A scientific roadmap of ocean carbon from space

Remarks for extreme events (Fang Shen & Thomas Frölicher)

Extreme events (EE) are generally defined as those events that occur in the upper or lower end of the range of historical measurements (Katz and Brown, 1992). Such events occur in the atmosphere (e.g., tropical cyclones, dust storms), ocean (e.g., marine heatwaves), and on land (e.g., volcanic eruption, extreme bushfires), affecting marine carbon cycling at multiple spatiotemporal scales (Bates et al., 1998; Jickells et al., 2005; Gruber et al., 2021). With continued global warming in the coming decades, EE will intensify, occur more frequently, last longer and extend over larger regions (Huang et al., 2015; Diffenbaugh et al., 2017, Frölicher et al. 2018, Collins et al. 2019, Seneviratne et al. 2021). Nowadays, extreme events and their effects on marine ecosystems and carbon cycling can be observed, to some extent, by various methods, including ships, buoy, autonomous platforms and satellite sensors (Hayashida et al., 2020; Le Grix et al. 2021; Wang et al., 2022). Here, the EE development and their impact assessment with a focus on satellite-based methods and combination with the multi-platform observations are reviewed.

Extremely high temperatures and droughts due to global warming will increase the risk of more frequent and intense wildfires and dust storm events in some regions (Huang et al., 2015; Abatzoglou et al., 2019; Harris and Lucas, 2019). Aerosols emitted from wildfire and dust storms can significantly impact marine biogeochemistry through wet and dry deposition (Gao et al., 2019), via supplying soluble nutrients (Schlosser et al., 2017; Barkley et al., 2019), especially bio-essential trace metals including iron for the high-nutrient low-chlorophyll waters (Jickells et al., 2005; Mahowald et al., 2005, Mahowald et al. 2011). Recent research comprehensively evaluated the record-breaking Australian wildfire from September 2019 to March 2020 using a combination of satellite, biogeochemical Argo float, in situ atmospheric sampling and primary productivity estimation (Li et al., 2021; Tang et al., 2021, Wang et al. 2022). The wildfire released aerosols that contained essential nutrients such as iron for growth of marine phytoplankton. These aersols were transported by westerly winds over the South Pacific Ocean and the deposition resulted in widespread phytoplankton blooms. Similar to the wildfires, it has been recorded recorded by optical remote sensing observations (Gabric et al., 2010; Yoon et al., 2017) that severe dust storms in arid or semi-arid regions can transports aeresols to the coastal and open ocean, altering the bio-optical conditions in the upper mixed layer of the water column (Chen et al., 2016) and increasing ocean primary productivity. The impacts of volcano ash and soot (with black carbon) from volcanic eruptions are poorly studied. The solubility and hence bioavailability of volcanic ash is much higher than mineral dust fertilizing the open ocean (Achterberg et al., 2013; Lindenthal et al., 2013), as the source of nutrients and/or organic carbon for microbial plankton, and influence aggregation processes (Weinbauer et al., 2017). The first multi-platform observation of the impact of volcano eruption was provided by Uematsu et al. (2004), who described enhancement of primary productivity caused by the additional atmospheric deposition from the Miyake-jima Volcano in the nutrient-deficient region south of the Kuroshio, which was analyzed from SeaWiFS images and self-cruising measurements. Lin et al. (2011) produced a comprehensive study on the abnormally high biomass from satellite and elevated concentrations of limiting nutrients from laboratory experiments caused by aerosol released by the Anatahan Volcano in 2003. Most recently, the eruption of Hunga Tonga–Hunga Ha‘apai ejected about 400,000 tonnes of SO_2, threw ash high into the stratosphere and caused catastrophic tsunami on Tonga’s nearby islands (Witze, 2022). However, detailed observations on its biochemical effects have not been reported yet.

Marine heatwaves (MHWs) are prolonged periods of anomalously high ocean temperatures (Hobday et al., 2016), which can have devastating impacts on marine organisms and socio-economics systems (Frölicher and Laufkötter 2018, Smith et al. 2021). MHWs are caused by a combination of local oceanic and atmospheric processes, and modulated by large-scale climate variability and change (Holbrook et al., 2019, Vogt et al. 2022). As a consequence of long-term ocean warming, MHWs have become longer-lasting and more frequent, and impact over larger regions (Frölicher et al., 2018; Oliver et al., 2018). Some MHWs related with abnormally high net heat fluxes fromr the atmosphere into the ocean were observed by satellite and autonomous platforms, e.g. in the Mediterranean Sea during the summers of 2003 (Olita et al., 2007) and 2006 (Bensoussan et al., 2010), in the East China Sea in 2016 (Tan and Cai, 2018), in the southwest Atlantic in 2013-2014 (Rodrigues et al. 2019) and in the Tasman Sea in 2017–2018 (Salinger et al., 2019). Some MHWs were caused by ocean processes including anomalous horizontal advection of warm waters, such as the Western Australia MHW in 2011 (Pearce and Feng 2013) or the Tasman Sea 2015-2016 MHW (Oliver et al. 2017). MHW have caused widespread ecological impacts including coral bleaching (e.g., Couch et al., 2017, Hughes et al. 2018), changes in distribution of marine species (Cavole et al. 2016; Cheung et al., 2020), loss of biodiversity (Wernberg et al. 2016), local extinctions of invertebrates, fishes, seabirds and marine mammals (Smale et al., 2019) and declines in fisheries and cultural values (Cheung et al. 2021).

Based on satellite data, in situ observations, and profiling floats, recent research showed remarkable changes during marine heatwaves in the oceanic carbon system (Long et al., 2021, Gruber et al. 2021, Burger et al.) and phytoplankton structures (Yang et al., 2018, Le Grix et al. 2021), which were also related to the local background nutrient concentration (Hayashida et al., 2020). Moreover, marine compound events defined as extremes in different hazards that occur simultaneously or in close spatiotemporal sequence, are a new phenomena (Gruber et al., 2021). The dual or even triple compound extremes such as ocean warming, deoxygenation and acidification could lead to particularly high biological and ecological impacts (Gruber, 2011; Zscheischler et al., 2018; Le Grix et al., 2021). However, our understanding of oceanic compound extremes as well as their impacts on marine ecosystems, remains limited.

Tropical cyclones are the non-frontal synoptic scale low-pressure systems over tropical or sub-tropical waters with organized convection (Lander and Holland, 1993), called hurricanes or typhoons in different regions. The tropical cyclones can bring the hypolimnetic nutrients up into the photic zone and lead local carbon system changing by cooling sea surface on their paths or in adjacent areas (Li et al., 2009; Chen et al., 2017; Osburn et al., 2019). Early researches of tropical cyclones were mainly based on satellite data, however, it was difficult to obtain clear images shortly after typhoon due to extensive cloud cover, and combined with the ship-based observations (e.g. Naik et al. (2008), Hung et al. (2010), and Zang et al. (2020)). Some works have combined more platforms as well as biogeochemical models to study local biogeochemical changes in greater detail. Shang et al. (2008) provided a comprehensive estimation of the local carbon fixation and bio-optical changes in the water column after Typhoon Lingling in 2001, using ocean colour data, Argo float and biogeochemical models. For example, D'Sa et al. (2018) have reported intense changes in dissolved organic matter dynamics after Hurricane Harvey in 2017 and then reported particulate and dissolved organic matter dynamics and fluxes changes after Hurricane Michael in 2018(D'Sa et al., 2019), by highlighting the importance of using multiple satellite data with different resolutions as well as hydrodynamic models.

Over the last few years, ocean extreme have emerged as a topic of great concern, given their potential large impacts on marine life (Collins et al. 2019). However, the understanding of extreme events and their impacts on marine ecosystem and carbon cycling is poor. Knowledge gaps results partly from sparse in situ observation, lack of profiling information, and satellite observation gaps due to unexceptional cloud coverage. The current available observation, especially at subsurface, are often to sparse to even provide a robust baseline against which extremes can be detected and attributed.

Although we face many challenges in extreme event observation and research, it is also a development opportunity for our future work and efforts. At present, it has become a trend on the synergy of multi-platforms observations with model simulations, which will benefit to reveal marine vertical biochemical response to extreme events. More reliable projections of extreme events such as biogeochemical extremes require both higher resolution Earth system models with improved representation of ecosystems as well as a better and higher resolution observational database concerning long time-series measurements both in-situ and remote sensing ways. There are large efforts on a long time and reliable satellite data project for synergy of different high-frequency and high-resolution remote sensing data allows to assess extreme events and their development in long terms, e.g. ocean colour products from the European Space Agency (ESA) Climate Change Initiative (CCI) (Sathyendranath et al., 2019) and NOAA's Climate Data Record Programme (Bates et al., 2016). The increased spectral, spatial and temporal resolution of the satellite sensors and platforms would help to improve the phytoplankton community and diel cycles responded to extreme eventsß, e.g. new NASA's PACE (Werdell et al., 2019) and Korean geostationary GOCI satellite platform (Choi et al., 2012). In the meanwhile, transdisciplinary research on the impact of extremes on marine organisms and ecosystem services is needed to close a critical knowledge gap. Therefore it is essential to follow the open data and research access and cross-disciplinary data contribution, to remove the knowledge barriers.

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