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Chapter 5
Trends in the physical and chemical state of the ocean

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Keynote points

- Thermal expansion from a warming ocean and land ice melt are the main causes of the accelerating global rise in the mean sea level.
- Global warming is also affecting many circulation systems. The Atlantic meridional overturning circulation has already weakened and will most likely continue to do so in the future. The impacts of ocean circulation changes include a regional rise in sea levels, changes in the nutrient distribution and carbon uptake of the ocean and feedbacks with the atmosphere, such as altering the distribution of precipitation.
- More than 90 per cent of the heat from global warming is stored in the global ocean. Oceans have exhibited robust warming since the 1950s from the surface to a depth of 2,000 m. The proportion of ocean heat content has more than doubled since the 1990s compared with long-term trends. Ocean warming can be seen in most of the global ocean, with a few regions exhibiting long-term cooling.
- The ocean shows a marked pattern of salinity changes in multidecadal observations, with surface and subsurface patterns providing clear evidence of a water cycle amplification over the ocean. That is manifested in enhanced salinities in the near-surface, high-salinity subtropical regions and freshening in the low-salinity regions such as the West Pacific Warm Pool and the poles.
- An increase in atmospheric CO_2 levels, and a subsequent increase in carbon in the oceans, has changed the chemistry of the oceans to include changes to pH and aragonite saturation. A more carbon-enriched marine environment, especially when coupled with other environmental stressors, has been demonstrated through field studies and experiments to have negative impacts on a wide range of organisms, in particular those that form calcium carbonate shells, and alter biodiversity and ecosystem structure.
- Decades of oxygen observations allow for robust trend analyses. Long-term measurements have shown decreases in dissolved oxygen concentrations for most ocean regions and the expansion of oxygen-depleted zones. A temperature-driven solubility decrease is responsible for most near-surface oxygen loss, though oxygen decrease is not limited to the upper ocean and is present throughout the water column in many areas.
- Total sea ice extent has been declining rapidly in the Arctic, but trends are insignificant in the Antarctic. In the Arctic, the summer trends are most striking in the Pacific sector of the Arctic Ocean, while, in the Antarctic, the summer trends show increases in the Weddell Sea and decreases in the West Antarctic sector of the Southern Ocean. Variations in sea ice extent result from changes in wind and ocean currents.

1. Introduction

In the present chapter, the current physical and chemical state of the ocean and its trends are analysed using seven key climate change indicators:

- **Sea level.** Sea level integrates changes occurring in the Earth's climate system in response to unforced climate variability, as well as natural and anthropogenic influences. It is therefore a leading indicator of global climate change and variability.

- **Ocean circulation.** Ocean circulation plays a central role in regulating the Earth's climate and influences marine life by transporting heat, carbon, oxygen and nutrients. The main drivers of ocean circulation are surface winds and density gradients (determined by ocean temperature and salinity), and any changes in those drivers can induce changes to ocean circulation.
- **Sea temperature and ocean heat content.** The rapid warming of the global ocean over the past few decades has affected the weather, climate, ecosystems, human society and economies (Intergovernmental Panel on Climate Change, 2019). More heat in the ocean is manifested in many ways, including an increasing interior ocean temperature (Cheng and others, 2019b), a rising sea level caused by thermal expansion, melting ice sheets, an intensified hydrological cycle, changing atmospheric and oceanic circulations and stronger tropical cyclones with heavier rainfall (Trenberth and others, 2018).
- **Salinity.** With the advent of improved observational salinity products, more attention has been paid to ocean salinity in Intergovernmental Panel on Climate Change assessment reports (fourth report, Bindoff and others, 2007; and fifth report, Rhein and others, 2013) and in the first *World Ocean Assessment* (United Nations, 2017). Changes to ocean salinity are important given that the global ocean covers 71 per cent of the Earth's surface and contains 97 per cent of the Earth's free water (Durack, 2015). Any global water changes will be expressed in the changing patterns of ocean salinity, a water cycle marker of the largest reservoir of the climate system.
- **Ocean acidification.** Rising concentrations of CO_2 in the atmosphere also have a direct effect on the chemistry of the ocean through the absorption of CO_2. The ocean absorbed roughly 30 per cent of all CO_2 emissions in the period from 1870 to 2015 (Le Quéré and others, 2016; Gruber and others, 2019), and the increased CO_2 level in the water lowers its pH through the formation of carbonic acid.
- **Dissolved oxygen.** Variations in oceanic oxygen have a profound impact on marine life, from nutrient cycling to pelagic fish habitat boundaries (e.g., Worm and others, 2005; Diaz and Rosenberg, 2008; Stramma and others, 2012; Levin, 2018) and can influence climate change through emissions of nitrous oxide, a potent greenhouse gas (e.g., Voss and others, 2013).
- **Sea ice.** Sea ice in the polar regions covers about 15 per cent of the global ocean and affects the global climate system through its influence on global heat balance and global thermohaline circulation. In addition, sea ice has a high albedo, reflecting more sunlight than the liquid ocean, and its melt releases fresh water, which slows the global ocean conveyor belt (the constantly moving system of deep-ocean circulation driven by temperature and salinity).

The present chapter, using those indicators, contains details of the impacts of climate change on the physical and chemical state of the ocean and its evolution and spatial patterns. It is to be read in conjunction with chapter 9, in which extreme climate events (marine heatwaves, extreme El Niño events and tropical cyclones) are analysed and the pressures of some of the physical and chemical changes on marine ecosystems and human populations are described in more detail. Some additional aspects are covered in the section on high-latitude ice in chapter 7 on trends in the state of biodiversity in marine habitats.

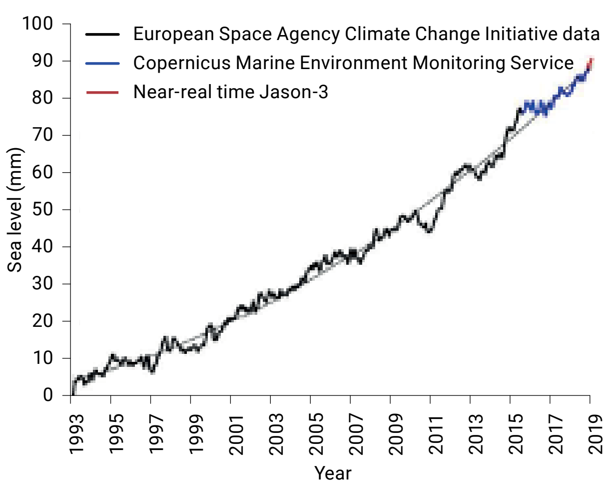
2. Physical and chemical state of the ocean

2.1. Sea level

Since the early 1990s, sea level has been routinely monitored at the global and regional levels by a series of high-precision altimetry missions (TOPEX/POSEIDON, Jason-1, Jason-2, Jason-3, Envisat, SARAL/AltiKa, Sentinel-3A and Sentinel-3B).

The most recently updated global mean sea level curve based on satellite altimetry is shown in figure I (update of Legeais and others, 2018). Since 1993, the global mean sea level has been rising at a mean rate of 3.1 ± 0.3 mm per year, with a clear superimposed acceleration of approximately 0.1 mm per year^2 (Chen and others, 2017; Dieng and others, 2017; Yi and others, 2017; Nerem and others, 2018; World Climate Research Programme Global Sea Level Budget Group, 2018).[1] Satellite altimetry has also revealed strong regional variability in the rates of sea level change, with regional rates up to 2–3 times more than the global mean in some regions over the altimetry era (see figure II).

Figure I
Global mean sea level evolution from multi-mission satellite altimetry



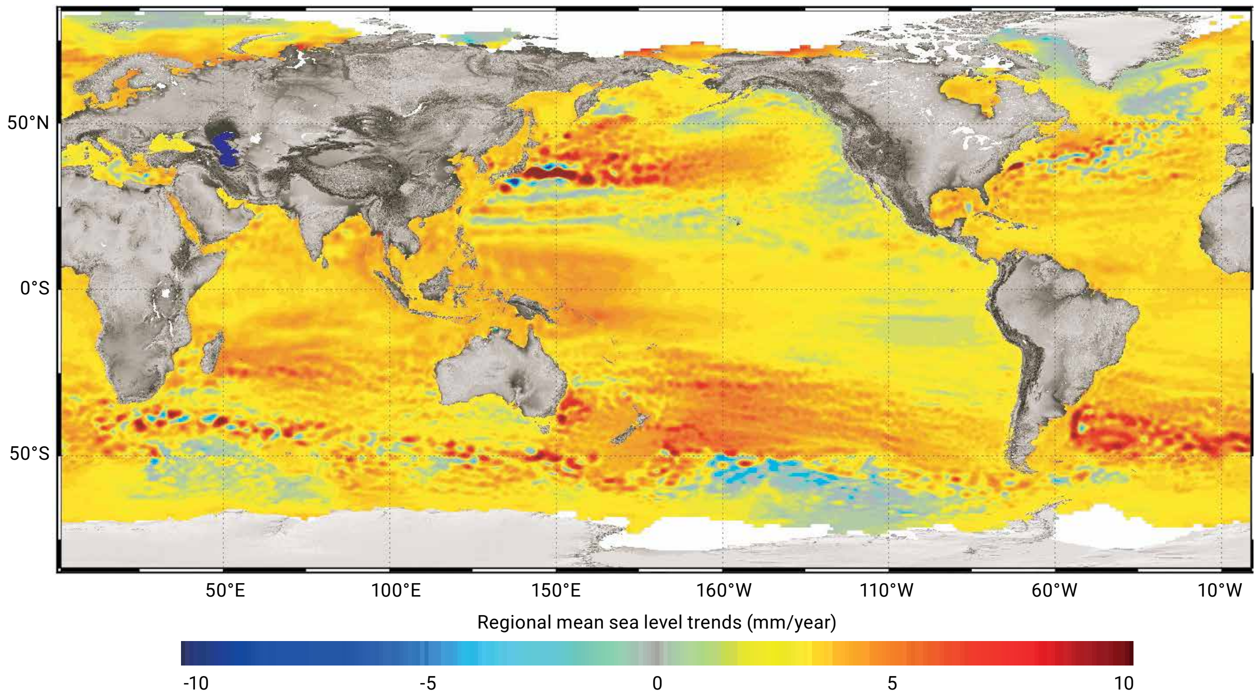
Source: Legeais and others, 2018 (updated).

There are now various observing systems that make it possible to quantify the different contributions of global and regional sea level changes. The Argo system of autonomous profiling floats[2] measures sea water temperature and salinity to a depth of 2,000 m with almost global coverage. The Gravity Recovery and Climate Experiment, a space gravimetry mission, allows for monitoring of ocean mass changes owing to glacier and ice sheet mass loss, as well as land water storage change. It also measures individual water mass changes of glaciers, ice sheets and terrestrial water bodies. Other techniques, such as interferometric synthetic aperture radar and radar and laser altimetry, are also used to estimate ice sheet mass balances.

The study of the sea level budget is important as it provides constraints on missing or poorly known contributions, such as the deep ocean, that are undersampled by current observing systems. Global mean sea level corrected for ocean mass change helps independently to estimate changes in total ocean heat content over time, from which the Earth's energy imbalance can be deduced. Figure III presents annual averages since 2005 of the global mean sea level and sum of ocean thermal expansion and ocean mass increase owing to land ice melt and terrestrial water storage change (World Climate Research Programme Global Sea Level Budget Group, 2018). The figure shows that annual residuals remain below the 2 mm level. In terms of trends, the sea level budget since 2005 is close to 0.3 mm per year, similar to the mean sea level rise uncertainty. Other studies (Dieng and others, 2017; Nerem and others, 2018) also show closure of the sea level budget over the whole altimetry era (since 1993).

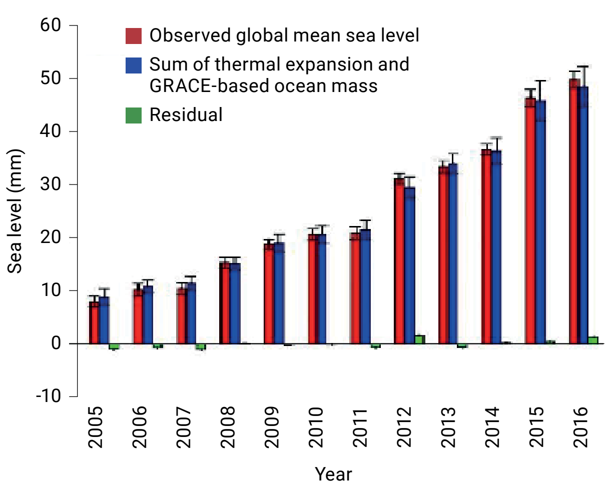
1 See General Assembly resolution 70/1.
2 See www.argo.net.

Figure II
Regional trend patterns in sea level from satellite altimetry (January 1993 to October 2019)



Source: Copernicus Marine Environment Monitoring Service.

Figure III
Yearly global mean sea level budget since 2005



Source: World Climate Research Programme Global Mean Sea Level Budget Group, 2018.
Abbreviation: GRACE, Gravity Recovery and Climate Experiment.

At the local level, in particular in coastal areas, additional small-scale processes are added to the global mean and regional sea level components and can make coastal sea level substantially deviate from open ocean sea level rise (Woodworth and others, 2019). For example, changes in wind, waves and small-scale currents close to the coast, as well as freshwater input in river estuaries, can modify the density structure of sea waters, and therefore the coastal sea level.

2.2. Ocean circulation

The observed changes in the ocean circulation system occur globally and are derived from a variety of data sources. Changes in sea level height, measured with high-precision satellite altimetry since 1993, seem to indicate a widening and strengthening of the subtropical gyres in the North Pacific (Qiu and Chen, 2012) and South Pacific (Cai, 2006; Hill and others, 2008). The data, furthermore, show a poleward movement of many ocean currents, including the Antarctic circumpolar current and the subtropical gyres in the southern hemisphere (Gille, 2008), as well as western boundary currents in all ocean basins (Wu and others, 2012).

The most severe changes, however, are observed in the Atlantic Ocean. One of the major ocean current systems, the Atlantic meridional overturning circulation, has long been predicted to slow down in response to global warming (Intergovernmental Panel on Climate Change, 2013). As the current system transports heat from the southern hemisphere and the tropics into the North Atlantic, its evolution can be deduced from that of sea surface temperature. The observed cooling in the subpolar North Atlantic since the end of the nineteenth century has already been linked to a slowing Atlantic meridional overturning circulation (Dima and Lohmann, 2010; Latif and others, 2006; Rahmstorf and others, 2015). Furthermore, different and largely independent proxy indicators of the evolution of the circulation published in recent years indicate that it is at its weakest for several hundreds of years (see figure IV) and has been weakening during the past century (see figure V; Caesar and others, 2018). Such weakening can also be seen in the direct measurements of the RAPID research programme[3] (Smeed and others, 2018) over the past decade.

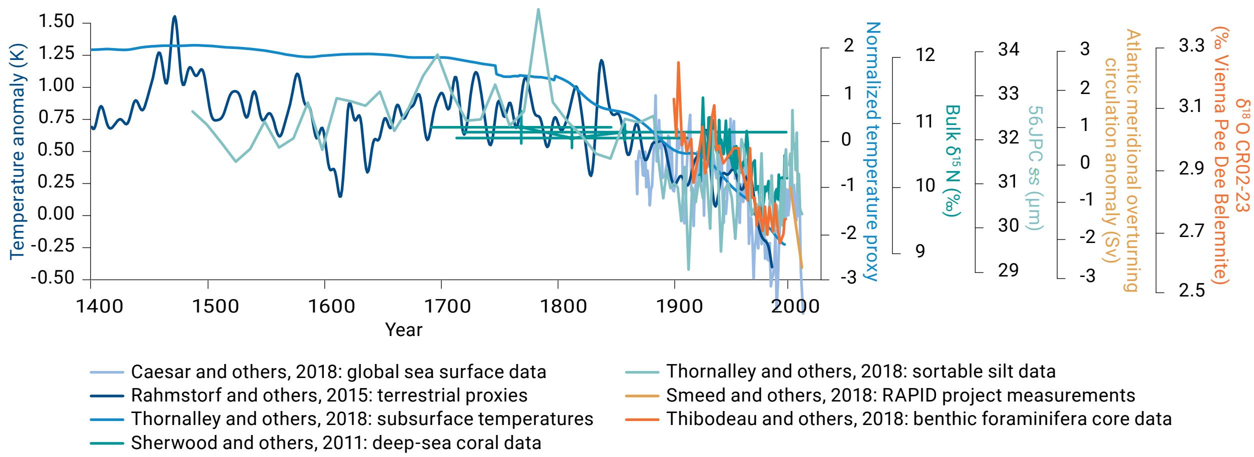
Information about the circulations and their changes can be inferred from direct measurements, proxies or model simulations. The main uncertainties regarding the trends in ocean circulation arise from the short timespans of direct, continuous measurements, the incompleteness when representing a circulation through proxies and the inherent uncertainties of the models. It is therefore important that the existing research programmes of observations, such as the Global Drifter Program (Dohan, 2010) and the Argo programme (Freeland and others, 2010), are sustained. That also includes the main projects for observing the Atlantic meridional overturning circulation, namely the RAPID array (Smeed and others, 2014) measuring the strength of the circulation since 2004 at roughly 26° north, the Overturning in the Subpolar North Atlantic Program[4] (Lozier and others, 2017) measuring the overturning that has been feeding the circulation since 2014 and the Observatoire de la variabilité interannuelle et décennale en Atlantique Nord[5] line measuring ocean parameters along a line between Greenland and Portugal (Mercier and others, 2015).

[3] The RAPID programme is aimed at determining the variability of the Atlantic meridional overturning circulation and its link to climate. An array deployed in 2004 continuously observes the strength of the circulation at about 26° north.

[4] This is an international program designed to provide a continuous record of the fluxes of heat, mass and fresh water in the subpolar North Atlantic.

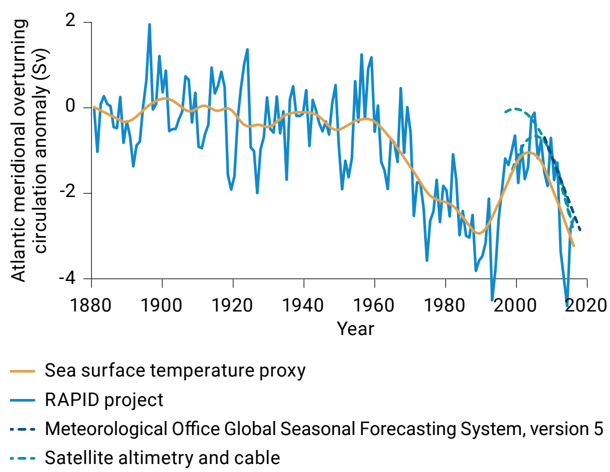
[5] The project documents the variability of the circulation and water mass properties in the northern North Atlantic.

Figure IV
Trend of the strength of the Atlantic meridional overturning circulation in observations since 1400 from various proxies



The figure shows the long-term evolution of the sea surface and land temperatures in the North Atlantic region (light blue (Caesar and others, 2018), navy (Rahmstorf and others, 2015), blue (Thornalley and others, 2018)), data from deep-sea cores (dark green (Sherwood and others, 2011), light green (Thornalley and others, 2018), orange (Thibodeau and others, 2018)) and the linear trend of in situ circulation monitoring by the RAPID project (tan (Smeed and others, 2018)).

Figure V
Trend of the strength of the Atlantic meridional overturning circulation in observations



The figure shows the long-term (20-year locally weighted scatterplot smoothing filtering; blue, navy and green lines are annual values) sea surface temperature proxy (tan), the quadratic trend of an ocean reanalysis product (Meteorological Office Global Seasonal Forecasting System, version 5; Jackson and others, 2016), a reconstruction from satellite altimetry and cable measurements (Frackja-Williams, 2015) and the linear trend of in situ circulation monitoring by the RAPID project.
Source: Caesar and others, 2018.

The impacts of the changes in the ocean circulation system vary. The Atlantic meridional overturning circulation is crucial for meridional heat transport and therefore strongly influences the climate in the North Atlantic region. Its slowdown can reduce ocean carbon uptake (Zickfeld and others, 2008) and will enhance sea level rise along the east coast of the United States of America (Goddard and others, 2015). The stronger North Pacific subtropical gyre, however, leads to regional sea level rise in the western tropical North Pacific Ocean (Timmermann and others, 2010). These are the dynamic responses of sea level height to changes in ocean circulation. The poleward displacement of the western boundary currents leads to warming in regions previously unaffected by those warm and strong currents. The consequent thermal expansion will cause a rise in sea level in adjacent coastal areas, such as in the Southern Ocean and the Indian Ocean (Alory and others, 2007; Gille, 2008). Other possible impacts that need further investigation include changes in marine ecosystems and primary production, given that currents transport nutrients, and effects on weather systems, such as the occurrence of heatwaves, droughts or flooding, because ocean circulation has a considerable impact on atmospheric circulation, and with that precipitation, patterns (Duchez and others, 2016).

2.3. Sea temperature and ocean heat content

Sea surface temperature

The global sea surface temperature analyses assessed here are derived from four published data sets (see figure VI). All data sets reveal an increase in global mean sea surface temperature since the early twentieth century. The globally averaged sea surface temperature data as calculated by a linear trend over the period 1900–2018 show an incontrovertible warming of 0.60°C ± 0.07°C (centennial in situ observation-based estimates of sea surface temperature, version 1, COBE1) (Ishii and others, 2005), 0.62°C ± 0.11°C (centennial in situ observation-based estimates of sea surface temperature, version 2, COBE2) (Hirahara and others, 2014), 0.56°C ± 0.07°C (Hadley Centre sea ice and sea surface temperature data set, HadISST) (Rayner and others, 2003), 0.72°C ± 0.10°C (extended reconstructed sea surface temperature, ERSST) (Huang and others, 2017) per century (c^{-1}), with a 90 per cent confidence interval provided. Considering all data sets, the mean sea surface temperature rate is 0.62°C ± 0.12°C c^{-1} over the same period. Differences between the data sets are mainly due to how each methodology treats areas with little or no data, and how each analysis accounts for changes in measurement methods. Among all data sets, the 10 warmest years on record have all occurred since 1997, with the 5 warmest years occurring since 2014. The recent decade (2009–2018) shows a much higher rate of warming than the long-term trend: 2.41°C ± 1.79°C (COBE1), 2.97°C ± 1.81°C (COBE2), 2.05°C ± 1.85°C (HadISST) and 2.81°C ± 1.98°C (ERSST) c^{-1}. The mean rate is 2.56°C ± 0.68°C c^{-1} in the period 2009–2018. In addition to the in situ observations, satellite-based data gave consistent changes in sea surface temperature in the period from 1981 to 2016 (Good and others, 2020; see also figure VI).

Most ocean areas around the globe are warming (see figure VI.B). The broad warming over the global ocean surface is direct evidence of human influence on the climate system (Bindoff and others, 2013). A few regions, such as the subpolar North Atlantic Ocean, have experienced cooling over the past century (often named the "cold blob" or the "North Atlantic warming hole"). A number of studies suggest that the "cold blob" indicates a weakening Atlantic meridional overturning circulation, possibly in response to increased CO_2 concentrations in the atmosphere (Caesar and others, 2018). On other hand, lower warming rates have characterized the Equatorial Pacific and Eastern Tropical Pacific. In the South-East Pacific, from central Peru to northern Chile, a multidecadal surface cooling trend was detected until the late 2000s (Gutiérrez and others, 2016, and references therein), probably associated with coastal upwelling enhancement or remotely driven circulation changes (Dewitte and others, 2012).

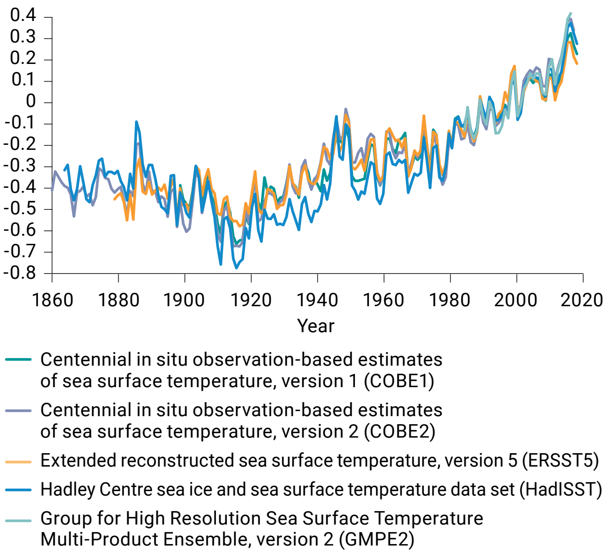
Ocean heat content

Climate change from human activities is mainly due to interference with the natural flows of energy through the climate system, creating an energy imbalance caused by increased heat-trapping (greenhouse) gases (Hansen and others, 2011; Trenberth and others, 2018) in the atmosphere. More than 90 per cent of the energy imbalance accumulates in the ocean (Rhein and others, 2013). The heat imbalance is manifested by the increase in ocean heat content. Locally, ocean heat content (OHC) can be estimated by integrating sea temperature (T) from ocean depth z_1 to z_2:

$$\text{OHC} = c_p \int_{z_1}^{z_2} \rho T dz$$

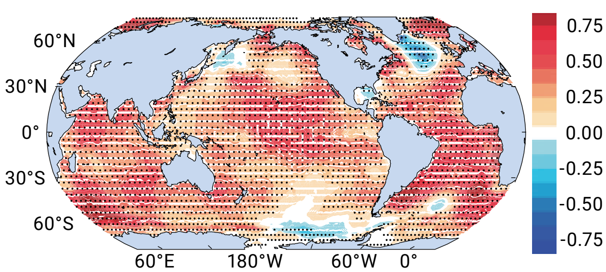
Where ρ is the density of the seawater and C_p is the specific heat capacity of the seawater.

Figure VI.A
Global average surface temperature anomalies (°C, annual mean)



Note: In situ estimates are shown from the COBE1, COBE2, ERSST5, HadISST and GMPE2 data sets

Figure VI.B
Spatial pattern of the long-term sea surface temperature trend (°C per century) from 1854 to 2018 for ERSST data



Note: All data use a common 1981–2010 baseline. Black dot signs indicate grid boxes where trends are significant (i.e., a trend of 0 lies outside the 90 per cent confidence interval).

The Earth's energy imbalance and ocean heat content are the fundamental metrics for global warming (Hansen and others, 2011; Trenberth and others, 2018; Von Schuckmann and others, 2016; Cheng and others, 2018). The ocean heat content record is much less affected by internal variability in the climate system than the more commonly used sea surface temperature records, so it is better suited to detecting and attributing human influences (Cheng and others, 2018) than other measures.

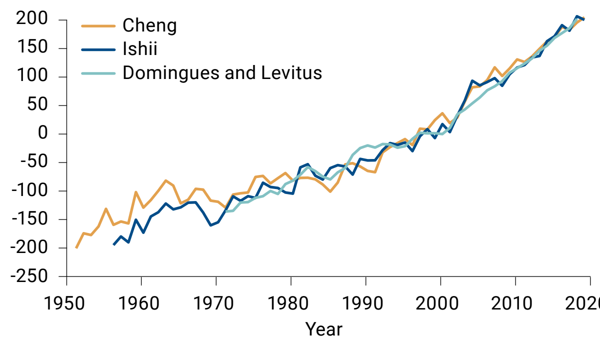
Since the fifth assessment report of the Intergovernmental Panel on Climate Change (Rhein and others, 2013), substantial progress has been made in improving long-term ocean heat content records, and a number of sources of uncertainty in prior measurements and analyses have been identified and are better accounted for (Abraham and others, 2013; Boyer and others, 2016; Cheng and others, 2016, 2017a; Ishii and others, 2017). At the same time, efforts have been made to improve how spatial or temporal gaps are accounted for in historical ocean temperature measurements. For example, a new spatial interpolation method was proposed (Cheng and others, 2017a), and a correction to an existing estimate was made available (Ishii and others, 2017). It is becoming clearer that many traditional gap-filling strategies introduced a conservative bias towards low-magnitude changes. Those with less bias include Cheng and others (2017a), Domingues and others (2008) and Ishii and others (2017).

The three recent ocean heat content estimates based on observations show highly consistent ocean warming since the late 1950s (see figure VII). They suggest a linear rate of 0.36 ± 0.06 Wm^{-2} (Ishii and others (2017) and 0.33 ± 0.10 Wm^{-2} (Cheng and others, 2017a) (averaged over the Earth's surface) in the period 1955–2018, with the mean rate of 0.34 ± 0.08 Wm^{-2} among all data sets. The new estimates are collectively higher than previous estimates (Rhein and others, 2013) and more consistent with each other (Cheng and others, 2019a). The rate of ocean warming for the upper 2,000 m has increased in the decades after the 1990s, with linear trends of 0.58 ± 0.06 Wm^{-2} (Cheng and others, 2017a), 0.61 ± 0.08 Wm^{-2} (Ishii and others, 2017) and 0.66 ± 0.02 Wm^{-2} (Domingues and others, 2008; Levitus and others, 2012) between 1999 and 2018. The mean rate is 0.62 ± 0.05 Wm^{-2}. In the recent decade (2009–2018), the rate of ocean heat content increase is: 0.56 ± 0.06 Wm^{-2} (Cheng and others, 2017a), 0.66 ± 0.09 Wm^{-2} (Ishii and others, 2017) and 0.66 ± 0.03 Wm^{-2} (Domingues and others, 2008; Levitus and others, 2012). The mean rate is 0.65 ± 0.07 Wm^{-2}. For ocean heat content, the past 10 years are the 10 warmest on record (Cheng and others, 2019a), as the heat content is less affected by natural variability.

Increases in ocean heat content are observed practically throughout the global ocean, to a depth of 2,000 m (see figure VII). Some intriguing patterns emerge for long-term content change in the period 1960–2018: stronger warming in the Southern Ocean (approximately 70° south to approximately 40° south) and Atlantic Ocean (approximately 40° south to approximately 50° north) than other regions and weaker warming throughout the Pacific Ocean and Indian Ocean (approximately 30° south to approximately 60° north) (see figure VII). The long-term warming of the Southern Ocean has been identified and attributed primarily to greenhouse gases (Cheng and others, 2017a; Swart and others, 2018), driven predominantly by air-sea flux changes associated with upper-ocean overturning circulation and mixing (Swart and others, 2018). Southern Ocean warming has important consequences owing to its influence on the southern hemisphere ice reservoir. Near-surface Southern Ocean heat content is key in limiting the seasonal development of sea ice, and warming can therefore feed back into the global climate by limiting the Earth's albedo. In addition, ocean warming accelerates the melting of Antarctic ice shelves, threatening the stability of the Antarctic ice sheet, with global implications in terms of sea level rise (Sallée and others, 2018).

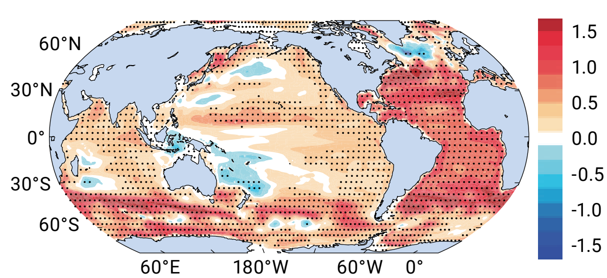
Over the period 1998–2013, a slowdown in the increase of sea surface temperature and global surface temperature led to numerous assertions about a "climate hiatus" (Hartmann, 2013). The updated record until 2018 (see figure V) shows that the linear trend of sea surface temperature for the period 1998–2018 is 1.25°C ± 0.52°C c^{-1}, which is greater than the linear trend during the reference period (1982–1997) (1.00°C ± 0.46°C c^{-1}). That effectively indicates the end of the slowdown in surface temperature increase with the appearance of the extreme 2015/16 El Niño event (Hu and Fedorov, 2017). In addition, it is clear that the rate of ocean heat content increase has risen since the late 1990s (see figure VII). The unabated increase in the rate of sea surface temperature and ocean heat content refute the concept of a slowdown of human-induced global warming.

Figure VII.A
Observational ocean heat content changes



Note: Annual mean for the upper 2,000 m, in zettajoules (10^{21} joules) (Cheng and others, 2017a; Domingues and others, 2008; Levitus and others, 2012; Ishii and others, 2017). The estimate of Domingues (0–700 m) is combined with that of Levitus (700–2,000 m) to produce a 0–2,000 m time series, following the fifth assessment report of the Intergovernmental Panel on Climate Change (Rhein and others, 2013).

Figure VII.B
Spatial pattern of long-term ocean heat content trend (Wm^{-2}), 1955–2018



Note: All data use a common 1981–2010 baseline. Black dot signs indicate grid boxes where trends are significant (i.e., a trend of 0 lies outside the 90 per cent confidence interval).
Source: Cheng and others, 2017a.

2.4. Salinity

The studies described in the fourth and fifth assessment reports of the Intergovernmental Panel on Climate Change documented spatial patterns in near-surface and subsurface salinity that represent long-term change (Bindoff and others, 2007; Rhein and others, 2013). In the first *World Ocean Assessment* (United Nations, 2017), the marked long-term multidecadal changes to global ocean salinity were documented throughout the historical period.

The studies noted above provide clear evidence that the near-surface, high-salinity subtropical ocean regions and the entire Atlantic basin have become more saline, and low-salinity regions, such as the West Pacific Warm Pool, and high latitude regions have become fresher when comparing the earlier historical data (from about the 1950s) with present-day salinities (e.g., Boyer and others, 2005; Hosoda and others, 2009; Durack and Wijffels, 2010; Helm and others, 2010; Skliris and others, 2014). The pattern of changes reflects an amplification of climatological mean salinity and has been linked through model simulations (e.g., Durack and others, 2012, 2013; Terray and others, 2012; Vinogradova and Ponte, 2013; Durack, 2015; Levang and Schmitt, 2015; Zika and others, 2015) to indicate a coincident amplification of the atmospheric water cycle (e.g., Held and Soden, 2006).

While long-term historical assessments of change are complicated by the sparse observing network extending back to the mid-twentieth century, recent assessments leverage the comprehensive global ocean coverage of Argo profile data from 2008 to the near-present. As the modern observations provide only 10 years of temporal coverage (2008 to the present), estimated changes are more strongly affected by unforced variability modes, which influence ocean salinity regionally more than long-term estimates, but their spatial and temporal coverage allows for more accurate estimates of change. The latest Argo-only analyses have shown for the first time that nearly all salinity anomalies in 2017 in the Atlantic between 0 and 1,500 m are positive (> 0.05 Practical Salinity Scale-78), mirroring the long-term trends noted above, with the Pacific showing a general freshening, similar to long-term trends.

Since the first Assessment, salinity retrievals from the Soil Moisture and Ocean Salinity Aquarius and Soil Moisture Active Passive satellites (e.g., Berger and others, 2002; Lagerloef and others, 2008; Tang and others, 2017) have become more prominent. While satellite salinity data are only available since 2010 and work is ongoing to intercompare and homogenize data products across satellite platforms, they are beginning to provide key insights into ocean salinity variability owing to precipitation events (e.g., Boutin and others, 2013, 2014; Drushka and others, 2016). In addition, the comparative high temporal and spatial coverage of satellite salinity, when contrasted with the in situ platforms (e.g., Argo), for the first time provides insights into water cycle interactions with the terrestrial and oceanic water cycles, such as the Amazon outlet plume (Grodsky and others, 2014).

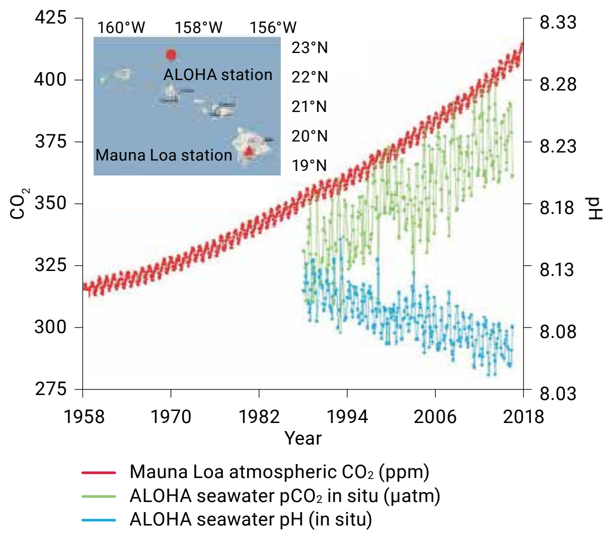
Considering all available analyses, it is extremely likely that near-surface and subsurface salinity changes have occurred across the globe since the 1950s. A salinity pattern amplification is apparent, with fresh regions becoming fresher and salty regions becoming saltier, and is supported by all available observational studies that have considered salinity change since the advent of instrumental records. For example, high-latitude oceans have shown significant rates of freshening. More modern assessments are currently too short to confirm consistent changes over the past decade. However, the most recent analyses suggest that consistent patterns are beginning to emerge for the Atlantic and, to a lesser degree, the upper Pacific Ocean basins.

2.5. Ocean acidification

Global surface ocean pH has declined on average by approximately 0.1 since the Industrial Revolution (Caldeira and others, 2003), an increase in acidity of about 30 per cent. Ocean pH is projected to decline, approximately, by an additional 0.2–0.3 over the next century (Caldeira and others, 2003; Feely and others, 2009) unless global carbon emissions are significantly curtailed. Those changes can be observed in extended ocean time series (see figure VIII), and the rate of change is likely to be unparalleled in at least the past 66 million years (Hönisch and others, 2012; Zeebe and others, 2016). Carbonate chemistry varies according to large-scale oceanic features, including depth, distance from continents owing to land influence, upwelling regime, freshwater and nutrient input and latitude (Jewett and Romanou, 2017). Owing to that variability, as determined by the various characteristics, only longer-term, observational time series can detect the predicted long-term increase in acidity at individual sites on account of rising atmospheric CO_2 levels. The time of emergence of the signal varies from 8 to 15 years for open ocean sites and from 16 to 41 years for coastal sites (Sutton and others, 2019), making it necessary to commit to long-term observational records, especially in the coastal zone where most commercially and culturally important marine resources reside.

It has now been documented that ocean acidification is making it harder for some marine organisms, such as corals, oysters and pteropods (Hoegh-Guldberg and others, 2017; Lemasson and others, 2017; Bednarsek and others, 2016; Feely and others, 2004; Orr and others, 2005), to form calcium carbonate shells and skeletons. In some cases, ocean acidification has also been shown to lower fitness in some species such as coccolithophores, crabs and sea urchins (Campbell and others, 2016; Dodd and others, 2015; Riebesell and others, 2017; Munday and others, 2009). Although individual species, when tested, are vulnerable to ocean acidification in laboratory settings, how that is going to translate into changes in actual ecosystems and species populations remains unclear and mostly undocumented (McElhany, 2017). Research efforts over the past decade have begun to build understanding of how marine species, ecosystems and biogeochemical cycles may be influenced by ocean acidification alone and in concert with other stressors, including eutrophication, warming and hypoxia (Baumann, 2019; Murray, 2019). The interaction of ocean acidification in coastal zones with coastal processes, such as upwelling of undersaturated water and land-based nutrient influxes, has become a high priority area of research (Borgesa and Gypensb, 2010; Feely and others, 2008). Natural variability in carbonate chemistry, such as coastal upwelling and seasonal fluctuations in primary productivity, is compounded by anthropogenic changes to create particularly extreme ocean acidification conditions in some regions of the global ocean (Feely and others, 2008; Cross and others, 2014). Intensive national and international efforts focused on carbonate chemistry monitoring, biological observations and biogeochemical or ecological forecast modelling over the past decade have shed light on the status and impacts of ocean acidification from the local to the global level. Gaps in the current understanding of ocean chemistry are being addressed through global monitoring capacity-building efforts, such as the Global Ocean Acidification Observing Network, increased biological impact studies and biogeochemical ecosystem modelling.

Figure VIII
Trends in surface (< 50 m) ocean carbonate chemistry calculated from observations obtained at the Hawaii Ocean Time-series Program in the North Pacific from 1988 to 2018



The figure shows the linked increase in atmospheric CO_2 concentrations (red), seawater pCO_2 concentrations (green) and a corresponding decline in seawater pH (blue, secondary y-axis). Ocean chemistry data were obtained from the Hawaii Ocean Time-series Data Organization and Graphical System
Source: National Oceanic and Atmospheric Administration Pacific Marine Environmental Laboratory Carbon Program.

2.6. Dissolved oxygen

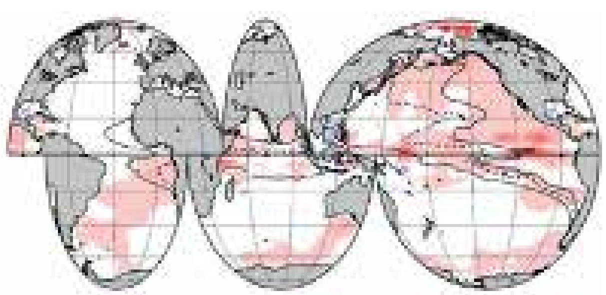
Since chemical analysis methods have essentially not changed (Carpenter, 1965; Wilcock and others, 1981; Knapp and others, 1991), long-term oceanic oxygen trends can be estimated fairly robustly where there is sufficient data coverage. Dissolved oxygen samples are analysed by Winkler titration, which was established in 1903 and has since been used to calibrate all means of oceanic dissolved oxygen measurements. That allows a robust analysis of long-term trends in all areas with sufficient data coverage. Modern Winkler titration is computer-aided, providing analysis with higher accuracy, though a bias of historic measurements could not be shown (Schmidtko and others, 2017). The postulated possible bias of 0.5 per cent reagent changes (Knapp and others, 1991) was tested on a global oxygen data set and found to be very unlikely, since the mapped pattern of oxygen change for a deliberately introduced bias does not match any observed pattern (Schmidtko and others, 2017).

In the open ocean, most regional long-term series data show a small long-term decrease despite temporal variations on many timescales (e.g., Keeling and others, 2010). Increasing oxygen levels are found only in very limited time series (Keeling and others, 2010). Coastal changes have mostly been fuelled by riverine run-off of fertilizers, but in some cases may have been affected by larger-scale oxygen changes. They can lead to an increased occurrence of dead zones, with consequences for the regional ecology and economy (Diaz and Rosenberg, 2008).

Globally, the ocean has been losing oxygen in recent decades. Both methods, comparing decadal oxygen data snapshots and local regression analyses (Schmidtko and others, 2017; Ito and others, 2017), show large-scale oxygen declines (see figures IX.A and IX.B). Despite various methods, the derived rates agree within the same water layers and given uncertainties. Deoxygenation rates vary with depth and region, resembling the manifold processes modifying the oxygen content, with isolated regions showing an increase in oxygen. The overall oxygen budget has decreased by 2 per cent in the past five decades, a loss of 4.8 ± 2.1 petamoles since 1960 (Schmidtko and others, 2017). In the upper water column, temperature-driven solubility decrease is dominating (see figure IX.C). For the period 1970–2010, the oxygen concentration in the upper 1,000 m has decreased by 0.046 ± 0.047 µmol l^{-1} yr^{-1}, including a solubility change of 0.025 µmol l^{-1} yr^{-1} (Schmidtko and others, 2017). Analysing shallower layers increases the solubility-related change significantly (see figure IX.C), in accordance with the heat gain in the upper water column (see figure IX.C, upper section). However, for the full ocean column, solubility-driven changes from 1970 to 2010 are small, -0.006 μmol l^{-1} yr^{-1} compared with the overall oxygen loss 0.063 ± 0.031 μmol l^{-1} yr^{-1}. Nevertheless, temperature cannot be ruled out as the key source of such changes, through mechanisms other than solubility change. The mechanisms include stratification increase, circulation changes and thermal impacts on biogeochemical cycles (e.g., Keeling and others, 2002; Bianchi and others, 2013; Stendardo and Gruber, 2012).

Figure IX.A
Mean dissolved water column oxygen concentration

Figure IX.B
Dissolved oxygen changes in per cent per decade



Note: Solid, dotted and dashed lines indicate the presence of low oxygen (40, 80 and 120 umol l^{-1}) at some depth within the water column.

Figure IX.C
Vertical distribution of oxygen loss per decade of oxygen change

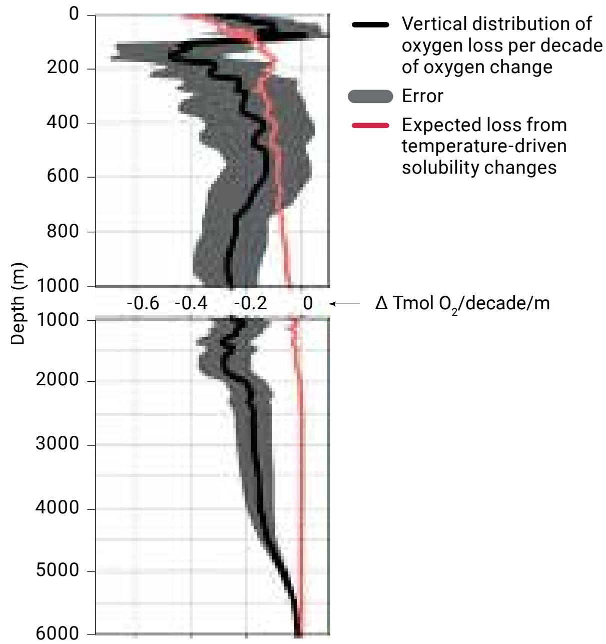
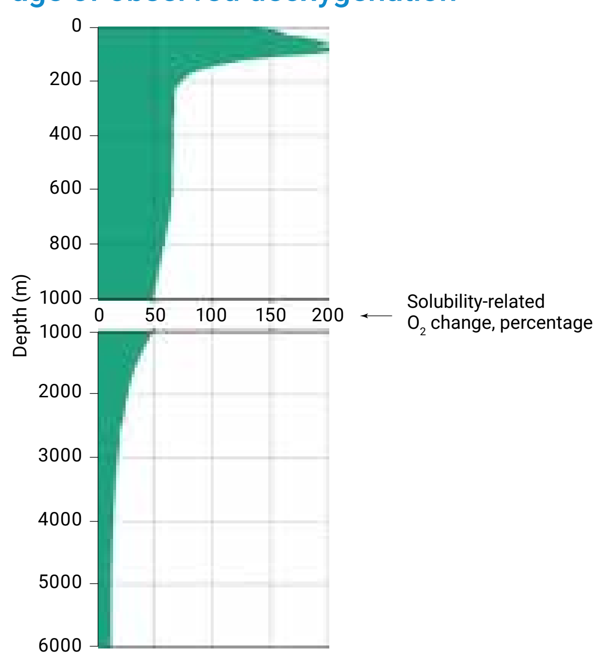


Figure IX.D
Water column cumulative oxygen loss owing to solubility change as a percentage of observed deoxygenation



Note: Solubility changes above 100 per cent are due to processes that increase upper-ocean oxygen content and counteract warming.
Source: Schmidtko and others, 2017.

The area of oxygen minimum zones has typically been expanding in recent decades, although there is significant regional variability (Diaz and Rosenberg, 2008). Oxygen minimum zones have potential impacts on climate change because they emit large quantities of nitrous oxide, a potent greenhouse gas, owing to denitrification processes under anoxic conditions (e.g., Codispoti, 2010; Santoro and others, 2011). In particular, oxygen minimum zones have increased in the Pacific Ocean and the Indian Ocean.

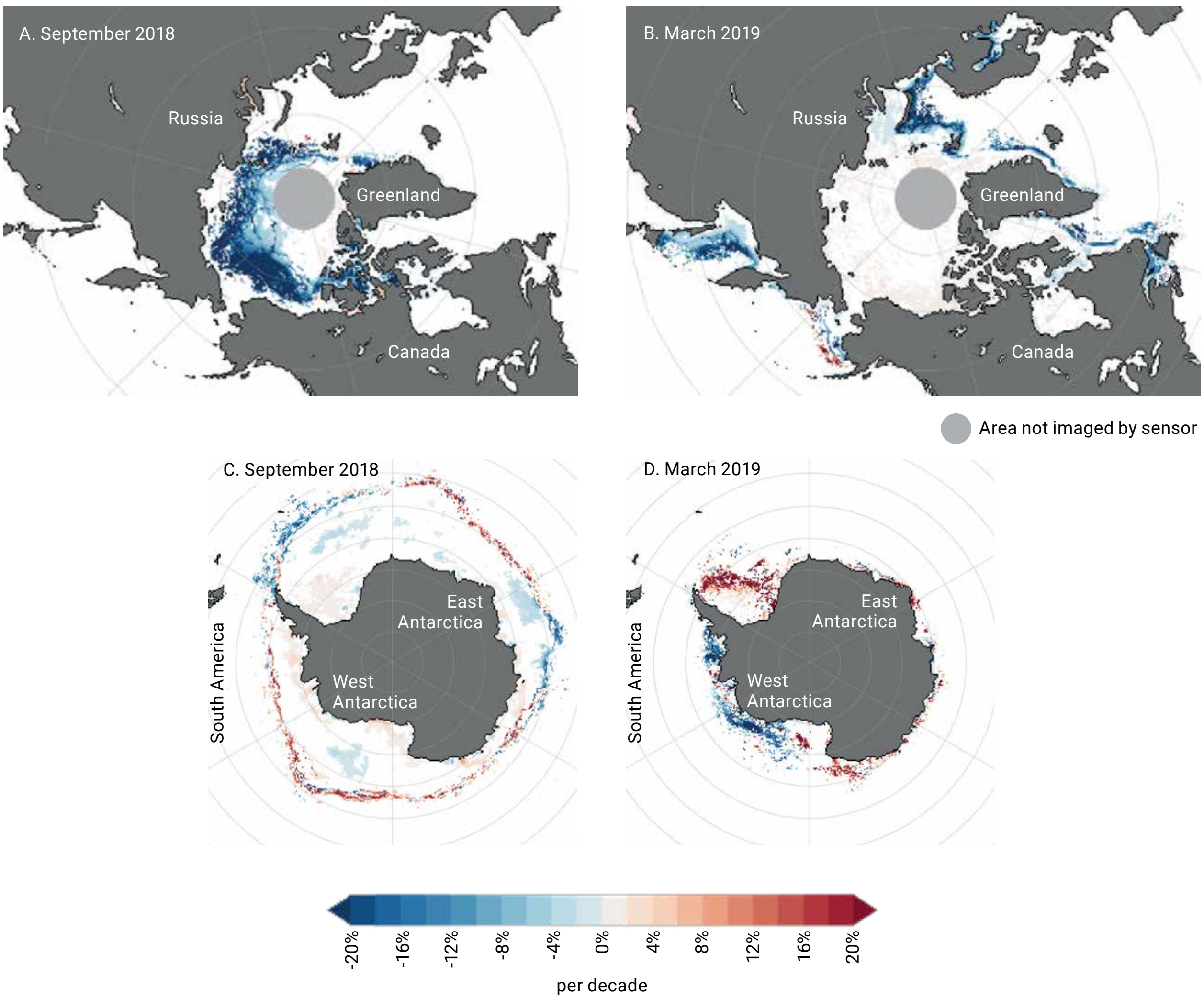
2.7. Sea ice

Sea ice in the Arctic has been one of the most iconic indicators of climate change. During the boreal winter, the areal extent of Arctic sea ice reaches a maximum area of 15.4 x 10^6 km^2 in March and, during the boreal summer, declines to 6.4 x 10^6 km^2 in September. Arctic sea ice areal extent is declining by -2.7 ± 0.4 per cent per decade during the winter (March 1979–2019), and -12.8 ± 2.3 per cent per decade during the summer (September 1979–2018) (see figure X; Feterrer and others, 2017). While the decreasing trends during the winter are more evenly distributed around the pole, the summer trends are almost twice as high in the Pacific sector of the Arctic Ocean (upper right of maps, figure X). In that area, the changes in wind related to the Arctic Oscillation have been increasingly blowing the ice away from coastal areas and into the North Atlantic (Rigor and others, 2002), leaving in its wake a much younger and thinner ice pack (Rigor and Wallace, 2004). The thickness of Arctic sea ice has decreased by at least 40 per cent (Rothrock and others, 1999, comparing submarine observations from 1958 to 1976 and from 1993 to 1997)), and Kwok (2018) shows that those changes persist today. The observed trends in sea ice extent (area) and thickness together indicate that the volume of Arctic sea ice has decreased by over 75 per cent since 1979. That estimate is coincident with many modelling studies, such as the Pan-Arctic Ice Ocean Modeling and Assimilation System (Zhang and Rothrock, 2003; Schweiger and others, 2011), which estimates that the average volume of Arctic sea ice of 11.5 x 10^3 km^3 in September has decreased between 1979 and 2017 by -2.8 × 10^3 km^3 per decade, with the record minimum in total ice volume set in 2010.

In Antarctica, sea ice advances to its maximum extent of 19–20 x 10^6 km^2 in September (austral winter) and decreases to a minimum of 3.1 x 10^6 km^2 in February (austral summer). The trends in Antarctic sea ice extent are 0.6 ± 0.6 per cent per decade during the summer (February 1979–2019) and 1.1 ± 3.7 per cent per decade during the winter (September 1979–2018). Net Antarctic sea ice extent showed a statistically significant increase from 1979 to 2015. From 2016 onwards, it has been consistently below average and has set new record low values. Given that the sudden variability in Antarctic sea ice cover is largely attributed to changes in the ocean mixed layer, it is highly relevant to expand the explanation. The net overall changes in sea ice cover have varied greatly between regions. That dichotomy between Arctic and Antarctic sea ice has been attributed to limits imposed by geography. During the winter, the maximum extent of sea ice is imposed by the Antarctic circumpolar currents and the underlying bathymetry of the Southern Ocean (Nghiem and others, 2016) and, during the summer, the sea ice can only retreat to the edge of the Antarctic continent. However, figure X (C and D) shows that, regionally, the trends are more pronounced. During the summer, sea ice extent is increasing in the Weddell Sea but decreasing in the Bellingshausen Sea and the Amundsen Sea (West Antarctica), where the ice sheet is more vulnerable to ocean processes. The regional trends in sea ice extent have been related to changes in wind (and ocean currents) related to the Southern Annular Mode and the El Niño Southern Oscillation (Parkinson, 2019; and references therein). The 40-year record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding those seen in the Arctic.

Since sea ice floats on the ocean, the contribution of melting sea ice to sea level rise is negligible. However, sea ice acts as a shield, keeping insolation from warming the ocean, and acts as a buttress for land ice, which terminates over the ocean, keeping warm waters and waves from the ocean from eroding the ice sheet. The loss of sea ice has made many ice sheets more vulnerable and increased the rate of sea level rise owing to the melt of the terrestrial ice sheets (e.g., Stewart and others, 2019).

Figure X
Arctic and Antarctic sea ice concentration trends (per cent per decade)



Trends for the Arctic are shown in the top row, and those for the Antarctic are shown in the bottom row, for September 1979–2018 in the left column, and for March 1979–2019 in the right column.

Source: National Snow and Ice Data Center, University of Colorado Boulder; Fetterer and others, 2017.

3. Knowledge gaps

3.1. Sea level

Unlike global mean and regional sea level measured by satellite altimetry missions, coastal sea level changes remain poorly known. Coastal zones are indeed highly undersampled by tide gauges and currently unsurveyed (within 10 kilometres of the coast) by conventional altimetry missions because of land contamination on the radar signal (Cipollini and others, 2018). However, dedicated reprocessing of the data from those missions now allow for estimating sea level change very close to the coast (Marti and others, 2019). In the near future, systematic use of new synthetic aperture radar technology implemented in recent European Space Agency missions (e.g., CryoSat-2 and Sentinel-3) will also allow for estimating sea level changes very close to the coast.

3.2. Ocean circulation

Some limitations remain for the current ocean observation network, in particular for coastal regions, marginal seas and deep ocean regions below 2,000 m. It is important to establish a deep ocean system in the future to monitor ocean changes below that depth, in order to provide a complete estimate of the Earth's energy imbalance (Johnson and others, 2015). Currently, boundary currents are not fully represented by Argo, as floats can swiftly pass through the energetic regions, such as the western boundary current and Atlantic circumpolar current regions, which could induce an inverse cascade of kinetic energy and affect large-scale low-frequency variability (Wang and others, 2017). Achieving adequate sampling will require an observing system design based on a mixture of observing technologies adapted to the different operating environments. There is a need to develop and maintain multiple platform observations for cross-validation and calibration purposes (Meyssignac and others, 2019), including the validation of climate models.

3.3. Sea surface temperature and ocean heat content

Temperature records are regulated by the modes of natural climate, such as the Pacific Decadal Oscillation (England and others, 2014; Kosaka and Xie, 2013), the El Niño-Southern Oscillation (Cheng and others, 2018) and the Atlantic Multidecadal Oscillation (Garcia-Soto and Pingree, 2012). The caveat of observation-based analyses is that the record is still too short: in other words, the typical period of the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation is approximately 30 to 70 years, similar to the length of the reliable ocean heat content record (about 60 years since the late 1950s). Combined analyses of models and observations are the proposed way forward (Cheng and others, 2018; Liu and others, 2016) to better understand the sea surface temperature and ocean heat content change and variability on different timescales. The lack of global long-term surface energy flux observations is an additional challenge that prevents full understanding of sea surface temperature and ocean heat content changes. There is insufficient knowledge of El Niño Southern Oscillation mechanisms and feedbacks, as well as its diversity related to global warming.

3.4. Salinity

While the observed salinity changes appear robustly in all observation-based analyses to date, knowledge gaps exist in the definite source of those changes, in particular in near-coastal regions, which are linked to terrestrial and cryospheric water reservoirs. Many observational and model studies have conclusively linked open ocean changes to surface-forced water cycle change, with coincident enhancement of evaporation and precipitation patterns as the primary driver of change. Continued changes will have significant impacts on marine ecosystems, including effects on the life cycle timing, fitness and survivability of ecologically and economically important species.

3.5. Ocean acidification

More research is needed to better inform models and improve predictions of the Earth system response to ocean acidification, its impacts on marine populations and communities and the capacity of organisms to acclimatize or adapt to the changes in ocean acidification-induced ocean chemistry. There remains a strong need for more extensive monitoring in coastal regions, and high-quality, low-cost sensors to do such monitoring, increased access to satellite data and research into the long-term trends in ocean chemistry beyond the observational record (paleo-ocean acidification). A good example is the extension of the Argo programme to include biogeochemical parameters, including pH.[6]

3.6. Sea ice

Maintaining the in situ observing networks in the polar regions is a challenge owing to the harsh environment and access being typically limited to the spring and summer seasons. Retrievals of geophysical parameters by satellite are improving, but in situ observations are required to validate such retrievals. In particular, in situ measurements of snow on sea ice, and the thickness of sea ice, are invaluable to advancing understanding of physical processes in the polar regions. Such measurements are rare in the Arctic, and even rarer in the Antarctic.

4. Summary

Ocean warming and land ice melt are the main causes of present-day accelerating global mean sea level rise. The global mean sea level has been rising since 1993 (the altimetry era) at a mean rate of 3.1 ± 0.3 mm per year, with a clear superimposed acceleration of approximately 0.1 mm per year.[7] Satellite altimetry has also revealed strong regional variability in the rates of sea level change, with regional rates up to two or three times greater than the global mean in some regions. Owing to global warming, many circulation systems also experience changes.

Changes in sea level height, measured with high-precision satellite altimetry, hint at the widening and strengthening of the subtropical gyres in the North and South Pacific. The studies, furthermore, show a poleward movement of many ocean currents, including the Antarctic circumpolar current and the subtropical gyres in the southern hemisphere, as well as western boundary currents in all ocean basins. One of the major ocean current systems, the Atlantic meridional overturning circulation, has already weakened, and it is very likely that it will continue to do so in the future. Impacts that follow such changes include regional sea level rise, changes in nutrient distribution and carbon uptake and feedbacks with the atmosphere.

The globally averaged ocean surface temperature data show a warming of 0.62±0.12 °C per century over the period 1900–2018. In the recent decade (2009–2018), the rate of ocean surface warming is 2.56±0.68 °C c^{-1}. The warming happens in most ocean regions,

[6] See https://biogeochemical-argo.org.
[7] See General Assembly resolution 70/1.

with some areas, such as in the North Atlantic, showing long-term cooling. Since 1955, the upper 2,000 m of the ocean has also exhibited signs of robust warming, as evidenced by the increase in ocean heat content.

The spatial patterns of multidecadal salinity changes provide convincing evidence of global-scale water cycle change in the global ocean coincident with warming over the period. The resolved changes are replicated in all observed analyses of long-term salinity changes, and more recently have been reproduced in forced climate model simulations. Those changes are manifested in enhanced salinities in the near-surface, high-salinity subtropical regions and corresponding freshening in the low-salinity regions such as the West Pacific Warm Pool and the poles. Similar changes are also seen in the ocean subsurface, with similar patterns of freshening low-salinity waters and enhanced high-salinity waters represented in each of the ocean basins, Atlantic, Pacific and Indian, and across the Southern Ocean.

Global surface ocean pH has declined on average by approximately 0.1 since the Industrial Revolution, an increase in acidity of about 30 per cent. Ocean pH is projected to decline by approximately an additional 0.3 over the next century unless global carbon emissions are significantly curtailed. The changes can be observed in extended ocean time series, and the rate of change is likely to be unparalleled in at least the past 66 million years. The time of emergence of the signal varies from 8 to 15 years for open ocean sites and 16 to 41 years for coastal sites, making it necessary to commit to long-term observational records, especially in the coastal zone, where most commercially and culturally important marine resources reside.

Oceanic oxygen levels have declined in recent decades, with strong regional variations. While the overall oxygen content has decreased by about 2 per cent in five decades, oxygen in coastal areas or near oxygen minimum zones shows larger variations. Coastal changes are mostly fuelled by riverine run-off, and the open ocean changes are likely related to a combination of changes in ocean circulation and biogeochemical cycles. Temperature-driven solubility decrease is responsible for most near-surface oxygen loss, while other processes have to be accountable for deep-ocean oxygen loss. A further decrease in oxygen in and near oxygen minimum zones can lead to climate feedback through consequent greenhouse gas emissions.

Sea ice covers 15 per cent of the global ocean and affects global heat balance and global thermohaline circulation. Total sea ice extent has been declining rapidly in the Arctic, but trends are insignificant in the Antarctic. Arctic sea ice extent is declining by -2.7 ± 0.4 per cent c^{-1} during the winter, and -2.8 ± 2.3 per cent c^{-1} during the summer. In contrast, trends in total Antarctic sea ice extent are insignificant, 0.6 ± 0.6 per cent c^{-1} during the summer and 1.1 ± 3.7 per cent c^{-1} during the winter. Regionally, the spatial distribution of the trends is dramatic. In the Arctic, the summer trends are most striking in the Pacific sector of the Arctic Ocean, while, in the Antarctic, the summer trends show increases in the Weddell Sea and decreases in the West Antarctic sector of the Southern Ocean. The spatial distribution of the changes in sea ice is attributed to changes in wind and ocean currents related to the Arctic Oscillation in the northern hemisphere and the Southern Annular Mode and El Niño in the southern hemisphere.

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