as a function of the solar irradiation flux (Fig. 3a and b) (Fransson et al., 2004b; Arakaki et al., 2005; Akhand et al., 2013). Furthermore, substantial fluctuations of the pH values during daytime are also observed (Fig. 3a and b) (Fransson et al., 2004a; Arakaki et al., 2005; Clark et al., 2010). The magnitude of the diurnal pH variation can be substantial, ranging from ~ 0.01 in waters with low biological activity to 1.60 in waters with high biological activity that are influenced by riverine inputs, particularly in coastal areas (Table S1).

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More specifically, pH has been observed to increase by 0.03 to 0.81 units in surface coastal seawater, from 0.26 to 1.60 in macroalgae, 0.01 to 0.75 in coral reefs, from 0.17 to > 1.00 in the seagrass community, from 0.03 to 1.59 in CO₂ venting sites, and from 0.04 to 0.10 in polar oceans (Table S1) (Semesei et al., 2009; Taguchi and Fujiwara, 2010; Hofmann et al., 2011). Diurnal pH changes in sea surface waters are apparently triggered by two phenomena. The first and key issue is the consumption or dissolution in seawater of CO₂ that is involved in primary production (Fig. 2a and b) (Akhand et al., 2013; Zhai et al., 2014). Depending on the ratio between photosynthesis and respiration, diurnal fluctuations of *PCO*₂ are observed in seawater and the *PCO*₂ maxima correspond to pH minima and vice versa. In the case of Fig. 2a and b the pH maxima are observed at noon or soon after noon; in other locations they may occur in different times of the day, but the anticorrelation between pH and *PCO*₂ is always observed. At the sea surface one may observe a diurnal decrease in *PCO*₂ with an increase in pH during the day time or in the presence of sunlight (due to the prevalence of photosynthesis), along with an increase in *PCO*₂ with decrease in pH at night when respiration prevails (Yates et al., 2007; Semesei et al., 2009).

A second issue that might affect pH is the photoinduced generation of H₂O₂, primarily by dismutation of superoxide radical anion ($2\text{O}_2^{\bullet-} + 2\text{H}^+ \rightarrow \text{H}_2\text{O}_2 + \text{O}_2$) (Fig. 3a and b) (Arakaki et al., 2005; Clark et al., 2010) and the subsequent production of the strong oxidant, hydroxyl radicals (HO[•]) via photolysis or Fenton and photo-Fenton processes, which are responsible for the degradation of DOM and POM (Vione et al., 2006; Minakata et al., 2009). The linear correlation between pH/[H₂O₂] and the UV intensity (Fig. 3c and d) can be elucidated by considering that both variables are directly influenced by solar irradiation.

Seawater pH is predominantly determined by the balance between consumption (photosynthesis) and release (respiration) of CO₂ as a consequence of the PP activity. In the reported cases the maximum consumption of dissolved CO₂ takes place at the same time of the maximum activity of the photo-stimulated biota. In addition, the positive correlation between [H₂O₂] and UV intensity (Fig. 3c and d) is linked to the fact

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that the $O_2^{\bullet-}$ production rate overlaps with the maximum of solar irradiation, because the biological and photochemical production of $O_2^{\bullet-}$ is activated by light absorption. The concentration of H_2O_2 in sea surface water gradually increases during the period before sunrise to noon and then decreases after sunset as a function of solar irradiation (Fig. 3a and b). The amplitude of the H_2O_2 diurnal cycle (highest concentration at noon time minus concentration during the period before sunrise) ranged from 20 to 365 nM in coastal seas to marine bathing waters (Table S1). Both the $O_2^{\bullet-}$ production and its dismutation with formation of H_2O_2 involve H^+ exchange and can consequently affect the ocean pH. $O_2^{\bullet-}$ is largely produced by the enzyme NADPH oxidase through the synthesis of HO_2^{\bullet} that is a weak acid ($pK_a=4.88$) (Bielski et al., 1985), which dissociates at the oceanic pH releasing H^+ ions according to the following reactions



The production and dismutation of $O_2^{\bullet-}$ is a H^+ -neutral process, but the fate of the superoxide anion is also a consequence of the redox state of the environment. Indeed, superoxide can be oxidized to O_2 ($O_2^{\bullet-} \rightarrow O_2 + e^-$) or reduced to H_2O_2 ($O_2^{\bullet-} + e^- + H^+ \rightarrow H_2O_2$). The prevalence of one of the two processes may not have the same effect on the overall H^+ budget and can consequently affect the acid-base equilibria of oceanic seawater. The generation of $O_2^{\bullet-}$ and consequently of H_2O_2 (Fig. 3a and b) would give an additional contribution to the daytime pH maxima and, as a consequence, could be a further actor in the definition of the daytime pH fluctuation.

Apart from the diurnal cycle, abrupt pH changes caused by both photoinduced and biological processes (overlapping to diurnal changes) have been observed in surface seawater and among the branches of *Pocillopora* colonies in the Great Barrier Reef (Gagliano et al., 2010), in the surface seawater of Okinawa Island (Fig. 3a and b) (Arakaki et al., 2005), in marine bathing waters (Southern California) (Clark et al., 2010), in the North Sea (Blackford and Gilbert, 2007), in the North Pacific Ocean (Byrne et al., 2010), in the Chwaka Bay (Semese et al., 2009) and in the northeast

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Atlantic (Findlay et al., 2014). Such rapid changes in pH are supposed to be a consequence of the primary production as well, although the details of the pH-modifying pathway(s) are still poorly understood. Proposals include several processes in which an intracellular microenvironment is produced, with very different pH values compared to the surrounding seawater, with possible release of intracellular material as a consequence of *e.g.* cell lysis. Among these processes the main are: (i) pH variation connected with aggregates present in photosynthetically active cells or inside colonies (Lubbers et al., 1990), (ii) polyanion-mediated formation of mineral-polymer composites inside alginate microgels or in the Golgi of coccolithophorid algae (Chin et al., 1998), (iii) processes occurring at the site of calcification such as conventional H⁺-channeling, Ca²⁺-H⁺ exchanging ATPase, transcellular symporter and co-transporter H⁺-solute shuttling (Ries, 2011), (iv) cellular extrusion of hydroxyl ions (OH⁻) into the calcifying medium (Ries, 2011); and (v) CO₂-consumption via photosynthesis (Ries, 2011). By the way, the ability to up-regulate pH at the site of calcification can provide corals with enhanced resilience to the effects of ocean acidification (McCulloch et al., 2012). Increased pH during high primary productivity can be justified by the observation of a parallel increase in the $\delta^{13}\text{C}$ values of POM, which may reflect a shift by phytoplankton from using CO₂ to using HCO₃⁻ for photosynthesis (Doi et al., 2006; Akhand et al., 2013). Therefore, uptake of HCO₃⁻ for phytoplankton photosynthesis at high pH might be the effect of its enhanced occurrence in seawater.

Homogeneous (longer-term and constant-rate) acidification in subsurface/deeper seawater is characteristically observed in oceans (Fig. 2c and Table S1; Feely et al., 2008; Byrne et al., 2010; Taguchi and Fujiwara, 2010; Cai et al., 2011; Zhai et al., 2012; Bates et al., 2013), estuaries (Feely et al., 2010), and experimentally in dark incubation (Lubbers et al., 1990). Such a homogeneous pH behavior is also followed in the subsurface water of a large freshwater lake (Fig. S2a). At the beginning of the summer stratification period, pH in subsurface water (at depths of 40 and 80 m) gradually decreases whilst pH in the surface lake water (at depths of 2.5 and 10 m) increases, while dissolved organic carbon (DOC, Fig. S2b) and PP (chlorophyll *a*, Fig. S2c) also

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increase. Similar results, particularly monthly pH variations in surface and deeper seawater, are observed in the Seto Inland Sea during the summer stratification period and during convective mixing periods (Taguchi and Fujiwara, 2010). Homogeneous acidification can vary on a time scale of days to weeks or even months in a wide range of subsurface water at a specific depth (Fig. S3; Byrne et al., 2010; Taguchi and Fujiwara, 2010). For example, pH was 7.4 at ~2000–2500 m depth and 7.5 at ~2500–3400 m depth along with 25° N to 55° N on North Pacific Ocean (Byrne et al., 2010), or pH was 7.0 at 80 m depth during the August–November period (Fig. S3). In the dark, pH decreases gradually inside colonies and also “nightly” decreases of pH occur (Lubbers et al., 1990). Such homogeneous acidification is primarily linked to the dissolution of CO₂ plus DIC originated from the biological degradation of sinking microorganisms (Bates and Mathis, 2009; Cai et al., 2011) and of the DOM originally produced by such organisms (Mostofa et al., 2013a). Enhanced acidification due to the biological degradation of OM can cause undersaturation of aragonite and calcite during the summer period in subsurface/deeper seawater in the Yellow Sea (Figs. 2b, 4) (Zhai et al., 2013), Gulf of Mexico (Cai et al., 2011; Sunda and Cai, 2012), North Pacific Ocean (Byrne et al., 2010), Arctic Ocean (Bates et al., 2013), and Arctic shelves (Bates and Mathis, 2009).

The biological degradation processes are constantly occurring in subsurface/deeper seawater after the onset of early summer, and they continue during the summer stratification period for several months, until the start of winter vertical mixing (Fig. 1). The occurrence and importance of these processes is shown by the increasing trend in subsurface CO₂ followed by a similar decreasing trend of pH. Significant anticorrelation between the two parameters ($r^2 = 0.5$) has been observed in subsurface seawater (13–75 m depth) along 37°25′–39°67′ N to 121°16′–124°10′ E in the Yellow Sea (Fig. 4a). Furthermore, the same evidence was observed in the Seto Inland Sea (Taguchi and Fujiwara, 2010) and in the diurnal samples of Luhuitou fringing reef (Sanya Bay) of South China Sea (Zhang et al., 2013). Strong anticorrelation between $PCO_{2[seawater]}$ and dissolved O₂ ($r^2 = 0.8$; Fig. 4b) supports the production of CO₂ plus DIC from

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the biological respiration/degradation of DOM and PP by heterotrophic bacteria as discussed earlier. Such bacteria also produce the superoxide radical anion ($O_2^{\bullet-}$) (Diaz et al., 2013) that might be further involved in the processing/oxidation of DOM or PP by producing H_2O_2 and consequently $\bullet OH$ via photolysis, photo-Fenton or Fenton-like processes. Such trends of CO_2 (or DIC) vs. dissolved O_2 are also observed in California coastal waters (DeGrandpre et al., 1998), in East China Sea (Zhai and Dai, 2009), in South China Sea (Zhai et al., 2009), and in Seto Inland Sea (Taguchi and Fujiwara, 2010). Biological respiration can be evidenced from an experiment conducted using subsurface water (37 m depth) collected from East China Sea, where the decline in dissolved O_2 is significantly coupled with an increase of DIC production during a 60 h study period (Fig. 4c). The heterotrophic bacteria carry out the largest fraction of respiration ($> 95\%$) in the ocean (Del Giorgio and Duarte, 2002). This means that the heterotrophic community catabolizes an important percentage of the OM produced by the autotrophs (e.g. plants, algae or bacteria) (Laws et al., 2000). Therefore, enhanced primary production or algal blooms in surface seawater and the subsequent sinking are the key processes for homogeneous acidification of the subsurface layer during the summer stratification period, through the degradation of sinking organic material.

4 Possible forthcoming impacts on ocean acidification

An increase in world population (9 billions estimated at 2050) with increasing needs of energy, food, medicines and habitats is one of the key issues (Mostofa et al., 2013a) that will probably contribute not only to the increase of atmospheric CO_2 , but also to the exacerbation of other factors that may also be related to ocean acidification. Such factors include enhanced photosynthesis (because of the release of terrestrial OM and nutrients from increased land use), the increment of OM and nutrients in wastewater, acid rain, and so on. The following issues can be foreseen in the next decades, unless remedial actions of some sort are taken:

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1. Long-term homogenous acidification in the deeper waters of both coastal and oligotrophic oceans, apparently caused by biological respiration of DOM and PP and their subsequent release of CO_2 or DIC, could have key impacts on marine organisms. Such homogenous effects of acidification are directly linked to the effects of GW that can enhance the surface water temperature. The consequence is an extension of the summer stratification period, which would determine acidification in deeper oceans.
2. Coastal seawater from all over the world is at risk of substantial acidification, to a higher extent compared to the open oceans. In fact, in addition to the dissolution of atmospheric CO_2 , coastal seawater would be subjected to acidification processes connected with eutrophication, acid rain and pollution-affected respiration (Doney et al., 2007; Cai et al., 2011; Sunda and Cai, 2012; Zeng et al., 2015). Indeed, OM is substantially increasing in coastal oceans (Bauer et al., 2013). Furthermore, transport phenomena (e.g. oceanic pump) will gradually increase the level of nutrients, DOM and PP from coastal areas in the direction of the oligotrophic open ocean (Fig. 1) (Thomas et al., 2004). Therefore, additional acidification processes in the oligotrophic open ocean could be operational and more significant in the coming decades.
3. Enhanced PP and respiration could increase PCO_2 in open-ocean water and decrease the ability of seawater itself to act as a sink of atmospheric CO_2 . The consequence will be an extension of the zones where seawater acts as a source of CO_2 , which has increased at an average rate of $1.5 \mu\text{atm yr}^{-1}$ in 1970–2007 (Takahashi et al., 2002, 2009). In addition to the contribution to ocean acidification, the decreasing ability of seawater to act as CO_2 sink will also exacerbate the problems related to GW.
4. The present sea–air fluxes of CO_2 (Takahashi et al., 2009) suggest that the equatorial oceans are prevailingly a CO_2 source to the atmosphere while the temperate ones are mainly a sink. Figure 5 reports the predicted pH changes by 2100

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(Mora et al., 2013), showing that acidification is expected to affect all the world's oceans but that the most important effects are predicted for the elevated northern and southern latitudes. Such locations are presently the sites that mostly act as CO₂ sinks, because seawater *PCO*₂ is lower than the atmospheric one, and they will experience the most important pH-associated increase of seawater *PCO*₂. It is thus likely that the global map of sea–air CO₂ fluxes will undergo important changes during the 21st century.

5 Impacts of acidification on marine organisms

Marine organisms at low and high latitudes do not respond uniformly to ocean acidification (Hendriks et al., 2010; Toseland et al., 2013), and the expected effects can thus be stimulative, inhibitive, or neutral (Anthony et al., 2008; Gao et al., 2012a; Hutchins et al., 2013). Considering the overall processes that are involved in ocean acidification (see Fig. 1), it can be assumed that marine organisms would face detrimental impacts under the following conditions: (i) they are peculiarly susceptible to pH changes with different time scales and particularly to acidification, which applies for instance to the majority of marine calcifiers; (ii) they live under hypoxia in long-term homogeneous acidified subsurface/deeper seawater, where they cannot carry out respiration and metabolism properly (this would happen during a stratification period of increasing duration due to GW, which can damage their natural growth and development); and (iii) they are subjected to death/damage in surface seawater by the action of algal toxins and pathogens (e.g. viruses, coliform bacteria, fungi), and/or to oxidative stress caused by reactive oxygen species (ROS) and increased water temperature. In many cases it is extremely difficult (or even next to impossible) to disentangle acidification from other processes that are taking place at the same time. Actually, the impacts of increasing acidification on marine organisms may derive from several processes that are closely interlinked: (i) acidification; (ii) synergistic effects of acidification and oxidative stress in

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surface seawater; (iii) low dissolved O₂ (hypoxia) and acidification in subsurface/deeper seawater, and (iv) stress by algal or red-tide toxins and pathogens.

5.1 Acidification

Impacts induced by seawater acidification or reduced seawater pH are recognized phenomena and they are discussed in many early reviews. However, seawater acidification or reduced seawater pH may produce undersaturation of aragonite and calcite, with the following effects in a variety of seawaters: (i) dissolution of biogenic shells or skeletons, mostly composed of CaCO₃ in the forms of calcite or aragonite, of adult marine calcifiers such as corals (Kleypas et al., 1999; Erez et al., 2011; Pandolfi et al., 2011; Wittmann and Pörtner, 2013), crustose coralline algae (Anthony et al., 2008; Hall-Spencer et al., 2008), shellfish (Talmage and Gobler, 2010; Barton et al., 2012; Wittmann and Pörtner, 2013), marine plankton including foraminifera (De Moel et al., 2009; Moy et al., 2009) and coccolithophores (Riebesell et al., 2000; Beaufort et al., 2011), mollusks (Doney et al., 2009; Wittmann and Pörtner, 2013) and echinoderms (Doney et al., 2009; Wittmann and Pörtner, 2013); sedimentary CaCO₃ would be affected as well (Kleypas et al., 1999; Bates et al., 2013), (ii) inability to form new shells or skeletons of framework builders by larvae or juvenile calcifiers (e.g. the larval and juvenile stages or smaller individuals), particularly at the early development stages. The effect would be operational through the decline of calcification rates, which substantially decreases the growth and development of the organisms including corals (Kleypas et al., 1999; Anthony et al., 2008; Kroeker et al., 2013). As discussed in earlier section, seawater pH varies in different time scales, showing short-term variations (e.g. min to hours: diurnal and abrupt) in upper surface seawater and long-term variations (e.g. weeks to several months: homogeneous) in subsurface and deeper seawater. Long-term homogenous acidification is apparently responsible for the majority of impacts on marine organisms. However, the impact on marine calcifiers of pH variations in different time scales, and most notably the diurnal ones, is presently poorly known and should be the focus for future research.

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5.2 Synergistic effects of acidification and oxidative stress in surface seawater

The rapidly rising levels of atmospheric CO₂ will result in ocean warming in addition to lowering the seawater pH (Solomon et al., 2009; McCulloch et al., 2012). Marine calcifiers are for instance more sensitive to increased temperature under low pH conditions, because of the combination of two stressors (Wood et al., 2010; Pandolfi et al., 2011; Hiebenthal et al., 2013; Kroeker et al., 2013). The synergistic effects of ocean acidification and oxidative stress, elevated water temperature or high irradiance, all connected with increasing CO₂ and GW, can affect marine ecosystems to a variable degree. In some cases the marine primary productivity is decreased (Boyce et al., 2010; Gao et al., 2012a), while in other cases the decrease is not so obvious as tolerance to elevated CO₂ levels may be developed (Feng et al., 2009; Gao et al., 2009; Connell and Russell, 2010). However, even in the latter instances one may observe deep changes in species composition (Meron et al., 2011; Witt et al., 2011), and sometimes even an increase in coral productivity in experimental studies (Anthony et al., 2008). However, a drop in biodiversity is generally observed that is always to the detriment of calcifying organisms (Hall-Spencer et al., 2008; Connell and Russell, 2010). The observed negative effects include bleaching and productivity loss in coral reef builders (Hoegh-Guldberg et al., 2007; Anthony et al., 2008), high mortality and reduction of shell growth and shell breaking force (Hobbs and McDonald, 2010; Lischka et al., 2010; Hiebenthal et al., 2013), declining calcification and enhanced dissolution (Rodolfo-Metalpa et al., 2010), decline in abundance of the juveniles population (Lischka et al., 2010), and increased N : P ratios of eukaryotic phytoplankton (Toseland et al., 2013).

The mechanism behind the oxidative stress at elevated WT or high irradiance is caused by a substantial generation of ROS, such as O₂^{•−}, H₂O₂, HO[•] or ¹O₂, in the surface water layer. The hydroxyl radical (HO[•]), a strong oxidizing agent, is produced from either endogenic or exogenic H₂O₂ through Fenton and photo-Fenton reactions in the presence of metal ions, and upon photolysis of NO₂[−] or NO₃[−] (Zepp et al., 1992; Mostofa et al., 2013c). Note that increasing amounts of NO₂[−] and NO₃[−] may be expected

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in coastal waters, as explained in earlier sections, although the parallel increase in the concentration of dissolved organic matter (DOM) as HO[•] scavenger would produce a partial or even total compensation (Maddigapu et al., 2010). Inside organisms, HO[•] can damage the photosystem II activities and finally cause cell death (Blokhina et al., 2003; Mostofa et al., 2013c). H₂O₂ concentration levels of approximately 100 nM (compared to up to 1700 nM values that have been detected in coastal waters) (Mostofa et al., 2013c) can cause oxidative stress to bacteria, as determined on the basis of increasing catalase enzyme concentration (Angel et al., 1999). H₂O₂ can also reduce bacterial abundances by inducing elevated mortality in seawater (Clark et al., 2008). The oxidative stress that is related to the Fenton processes would even increase in acidified water, where the HO[•] yield is higher (Zepp et al., 1992). Furthermore, in oceanic water, bromide anions can act as major HO[•] scavengers to give the Br[•] radical, which would mainly react with a bromide ion to yield the dibromide radical anion (Br₂^{•-}) (De Laurentiis et al., 2012; Mostofa et al., 2013c). Br₂^{•-} is a moderately strong oxidant ($E_{\text{Br}_2^{\bullet-}/2\text{Br}^-} = 1.63 \text{ V vs. NHE}$) and a brominating agent (Neta et al., 1988; Nair et al., 2001), which is able to promote the formation of bromoderivatives that are usually persistent and toxic pollutants (Steen et al., 2009). Interestingly and coherently with the expected HO[•] yield, the degree of oxidative stress in mollusks has been found to increase with decreasing pH (Tomanek et al., 2011), and the pH effect is further exacerbated by an increase in temperature (Matozzo et al., 2013). Furthermore, the synergistic effect of high H₂O₂ combined with high seawater temperature resulted in a 134 % increase in coral metabolism/respiration rates (Higuchi et al., 2009).

Moreover, one should not only focus on the direct detrimental effects at the organism or single-species level: the negative impacts on the dynamics, structure, composition and biodiversity of the coral reefs (Findlay et al., 2010; Wittmann and Pörtner 2013), of other marine calcifiers (Feng et al., 2009; Wittmann and Pörtner 2013) and of marine ecosystem processes would be linked to changes in species abundance, distribution, predator vulnerability and competitive fitness (Hiscock et al., 2004; Feng et al., 2009; Gao et al., 2012b).

5.3 Synergistic effects of low dissolved O₂ (hypoxia) and acidification in subsurface/deeper seawater

Declining dissolved O₂ in deeper seawater would mostly be caused by reduced vertical mixing as a consequence of GW (Huisman et al., 2006; Keeling et al., 2010), which inhibits reoxygenation while O₂ in deep water is consumed by biological respiration/degradation of sinking organisms and DOM (Fig. 1) (Stramma et al., 2008; Cai et al., 2011; Sunda and Cai, 2012; Zhai et al., 2012; Mostofa et al., 2013a). The key reason for hypoxia is the long-term biological respiration/degradation of sinking OM in the absence of mixing, which is also a key pathway for acidification in sea subsurface water during the summer stratification period, as is discussed in earlier sections. The net decrease of dissolved O₂ in subsurface seawater in the Bohai Sea (China) between June and August 2011 was 34–62 % (see Fig. S3a), which would be the result of OM respiration during the summer stratification period. The hypoxia in subsurface water (40 and 70–80 m depths) (Fig. S3b) along with changes in pH, DOC and primary producers (PP) or Chl *a* (Fig. S2) is linked with enhanced sinking of PP at the end of the summer stratification period. The connection between hypoxia (through respiration of OM) and acidification can be assessed by the positive correlation between pH and dissolved O₂ (Fig. S4), which shows that declining O₂ is directly associated with reduced pH in subsurface/deeper seawaters (Fig. S4; Cai et al., 2011; Zhai et al., 2012; Zhang et al., 2013). The connection between hypoxia and acidification could be exacerbated, and long-term hypoxia could be induced, by two important factors, namely (i) the increase in algal blooms and the subsequently enhanced sinking of dead algae in subsurface/deeper seawater, and (ii) the effects of GW that would induce longer stratification periods as a consequence of a longer summer season, as previously discussed.

Recent study reveals that hypoxia and acidification have synergistic detrimental effects on living organisms, because they can separately affect growth and mortality and their combination can cause damage to organisms that are resistant to the separate stresses (Gobler et al., 2014). Moreover, acidification can cause an additional worsen-

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ing of survival conditions in oxygen-poor waters, which are already made more acidic by the degradation of OM (Melzner et al., 2013). The overall consequences of hypoxia and acidification affect the natural growth and development of organisms (Boyce et al., 2010) and have implications for habitat loss (Keeling et al., 2010; Stramma et al., 2010), fish mortality (Hobbs and McDonald, 2010), nutrient cycling (Keeling et al., 2010; Tose-land et al., 2013), carbon cycling (Keeling et al., 2010), ecosystem functioning (Diaz and Rosenberg, 2008) and diversity, with possible changes of species composition in the benthic-pelagic communities (Diaz and Rosenberg, 2008; Stramma et al., 2010).

5.4 Stress caused by algal or red-tide toxins and pathogens

Harmful algal blooms are expected to increase in coastal waters because of increasing WT and eutrophication (Anderson et al., 2008; Glibert et al., 2010; Mostofa et al., 2013a), which would enhance net primary productivity that is the essential backdrop for the development of such blooms. The same phenomena are also involved in acidification, thus it can be expected that more frequent algal blooms will take place along with ongoing acidification as an additional stress to marine organisms. Algal blooms and acidification could also be more closely linked (Cai et al., 2011; Sunda and Cai, 2012), because the decline of marine algae with a calcareous skeleton could produce a selective advantage for harmful species (Irigoien et al., 2005; Mostofa et al., 2013a).

Harmful algal blooms can produce algal toxins (e.g. microcystins) or red-tide toxins (e.g., brevetoxins) (Flewelling et al., 2005; Anderson et al., 2008), and the occurrence of pathogens (e.g. potentially hazardous fecal-oral viruses, coliform bacteria, parasites, or fungi) (Littler and Littler, 1995; Suttle, 2005) is also more likely in the presence of large phytoplankton cells and during algal blooms (Fuhrman, 1999; Suttle, 2005). Toxins and pathogens are a major cause of morbidity and mortality for marine organisms and they can affect humans as well (Harvell et al., 1999; Flewelling et al., 2005; Anderson et al., 2008). The most common toxins are microcystins, cyanotoxins (blue green algal toxins), okadaic acid (OA), dinophysis toxins (DTXs) and pectenotoxins (PTXs) produced by dinoflagellates (Takahashi et al., 2007), domoic acid (DA) produced by

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diatoms (Takahashi et al., 2007), and brevetoxins produced by the “red tide” dinoflagellate *Karenia brevis* (Flewelling et al., 2005; Anderson et al., 2008). Brevetoxins are potent neurotoxins that kill vast numbers of fish and even large marine mammals: for instance, 34 endangered Florida manatees (*Trichechus manatus latirostris*) died in southwest Florida in the spring of 2002, and 107 bottlenose dolphins (*Tursiops truncatus*) died in waters off the Florida panhandle in the spring of 2004 as a consequence of exposure to brevetoxins (Flewelling et al., 2005). Furthermore, brevetoxins cause illness in humans who ingest contaminated filter-feeding shellfish or inhale toxic aerosols (Flewelling et al., 2005).

Elevated PCO_2 causes bacterial community shifts, with different effects depending on the environment (Allgaier et al., 2008; Witt et al., 2011). However, acidification is also connected to an increase of pathogenic microbiota in corals (Meron et al., 2011). The latter effect is particularly alarming, because coral reefs are already directly endangered by acidification (inhibition of the calcification process, as already discussed) and GW. The reduction in reef-building coral species would be exacerbated by 18 coral diseases identified so far, with increasing prevalence and virulence in most marine taxa (Sutherland et al., 2004). The most concerning diseases are: the black band disease (BBD), probably caused by several species of cyanobacteria including most notably *Phormidium corallyticum* (Rudnick and Ferrari, 1999); the coralline lethal orange disease (CLOD, a bacterial disease affecting coralline algae), which impacts greatly on coral reefs and reef-building processes (Rudnick and Ferrari, 1999); a virulent disease known as white plague type II, which caused widespread mortality in most Caribbean coral species through physical contact with the macroalga *Halimeda opuntia* (Nugues et al., 2004) and, finally, corals bleaching or disease caused by the temperature-dependent bacteria *Vibrio shiloi* (Vidal-Dupiol et al., 2011). Further proposed pathogens for BBD, in addition to *Phormidium corallyticum*, include different genera of cyanobacteria, sulfate-reducing bacteria including *Desulfovibrio* spp., sulfide-oxidizing bacteria presumed to be *Beggiatoa* spp., several other heterotrophs, and ma-

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rine fungi (Sekar et al., 2006). Any bacterial community shifted by elevated CO₂ could thus impact on other marine organisms.

6 Perspectives

Ocean acidification is the outcome of a series of anthropic and natural processes that take place at the same time and are often interlinked. The dissolution of increasing atmospheric CO₂ into seawater obviously plays an important role (Pearson and Palmer, 2000; Feely et al., 2008; Beaufort et al., 2011), but there are also important contributions from the degradation of primary producers and DOM (Cai et al., 2011; Sunda and Cai, 2012; Mostofa et al., 2013a). The latter process could be enhanced by an increased oceanic primary productivity (Feng et al., 2009; Sunda and Cai, 2012; Mostofa et al., 2013a), which is one of the possible consequences of global warming (see also Fig. S1) (Feng et al., 2009; Mostofa et al., 2013c). In coastal areas, acid rains and eutrophication caused by the runoff of terrestrial organic matter including DOM and nutrients (Sunda and Cai, 2012; Bauer et al., 2013), combined with microbial and photochemical degradation (Mostofa et al., 2013a), may be important or even the major causes of acidification. All the described processes would increase the supersaturation of the seawater CO₂ that correspondingly reduces the ability of seawater to take up atmospheric CO₂, thereby extending the oceanic areas that constitute a source instead of a sink or carbon dioxide (presently, such areas are mostly concentrated in the equatorial zone) (see Fig. 1). An important issue is that acidification takes place at varying degrees, with different roles of the factors involved and with different impacts depending on the latitude, on the water temperature range as modified by the effects of GW, and on the distance from the coast (Vitousek et al., 1997; Copin-Montégut et al., 2004; Feely et al., 2008; Yamamoto-Kawai et al., 2009; Beaufort et al., 2011; Bates et al., 2013; Kroeker et al., 2013).

Acidification of seawater would be detrimental to marine organisms, and particularly to marine calcifiers for the long-term (e.g. homogeneous) acidification of subsur-

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face/deeper seawater and possibly also the short-term (e.g. diurnal and abrupt) acidification of upper surface seawater. Therefore, living organisms will have to face multiple stresses at the same time, such as increasing occurrence of reactive oxygen species in the sea surface water, hypoxia in subsurface water, toxic algal blooms and pathogens.

Some of these additional stressors and/or their effects could be enhanced by acidification: the oxidative stress tends to be more severe at lower pH values and in the presence of diurnal and abrupt pH variations in surface water; the effects of hypoxia are exacerbated in long-term homogeneously acidified subsurface/deeper seawater, and a decline in marine calcifiers could provide a competitive advantage for toxic algae. Therefore, ocean acidification is expected to introduce deep changes in marine habitats, and food web processes.

Based on the discussed mechanisms, some of the possible actions that could be taken to limit the future impacts of acidification can be listed here: (i) a reduction of anthropic CO₂ emissions to the atmosphere, which should be carried out in the wider context of fighting global warming and will face the same difficulties; (ii) the implementation of measures aimed at CO₂ capture, such as a worldwide increase in green plantation. In coastal areas, to limit the effects of acidification, some measures could be taken that are probably of somewhat easier implementation: (a) reduction of the inputs to seawater of OM from soil runoff, which implies the control and limitation of land use practices, of soil erosion and of wastewater discharges, (b) limitation of the primary productivity by controlling eutrophication, including the release of nutrients from agricultural activities, (c) removal of algae (e.g. by means of nets) during bloom periods, to avoid fertilization of seawater by the associated nutrients, (d) limitation of the emission of pollutants such as nitrogen and sulfur oxides to the atmosphere, as they are precursors of HNO₃ and H₂SO₄ that are involved in acid rains. Finally, marine oceanographers should focus on how marine organisms are affected by short-term pH variations (e.g. diurnal and abrupt) in surface waters and by long-term (e.g. homogeneous) ones in response to the effects of GW, which may further influence such pH variations.

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References

- Abril, G., Martinez, J.-M., Artigas, L. F., Moreira-Turcq, P., Benedetti, M. F., Vidal, L., Meziane, T., Kim, J.-H., Bernardes, M. C., Savoye, N., Deborde, J., Souza, E. L., Alberic, P., Landim de Souza, M. F., and Roland, F.: Amazon River carbon dioxide outgassing fuelled by wetlands, *Nature*, 505, 395–398, 2014.
- Akhand, A., Chanda, A., Dutta, S., Manna, S., Sanyal, P., Hazra, S., Rao, K., and Dadhwal, V.: Dual character of Sundarban estuary as a source and sink of CO₂ during summer: an investigation of spatial dynamics, *Environ. Monit. Assess.*, 185, 6505–6515, 2013.
- Allgaier, M., Riebesell, U., Vogt, M., Thyrhaug, R., and Grossart, H.-P.: Coupling of heterotrophic bacteria to phytoplankton bloom development at different pCO₂ levels: a mesocosm study, *Biogeosciences*, 5, 1007–1022, doi:10.5194/bg-5-1007-2008, 2008.
- Anderson, D. M., Burkholder, J. M., Cochlan, W. P., Glibert, P. M., Gobler, C. J., Heil, C. A., Kudela, R. M., Parsons, M. L., Rensel, J., and Townsend, D. W.: Harmful algal blooms and eutrophication: examining linkages from selected coastal regions of the United States, *Harmful Algae*, 8, 39–53, 2008.
- Angel, D. L., Fiedler, U., Eden, N., Kress, N., Adelung, D., and Herut, B.: Catalase activity in macro- and microorganisms as an indicator of biotic stress in coastal waters of the eastern Mediterranean Sea, *Helgoland Mar. Res.*, 53, 209–218, 1999.

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Anthony, K., Kline, D., Diaz-Pulido, G., Dove, S., and Hoegh-Guldberg, O.: Ocean acidification causes bleaching and productivity loss in coral reef builders, *P. Natl. Acad. Sci. USA*, 105, 17442–17446, 2008.

Arakaki, T., Fujimura, H., Hamdun, A. M., Okada, K., Kondo, H., Oomori, T., Tanahara, A., and Taira, H.: Simultaneous measurement of hydrogen peroxide and Fe species (Fe (II) and Fe_(tot)) in Okinawa Island seawater: impacts of red soil pollution, *J. Oceanogr.*, 61, 561–568, 2005.

Asper, V. L., Deuser, W., Knauer, G., and Lohrenz, S.: Rapid coupling of sinking particle fluxes between surface and deep ocean waters, *Nature*, 357, 670–672, 1992.

Baker, A. R., Weston, K., Kelly, S. D., Voss, M., Streu, P., and Cape, J. N.: Dry and wet deposition of nutrients from the tropical Atlantic atmosphere: links to primary productivity and nitrogen fixation, *Deep-Sea Res. Pt. I*, 54, 1704–1720, 2007.

Barton, A., Hales, B., Waldbusser, G. G., Langdon, C., and Feely, R. A.: The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects, *Limnol. Oceanogr.*, 57, 698–710, 2012.

Bates, N. R. and Mathis, J. T.: The Arctic Ocean marine carbon cycle: evaluation of air-sea CO₂ exchanges, ocean acidification impacts and potential feedbacks, *Biogeosciences*, 6, 2433–2459, doi:10.5194/bg-6-2433-2009, 2009.

Bates, N. R., Orchowska, M. I., Garley, R., and Mathis, J. T.: Summertime calcium carbonate undersaturation in shelf waters of the western Arctic Ocean – how biological processes exacerbate the impact of ocean acidification, *Biogeosciences*, 10, 5281–5309, doi:10.5194/bg-10-5281-2013, 2013.

Bauer, J. E., Cai, W.-J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., and Regnier, P. A.: The changing carbon cycle of the coastal ocean, *Nature*, 504, 61–70, 2013.

Beaufort, L., Probert, I., de Garidel-Thoron, T., Bendif, E., Ruiz-Pino, D., Metzl, N., Goyet, C., Buchet, N., Coupel, P., and Grelaud, M.: Sensitivity of coccolithophores to carbonate chemistry and ocean acidification, *Nature*, 476, 80–83, 2011.

Behrenfeld, M. J. and Falkowski, P. G.: Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnol. Oceanogr.*, 42, 1–20, 1997.

Behrenfeld, M. J., O'Malley, R. T., Siegel, D. A., McClain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., Falkowski, P. G., Letelier, R. M., and Boss, E. S.: Climate-driven trends in contemporary ocean productivity, *Nature*, 444, 752–755, 2006.

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- Bielski, B. H. J., Cabelli, D. E., Arudi, R. L., and Ross, A. B.: Reactivity of HO₂/O₂⁻ radicals in aqueous solution, *J. Phys. Chem. Ref. Data*, 14, 1041–1100, 1985.
- Blackford, J. and Gilbert, F.: pH variability and CO₂ induced acidification in the North Sea., *J. Marine Syst.*, 64, 229–241, 2007.
- 5 Blokhina, O., Virolainen, E., and Fagerstedt, K. V.: Antioxidants, oxidative damage and oxygen deprivation stress: a review, *Ann. Bot.-London*, 91, 179–194, 2003.
- Boyce, D. G., Lewis, M. R., and Worm, B.: Global phytoplankton decline over the past century, *Nature*, 466, 591–596, 2010.
- Byrne, R. H., Mecking, S., Feely, R. A., and Liu, X.: Direct observations of basin-wide acidification of the North Pacific Ocean, *Geophys. Res. Lett.*, 37, L02601, doi:10.1029/2009GL040999, 2010.
- 10 Cai, W.-J.: Estuarine and coastal ocean carbon paradox: CO₂ sinks or sites of terrestrial carbon incineration?, in: *Annual Review of Marine Science*, edited by: Carlson, C. A. and Giovannoni, S. J., *Annual Reviews*, Palo Alto, 3, 123–145, 2011.
- 15 Cai, W. J., Dai, M., and Wang, Y.: Air–sea exchange of carbon dioxide in ocean margins: a province-based synthesis, *Geophys. Res. Lett.*, 33, L12603, doi:10.1029/2006GL026219, 2006.
- Cai, W.-J., Chen, L., Chen, B., Gao, Z., Lee, S. H., Chen, J., Pierrot, D., Sullivan, K., Wang, Y., Hu, X., Huang, W.-J., Zhang, Y., Xu, S., Murata, A., Grebmeier, J. M., Jones, E. P., and Zhang, H.: Decrease in the CO₂ uptake capacity in an ice-free Arctic Ocean basin, *Science*, 20 329, 556–559, 2010.
- Cai, W. J., Hu, X., Huang, W. J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W. C., Zhai, W., Hollibaugh, J. T., and Wang, Y.: Acidification of subsurface coastal waters enhanced by eutrophication, *Nat. Geosci.*, 4, 766–770, 2011.
- 25 Chen, C.-T. A. and Borges, A. V.: Reconciling opposing views on carbon cycling in the coastal ocean: continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO₂, *Deep-Sea Res. Pt. II*, 56, 578–590, 2009.
- Chin, W.-C., Orellana, M. V., and Verdugo, P.: Spontaneous assembly of marine dissolved organic matter into polymer gels, *Nature*, 391, 568–572, 1998.
- 30 Clark, C. D., De Bruyn, W. J., Jakubowski, S. D., and Grant, S. B.: Hydrogen peroxide production in marine bathing waters: implications for fecal indicator bacteria mortality, *Mar. Pollut. Bull.*, 56, 397–401, 2008.

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Clark, C. D., De Bruyn, W. J., Hirsch, C. M., and Jakubowski, S. D.: Hydrogen peroxide measurements in recreational marine bathing waters in Southern California, USA, *Water Res.* 44, 2203–2210, 2010.

Connell, S. D. and Russell, B. D.: The direct effects of increasing CO₂ and temperature on non-calcifying organisms: increasing the potential for phase shifts in kelp forests, *Proc. R. Soc. B-Biol. Sci.*, 277, 1409–1415, 2010.

Cooley, S. R., Kite-Powell, H. L., and Doney, S. C.: Ocean acidification's potential to alter global marine ecosystem services, *Oceanography*, 22, 172–181, 2009.

Copin-Montégut, C., Bégovic, M., and Merlivat, L.: Variability of the partial pressure of CO₂ on diel to annual time scales in the Northwestern Mediterranean Sea, *Mar. Chem.*, 85, 169–189, 2004.

De Laurentiis, E., Minella, M., Maurino, V., Minero, C., Mailhot, G., Sarakha, M., Brigante, M., and Vione, D.: Assessing the occurrence of the dibromide radical (Br₂^{•-}) in natural waters: measures of triplet-sensitised formation, reactivity, and modelling, *Sci. Total Environ.*, 439, 299–306, 2012.

de Moel, H., Ganssen, G. M., Peeters, F. J. C., Jung, S. J. A., Kroon, D., Brummer, G. J. A., and Zeebe, R. E.: Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification?, *Biogeosciences*, 6, 1917–1925, doi:10.5194/bg-6-1917-2009, 2009.

DeGrandpre, M., Hammar, T., and Wirick, C.: Short-term pCO₂ and O₂ dynamics in California coastal waters, *Deep-Sea Res. Part II*, 45, 1557–1575, 1998.

Del Giorgio, P. A. and Duarte, C. M.: Respiration in the open ocean, *Nature*, 420, 379–384, 2002.

del Giorgio, P. A. and Williams, P.: The global significance of respiration in aquatic ecosystems: from single cells to the biosphere, in: *Respiration in Aquatic Ecosystems*, edited by: del Giorgio, P. A. and Williams, P., Oxford University Press, New York, 267–303, 2005.

Diaz, J. M., Hansel, C. M., Voelker, B. M., Mendes, C. M., Andeer, P. F., and Zhang, T.: Widespread production of extracellular superoxide by heterotrophic bacteria, *Science*, 340, 1223–1226, 2013.

Diaz, R. J. and Rosenberg, R.: Spreading dead zones and consequences for marine ecosystems, *Science*, 321, 926–929, 2008.

Doi, H., Zuykova, E. I., Kikuchi, E., Shikano, S., Kanou, K., Yurlova, N., and Yadrenkina, E.: Spatial changes in carbon and nitrogen stable isotopes of the plankton food web in a saline lake ecosystem, *Hydrobiologia*, 571, 395–400, 2006.

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Doney, S. C., Mahowald, N., Lima, I., Feely, R. A., Mackenzie, F. T., Lamarque, J. F., and Rasch, P. J.: Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system, *P. Natl. Acad. Sci. USA*, 104, 14580–14585, 2007.

5 Doney, S. C., Fabry, V. J., Feely, R. A., and Kleypas, J. A.: Ocean acidification: the other CO₂ problem, *Mar. Sci.*, 1, 169–192, 2009.

Doney, S. C., Ruckelshaus, M., Duffy, J. E., Barry, J. P., Chan, F., English, C. A., Galindo, H. M., Grebmeier, J. M., Hollowed, A. B., Knowlton, N., Polovina, J., Rabalais, N. N., Sydeman, W. J., and Talley, L. D.: Climate change impacts on marine ecosystems, in: *Annual Review of Marine Science*, edited by: Carlson, C. A. and Giovannoni, S. J., *Annual Reviews*, Palo Alto, 4, 11–37, 2012.

Engel, A., Borchard, C., Piontek, J., Schulz, K. G., Riebesell, U., and Bellerby, R.: CO₂ increases ¹⁴C primary production in an Arctic plankton community, *Biogeosciences*, 10, 1291–1308, doi:10.5194/bg-10-1291-2013, 2013.

15 Erez, J., Reynaud, S., Silverman, J., Schneider, K., and Allemand, D.: Coral calcification under ocean acidification and global change, in: “Coral Reefs: an Ecosystem in Transition”, edited by: Dubinsky, Z. and Stambler, N., Springer, Dordrecht, the Netherlands, 151–176, 2011.

Falkowski, P. G., Barber, R. T., and Smetacek, V.: Biogeochemical controls and feedbacks on ocean primary production, *Science*, 281, 200–206, 1998.

20 Feely, R. A., Sabine, C. L., Hernandez-Ayon, J. M., Janson, D., and Hales, B.: Evidence for upwelling of corrosive “acidified” water onto the continental shelf, *Science*, 320, 1490–1492, 2008.

Feely, R. A., Alin, S. R., Newton, J., Sabine, C. L., Warner, M., Devol, A., Krembs, C., and Maloy, C.: The combined effects of ocean acidification, mixing, and respiration on pH and carbonate saturation in an urbanized estuary, *Estuar. Coast. Shelf S.*, 88, 442–449, 2010.

25 Feng, Y., Hare, C. E., Leblanc, K., Rose, J. M., Zhang, Y., DiTullio, G. R., Lee, P., Wilhelm, S., Rowe, J. M., and Sun, J.: The effects of increased *p*CO₂ and temperature on the North Atlantic spring bloom: I. The phytoplankton community and biogeochemical response, *Mar. Ecol.-Prog. Ser.*, 388, 13–25, 2009.

30 Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P.: Primary production of the biosphere: integrating terrestrial and oceanic components, *Science*, 281, 237–240, 1998.

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Findlay, H. S., Kendall, M. A., Spicer, J. I., and Widdicombe, S.: Relative influences of ocean acidification and temperature on intertidal barnacle post-larvae at the northern edge of their geographic distribution, *Estuar. Coast. Shelf S.*, 86, 675–682, 2010.

Findlay, H. S., Hennige, S. J., Wicks, L. C., Navas, J. M., Woodward, E. M. S., and Roberts, J. M.: Fine-scale nutrient and carbonate system dynamics around cold-water coral reefs in the northeast Atlantic, *Sci. Rep.*, 4, 1–10, 2014.

Flewelling, L. J., Naar, J. P., Abbott, J. P., Baden, D. G., Barros, N. B., Bossart, G. D., Bottein, M.-Y. D., Hammond, D. G., Haubold, E. M., and Heil, C. A.: Brevetoxicosis: red tides and marine mammal mortalities, *Nature*, 435, 755–756, 2005.

Frankignoulle, M., Abril, G., Borges, A., Bourge, I., Canon, C., Delille, B., Libert, E., and Théate, J.-M.: Carbon dioxide emission from European estuaries, *Science*, 282, 434–436, 1998.

Fransson, A., Chierici, M., Anderson, L., and David, R.: Transformation of carbon and oxygen in the surface layer of the eastern Atlantic sector of the Southern Ocean, *Deep-Sea Res. Pt. II*, 51, 2757–2772, 2004a.

Fransson, A., Chierici, M., and Anderson, L. G.: Diurnal variability in the oceanic carbon dioxide system and oxygen in the Southern Ocean surface water, *Deep-Sea Res. Pt. II*, 51, 2827–2839, 2004b.

Fuhrman, J. A.: Marine viruses and their biogeochemical and ecological effects, *Nature*, 399, 541–548, 1999.

Gagliano, M., McCormick, M. I., Moore, J. A., and Depczynski, M.: The basics of acidification: baseline variability of pH on Australian coral reefs, *Mar. Biol.*, 157, 1849–1856, 2010.

Gao, K., Ruan, Z., Villafane, V. E., Gattuso, J.-P., and Helbling, E. W.: Ocean acidification exacerbates the effect of UV radiation on the calcifying phytoplankter *Emiliania huxleyi*, *Limnol. Oceanogr.*, 54, 1855–1862, 2009.

Gao, K., Helbling, E. W., Häder, D.-P., and Hutchins, D. A.: Responses of marine primary producers to interactions between ocean acidification, solar radiation, and warming, *Mar. Ecol.-Prog. Ser.*, 470, 167–189, 2012a.

Gao, K., Xu, J., Gao, G., Li, Y., Hutchins, D. A., Huang, B., Wang, L., Zheng, Y., Jin, P., and Cai, X.: Rising CO₂ and increased light exposure synergistically reduce marine primary productivity, *Nature Climate Change*, 2, 519–523, 2012b.

Ocean acidification and its potential impacts on marine ecosystems

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Glibert, P. M., Allen, J., Bouwman, A., Brown, C. W., Flynn, K. J., Lewitus, A. J., and Mad-
den, C. J.: Modeling of HABs and eutrophication: status, advances, challenges, *J. Marine*
Syst., 83, 262–275, 2010.

Gobler, C. J., DePasquale, E. L., Griffith, A. W., and Baumann, H.: Hypoxia and acidification
have additive and synergistic negative effects on the growth, survival, and metamorphosis of
early life stage bivalves, *PLoS one*, 9, e83648, doi:10.1371/journal.pone.0083648, 2014.

Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M.,
Rowley, S. J., Tedesco, D., and Buia, M.-C.: Volcanic carbon dioxide vents show ecosystem
effects of ocean acidification, *Nature*, 454, 96–99, 2008.

Haroon, M. F., Hu, S., Shi, Y., Imelfort, M., Keller, J., Hugenholtz, P., Yuan, Z., and Tyson, G. W.:
Anaerobic oxidation of methane coupled to nitrate reduction in a novel archaeal lineage,
Nature, 500, 567–570, 2013.

Harvell, C., Kim, K., Burkholder, J., Colwell, R., Epstein, P. R., Grimes, D., Hofmann, E., Lipp, E.,
Osterhaus, A., and Overstreet, R. M.: Emerging marine diseases—climate links and anthro-
pogenic factors, *Science*, 285, 1505–1510, 1999.

Hein, M. and Sand-Jensen, K.: CO₂ increases oceanic primary production, *Nature*, 388, 526–
527, 1997.

Hendriks, I. E., Duarte, C. M., and Álvarez, M.: Vulnerability of marine biodiversity to ocean
acidification: a meta-analysis, *Estuar. Coast. Shelf S.*, 86, 157–164, 2010.

Hiebenthal, C., Philipp, E. E., Eisenhauer, A., and Wahl, M.: Effects of seawater pCO₂ and
temperature on shell growth, shell stability, condition and cellular stress of Western Baltic
Sea *Mytilus edulis* (L.) and *Arctica islandica* (L.), *Mar. Biol.*, 160, 2073–2087, 2013.

Higuchi, T., Fujimura, H., Arakaki, T., and Oomori, T.: The synergistic effects of hydrogen per-
oxide and elevated seawater temperature on the metabolic activity of the coral *Galaxea fas-*
cicularis, *Mar. Biol.*, 156, 589–596, 2009.

Hiscock, K., Southward, A., Tittley, I., and Hawkins, S.: Effects of changing temperature on
benthic marine life in Britain and Ireland, *Aquat. Conserv.*, 14, 333–362, 2004.

Hobbs, J. and McDonald, C.: Increased seawater temperature and decreased dissolved oxygen
triggers fish kill at the Cocos (Keeling) Islands, Indian Ocean, *J. Fish Biol.*, 77, 1219–1229,
2010.

Hoegh-Guldberg, O., Mumby, P., Hooten, A., Steneck, R., Greenfield, P., Gomez, E., Harvell, C.,
Sale, P., Edwards, A., and Caldeira, K.: Coral reefs under rapid climate change and ocean
acidification, *Science*, 318, 1737–1742, 2007.

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- Hofmann, G. E., Smith, J. E., Johnson, K. S., Send, U., Levin, L. A., Micheli, F., Paytan, A., Price, N. N., Peterson, B., and Takeshita, Y.: High-frequency dynamics of ocean pH: a multi-ecosystem comparison, *PloS one*, 6, e28983, doi:10.1371/journal.pone.0028983, 2011.
- Hu, X., Pollack, J. B., McCutcheon, M. R., Montagna, P. A., and Ouyang, Z.: Long-term alkalinity decrease and acidification of estuaries in northwestern Gulf of Mexico, *Environ. Sci. Technol.*, 49, 3401–3409, 2015.
- Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J., and Kleypas, J.: Climate change, human impacts, and the resilience of coral reefs, *Science*, 301, 929–933, 2003.
- Huisman, J., Thi, N. N. P., Karl, D. M., and Sommeijer, B.: Reduced mixing generates oscillations and chaos in the oceanic deep chlorophyll maximum, *Nature*, 439, 322–325, 2006.
- Hutchins, D. A., Fu, F.-X., Webb, E. A., Walworth, N., and Tagliabue, A.: Taxon-specific response of marine nitrogen fixers to elevated carbon dioxide concentrations, *Nat. Geosci.*, 6, 790–795, 2013.
- Irigoien, X., Flynn, K., and Harris, R.: Phytoplankton blooms: a “loophole” in microzooplankton grazing impact?, *J. Plankton Res.*, 27, 313–321, 2005.
- Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., Kirchman, D. L., Weinbauer, M. G., Luo, T., and Chen, F.: Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean, *Nature Rev. Microbiol.*, 8, 593–599, 2010.
- Keeling, R. F., Körtzinger, A., and Gruber, N.: Ocean deoxygenation in a warming world, *Ann. Rev. Mar. Sci.*, 2, 199–229, 2010.
- King, J. Y., Brandt, L. A., and Adair, E. C.: Shedding light on plant litter decomposition: advances, implications and new directions in understanding the role of photodegradation, *Biogeochemistry*, 111, 57–81, 2012.
- Kleypas, J. A., Buddemeier, R. W., Archer, D., Gattuso, J.-P., Langdon, C., and Opdyke, B. N.: Geochemical consequences of increased atmospheric carbon dioxide on coral reefs, *Science*, 284, 118–120, 1999.
- Knorr, W., Prentice, I. C., House, J. I., and Holland, E. A.: Long-term sensitivity of soil carbon turnover to warming, *Nature*, 433, 298–301, 2005.
- Kranz, S., Sültemeyer, D., Richter, K.-U., and Rost, B.: Carbon acquisition in *Trichodesmium*: the effect of $p\text{CO}_2$ and diurnal changes, *Limnol. Oceanogr.*, 54, 548–559, 2009.

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- Kroeker, K. J., Micheli, F., and Gambi, M. C.: Ocean acidification causes ecosystem shifts via altered competitive interactions, *Nature Climate Change*, 3, 156–159, 2013.
- Lapola, D. M., Martinelli, L. A., Peres, C. A., Ometto, J. P., Ferreira, M. E., Nobre, C. A., Aguiar, A. P. D., Bustamante, M. M., Cardoso, M. F., and Costa, M. H.: Pervasive transition of the Brazilian land-use system, *Nature Climate Change*, 4, 27–35, 2014.
- Laws, E. A., Falkowski, P. G., Smith, W. O., Ducklow, H., and McCarthy, J. J.: Temperature effects on export production in the open ocean, *Global Biogeochem. Cy.*, 14, 1231–1246, 2000.
- Le Quéré, C., Raupach, M. R., Canadell, J. G., and Marland, G.: Trends in the sources and sinks of carbon dioxide, *Nat. Geosci.*, 2, 831–836, 2009.
- Lischka, S., Büdenbender, J., Boxhammer, T., and Riebesell, U.: Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth, *Biogeosciences*, 8, 919–932, doi:10.5194/bg-8-919-2011, 2011.
- Littler, M. M. and Littler, D. S.: Impact of CLOD pathogen on Pacific coral reefs, *Science*, 267, 1356–1356, 1995.
- Lubbers, G., Gieskes, W., Del Castilho, P., Salomons, W., and Bril, J.: Manganese accumulation in the high pH microenvironment of *Phaeocystis* sp. (*Haptophyceae*) colonies from the North Sea, *Mar. Ecol.-Prog. Ser.*, 59, 285–293, 1990.
- Maddigapu, P. R., Minella, M., Vione, D., Maurino, V., and Minero, C.: Modeling phototransformation reactions in surface water bodies: 2, 4-Dichloro-6-nitrophenol as a case study, *Environ. Sci. Technol.*, 45, 209–214, 2010.
- Matozzo, V., Chinellato, A., Munari, M., Bressan, M., and Marin, M. G.: Can the combination of decreased pH and increased temperature values induce oxidative stress in the clam *Chamelea gallina* and the mussel *Mytilus galloprovincialis*?, *Mar. Pollut. Bull.*, 72, 34–40, 2013.
- McCulloch, M., Falter, J., Trotter, J., and Montagna, P.: Coral resilience to ocean acidification and global warming through pH up-regulation, *Nature Climate Change*, 2, 623–627, 2012.
- Melzner, F., Thomsen, J., Koeve, W., Oschlies, A., Gutowska, M. A., Bange, H. W., Hansen, H. P., and Körtzinger, A.: Future ocean acidification will be amplified by hypoxia in coastal habitats, *Mar. Biol.*, 160, 1875–1888, 2013.
- Meron, D., Atias, E., Kruh, L. I., Elifantz, H., Minz, D., Fine, M., and Banin, E.: The impact of reduced pH on the microbial community of the coral *Acropora eurystoma*, *ISME J.*, 5, 51–60, 2011.

- Minakata, D., Li, K., Westerhoff, P., and Crittenden, J.: Development of a group contribution method to predict aqueous phase hydroxyl radical (HO^\bullet) reaction rate constants, *Environ. Sci. Technol.*, 43, 6220–6227, 2009.
- Mora, C., Wei, C.-L., Rollo, A., Amaro, T., Baco, A. R., Billett, D., Bopp, L., Chen, Q., Collier, M., and Danovaro, R.: Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century, *PLoS Biol.*, 11, e1001682, doi:10.1371/journal.pbio.1001682, 2013.
- Mostofa, K. M. G., Liu, C.-Q., Vione, D., Gao, K., and Ogawa, H.: Sources, factors, mechanisms and possible solutions to pollutants in marine ecosystems, *Environ. Pollut.*, 182, 461–478, 2013a.
- Mostofa, K. M. G., Liu, C.-Q., Minella, M., and Vione, D.: Balancing of ocean acidification by superoxide redox chemistry?, *Environ. Sci. Technol.*, 47, 11380–11381, 2013b.
- Mostofa, K. M. G., Yoshioka, T., Mottaleb, A., and Vione, D.: *Photobiogeochemistry of Organic Matter: Principles and Practices in Water Environments*, Springer, Berlin Heidelberg, 2013c.
- Moy, A. D., Howard, W. R., Bray, S. G., and Trull, T. W.: Reduced calcification in modern Southern Ocean planktonic foraminifera, *Nat. Geosci.*, 2, 276–280, 2009.
- Nair, V., Panicker, S. B., Augustine, A., George, T. G., Thomas, S., and Vairamani, M.: An efficient bromination of alkenes using cerium (IV) ammonium nitrate (CAN) and potassium bromide, *Tetrahedron*, 57, 7417–7422, 2001.
- Neta, P., Huie, R. E., and Ross, A. B.: Rate constants for reactions of inorganic radicals in aqueous solution, *J. Phys. Chem. Ref. Data*, 17, 1027–1284, 1988.
- Nugues, M. M., Smith, G. W., Hoodonk, R. J., Seabra, M. I., and Bak, R. P.: Algal contact as a trigger for coral disease, *Ecol. Lett.*, 7, 919–923, 2004.
- Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R. M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R. G., Plattner, G.-K., Rodgers, K. B., Sabine, C. L., Sarmiento, J. L., Schlitzer, R., Slater, R. D., Totterdell, I. J., Weirig, M.-F., Yamanaka, Y., and Yool, A.: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, 437, 681–686, 2005.
- Pandolfi, J. M., Connolly, S. R., Marshall, D. J., and Cohen, A. L.: Projecting coral reef futures under global warming and ocean acidification, *Science*, 333, 418–422, 2011.
- Pearson, P. N. and Palmer, M. R.: Atmospheric carbon dioxide concentrations over the past 60 million years, *Nature*, 406, 695–699, 2000.

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- Richardson, T. L. and Jackson, G. A.: Small phytoplankton and carbon export from the surface ocean, *Science*, 315, 838–840, 2007.
- Riebesell, U., Zondervan, I., Rost, B., Tortell, P. D., Zeebe, R. E., and Morel, F. M.: Reduced calcification of marine plankton in response to increased atmospheric CO₂, *Nature*, 407, 364–367, 2000.
- Ries, J. B.: A physicochemical framework for interpreting the biological calcification response to CO₂-induced ocean acidification, *Geochim. Cosmochim. Ac.*, 75, 4053–4064, 2011.
- Rodolfo-Metalpa, R., Lombardi, C., Cocito, S., Hall-Spencer, J. M., and Gambi, M. C.: Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO₂ vents, *Mar. Ecol.*, 31, 447–456, 2010.
- Rudnick, D. L. and Ferrari, R.: Compensation of horizontal temperature and salinity gradients in the ocean mixed layer, *Science*, 283, 526–529, 1999.
- Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., Bullister, J. L., Wanninkhof, R., Wong, C., Wallace, D. W., and Tilbrook, B.: The oceanic sink for anthropogenic CO₂, *Science*, 305, 367–371, 2004.
- Sarmiento, H., Montoya, J. M., Vázquez-Domínguez, E., Vaqué, D., and Gasol, J. M.: Warming effects on marine microbial food web processes: how far can we go when it comes to predictions?, *Philos. T. Roy. Soc. B*, 365, 2137–2149, 2010.
- Sekar, R., Mills, D. K., Remily, E. R., Voss, J. D., and Richardson, L. L.: Microbial communities in the surface mucopolysaccharide layer and the black band microbial mat of black band-diseased *Siderastrea siderea*, *Appl. Environ. Microb.*, 72, 5963–5973, 2006.
- Semesi, I. S., Beer, S., and Björk, M.: Seagrass photosynthesis controls rates of calcification and photosynthesis of calcareous macroalgae in a tropical seagrass meadow, *Mar. Ecol.-Prog. Ser.*, 382, 41–47, 2009.
- Sobek, S., Tranvik, L. J., and Cole, J. J.: Temperature independence of carbon dioxide supersaturation in global lakes, *Global Biogeochem. Cy.*, 19, GB2003, doi:10.1029/2004GB002264, 2005.
- Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P.: Irreversible climate change due to carbon dioxide emissions, *P. Natl. Acad. Sci. USA*, 106, 1704–1709, 2009.
- Steen, P. O., Grandbois, M., McNeill, K., and Arnold, W. A.: Photochemical formation of halogenated dioxins from hydroxylated polybrominated diphenyl ethers:OH-PBDEs) and chlorinated derivatives (OH-PBCDEs), *Environ. Sci. Technol.*, 43, 4405–4411, 2009.

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- Stramma, L., Johnson, G. C., Sprintall, J., and Mohrholz, V.: Expanding oxygen-minimum zones in the tropical oceans, *Science*, 320, 655–658, 2008.
- Stramma, L., Schmidtko, S., Levin, L. A., and Johnson, G. C.: Ocean oxygen minima expansions and their biological impacts, *Deep-Sea Res. Pt. I*, 57, 587–595, 2010.
- 5 Sunda, W. G. and Cai, W.-J.: Eutrophication induced CO₂-acidification of subsurface coastal waters: interactive effects of temperature, salinity, and atmospheric PCO₂, *Environ. Sci. Technol.*, 46, 10651–10659, 2012.
- Sutherland, K. P., Porter, J. W., and Torres, C.: Disease and immunity in Caribbean and Indo-Pacific zooxanthellate corals, *Mar. Ecol.-Prog. Ser.*, 266, 265–272, 2004.
- 10 Suttle, C. A.: Viruses in the sea, *Nature*, 437, 356–361, 2005.
- Taguchi, F. and Fujiwara, T.: Carbon dioxide stored and acidified low oxygen bottom waters in coastal seas, Japan, *Estuarine, Coast. Shelf Sci.*, 86, 429–433, 2010.
- Takahashi, E., Yu, Q., Eaglesham, G., Connell, D. W., McBroom, J., Costanzo, S., and Shaw, G. R.: Occurrence and seasonal variations of algal toxins in water, phytoplankton and shellfish from North Stradbroke Island, Queensland, Australia, *Mar. Environ. Res.*, 64, 429–442, 2007.
- 15 Takahashi, T., Sutherland, S. C., Sweeney, C., Poisson, A., Metz, N., Tilbrook, B., Bates, N., Wanninkhof, R., Feely, R. A., and Sabine, C.: Global sea–air CO₂ flux based on climatological surface ocean pCO₂, and seasonal biological and temperature effects, *Deep-Sea Res. Pt. II*, 49, 1601–1622, 2002.
- 20 Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W., Hales, B., Friederich, G., Chavez, F., and Sabine, C.: Climatological mean and decadal change in surface ocean pCO₂, and net sea–air CO₂ flux over the global oceans, *Deep-Sea Res. Pt. II*, 56, 554–577, 2009.
- 25 Talmage, S. C. and Gobler, C. J.: Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish, *P. Natl. Acad. Sci. USA*, 107, 17246–17251, 2010.
- Thomas, H., Bozec, Y., Elkalay, K., and de Baar, H. J. W.: Enhanced open ocean storage of CO₂ from shelf sea pumping, *Science*, 304, 1005–1008, 2004.
- 30 Thomas, H., Schiettecatte, L.-S., Suykens, K., Koné, Y. J. M., Shadwick, E. H., Prowe, A. E. F., Bozec, Y., de Baar, H. J. W., and Borges, A. V.: Enhanced ocean carbon storage from anaerobic alkalinity generation in coastal sediments, *Biogeosciences*, 6, 267–274, doi:10.5194/bg-6-267-2009, 2009.

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Tomanek, L., Zuzow, M. J., Ivanina, A. V., Beniash, E., and Sokolova, I. M.: Proteomic response to elevated PCO_2 level in eastern oysters, *Crassostrea virginica*: evidence for oxidative stress, *J. Exp. Biol.*, 214, 1836–1844, 2011.

Torres, M. A., West, A. J., and Li, G.: Sulphide oxidation and carbonate dissolution as a source of CO_2 over geological timescales, *Nature*, 507, 346–349, 2014.

Toseland, A., Daines, S. J., Clark, J. R., Kirkham, A., Strauss, J., Uhlig, C., Lenton, T. M., Valentin, K., Pearson, G. A., Moulton, V., and Mock, T.: The impact of temperature on marine phytoplankton resource allocation and metabolism, *Nature Climate Change*, 3, 979–984, 2013.

van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J., and Randerson, J.: CO_2 emissions from forest loss, *Nat. Geosci.*, 2, 737–738, 2009.

Vázquez-Domínguez, E., Vaqué, D., and Gasol, J. M.: Ocean warming enhances respiration and carbon demand of coastal microbial plankton, *Glob. Change Biol.*, 13, 1327–1334, 2007.

Vidal-Dupiol, J., Ladrière, O., Meistertzheim, A.-L., Fouré, L., Adjeroud, M., and Mitta, G.: Physiological responses of the scleractinian coral *Pocillopora damicornis* to bacterial stress from *Vibrio coralliilyticus*, *J. Exp. Biol.*, 214, 1533–1545, 2011.

Vione, D., Falletti, G., Maurino, V., Minero, C., Pelizzetti, E., Malandrino, M., Ajassa, R., Olariu, R.-I., and Arsene, C.: Sources and sinks of hydroxyl radicals upon irradiation of natural water samples, *Environ. Sci. Technol.*, 40, 3775–3781, 2006.

Vitousek, P. M., Aber, J. D., Howarth, R. W., Likens, G. E., Matson, P. A., Schindler, D. W., Schlesinger, W. H., and Tilman, D. G.: Human alteration of the global nitrogen cycle: sources and consequences, *Ecol. Appl.*, 7, 737–750, 1997.

Witt, V., Wild, C., Anthony, K. R. N., Diaz-Pulido, G., and Uthicke, S.: Effects of ocean acidification on microbial community composition of, and oxygen fluxes through, biofilms from the Great Barrier Reef, *Environ. Microbiol.*, 13, 2976–2989, 2011.

Wittmann, A. C. and Pörtner, H.-O.: Sensitivities of extant animal taxa to ocean acidification, *Nature Climate Change*, 3, 995–1001, 2013.

Wood, H. L., Spicer, J., Lowe, D., and Widdicombe, S.: Interaction of ocean acidification and temperature; the high cost of survival in the brittlestar *Ophiura ophiura*, *Mar. Biol.*, 157, 2001–2013, 2010.

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Yamamoto-Kawai, M., McLaughlin, F. A., Carmack, E. C., Nishino, S., and Shimada, K.: Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt, *Science*, 326, 1098–1100, 2009.

Yates, K. K., Dufore, C., Smiley, N., Jackson, C., and Halley, R. B.: Diurnal variation of oxygen and carbonate system parameters in Tampa Bay and Florida Bay, *Mar. Chem.*, 104, 110–124, 2007.

Yoshioka, T.: Phytoplanktonic carbon isotope fractionation: equations accounting for CO₂-concentrating mechanisms, *J. Plankton Res.*, 19, 1455–1476, 1997.

Zeng, X., Chen, X., and Zhuang, J.: The positive relationship between ocean acidification and pollution, *Mar. Pollut. Bull.*, 91, 14–21, 2015.

Zepp, R. G., Faust, B. C., and Hoigne, J.: Hydroxyl radical formation in aqueous reactions (pH 3–8) of iron (II) with hydrogen peroxide: the photo-Fenton reaction, *Environ. Sci. Technol.*, 26, 313–319, 1992.

Zhai, W. D. and Dai, M.: On the seasonal variation of air–sea CO₂ fluxes in the outer Changjiang (Yangtze River) estuary, East China Sea, *Mar. Chem.*, 117, 2–10, 2009.

Zhai, W. D., Dai, M., Cai, W.-J., Wang, Y., and Hong, H.: The partial pressure of carbon dioxide and air–sea fluxes in the northern South China Sea in spring, summer and autumn, *Mar. Chem.*, 96, 87–97, 2005.

Zhai, W. D., Dai, M., and Cai, W.-J.: Coupling of surface pCO₂ and dissolved oxygen in the northern South China Sea: impacts of contrasting coastal processes, *Biogeosciences*, 6, 2589–2598, doi:10.5194/bg-6-2589-2009, 2009.

Zhai, W. D., Zhao, H., Zheng, N., and Xu, Y.: Coastal acidification in summer bottom oxygen-depleted waters in northwestern-northern Bohai Sea from June to August in 2011, *Chinese Sci. Bull.*, 57, 1062–1068, 2012.

Zhai, W.-D., Dai, M.-H., Chen, B.-S., Guo, X.-H., Li, Q., Shang, S.-L., Zhang, C.-Y., Cai, W.-J., and Wang, D.-X.: Seasonal variations of sea–air CO₂ fluxes in the largest tropical marginal sea (South China Sea) based on multiple-year underway measurements, *Biogeosciences*, 10, 7775–7791, doi:10.5194/bg-10-7775-2013, 2013.

Zhai, W.-D., Zheng, N., Huo, C., Xu, Y., Zhao, H.-D., Li, Y.-W., Zang, K.-P., Wang, J.-Y., and Xu, X.-M.: Subsurface pH and carbonate saturation state of aragonite on the Chinese side of the North Yellow Sea: seasonal variations and controls, *Biogeosciences*, 11, 1103–1123, doi:10.5194/bg-11-1103-2014, 2014.

Zhang, C., Huang, H., Ye, C., Huang, L., Li, X., Lian, J., and Liu, S.: Diurnal and seasonal variations of carbonate system parameters on Luhuitou fringing reef, Sanya Bay, Hainan Island, South China Sea, Deep-Sea Res. Pt. II, 96, 65–74, 2013.

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12, 10939–10983, 2015

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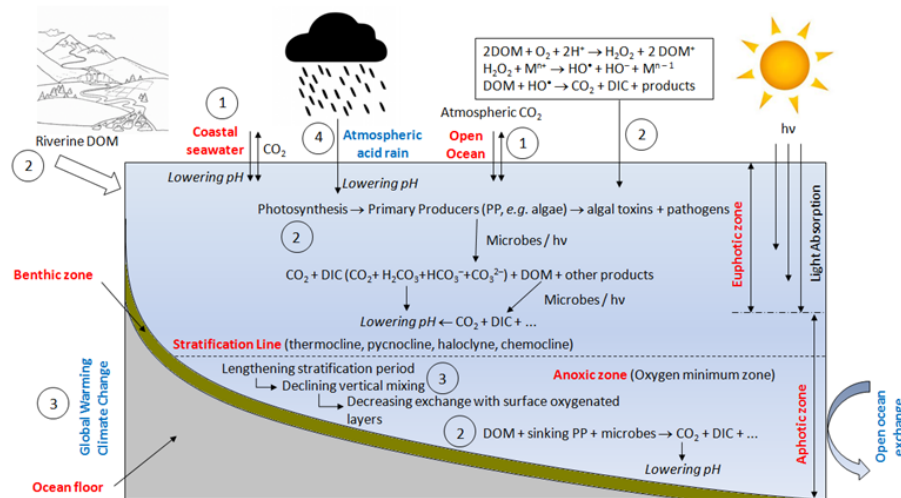


Figure 1. A conceptual model of acidification in coastal to open oceans, showing either dissolution of atmospheric CO_2 or emission of aquatic CO_2 plus DIC originated from the photoinduced and/or biological respiration of primary producers (PP). The latter includes both dissolved organic matter (DOM) and PP (1). Uptake of such CO_2 is primarily responsible for the occurrence of photosynthesis and PP (2) that can generate algal toxins or pathogens in the euphotic zone, along with generation of CO_2 , DIC and other products; PP can also be enhanced by autochthonous DOM (2), by DOM or sinking cells in subsurface or deeper seawater (2), and by riverine DOM (2). Atmospheric acid rain (mostly HNO_3 and H_2SO_4) can contribute directly to the acidification (3). Global warming can lengthen the stratification period with a subsequent decline in vertical mixing, which reduces the exchange with surface oxygenated water (4).

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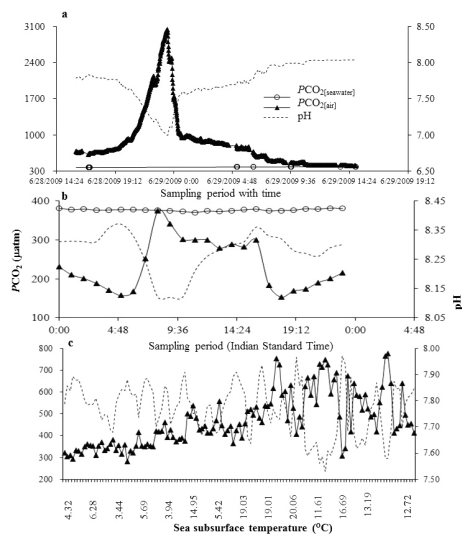


Figure 2. Diurnal variation of pH along with $f\text{CO}_2$ _[seawater] (μatm) and $f\text{CO}_2$ _[air] (μatm) in surface seawater of the Jiulongjiang estuary (a) and the Bay of Bengal (b). pH, $f\text{CO}_2$ _[seawater] (μatm) and sea subsurface temperature for seawater samples (from 13 to 75 m depth) in the North Yellow Sea (c). Samples from the Jiulongjiang estuary were collected from 28 June 2009 at 16:00 local time (Chinese Standard Time) to 29 June 2009 at 14:55 local time, from 24°25' to 24°46' N and 118°00' to 119°19' E. Throughout the sampling period (a) there was a range of salinity (4.4–33.9 psu) and of sea surface water temperature (26.59–29.12 °C). Samples from the Bay of Bengal were collected on May whereas pH, $f\text{CO}_2$ _[seawater] and $f\text{CO}_2$ _[air] varied from 8.12 to 8.37, 153 to 373 and 370 to 381 μatm , respectively, along with salinity (27.82 ± 0.26 psu), chlorophyll *a* (12.35 ± 2.23 $\mu\text{g L}^{-1}$), sea surface water temperature (SST: 28.50–31.70 °C) and day-time solar intensity flux (556–109700–17 Lux at 05:00, 12:00 and 18:00 local time, respectively) (b). The calculated pH, salinity, $f\text{CO}_2$ _[seawater] at in situ DIC and SST varied in the respective ranges 7.53–7.97, 28.24–32 psu, 280–776 μatm and 3.44–20.58 °C for the subsurface samples collected from North Yellow Seawith the range of latitudes is 37°25'–39°67' N and that of longitudes is 121°16'–124°10' E (c).

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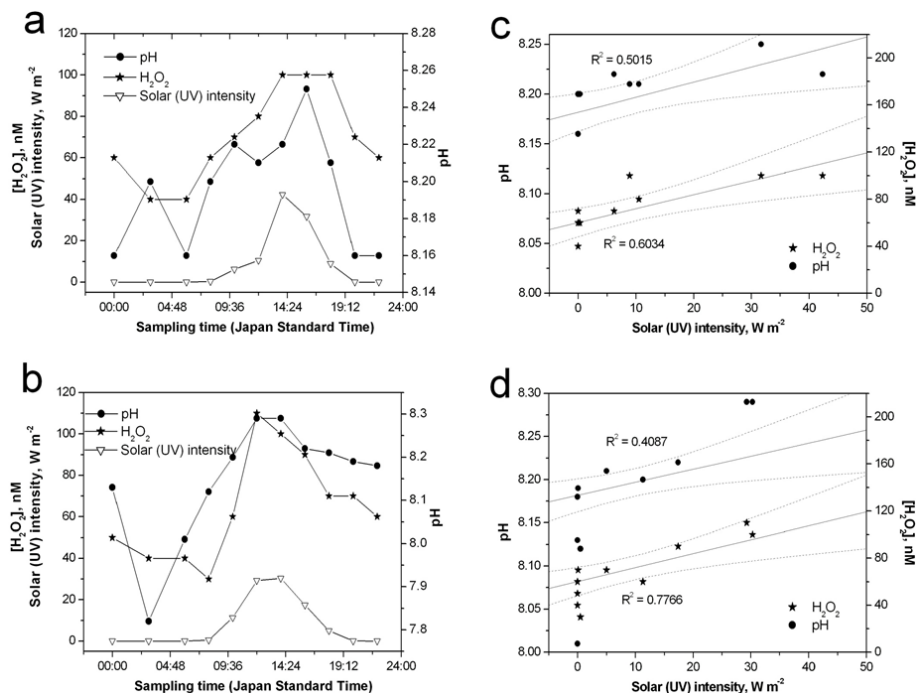


Figure 3. Diurnal changes of pH, H₂O₂ and solar (UV) intensity in the seawater of Taira Bay on 09–10 January 2003 **(a)** and Sesoko Bay on 19–20 January 2003 **(b)**. **(c and d):** pH and concentration of H₂O₂ as a function of the solar UV intensity with the related linear fit regressions in the case of Taira Bay and Sesoko Bay samples, respectively. In the seawater of Taira Bay the pH, H₂O₂, dissolved organic carbon (DOC) and sea surface water temperature (SST) varied in the following ranges: 8.16–8.25, 40–100 nM, 1.14–1.42 ppm, and 18.8–20.9 °C, respectively. In the seawater of Sesoko Bay the relevant ranges were as follows: 7.82–8.28, 30–110 nM, 0.84–1.41 ppm, and 17.7–20.2 °C, respectively.

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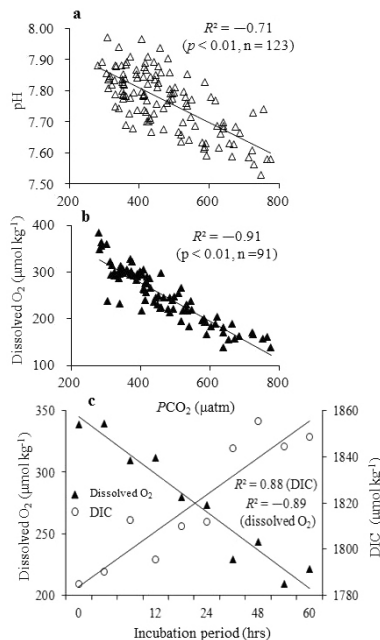


Figure 4. Relationship of $PCO_{2[\text{seawater}]}$ with pH **(a)** and dissolved O_2 **(b)** in subsurface seawater of the Yellow Sea. Decline in dissolved O_2 combined with an increase in dissolved inorganic carbon (DIC), as a function of the incubation time (60 h), in an experiment conducted using subsurface seawater from East China Sea **(c)**. Depth ranged from 13 to 75 m for a variety of subsurface seawater samples, with latitudes at $37^\circ 25' - 39^\circ 67' N$ and longitudes at $121^\circ 16' - 124^\circ 10' E$. Ten 60 mL bottles for dissolved O_2 and ten 60 mL borosilicate glass bottles for DIC wrapped with black polyethylene were submerged into an in-flow water bath, in which surface seawater was continuously supplied to control the water bath temperature. Dark incubated samples were collected after 12, 24, and 60 h of incubation. Seawater samples for the experiment were collected at 37 m depth on 02 July 2013 using a 10 L Niskin Bottle in East China Sea at $28^\circ 50' N, 122^\circ 15' E$.

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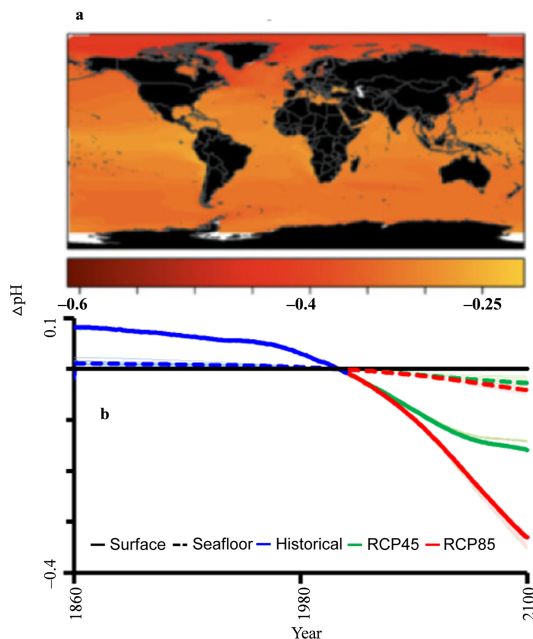


Figure 5. Possible forthcoming changes in pH in the world's oceans. Figure (a) shows the spatial difference between future (i.e., the average from 2091 to 2100) and contemporary (i.e., the average from years 1996 to 2005) values under the RCP85 scenario (decadal averages were chosen to minimize aliasing by interannual variability). Aside each color scale it is provided the absolute change, whereas the numbers on top indicate the rescaled values; complete results for the RCP85 and RCP45 scenarios for the ocean surface and floor are shown in the reference (Mora et al., 2013). Figure (b) shows the global average change relative to contemporary values under the Representative Concentration Pathways 4.5 (RCP45) and 8.5 (RCP85) scenarios at the ocean surface and seafloor; semitransparent lines are the projections for the model.

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