Section 4

Chapter 3

Trends in the physical and chemical state of the ocean

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Key points

- Tracking changes in the physical and chemical properties of ocean regions is critical to understanding the future of the planet, with significant geopolitical and socioeconomic consequences.
- These changes are under way, and nations will need to plan to adapt to them strategically to minimize damage to ecosystems and communities that rely upon them.
- Since the publication of the second *World Ocean Assessment* (see chap. 5 thereof), trends continue to reflect accelerated warming and sea level rise in the global ocean, as well as prominent regional increases in surface salinity, particularly in the Mid-Atlantic and Southern Atlantic, and decreases in annual global sea ice coverage.
- These changes are affecting global water circulation and air-sea-ice interaction processes while also leading to changes in nutrient distribution, species shifts (see sect. 4, chap. 4) and accelerating ocean hazards (see subsect. 5B, chap. 4). There will be significant changes to coastal ocean dynamics associated with sea level rise, warming and shifts in circulation, leading to significant impacts on regional communities over the next few decades. One of the most impactful changes anticipated is the frequent occurrence of an ice-free Arctic Ocean in September by the middle of the twenty-first century.

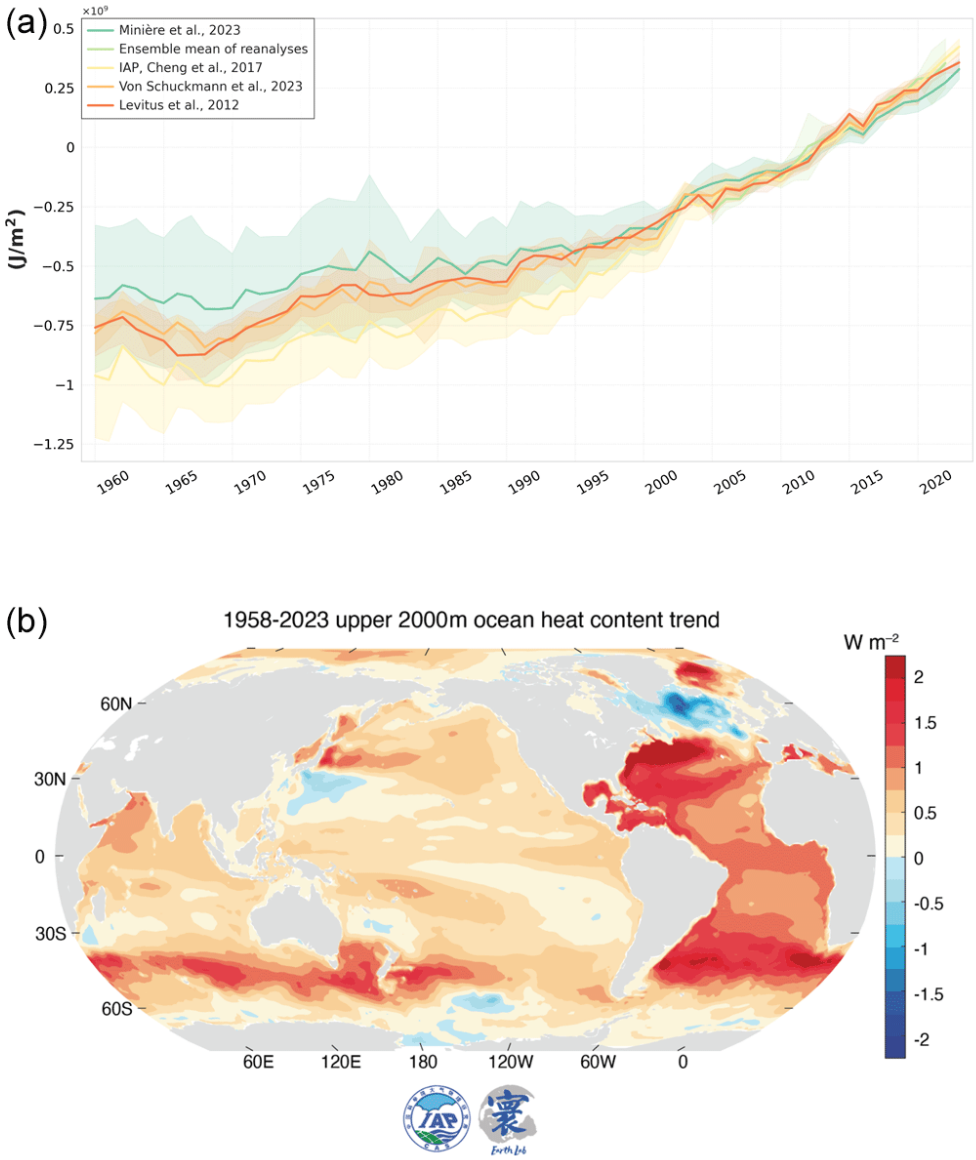
1 Physical trends

Ocean temperature (including ocean heat content)

The great capacity of the ocean to capture and store heat moderates the temperature of the planet. Over 90% of the heat absorbed by the Earth since 1955 has been accumulated in the oceans. Figure I (a) illustrates the heat increase in the upper 2,000 m of the ocean since 1955 and shows a continuous rise that peaks in 2023 (von Schuckmann and others, 2024). Some 16% of this increase occurred between 2018 and 2023 even though those years represent only 7% of the time period. This heat energy accounts for 30 to 50% of sea level rise in the ocean through thermal expansion. In addition, warming contributes to changes in the migration of oceanic species, damage to coral reef systems and the accelerated melting of ice sheets (see sect. 4, subchap. 5K; and subsect. 5B, chap. 4). While the Pacific Ocean holds the largest heat reservoir due to its vast size, the greatest warming has been observed in most of the Atlantic Ocean and in the parts of the South Ocean adjacent to the Indian and Western Pacific Oceans (see figure I (b)), with notable cooling regions observed in the North Atlantic (~ 50–70° N) and in the North-West and South-West Pacific (Cheng and others, 2022; von Schuckmann and others, 2024). The ocean surface is where the most important heat exchange between the ocean and the atmosphere occurs. Shifts in sea surface temperature translate to important differences in water evaporation rates, atmospheric heating and cooling, marine heat waves and the thawing of sea ice, in addition to broader impacts on continental climate, as discussed in the second *World Ocean Assessment*.

Figure I

(a) Global mean ocean heat content (0–2,000 m); (b) Regional trends of ocean heat content (0–2,000 m)



Source: von Schuckmann and others, 2024.

Note: (a) Global mean ocean heat content (60° S–60° N) integrated from the surface down to a depth of 2,000 m based on different products. Shaded areas indicate the uncertainty of each method. The trend is estimated using a locally weighted scatterplot smoothing approach and amounts to 0.58 ± 0.13 W m^{-2} over the period 1960–2023 and 1.05 ± 0.17 W m^{-2} over the period 2005–2023. (b) Regional trend in the period 1960–2023 for ocean heat content in the upper 2,000 m, in W m^{-2}

Ocean salinity

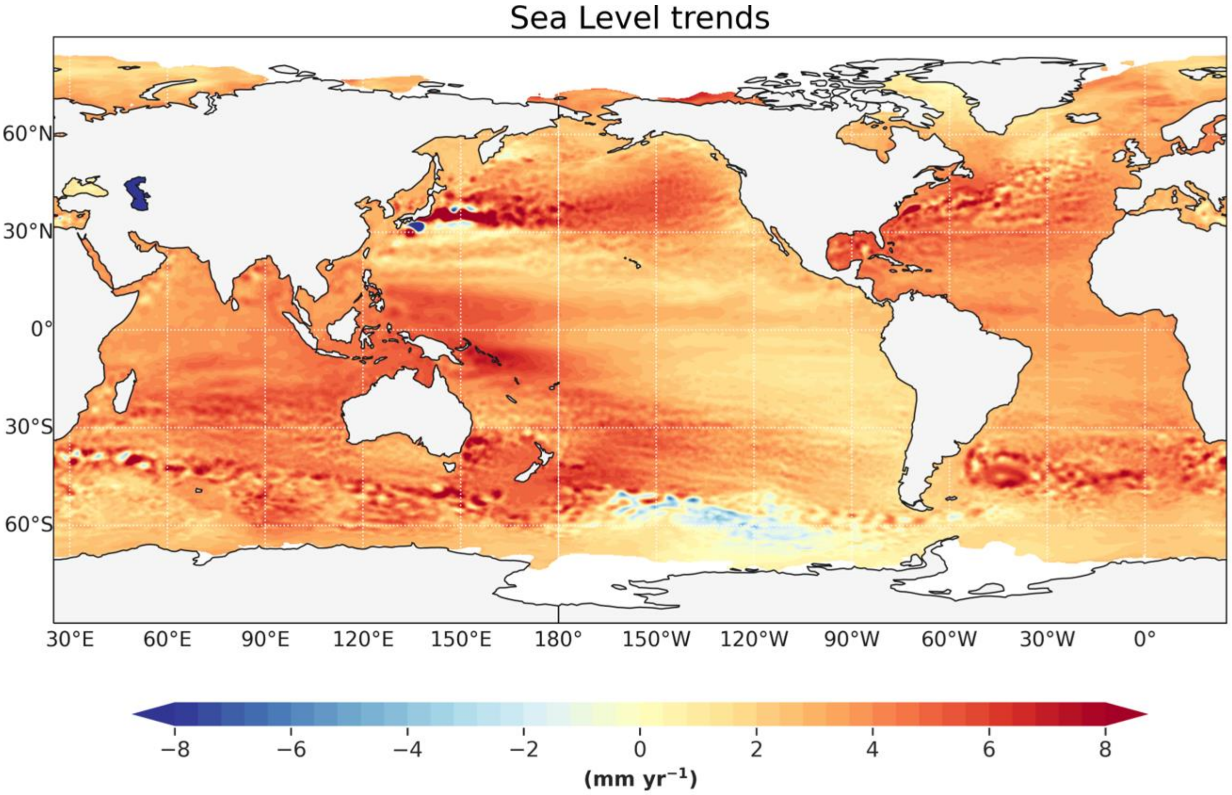
The warming climate is causing an intensification of the global water cycle due to increased rates of ocean evaporation. The impacts on ocean salinity vary based on whether a region will experience greater net evaporation (raising salinity) or greater net precipitation (reducing salinity). The long-term trends indicate that there has been relative freshening or salinity decreases over the entire Pacific, North Atlantic and Southern Oceans, but salinity increases in the Mid-Atlantic, Southern Atlantic and Indian Oceans (Cheng and others, 2020). These trends are expected to continue throughout the century, likely spanning the 0–1,000 m layer, with a further increase in salinity by 4 to 8% in a world warmed by +2ºC (expected in 2046).

Sea level

Sea level rise is driven mainly by the combination of thermal expansion and extended ice sheet melting. In some coastal zones, additional changes in storm surges and waves and local tectonic or isostatic processes may contribute to absolute sea level changes of up to a few millimetres per year. Locally, storm surges and waves may account for up to 10% of the sea level rise (Jevrejeva and others, 2023). The simultaneous occurrence of storm surge and spring tides, resulting in storm tides, adds a significant threat to coastal communities (Moftakhari and others, 2024). Rates of global mean sea level rise show an increasing tendency, from 1.3 to 1.9 mm per year during the period 1901–2015 to 2.1 mm per year for the first 10 years of the altimetry era (1993–2002) and 4.3 mm per year for the past 10 years (2013–2023), with faster rates in the Indian Ocean and in some regions of the Pacific and Atlantic Oceans (see figure II). Rates are projected to reach between 5.2 mm per year (lowest carbon dioxide (CO_2) scenario) and 12.1 mm per year (highest CO_2 scenario) during the period 2080–2100 (Fox-Kemper and others, 2021). Sea level rise is not projected to be uniform up to 2100, as tropical areas seem more likely to undergo the largest changes. Extreme sea level scenarios under storm conditions (as a combination of sea surface height associated with storm surges, waves, high tides and a low-probability sea level rise scenario) may reach 4.2 m by 2100, compared with 2.6 m in the period 1980–2014 (Jevrejeva and others, 2023). Overall, a significant proportion of the world's coasts will be inundated by 2100, although inundation will not be uniform, as countries with flat coasts will be more threatened (Vernimmen and Hooijer, 2023). Further sea level rise concerns are addressed in United Nations technical reports (United Nations Framework Convention on Climate Change (UNFCCC), 2024).

Figure II

Regional sea level trends, January 1993 to June 2023



Source: Adapted from von Schuckmann and others, 2024.

Sea ice

The well-documented decrease in Arctic sea-ice extent (more precisely, in Arctic Ocean and other northern hemisphere areas with seasonal ice cover) continues (Meier and others, 2023; Stroeve and others, 2025), and in the period 2021–2025 seasonal sea ice extent remained close to the lowest in the satellite record for the period from 1979 to the present. The area of multi-year ice (>4 years old), as well as the age, thickness and volume of sea ice, have remained consistently low since the 2010s and close to minimum values for the period of observations from 1979 to 2025, with the marginal ice zone moving further north in the summer (Thoman and others, 2023), although significant regional and seasonal positive variations do occur. On 22 March 2025, Arctic winter ice reached a minimum extent of 14.33 million km^2, below the prior low of 14.41 million km^2 in 2017 (see figure III). In the most recent climate predictions based on the Climate Model Intercomparison Project 6, the earliest ice-free[1] conditions could occur in the 2030s under all emission trajectories and are likely to occur by 2050 (Jahn and others, 2024). Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by

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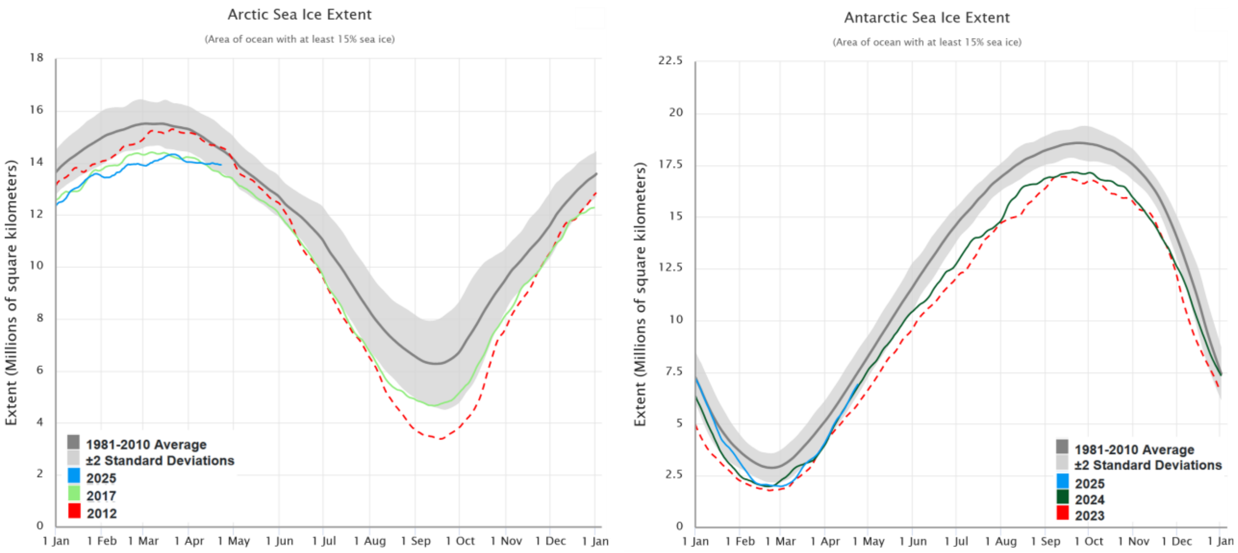
[1] The use of the term “ice-free” in the present chapter should not be confused with the navigational term “ice-free” used by relevant United Nations bodies such as the World Meteorological Organization (WMO) or the International Maritime Organization (IMO). Since icebergs will continue to be present within the domains of the Arctic and Southern Oceans, the navigational term “ice-free” is not applicable here.

the middle of the twenty-first century (2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice-free.

Figure III

Arctic and Antarctic sea-ice average and extreme extents



Source: https://earth.gsfc.nasa.gov/cryo/data/current-state-sea-ice-cover.

Note: The red dashed lines indicate the current record minimum extents for the summer (Arctic, 2012) and for the summer and winter (Antarctic, 2023), and the grey line and zones in the time series indicate the average for 1981–2010, with a standard deviation range of +/-2.[2]

In contrast to Arctic sea ice, the extent of sea ice in the Southern Ocean has only very recently (since 2021) shown a significant decrease, with the record minimum summer and winter sea ice observed in February and September 2023 (Purich and Doddridge, 2023). Southern Ocean declines in sea ice are most pronounced in regions south and west of the Antarctic Peninsula. The impacts of such decreases are widespread, including changes in dense shelf water and associated Antarctic bottom water formation, and increased heating of surface waters with subsequent changes in stratification and mixing dynamics. On 1 March 2025, Antarctic Sea ice reached its minimum extent of 1.98 million km^2, tying for the second lowest extent with 2022–2024 in the 47-year satellite record (see figure III).

Global ocean circulation patterns at all scales, including vertical and horizontal patterns such as stratification, and boundary currents

The potential decline of the Atlantic Meridional Overturning Circulation is a major concern related to ongoing changes in global circulation patterns. Previous results from Climate Model Intercomparison Project 5 had predicted the slowdown of the Atlantic Meridional Overturning Circulation, and some models predicted an abrupt collapse during the twenty-first century. However, weakening during the twenty-first century (see figure IV) has a medium to low confidence level and none of the models in Climate Model Intercomparison Project 6 predict the collapse of the Atlantic Meridional Overturning

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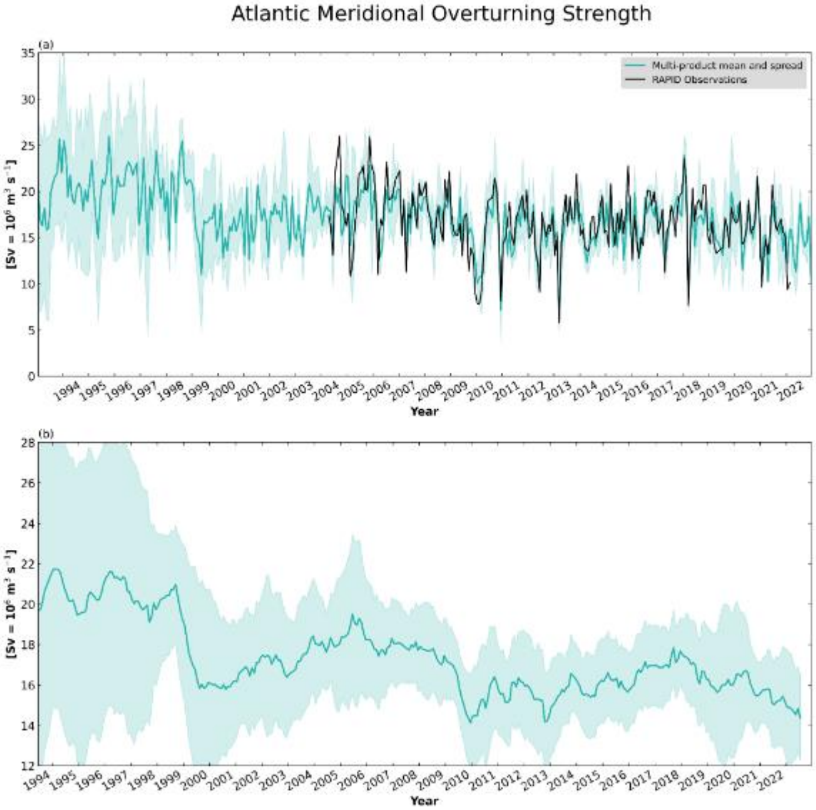
[2] See https://nsidc.org/sea-ice-today.

Circulation during the present century. A weakening of northward heat transport would result in a decrease in sea surface temperature and surface atmospheric temperature in the North Atlantic subpolar gyre, ultimately reducing the delivery of heat to Northern Europe. Swingedouw and others (2021) estimated that the probability of this cooling was 45.5% in Climate Model Intercomparison Project 5, but had decreased to 36.4% in Climate Model Intercomparison Project 6. On the other hand, Caesar and others (2018, 2021) found that the Atlantic Meridional Overturning Circulation was weakening and could reach a tipping point and abrupt collapse during the mid-twenty-first century (van Westen and others, 2024). This would result in significant climate shifts in the northern hemisphere, particularly in Europe, followed by significant shifts globally due to the redistribution of ocean heat energy. Changes in the Atlantic Meridional Overturning Circulation remain a research priority.

Figure IV

Temporal evolution of Atlantic Meridional Overturning Circulation strength at 26.5° N



Source: Adapted from von Schuckmann and others, 2024.

Note: Temporal evolution of the Atlantic Meridional Overturning Circulation strength at 26.5° N obtained by integrating meridional transport at 26.5° N across the Atlantic basin (zonally) and then cumulatively integrating over depth. The green line and shading (twice the standard deviation) are based on modelled products. The black line shows the observational record from the RAPID array (Moat and others, 2023). Panel A shows monthly mean values, and panel B shows inter-annual variations by applying a 12-month running mean.

These changes in heat and freshwater transport in the North Atlantic are likely related to changes in the South Atlantic and Indian Oceans. According to the Intergovernmental Panel on Climate Change (IPCC) (2019), the Agulhas leakage, an inflow of anomalously warm and saline water from the Indian Ocean into the South Atlantic, has intensified since the 1960s, contributing to the warming of the upper 300 m in the South Atlantic. The Agulhas leakage is likely to continue to increase during the twenty-first century contributing to the slowdown of the Atlantic Meridional Overturning Circulation (Loveday and others, 2015). This intensification of the Agulhas and Benguela Currents would be produced by an intensification of westerlies in the southern hemisphere and the southward displacement of the southern currents. This result should, however, be further analysed carefully in the future. Majumder and Schmid (2018) used temperature and salinity profiles from Argo profilers and sea surface height data to calculate the transport associated with the Agulhas Current and found no significant changes since 1993.

Against a backdrop of ocean warming, freshening changes to Arctic Ocean oceanography induced by declining sea ice are certain, as reviewed by Timmermans and Marshall (2020). Decreased summer sea ice is resulting in reduced reflection of solar radiation back into space (reduced albedo) and an associated increase in surface ocean mixed-layer temperatures at a rate of about 0.5ºC per decade. Additional trends in increased heat advecting from the Pacific Ocean have triggered increased sea ice decline in the Chukchi Sea at the fastest rate of sea ice decline of the entire Arctic Ocean. The Atlantification of the Arctic Ocean, resulting from increased Atlantic water layer heat fluxes into the Eurasian basin, is resulting in reduced sea ice and changes in stratification (Polyakov and others, 2023, 2025). The total freshwater content of the Arctic Ocean continues to increase, especially in the Beaufort gyre region (increase of liquid freshwater content from 2003 to 2018 by 40% relative to the climatology of the 1970s) as a result of persistent anticyclonic atmospheric wind forcing, sea ice melt, a wind-forced redirection of the Mackenzie River discharge and a contribution of low-salinity waters of Pacific Ocean origin through the Bering Strait (Proshutinsky and others, 2019). In the Arctic shelf seas, there has been a decrease in freshwater content, combined with deeper mixed layers as winds drive surface freshwater offshore.

In general, there has been a freshening and warming of the Southern Ocean and associated increased stratification of the uppermost 200 m since the 1970s. This potentially restricts the vertical exchange of heat, salt, nutrients and gases between surface, intermediate and deep waters (Carter, Bostock-Lyman and Bowen, 2022). The freshening of Antarctic shelf waters in Southern Ocean surface waters has led to a freshening and contraction of Antarctic bottom water formed in the Weddell Sea, Cape Darnley, the Adélie coast and the Ross Sea. This trend is certain to have profound implications in slowing down deep ocean ventilation and global overturning circulation (Gunn and others, 2023; Lee and others, 2023; Li and others, 2023) and in turn on marine productivity, with a consequent impact on fisheries. The societal implications of these changing resources are profound (Huntington and others, 2022; Stroeve and others, 2025).

2 Chemical trends[3]

Ocean acidification

About 20 to 30% of the CO_2 released by human activity into the atmosphere has been absorbed by the ocean, leading to an increase in the average surface ocean acidity of 0.1 pH units since pre-industrial levels. The transport of CO_2 to the deeper ocean via currents and mixing has meant that ocean acidification now surpasses a depth of 2,000 m in the North Atlantic and Southern Oceans (IPCC, 2022). International initiatives such as the Global Ocean Acidification Observing Network are reporting large

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[3] Trends in contaminants are described in sect. 4, chap. 6.

spatial and temporal variability in carbonate chemistry in the coastal zones as consequences of biological activity, water mixing and run-off from land. There is a large body of evidence reporting the negative impact of ocean acidification on marine species, ecosystems and their associated services (see sect. 4, chaps. 4 and 5). Species adaptation to changes in carbonate chemistry has been utilized as one of the representative stressors studied to understand species and ecosystem sensitivity (Vargas and others, 2022) in future marine conditions (Widdicombe and others, 2022).

Changes in carbon

The ocean is the second largest carbon reservoir on Earth at 37,300 GtC (10^{15}gC) and holds over 60 times the carbon of the atmosphere (DeVries, 2022). Ocean CO_2 uptake rates have tripled over the past 60 years to 2.7 ± 0.3 PgC per year (over the period 1990–2019) and are expected to continue increasing by 0.4 ± 0.1 PgC per decade (Gruber and others, 2023). These values are affected spatially and interannually by shifts in weather and climate. It is expected that eventually the average net warming of surface waters will reduce ocean uptake rates due to the reduction in CO_2 solubility at higher temperatures.

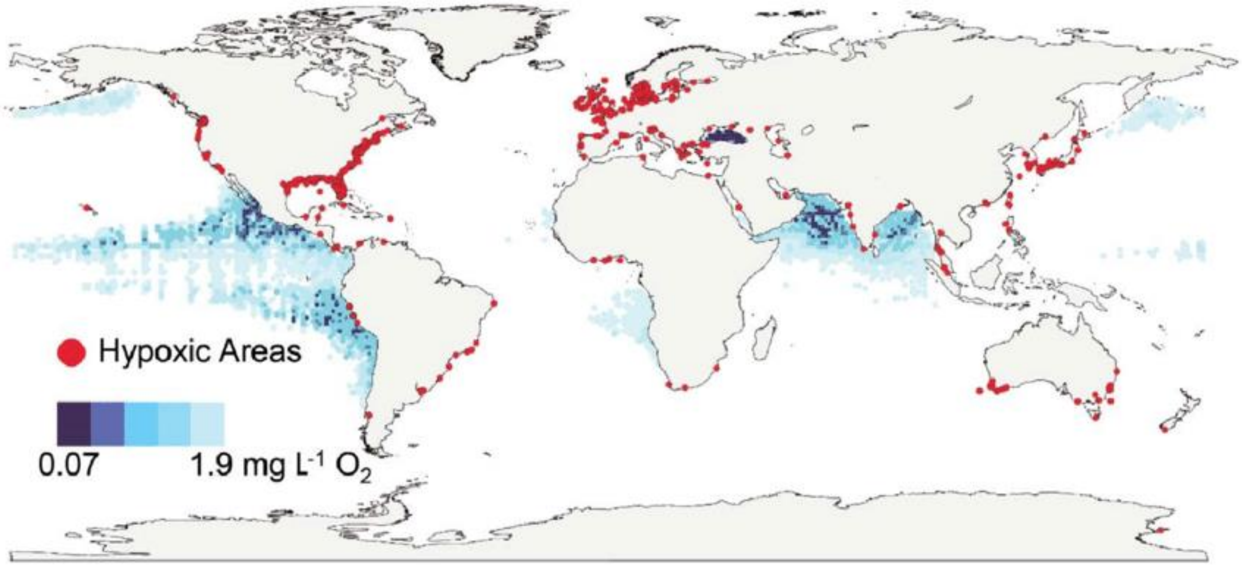
Total alkalinty is a measurement of the buffering capacity of the ocean or its ability to counter changes in pH and is dominated by inorganic carbon (i.e. bicarbonate and carbonate). Total alkalinity in subtropical regions has increased due to changes in the global water cycle (increased evaporation) and is expected to continue to do so. The northern hemisphere has more spatial variability in total alkalinity and salinity than the Southern Ocean due to fewer changes in salinity and the contribution of upwelling of total alkalinity-enriched waters (Fine and others, 2017).

Dissolved oxygen

The trend of global deoxygenation in the oceans continues and is driven by a combination of lower oxygen solubility associated with increasing water temperatures, intensified stratification (particularly in the open ocean) and higher nutrient additions to primarily coastal areas that drive bacterial activity and oxygen consumption. Figure V shows the areas with increasing oxygen minimum zones (blue) and coastal areas that are experiencing primarily anthropogenically driven hypoxia (red). It should be noted that over the past 50 years the hypoxic zone area has increased by 4.5 million km^2 and the world's oceans continue to lose roughly 1 GtO_2 per year (Keeling and Garcia, 2002), decreasing by more than 2% (4.8 ± 2.1 petamoles) since 1960 (Schmidtko and others, 2017).

Figure V

Ocean minimum zones (blue) and areas with coastal hypoxia (red) in the world's ocean



Source: GO2NE, 2018. Adapted from Isensee and others (2015) and Breitburg and others (2018), including oxygen effects from Keeling and Garcia (2002), Diaz and Rosenberg (2008) and Carstensen and others (2014)).

Nutrients

Nitrogen

Since 2018, changes in the climate have significantly altered oceanic nitrogen dynamics, affecting phytoplankton productivity, carbon sequestration and greenhouse gas emissions (see sect. 4, subchaps. 4A and 5N). Although ocean warming, changes in stratification and acidification are major influences on the ocean's nitrogen cycle, ocean deoxygenation is expected to have one of the largest impacts on microorganisms involved in nitrogen transformation pathways (Hutchins and Capone, 2022). Adaptable anammox bacteria in oxygen-deficient zones (Zhao and others, 2024) reflect diverse responses, and increased nitrogen fixation rates linked to higher diazotroph richness underscore the role of biodiversity (Shao and others, 2023). Comparing recent studies with historical data such as the World Ocean Atlas II reveals differing trends across regions, emphasizing the need for ongoing monitoring to capture dynamic regional responses to climate change (Pitcher and others, 2021), such as in the Southern Ocean, where regional variability in nitrogen dynamics and phytoplankton responses reflect localized impacts (Boyd and others, 2024). Understanding these complexities is crucial for predicting climate feedback and guiding effective mitigation strategies.

Phosphorus

Since 2018, studies have highlighted shifting oceanic phosphorus availability and cycling driven by climate change. Changes in ocean temperature, stratification and circulation affect phosphorus availability and cycling (Gerace and others, 2025). Further studies have demonstrated the significant role that phosphorus plays in nitrogen fixation by important groups of phytoplankton, with implications for marine productivity and ecosystems (Moisander and others, 2022; Boyd and others, 2024). These recent studies highlight deviations in contemporary phosphorus trends from historical baselines, emphasizing the need for updated monitoring to accurately predict future biogeochemical cycles.

Silica

Rising ocean acidification lowers the dissolution rate of biogenic silica and therefore increases the burial rate in sediments (Taucher and others, 2022). This is expected to favour diatoms that require silicic acid to grow and account for nearly 40% of marine primary productivity in the short term. Over the long term (150 years), the increased burial of silica will lead to silica limitation, which may have a negative impact on diatom productivity and shift the primary production assemblages in the global surface ocean waters. The areas most affected are expected to be those undergoing the fastest rates of acidification, particularly coastal zones where burial rates are greatest.

3 Gaps

There remain important uncertainties in mechanistic understanding of how ocean circulation will respond to warming and changes in freshwater inputs, especially at regional scales. The ocean is an important distributer of heat on the planet and any changes in circulation patterns alter how heat will be distributed. In addition to heat, circulation patterns determine where and when nutrients will be depleted and replenished, which is translated to regional ecosystem dynamics, regional fisheries and regional economies. To improve the ability to predict future conditions and plan for and achieve some degree of resilience in response to the changes, it is necessary to invest in observations (including long-term time series) and models in key regions and help communities to prepare and adapt infrastructure planning. These include the areas known to be changing most rapidly, such as the Arctic Ocean and the Southern Ocean. It is also necessary to identify ecosystem thresholds where key species are most at risk, in order to avoid fisheries collapse. These efforts are critical to inform communities and help to guide adaptive management.

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