State Planet, 1-osr7, 1, 2023
https://doi.org/10.5194/sp-1-osr7-1-2023

Introduction to the 7th edition of the Copernicus Ocean State Report (OSR7)

Karina von Schuckmann, Lorena Moreira, and Pierre-Yves Le Traon

Mercator Ocean International, Toulouse, France

Correspondence: Karina von Schuckmann (karina.von.schuckmann@mercator-ocean.fr)

Published: 27 September 2023

Changes in the state of the ocean affect the well-being of the planet, its ecosystems, and human societies (IPCC, 2019). The ocean is home to a vast array of plant and animal species, many of which are still undiscovered (Census of Marine Life, 2010), and it is hence critical in supporting global biodiversity and sustaining complex ecosystems (Pörtner et al., 2021; IPCC, 2022). The ocean supports various industries, such as fishing, shipping, tourism, and renewable and non-renewable resources, and provides job opportunities, income, and economic growth (OECD, 2016; European Commission, 2022). The ocean plays a vital role in regulating Earth's climate. It acts as a massive heat sink, absorbing and storing vast amounts of surplus heat accumulated in the Earth system from human activities (von Schuckmann et al., 2023). It absorbs significant quantities of anthropogenic carbon through physical and biological processes, helping to mitigate climate change by reducing the greenhouse gas concentration in the atmosphere (Friedlingstein et al., 2022; Crisp et al., 2022). The ocean is intricately affected by climate change. Rising sea levels, warming, deoxygenation and acidification of the ocean, changing currents, and loss of sea ice and biodiversity all pose significant risks to coastal communities, infrastructure, economies, and vulnerable ecosystems (IPCC, 2021, 2022). In addition, overexploitation and ocean pollution, including plastic waste and chemical contaminants, can harm both marine life and human health, posing risks through the food chain and direct exposure (e.g., Landrigan et al., 2020; Lamb et al., 2018). The degradation of the ocean and increased pressure on its functioning and services can lead to economic losses, unemployment, and reduced opportunities for sustainable development (OECD, 2016). Protecting and preserving the ocean is essential for ensuring a sustainable future, maintaining biodiversity, regulating climate, supporting economies, and safeguarding human health and well-being (IPCC, 2019; Pörtner et al., 2021). Monitoring and reporting on any change in the state of the ocean can help to achieve this goal, while at the same time it allows developing timely strategies for adaptation measures as well as to raise awareness, inform decision-making, encourage action to protect and conserve the ocean, and hence transition towards sustainable ocean stewardship (e.g., von Schuckmann et al., 2020; Blunden and Boyer, 2022; IOC-UNESCO, 2022). Most recently, on 19 June 2023, the Treaty of the High Seas was adopted by consensus and standing ovation during the United Nations meeting in New York. This treaty, also known as BBNJ (Biodiversity Beyond National Jurisdiction), is key to protecting the ocean, promoting equity and fairness, tackling environmental degradation, fighting climate change, and preventing biodiversity loss in the high seas (An historic achievement: Treaty of the High Seas is adopted, 2023).

Regular reporting on the state, variability, and change of the ocean provides state-of-the-art science-driven findings to various stakeholders, including policymakers, scientists, industries, and the general public. Ocean reporting involves several components as part of a so-called added value chain (von Schuckmann et al., 2020). Firstly, data collection from different methods including satellite observations (e.g., sea level, sea surface temperature (SST), sea surface salinity (SSS), ocean color, waves) and in situ measurements – autonomous, moored, and taken during research expeditions – are paramount for building data products from the global to regional scale (IOC, 2019). Reprocessed data are also used to feed ocean reanalyses that combine them with numerical models through data assimilation schemes (Decade Collaborative Centre for Ocean Prediction, DCC-OP, 2023). All these different products build the baseline of the Copernicus Marine Service and include information about ocean physics (blue ocean; e.g., temperature, salinity, currents, waves), biogeochemistry and biodiversity (green ocean; e.g., chlorophyll

Published by Copernicus Publications.

a, ocean pH), and sea ice parameters (white ocean; e.g., sea ice concentration, extent, or thickness), which are all relevant to understanding and reporting on the ocean state (Le Traon et al., 2019). Combined with scientific expertise, they provide the fundamental ingredients for the development of ocean monitoring indicators that are fit for purpose for ocean reporting. At this higher level of the added value chain, the tools then help identify trends, patterns, and changes in the ocean environment triggered by climate change and other human-made pressures, climate variability, and ocean processes.

This 7th edition of the Copernicus Ocean State Report covers a wide range of topics tackling variations, trends, and new tools for socioeconomic applications for Europe and on a global scale. The studies are built on the suite of Copernicus Marine products and are complemented with other products from the global community.

1 The ocean in Europe

During summer 2021, two unusual coccolithophore blooms were observed in Scottish waters, one in the Clyde Sea and the other by the east coast of the Shetland Islands. These blooms have attracted lot of public attention because they turned the sea a turquoise color (BBC News, 2023). The OSR7 is taking a close look at these events back-boned by the use of reanalysis and satellite data to examine the environment that led to these blooms. Unusual weather conditions were a contributory factor in both cases, leading to high concentrations of nutrients in summer as cold temperatures restricted the regular spring bloom of diatoms in this area. These factors provide ideal conditions for coccolithophores to flourish as temperatures and sunlight increase (see Renshaw et al. in OSR7 Chap. 4). Widespread routine monitoring of nutrient levels and phytoplankton components could greatly help in understanding future blooms.

The OSR7 explored dissolved oxygen variations in the Mediterranean Sea, more precisely in the southern Adriatic Sea, over the period 1999–2021, which is an essential undertaking to further enhance our understanding of marine ecosystem functioning and for assessing the marine environmental status (see Di Biagio et al. in OSR7 Chap. 3). The results, derived from a regional ocean reanalysis system, highlight the critical role of heat fluxes, ocean currents, and biological production in driving dissolved oxygen variations in this area. A potential regime shift in the regional circulation was identified. It can have substantial implications for the ventilation of the Ionian–Adriatic Ocean region and hence for marine organisms, and it needs to be further analyzed in future studies.

Ocean warming is one of the major indicators of monitoring the state and evolution of climate change (von Schuckmann et al., 2016). The OSR7 is tackling this indicator aiming to regionalize capacities for reporting on ocean warming (see de Pascual-Collar et al. in OSR7 Chap. 2), while developing a multi-product approach based on data from observations and ocean reanalysis systems for the Iberia–Biscay–Ireland region. Over the period 1993–2021, the results reveal that the upper near-surface layer of the ocean (0–150 m) is dominated by natural variations at the interannual to decadal scale and that the long-term ocean warming trend is emerging in the intermediate to deep-ocean layers (> 150 m) in this region. This trend amounts to about 50 % of the global ocean warming trend and is strongly affected by interannual- to decadal-scale variations. Moreover, the study could elevate the major players of these changes that are linked to the Sub-Arctic Intermediate Water and Mediterranean Outflow Water variations, leveraging the role of major characteristics of the ocean in redistributing heat and hence triggering regional variations of ocean warming remotely, i.e., from the Mediterranean Sea and the North Atlantic Ocean.

In OSR7, a new scientific method has been developed for monitoring coastal upwelling, a process which is a major communicator between offshore waters and coastal ecosystems (see Lorente et al. in OSR7 Chap. 2). Any change in coastal upwelling can have implications for, for example, water quality, fisheries, and aquaculture production in coastal areas (Sydeman et al., 2014). The method incorporates information on ocean currents, wind, sea level pressure, and sea surface temperature, and it has been developed based on various data products ranging from direct coastal observations provided by a high-frequency radar (HFR), buoy measurements, and ocean reanalysis. Two pilot areas have been chosen, i.e., the northwestern Iberian Peninsula and the Bay of Biscay. This new indicator, the so-called coastal upwelling index, has been scientifically tested in OSR7, and its proof of concept revealed that this new method can be used for direct upwelling monitoring over any coastal area of the global ocean.

The OSR7 has also analyzed the interference of extreme events with ocean processes, like the coastal upwelling of the Balearic Islands (see Mourre et al. in OSR7 Chap. 4), and has demonstrated the implications of long-lasting storms of record strength on the ocean and coasts. In November 2021, an intense and long-lasting storm named "Blas" hit the area of the Balearic Islands, which resulted in intense upwelling along the northwestern coasts of the islands of Mallorca and Ibiza, as well as a reversal of the regional current system. These record implications have in turn resulted in extreme cold coastal surface temperatures up to 6 °C colder than usual. This study demonstrates the benefits of operational oceanography for the characterization of extreme events through the provision of time series of high-resolution modeling results in coastal areas.

Change in ocean salinity can have important implications for ocean density and ocean currents, the water cycle, and ocean biodiversity. The OSR7 has tackled an important indicator based on ocean salinity in the Mediterranean Sea during the last decades using Copernicus Marine reanalysis and ob-

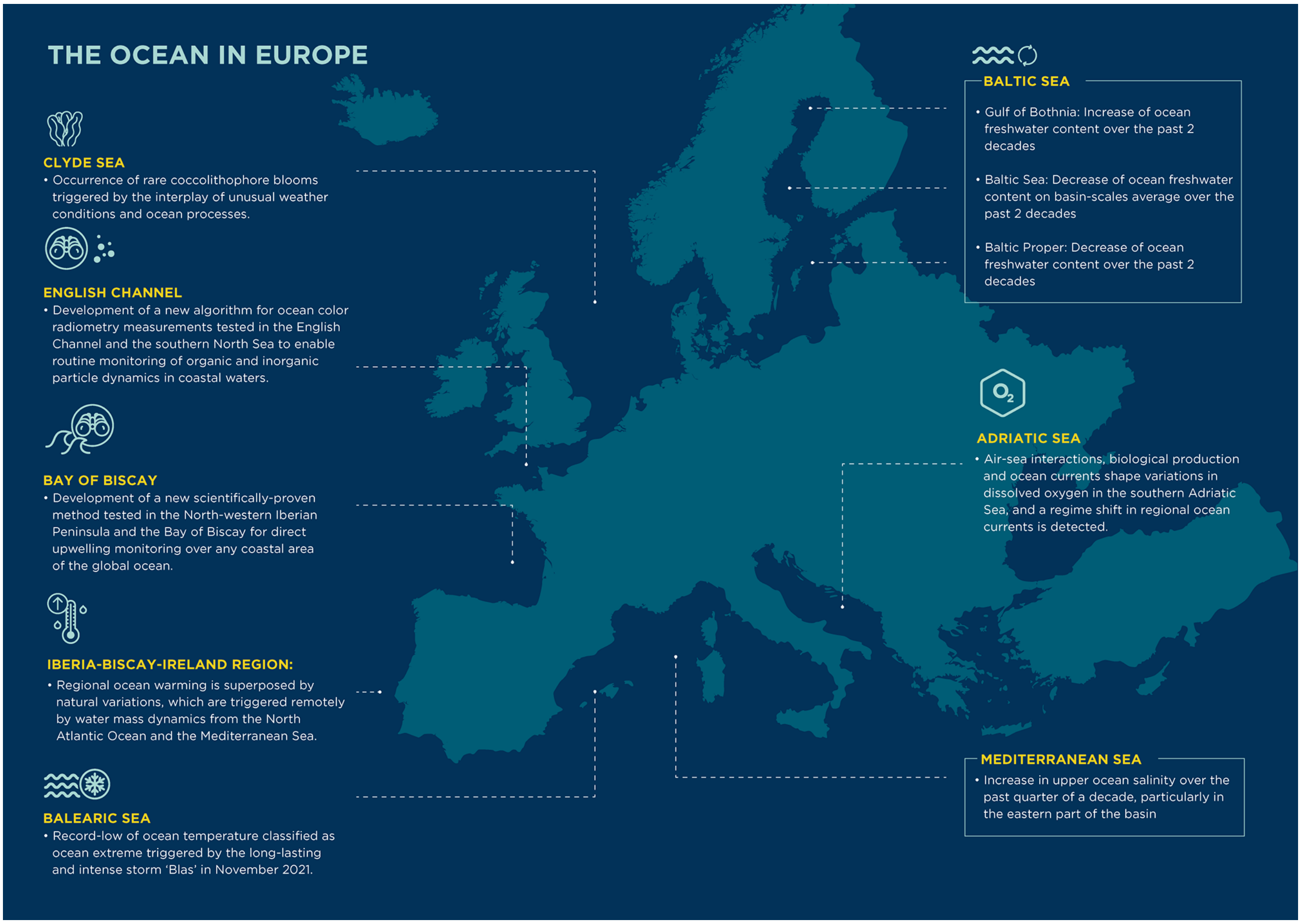

Figure 1. Overview of major outcomes for the European regional seas in the 7th edition of the Copernicus Ocean State Report.

servation products (see Aydogdu et al. in OSR7 Chap. 2). The results show that, overall, salinity has increased in the upper (< 300 m) Mediterranean Sea at particularly strong rates in the eastern basin. A similar analysis has been performed for the Baltic Sea area (see Raudsepp et al. in OSR7 Chap. 2). Particularly, freshwater content has been calculated from the Copernicus Marine regional reanalysis, which allows monitoring the specific hydro-physical conditions of each subbasin of the Baltic Sea. Results show that the total freshwater content in the Baltic Sea shows a steady decrease on average over the past 2 decades. However, at the regional scale, changes in freshwater content are not spatially uniform and are affected in the Baltic Sea by different processes, such as changes in ocean circulation, precipitation, river runoff, and sea ice formation. For example, the Gulf of Bothnia shows a freshwater content increase, and the freshwater content in the Baltic proper decreased over the past 2 decades.

Monitoring coastal waters is of uppermost importance to provide insight into changes in these complex and highly variable environments. In OSR7, a new algorithm has been developed to estimate the organic and inorganic particulate fraction of suspended material needed to monitor particle dynamics and biogeochemical cycles in coastal waters (see Loisel et al. in OSR7 Chap. 3). This new algorithm is based on a neural network approach and has been applied as a test bed to satellite observations from ocean color radiometry in the English Channel and the southern North Sea. The scientific evaluations as done in OSR7 have shown that this algorithm can be directly applied to all ocean color radiometry measurements, which enables routine monitoring of particulate composition over the global coastal ocean.

2 The ocean around the globe

Climate change is causing extreme climate events to become more frequent and more severe (Seneviratne et al., 2021). Marine heatwaves and marine cold spells are prolonged; discrete periods of anomalously high or low ocean temperatures have wide-ranging impacts from dramatic shifts in biodiversity to changes in fishery yields. In OSR7, global sea surface temperature measurements have been used to study the intensity and frequency of marine heatwaves and marine cold

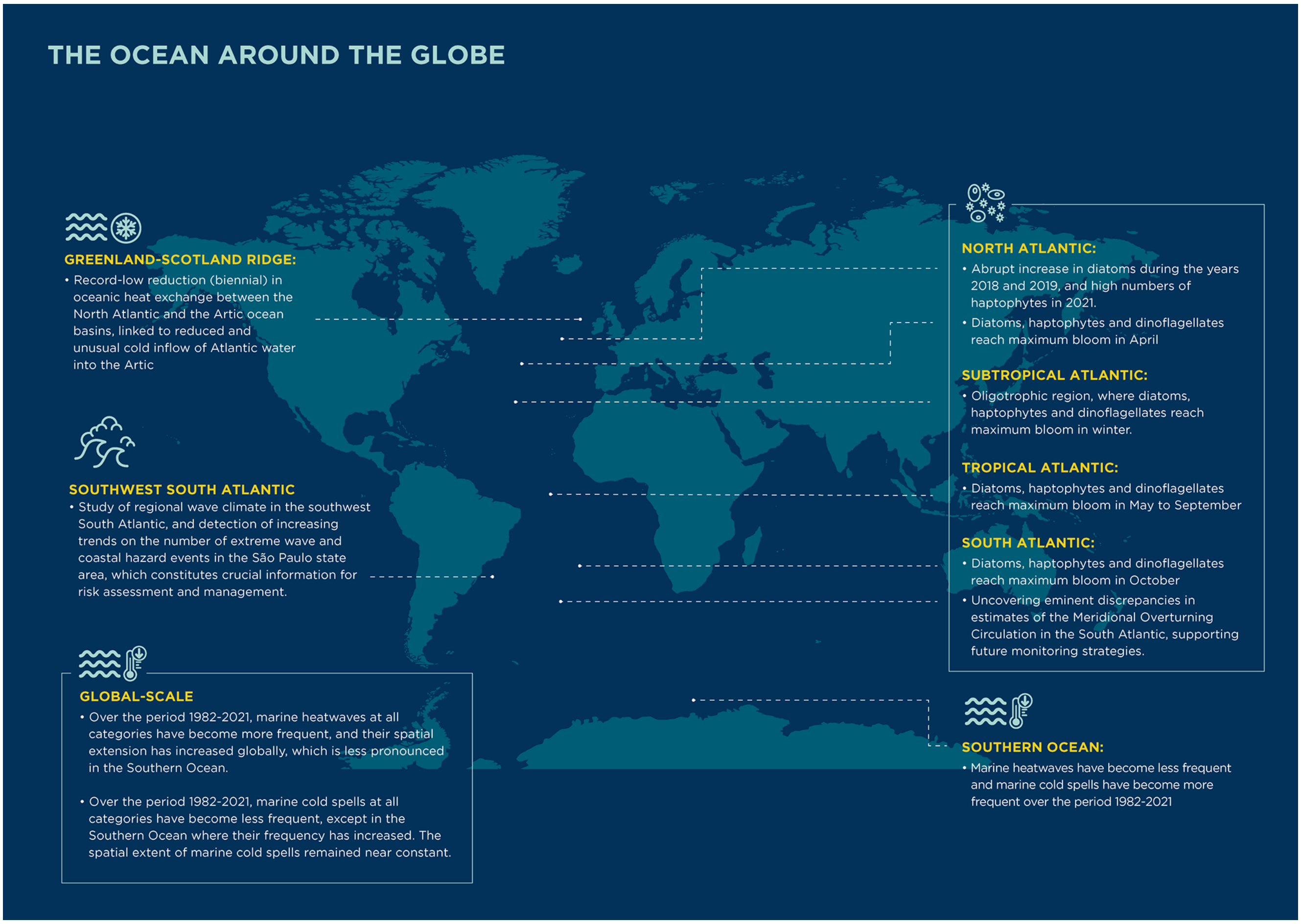

Figure 2. Overview of major outcomes for the global ocean in the 7th edition of the Copernicus Ocean State Report.

spells over several decades from 1982 to 2021 across different categories from moderate (category 1) to extreme (category 4). The findings show that in large areas of the ocean it can be said with 99 % confidence that marine heatwaves have become more frequent globally, whereas marine cold spells have become less frequent (see Peal et al. in OSR7 Chap. 2). An exception is the Southern Ocean where marine heatwaves are becoming slightly less frequent and marine cold spells are becoming more frequent. The most extreme events in categories 3 and 4 follow this trend, but at a lower rate. This evolution for marine heatwaves is accompanied by an even faster trend with respect to their spatial extension, whereas the spatial extent of marine cold spells remained nearly constant.

Extreme events can induce major hazards along coastlines. The OSR7 has investigated extreme events and coastal hazards in the southwestern South Atlantic over the past quarter of a decade, which hosts the most economically important harbors in South America, high oil and gas production demands, and rich biodiversity (see Gramcianinov et al. in OSR7 Chap. 3). Particularly, Copernicus Marine reanalysis and near-real-time data have been used to investigate extreme wave indicators impacting offshore regions and the coasts in this area and have provided a comprehensive overview of the regional wave climate across timescales and space scales. In addition, national monitoring and warning system data in the São Paulo state area have been combined with Copernicus Marine data, and these results reveal that the increasing number of coastal hazards in this area are strongly linked to the increasing number of extreme wave events from the coast to adjacent offshore regions.

The Southern Ocean region is a major player triggering changes in the global ocean circulation (Lee et al., 2023), and the OSR7 has addressed inter-basin transports in this region (see Baker et al. in OSR7 Chap. 2). To allow for reliable monitoring of changes in the regional circulation in this sensitive area for global climate, the accuracy and feasibility of the available ocean products must be analyzed. The analysis in this issue of the ocean state report has investigated the variability of the South Atlantic meridional overturning circulation and the meridional heat transport focusing on the period from 2013 to 2017, i.e., when direct observations in this region are available. The findings have manifested a surprising discrepancy in seasonal to multi-annual circulation change between the observations and model results. This prevents a reliable estimate of how the meridional overturning circulation and heat transport are changing at the latitude that connects the Atlantic Ocean to the Southern Ocean. The mean and variation of real-world South Atlantic transports and the amplitude of their fluctuations are uncertain. This in turn provides fundamental guidance for future strategies as well as investments in urgently needed sustained monitoring and improved modeling in this important area of the ocean for global climate.

Given its crucial importance, circulation variations linked to the meridional overturning circulation have also been analyzed in the North Atlantic in OSR7 (see Mayer et al. in OSR7 Chap. 4). Particularly, focus had been set on the oceanic exchange across the Greenland–Scotland Ridge, which not only links to the meridional overturning circulation, but is also shaping Arctic climate. The results of this study have uncovered a record-low biennial reduction in oceanic heat exchange across the Greenland–Scotland Ridge around the year 2018. This reduction, amounting to 4 %–9 % of the usual heat exchange with respect to the reference period 1993–2020, occurred because of a reduction in the inflow of water from the Atlantic into the Arctic area through the Faroe–Shetland branch, which was exacerbated by the unusually cold temperatures of Atlantic Water arriving at the Greenland–Scotland Ridge. These low temperatures have been triggered by a stronger North Atlantic subpolar gyre varying naturally at interannual to decadal timescales.

Ocean phytoplankton prevails in the upper part of the ocean, where sunlight penetrates the water, and constitutes the base of the marine food web fueling fisheries and regulating key biogeochemical processes (Xi et al., 2021). There are different classes of phytoplankton – so-called phytoplankton functional types – which include haptophytes, prokaryotes, dinoflagellate, and diatoms. OSR7 investigated the mean status, trends, phenology, and most recent anomalies in the Atlantic Ocean (see Xi et al. in OSR7 Chap. 2). Their phenology ranges with different climate zones, reaching seasonal maximum blooms (Fig. 1). The results also reveal that most phytoplankton functional types remained stable over the period 2002–2021, except for prokaryotes, which slightly declined over this period. The study also uncovered, for example, an abrupt increase in diatoms during the years 2018 and 2019 in the northern part of the basin.

Disclaimer. Please note that this article has undergone editorial review only.

References

An historic achievement: Treaty of the High Seas is adopted: https://oceans-and-fisheries.ec.europa.eu/news/historic-achievement-treaty-high-seas-adopted-2023-06-19_en, last access: 20 June 2023.

BBC News: Marine algae turned Scotland's water bright blue, BBC News, https://www.bbc.com/news/uk-scotland-57720790, last access: 12 June 2023.

Blunden, J. and Boyer, T.: State of the Climate in 2021, B. Am. Meteorol. Soc., 103, S1–S465, https://doi.org/10.1175/2022BAMSStateoftheClimate.1, 2022.

Census of Marine Life: First Census of Marine Life 2010: Highlights of a Decade of Discovery, edited by: Ausubel, J. H., Crist, D. T., and Waggoner, P. E., Census of Marine Life, ISBN 978-1-4507-3102-7, 2010.

Crisp, D., Dolman, H., Tanhua, T., McKinley, G. A., Hauck, J., Bastos, A., Sitch, S., Eggleston, S., and Aich, V.: How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle?, Rev. Geophys., 60, e2021RG000736, https://doi.org/10.1029/2021RG000736, 2022.

Decade Collaborative Centre for Ocean Prediction (DCC-OP): https://oceandecade.org/actions/decade-collaborative-centre-for-ocean-prediction-dcc-op/, last access: 12 June 2023.

European Commission: The EU blue economy report 2022, Publications Office of the European Union, Luxembourg, https://doi.org/10.2771/793264, 2022.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., Arneth, A., Arora, V. K., Bates, N. R., Becker, M., Bellouin, N., Bittig, H. C., Bopp, L., Chevallier, F., Chini, L. P., Cronin, M., Evans, W., Falk, S., Feely, R. A., Gasser, T., Gehlen, M., Gkritzalis, T., Gloege, L., Grassi, G., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Jain, A. K., Jersild, A., Kadono, K., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lindsay, K., Liu, J., Liu, Z., Marland, G., Mayot, N., McGrath, M. J., Metzl, N., Monacci, N. M., Munro, D. R., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pan, N., Pierrot, D., Pocock, K., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Rodriguez, C., Rosan, T. M., Schwinger, J., Séférian, R., Shutler, J. D., Skjelvan, I., Steinhoff, T., Sun, Q., Sutton, A. J., Sweeney, C., Takao, S., Tanhua, T., Tans, P. P., Tian, X., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G. R., Walker, A. P., Wanninkhof, R., Whitehead, C., Willstrand Wranne, A., Wright, R., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J., and Zheng, B.: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

IOC: The Global Ocean Observing System 2030 Strategy, IOC, Paris, IOC Brochure 2019-5, IOC/BRO/2019/5 rev.2, GOOS Report No. 239, 2019.

IOC-UNESCO: State of the Ocean Report, pilot edition, Paris, IOC-UNESCO, IOC Technical Series, 172, 2022.

IPCC: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by: Pörtner, H.-O., Roberts, D.

C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N. M., Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp., https://doi.org/10.1017/9781009157964, 2019.

IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp., https://doi.org/10.1017/9781009157896, 2021.

IPCC: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., and Rama, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., https://doi.org/10.1017/9781009325844, 2022.

Lamb, J. B., Willis, B. L., Fiorenza, E. A., Couch, C. S., Howard, R., Rader, D. N., True, J. D., Kelly, L. A., Ahmad, A., Jompa, J., and Harvell, C. D.: Plastic waste associated with disease on coral reefs, Science, 359, 460–462, https://doi.org/10.1126/science.aar3320, 2018.

Landrigan, P. J., Stegeman, J. J., Fleming, L. E., Allemand, D., Anderson, D. M., Backer, L. C., Brucker-Davis, F., Chevalier, N., Corra, L., Czerucka, D., Bottein, M. Y. D., Demeneix, B., Depledge, M., Deheyn, D. D., Dorman, C. J., Fénichel, P., Fisher, S., Gaill, F., Galgani, F., Gaze, W. H., Giuliano, L., Grandjean, P., Hahn, M. E., Hamdoun, A., Hess, P., Judson, B., Laborde, A., McGlade, J., Mu, J., Mustapha, A., Neira, M., Noble, R. T., Pedrotti, M. L., Reddy, C., Rocklöv, J., Scharler, U. M., Shanmugam, H., Taghian, G., Van De Water, J. A. J. M., Vezzulli, L., Weihe, P., Zeka, A., Raps, H., and Rampal, P.: Human Health and Ocean Pollution, Ann. Glob. Health, 86, 1–64, https://doi.org/10.5334/AOGH.2831, 2020.

Lee, S.-K., Lumpkin, R., Gomez, F., Yeager, S., Lopez, H., Takglis, F., Dong, S., Aguiar, W., Kim, D., and Baringer, M.: Human-induced changes in the global meridional overturning circulation are emerging from the Southern Ocean, Commun. Earth Environ., 4, 69, https://doi.org/10.1038/s43247-023-00727-3, 2023.

Le Traon, P. Y., Reppucci, A., Alvarez-Fanjul, E., Aouf, L., Behrens, A., Belmonte, M., Bentamy, A., Bertino, L., Brando, V. E., Brandt Kreiner, M., Benkiran, M., Carval, T., Ciliberti, S. A., Claustre, H., Clementi, E., Coppini, G., Cossarini, G., De Alfonso Alonso-Muñoyerro, M., Delamarche, A., Dibarboure, G., Dinessen, F., Drevillon, M., Drillet, Y., Faugere, Y., Fernandez, V., Fleming, A., Garcia-Hermosa, M. I., Garcia Sotillo, M., Garric, G., Gasparin, F., Giordan, C., Gehlen, M. Gregoire, M. L., Guinehut, S., Hamon, M., Harris, C., Hernandez, F., Hinkler, J. B., Hoyer, J., Karvonens, J., Kay, S., King, R., Lavergne, T., Lemiuex-Dudon, B., Lima, L., Mao, C., Martin, M. J., Masina, S., Melet, A., Nardelli, B. B., Nolan, G., Pascual, A., Pistoia, J., Palazov, A., Piolle, J. F., Pujol, M. I., Pequignet, A. C., Peneva, E., Perez Gomez, B., Peiti de la Velleon, L., Pinardi, N., Pisano, A., Pouliquen, S., Reid, R., Remy, E., Santoleri, R., Siddorn, J., She, J., Staneva, J., Stoffelen, A., Tonani, M., Vandenbulcke, L., von Schuckmann, K., Volpe, G., Wettre, C., and Zacharioudaki, A.: From Observation to Information and Users: The Copernicus Marine Service Perspective, Front. Mar. Sci., 6, https://doi.org/10.3389/fmars.2019.00234, 2019.

Mohrholz, V.: Major Baltic inflow statistics – Revised, Front. Mar. Sci., 5, 385391, https://doi.org/10.3389/FMARS.2018.00384, 2018.

OECD: The Ocean Economy in 2030, OECD Publishing, Paris, https://doi.org/10.1787/9789264251724-EN, 2016.

Pörtner, H.-O., Scholes, R. J., Agard, J., Archer, E., Arneth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung, W. L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M. A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P. A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Osman Elasha, B., Pandit, R., Pascual, U., Pires, A. P. F., Popp, A., Reyes-García, V., Sankaran, M., Settele, J., Shin, Y.-J., Sintayehu, D. W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A. L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D. C., Rogers, A. D., Díaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., and Ngo, H.: Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change, IPBES secretariat, Bonn, Germany, https://doi.org/10.5281/zenodo.4659158, 2021.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., and Zhou, B.: Weather and Climate Extreme Events in a Changing Climate, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1513–1766, https://doi.org/10.1017/9781009157896.013, 2021.

Sydeman, W. J., García-Reyes, M., Schoeman, D. S., Rykaczewski, R. R., Thompson, S. A., Black, B. A., and Bograd, S. J.: Climate change and wind intensification in coastal upwelling ecosystems, Science, 345, 77–80, https://doi.org/10.1126/science.1251635, 2014.

von Schuckmann, K., Palmer, M. D., Trenberth, K. E., Cazenave, A., Chambers, D., Champollion, N., Hansen, J., Josey, S. A., Loeb, N., Mathieu, P. P., Meyssignac, B., and Wild, M.: An imperative to monitor Earth's energy imbalance, Nat. Clim. Change, 6, 138–144, https://doi.org/10.1038/nclimate2876, 2016.

von Schuckmann, K., Cheng, L., Palmer, M. D., Hansen, J., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F. J., Desbruyères, D., Domingues, C., García-García, A., Gentine, P., Gilson, J., Gorfer, M., Haimberger, L., Ishii, M., Johnson, G. C., Killick, R., King, B. A., Kirchengast, G., Kolodziejczyk, N., Lyman, J., Marzeion, B., Mayer, M., Monier, M., Monselesan, D. P., Purkey, S., Roemmich, D., Schweiger, A., Seneviratne, S. I., Shepherd, A., Slater, D. A., Steiner, A. K., Straneo, F., Timmermans, M.-L., and Wijffels, S. E.: Heat stored in the Earth system: where does the energy go?, Earth Syst. Sci. Data, 12, 2013–2041, https://doi.org/10.5194/essd-12-2013-2020, 2020.

von Schuckmann, K., Minière, A., Gues, F., Cuesta-Valero, F. J., Kirchengast, G., Adusumilli, S., Straneo, F., Ablain, M., Allan, R. P., Barker, P. M., Beltrami, H., Blazquez, A., Boyer, T., Cheng, L., Church, J., Desbruyeres, D., Dolman, H., Domingues, C. M., García-García, A., Giglio, D., Gilson, J. E., Gorfer, M., Haimberger, L., Hakuba, M. Z., Hendricks, S., Hosoda, S., Johnson, G. C., Killick, R., King, B., Kolodziejczyk, N., Korosov, A., Krinner, G., Kuusela, M., Landerer, F. W., Langer, M., Lavergne, T., Lawrence, I., Li, Y., Lyman, J., Marti, F., Marzeion, B., Mayer, M., MacDougall, A. H., McDougall, T., Monselesan, D. P., Nitzbon, J., Otosaka, I., Peng, J., Purkey, S., Roemmich, D., Sato, K., Sato, K., Savita, A., Schweiger, A., Shepherd, A., Seneviratne, S. I., Simons, L., Slater, D. A., Slater, T., Steiner, A. K., Suga, T., Szekely, T., Thiery, W., Timmermans, M.-L., Vanderkelen, I., Wjiffels, S. E., Wu, T., and Zemp, M.: Heat stored in the Earth system 1960–2020: where does the energy go?, Earth Syst. Sci. Data, 15, 1675–1709, https://doi.org/10.5194/essd-15-1675-2023, 2023.

Xi, H., Losa, S. N., Mangin, A., Garnesson, P., Bretagnon, M., Demaria, J., Soppa, M. A., Hembise Fanton d'Andon, O., and Bracher, A.: Global Chlorophyll a Concentrations of Phytoplankton Functional Types With Detailed Uncertainty Assessment Using Multisensor Ocean Color and Sea Surface Temperature Satellite Products, J. Geophys. Res.-Oceans, 126, e2020JC017127, https://doi.org/10.1029/2020JC017127, 2021.