Chapter 20

Future projections for the tropical Indian Ocean

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Abstract

The tropical Indian Ocean has undergone basin-wide surface warming since the start of the 20th century, with a rate of 0.12°C per decade between 1950 and 2020 that is fastest among the tropical basins. The warming penetrates the deep ocean, with an increase in the ocean heat content from surface to 2000 m (OHC_{2000}) at a rate of 3.7 zetta-joules per decade during 1960–2016. Here we summarize our current understanding of the future changes in the Indian Ocean state based on climate model projections. Climate models under the Coupled Model Intercomparison Project Phase 6 project that in response to mid-to-high greenhouse gas emissions the Indian Ocean will very likely experience surface warming of 1.4°C –3°C between 2020–2100, at a rate of 0.17°C–0.38°C per decade. The OHC_{2000} is projected to increase at a rate of 16-22 zetta-joules per decade under mid-to-high emission scenarios. Marine heatwaves are projected to increase from 20 days per year (during 1970–2000) to 220–250 days per year, pushing the tropical Indian Ocean into a basin-wide near-permanent heatwave state by the end of the 21st century. In response to the ocean warming, Earth system models project a significant decline in surface chlorophyll and annual net primary productivity, with the strongest decrease of about 8-10% in the western Arabian Sea. The Indian Ocean is projected to acidify further, with the surface pH of the tropical Indian Ocean decreasing to a pH below 7.7 by the end of the 21st century, compared to a pH above 8.1 during the early 20th century. Earth system model projections do not agree on the evolution of subsurface oxygen concentrations, calling for an improvement in the representation of biogeochemical processes or improved bias correction techniques. The rapid warming, decline in primary productivity, and acidification will continue to increase the pressure on the marine ecosystem and coral reefs.

Keywords: Indian Ocean warming, climate change, global warming, ocean heat content, marine heatwave, ocean biogeochemistry, ocean acidification, hypoxia

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1 Introduction

The tropical Indian Ocean (40–120°E, 30°S–30°N) underwent basin-wide warming during the last 150 years (1871–2020). From an average sea surface temperature (SST) of 26.44°C in the 1870s, the basin recorded an average 0.76°C increase, raising the basin-average SSTs to 27.2°C by the 2010s (Fig. 1). Recent research and the Intergovernmental Panel on Climate Change (IPCC) reports point out that the fastest ocean surface warming since the 1950s has occurred in the Indian Ocean and western boundary currents, while ocean circulation has slowed down the warming or even slightly cooled the surface in parts of the Southern Ocean, equatorial Pacific, North Atlantic, and coastal upwelling systems (Collins et al., 2019; Fox-Kemper et al., 2021; IPCC, 2021). The SST warming trend in the Indian Ocean was strongest during the last seven decades (1950–2020), at a rate of 0.12°C per decade. These SST changes are dwarfed by the projected surface warming of 3°C between 2020 and the end of the century (at a rate of 0.38°C per decade), if anthropogenic emissions continue to increase at the current rate (Fig. 1, SSP5-8.5 scenario).

The rapid warming in the Indian Ocean is not limited to the surface. The heat gain in the Indian Ocean represents about one-quarter of the global ocean heat gain since 1990, primarily due to a redistribution of heat from the Pacific to the Indian Ocean (Beal et al., 2020; Cheng et al., 2017). There are uncertainties regarding monitoring the change in the total heat content and exchange in and out of the basin (e.g., the heat exchange via the Indonesian Throughflow and the Agulhas Current (Sprintall et al., 2024; Tozuka et al., 2024). However, it is certain that the Indian Ocean exhibits the fastest surface warming among all the other tropical oceans, in recent decades (Beal et al., 2020; Gnanaseelan et al., 2017; Hermes et al., 2019; Roxy et al., 2020). The IPCC Special Report on Ocean and Cryosphere in a Changing Climate indicates that global ocean warming in the upper 2000 m would be 5–7 times higher than the warming recorded since 1970 under the business-as-usual scenario by 2100, and 2–4 times higher under the low emission scenario (Collins et al., 2019).

SST variations mediate heat exchange across the air-sea interface, with high SSTs over the tropics accompanied by changes in atmospheric convection and circulation. A large part of the Indian Ocean is covered by the tropical warm pool, characterized by permanently warm SSTs greater than 28°C, and is therefore often called the heat engine of the globe (De Deckker, 2016; Rao et al., 2012; Roxy et al., 2019). Warming SSTs in the Indian Ocean imply a ramping up of this heat engine through intensification and expansion of the warm pool, thereby impacting the local and global climate (Beal et al., 2020; Roxy et al., 2020).

Indian Ocean warming contributes to increasing monsoon droughts and floods, and premonsoon heatwaves over South Asia (Li et al., 2022; Rohini et al., 2016; Roxy et al., 2015, 2017; Wang et al., 2021). Warming of the tropical Indian Ocean

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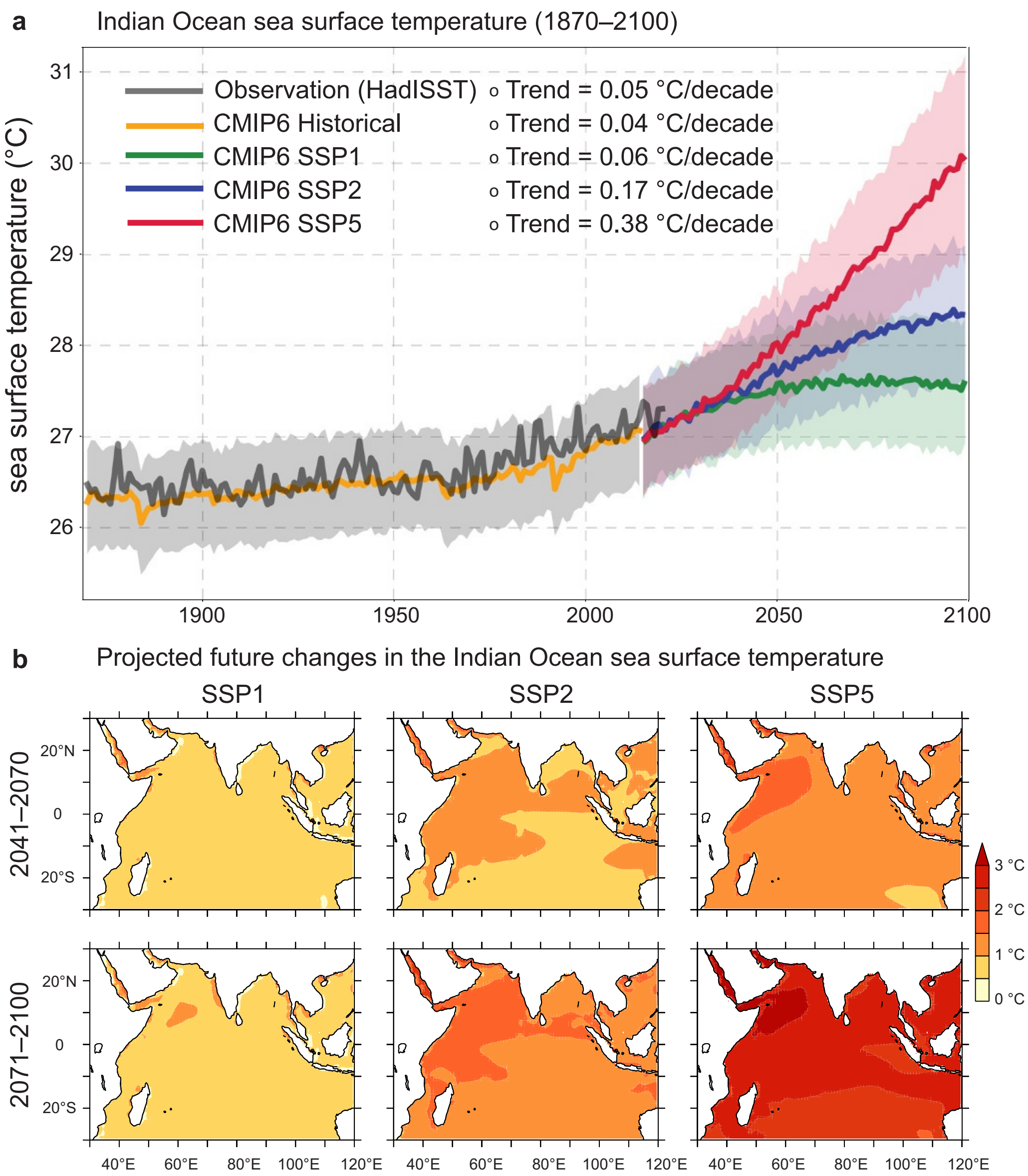

FIG. 1 (a) Time series of SST in the Indian Ocean (40–120°E, 30°S–30°N) in observations and CMIP6 simulations. The lines represent the observations (HadISST, 1870–2020, *black*) and CMIP6 multimodel ensemble mean of historical simulations (1870–2014, orange) and the future projections (2015–2100) under SSP1-2.6 (*green*), SSP2-4.5 (*blue*), and SSP5-8.5 (*red*) emission scenarios. Shading represents the intermodel uncertainty (intermodel standard deviation). (b) The projected multimodel mean changes in SST over the Indian Ocean for near (2041–2070) and far future (2071–2100) periods in different emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5), with respect to the historical simulations for the period 1985–2014.

in the recent decades has led to frequent droughts and occasional locust outbreaks in eastern Africa, threatening food security in this region (Funk et al., 2008; Salih et al., 2020). The effect of long-term warming in the Indian Ocean is reinforced by the occasional Indian Ocean Dipole (IOD) events, which preconditions and exacerbates bushfires over Australia since 1950 (Cai et al., 2009). The increase in ocean heat content has resulted in a rise in sea level via thermal expansion of seawater (Swapna et al., 2020), a potential increase in extremely severe cyclones and their rapid intensification (Bhatia et al., 2018; Deshpande et al., 2021; Murakami et al., 2017; Singh & Roxy, 2022) and consistent rise in the frequency and intensity of marine heatwaves in the Indian Ocean (Oliver et al., 2018; Qi et al., 2022; Saranya et al., 2022). The warming of the Indian Ocean also has far-reaching global impacts on intraseasonal-to-climate timescales. It modulates the Madden Julian Oscillation (MJO) and monsoon intraseasonal oscillation, which alters regional rainfall patterns (Rodrigues et al., 2019; Roxy et al., 2019; Sabeerali et al., 2014), and strengthens the Atlantic meridional overturning circulation thereby influencing the global climate (Hu & Fedorov, 2019, 2020).

The increase in atmospheric CO_2 and the associated ocean warming have very likely contributed to biogeochemical changes in the tropical Indian Ocean. These biogeochemical changes include the observed decreasing trends in pH (Piontkovski & Queste, 2016), dissolved oceanic oxygen (O_2) concentrations (Helm et al., 2011; Ito et al., 2017; Lévy et al., 2021; Stramma et al., 2008), and marine phytoplankton distribution (Piontkovski & Queste, 2016; Prakash et al., 2012; Roxy et al., 2016) in the tropical Indian Ocean. Combined, the more frequent marine heatwaves and biogeochemical changes potentially impact the marine ecosystem and fisheries in the tropical Indian Ocean (e.g., do Rosário Gomes et al., 2014; Frölicher & Laufkötter, 2018; Hood et al., 2024a, 2024b; Marsac et al., 2024; Naqvi et al., 2009; Piontkovski & Queste, 2016).

Given the magnitude and impact of the rapid warming in the tropical Indian Ocean, it is important to quantify and assess the future evolution of this warming under different climate change scenarios. This chapter discusses the future projections of the physical and biogeochemical changes in the Indian Ocean using existing literature based on Coupled Model Intercomparison Project (CMIP) Phase 5 (CMIP5) and available Phase 6 (CMIP6) simulations. The CMIP6 simulations are used to prepare the analysis and figures for historical simulations and future projections in the current chapter. The future scenarios are represented by Shared Socioeconomic Pathways (SSPs) of projected socioeconomic global changes up to 2100, based on greenhouse gas emissions scenarios with different climate policies (O'Neill et al., 2016; Riahi et al., 2017). Here we utilize three pathways: a world of sustainability-focused growth and equality where the radiative forcing is limited to $2.6\,W\,m^{-2}$ by the end of the 21st century (SSP1-2.6, low-forcing scenario); a "middle of the road" world where trends broadly follow their historical patterns and the radiative forcing is limited to $4.5\,W\,m^{-2}$ (SSP2-4.5, medium-forcing scenario); and the high road—a world of rapid and unconstrained fossil fuel-driven growth in economic output and energy use where the radiative forcing is high at $8.5\,W\,m^{-2}$ (SSP5-8.5, high-forcing scenario).

2 Projected changes in sea surface temperature, Indian Ocean Dipole, and heat content

The CMIP6 projections of future SSTs in the Indian Ocean show basin-wide warming but with substantial regional and seasonal variations as documented in previous studies (Cai et al., 2013). Fig. 1 shows the projected changes in SST over the Indian Ocean for the near (2041–2070) and far future (2071–2100) in different CMIP6 scenarios with respect to the historical period 1985–2014. All the CMIP6 future projections, regardless of the specific scenario, show maximum warming in the northwestern Indian Ocean, including the Arabian Sea, and reduced warming off the Sumatra and Java coasts in the southeast Indian Ocean (Fig. 1). These patterns are also simulated by the CMIP5-type of models (Zhao & Zhang, 2016; Zheng et al., 2010). While the CMIP6 SSP1-2.6 projects a basin-wide Indian Ocean warming of 0.06°C per decade, SSP2-4.5 and SSP5-8.5 projects an increased rate at 0.17°C and 0.38°C per decade, respectively (Fig. 1).

The strong warming pattern in the northwestern Indian Ocean and relatively weaker warming over the southeastern Indian Ocean in the future projections is consistent with a corresponding increase and decrease in precipitation over these regions, respectively, and strong easterly winds over the tropical Indian Ocean (Li et al., 2016). The changes in the easterlies along the equator and the faster warming in the west than the east in the Indian Ocean accompany a reduced strength of the Walker circulation in response to global warming (Vecchi et al., 2006). These environmental conditions create a conducive condition for the formation of the IOD pattern through the shoaling of thermocline over the eastern equatorial Indian Ocean (Zheng et al., 2010), and ease at which the atmospheric convergence moves to the west (Cai et al., 2014).

Regardless of the skewness in warming patterns in the Indian Ocean, instrumental records do not show any significant trends in IOD behavior. Also, the projected changes in the frequency and intensity of future IOD events remain uncertain in terms of the amplitude of the traditional dipole mode index using SSTs (Hui & Zheng, 2018; McKenna et al., 2020; Saji et al., 1999). Meanwhile, in terms of IOD-induced rainfall anomalies, climate models project that the frequency of extreme positive IOD events could increase by almost a factor of three, from a one-in-seventeen-year event in the 20th century to a one-in-six-year event in the 21st century (Cai et al., 2014; Collins et al., 2019). However, the frequency of IODs flattens if the global mean temperature is maintained below 1.5–2.0°C warming by 2050 (relative to the preindustrial level), as in the Paris Climate Agreement (Cai et al., 2018).

However, it is important to note that there is a debate about the dynamic processes related to the projected changes in IOD under global warming. The IOD simulations have a significant bias and intermodel spread that could lead to an over-estimation of the projected increase in extreme positive IOD events (Li et al., 2016) while other studies suggest the bias could lead to an under-estimate of the projected increase (Wang et al., 2017). In fact, the CMIP historical simulations fail in reproducing the observed changes in the zonal SST gradients over the Indian Ocean in response to greenhouse gas forcing (Roxy et al., 2014).

Recent studies show that dynamics for extreme IOD events as in 1997 and 2019 and for moderate IOD events as in 1982 and 2015 are different, with nonlinear subsurface ocean dynamics playing a more important role in the extreme

IOD events (Cai et al., 2014, 2021; Yang et al., 2020). As such, extreme and moderate IOD feature vastly different SST anomaly patterns, and two indices are required to represent their difference. Examining the response of the two types of IOD events in terms of IOD SST anomalies finds that the frequency of extreme IOD increases by 66% whereas the frequency of moderate IOD events decreases by 52% in the 21st century climate projections, as compared to the 20th century model historical simulations (Cai et al., 2021).

An increase in greenhouse gas emissions will not only raise the SSTs on interannual to decadal timescales but will also change its variability and seasonal cycle. On annual and longer time scales, the seasonal cycle is responsible for around 90% of the total surface temperature variance (Dwyer et al., 2012). CMIP6 models project a large increase in the magnitude of the seasonal cycle, in response to increased emissions under various SSPs (Fig. 2). The magnitude shift is largest during March–May when the mean temperatures are also at the highest (Fig. 2b, SST change of 2.75°C under high emission scenario). It is important to note that while the maximum basin mean temperatures in the Indian Ocean during 1980–2020 (observations and historical simulations) remained below 28°C (26–28°C) throughout the year, the minimum temperatures under SSP5-8.5 by the end of the 21st century is above 28°C (28.5–30.7°C) year around. This could have a potential response on the intensity of convection and the genesis and evolution of cyclones in the Indian Ocean region, where SSTs above 28°C are generally conducive for deep convection and cyclogenesis (Gadgil et al., 1984; Roxy, 2014; Singh et al., 2021). Heavy rainfall events and extremely severe cyclones have already increased since the 1950s (Deshpande et al., 2021; Roxy et al., 2017) and are projected to increase further with increasing SSTs in the tropical Indian Ocean region (Collins et al., 2019; Murakami et al., 2017; Wang et al., 2021).

The rapid warming in the Indian Ocean is not limited to the surface. Similar to the SSTs, the ocean heat content (OHC) also exhibits an increasing trend in the Indian Ocean since the 1950s (Han et al., 2014), though somewhat modulated by multidecadal variations (Ummenhofer et al., 2020, 2021). The paucity of long-term in situ observations makes it difficult to accurately quantify the relative contributions of warming trends and multidecadal variations to the changes in OHC and sea level (Beal et al., 2020; Nidheesh et al., 2017). The heat gain in the Indian Ocean represents about one-quarter of the global ocean heat gain since 1990, primarily due to a redistribution of heat from the Pacific to the Indian Ocean (Beal et al., 2020;

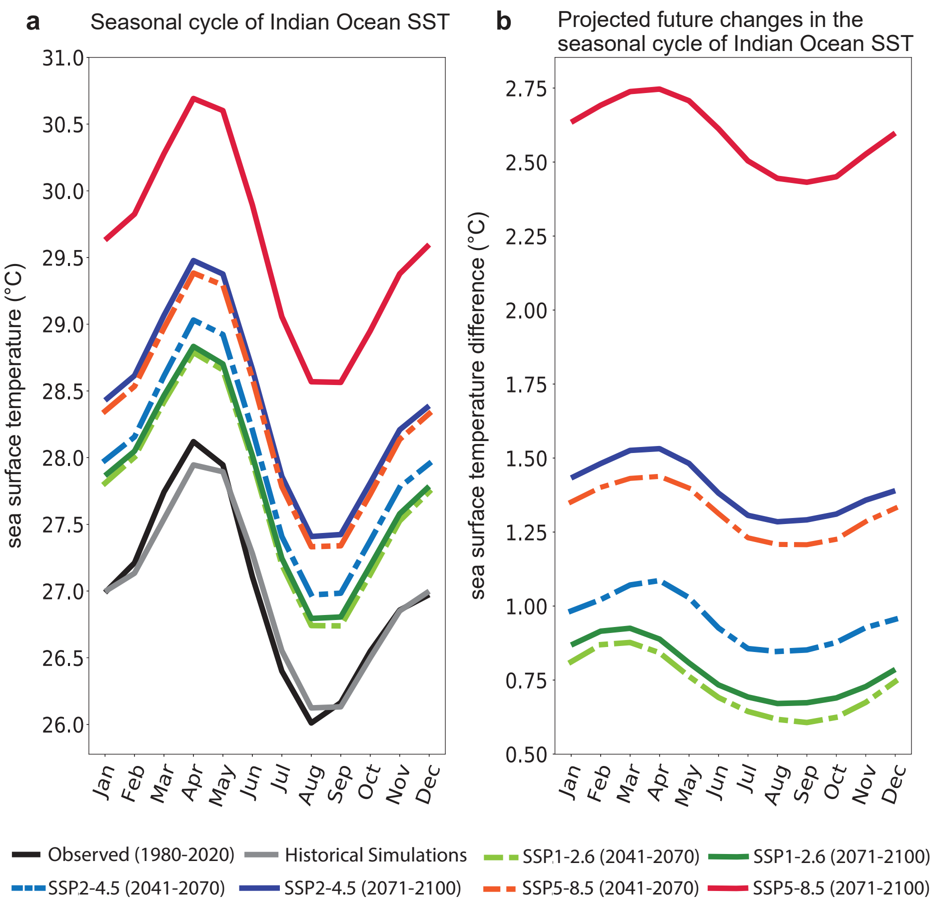

FIG. 2 (a) The seasonal cycle of SSTs over the Indian Ocean in the historical simulations (1985–2014) and as projected in different emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) in CMPI6, for the periods 2041–2070 and 2071–2100. (b) The change in SSTs in near and far future projections, with respect to the historical simulations (1985–2014).

Cheng et al., 2017; Sprintall et al., 2024; Tozuka et al., 2024). The long-term trends in the upper (0–700 m) ocean heat content (OHC_{700}) exhibit decadal variations, associated mainly with the transport from the Pacific to the Indian Ocean via the Indonesian throughflow, which is tightly linked to the decadal variability of the El Niño Southern Oscillation (ENSO) (Han et al., 2014).

The rate of increase in the tropical Indian Ocean heat content was at 3.7 zetta-joules (1 zetta-joule = 10^{21} J) per decade for OHC_{700}, and 4.5 zetta-joules per decade for deep (0–2000 m) ocean heat content (OHC_{2000}), during 1960–2016 (Fig. 3). While the OHC_{700} is projected to increase at a rate of 7 zetta-joules per decade for the low emission scenario, a trend of 11–17 zetta-joules per decade is projected under a mid-to-high emission scenario, between 2020 and the end of the 21st

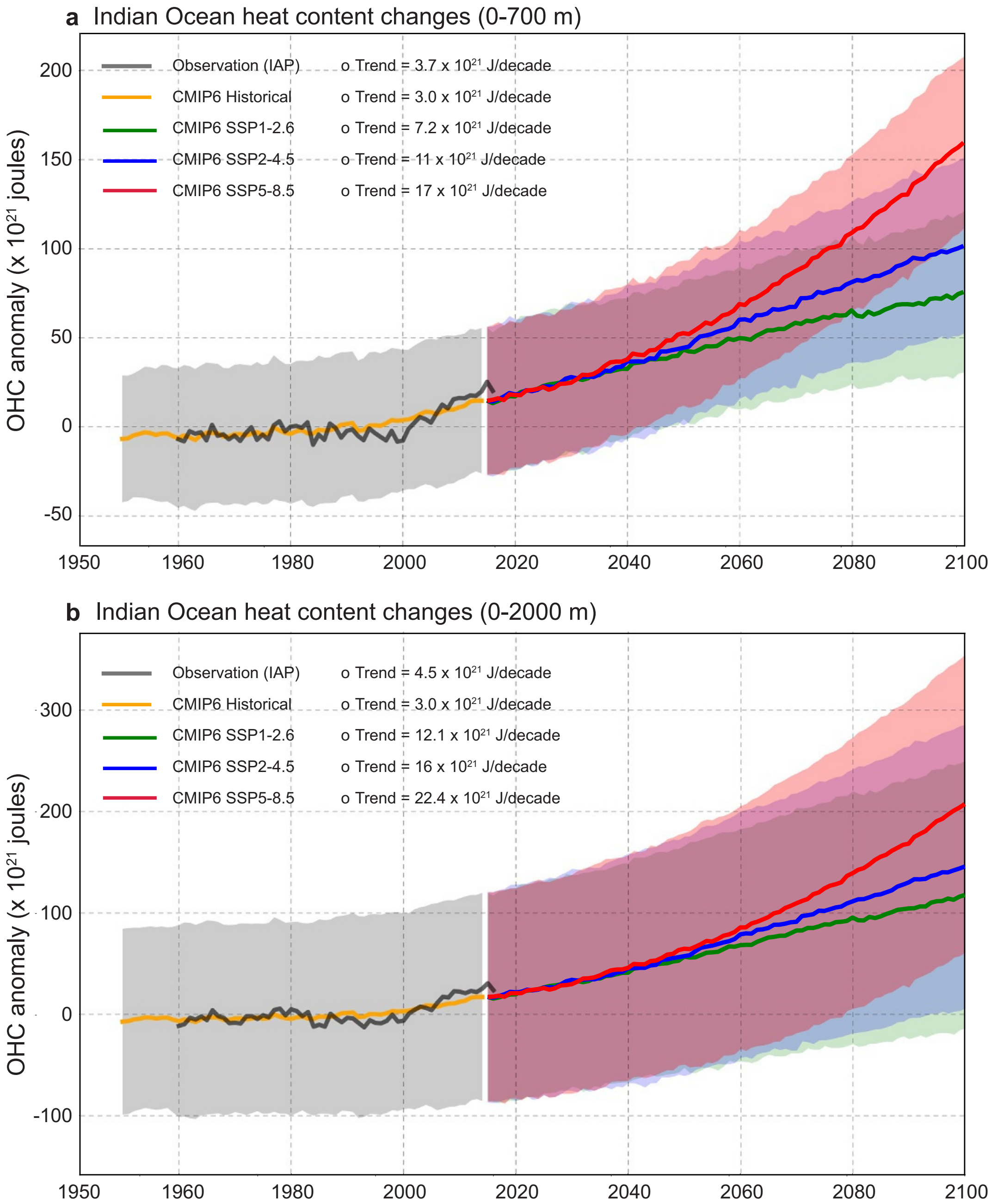

FIG. 3 Time series of ocean heat content anomaly (OHC) in the Indian Ocean (40–120°E, 30°S–30°N) in observation (Institute of Atmospheric Physics (IAP) ocean temperature analysis) and CMIP6 simulations relative to period 1960–2016, for (a) 0–700 m and (b) 0–2000 m. The *black*, *orange*, *green*, *blue*, and *red* lines represent the observations (Cheng et al., 2017) and CMIP6 multimodel ensemble mean of historical simulations (1950–2014) and future projections (2015–2100) under different emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5), respectively. The trend (slope) is estimated for the period represented by the respective lines in the figure. The shaded region represents the intermodel uncertainty (intermodel standard deviations).

century. The OHC_{2000} is projected to increase at a rate of 16–22 zetta-joules per decade under mid-to-high emission scenarios during the same period. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate and Sixth Assessment Report projects a global OHC increase at about 256 zetta-joules/decade for high emission scenarios (Bindoff et al., 2019; Fox-Kemper et al., 2021), which indicates that the Indian Ocean OHC increase may contribute to about 1/9th of the global OHC rise.

3 Projected changes in marine heatwaves

The basin-wide warming in the Indian Ocean is a significant factor contributing to the increased occurrence of marine heatwaves (Frölicher et al., 2018; Oliver et al., 2018; Saranya et al., 2022). Marine heatwaves (Hobday et al., 2016) are periods of extremely high temperatures (i.e., SSTs exceeding the seasonally-varying 90th percentile threshold based on the 1970–1999 reference period in our case) in the ocean that can significantly impact marine organisms and ecosystems (Collins et al., 2019; Hughes et al., 2017; Smale et al., 2019). Oliver et al. (2018) show that globally, the frequency of marine heatwaves has increased on average by 34% and the duration by 17% during the last century. CMIP5 and CMIP6 projections indicate a significant further increase in the frequency, intensity, and duration of marine heatwaves in the future due to global warming (Frölicher et al., 2018; Plecha & Soares, 2020). These projections indicate that by the end of the century, global oceans will be in a near-permanent marine heatwave state (Frölicher et al., 2018; Oliver et al., 2019). Notably, the number of marine heatwave days in the Indian Ocean is projected to increase from 20 days per year (in historical simulations, 21 days per year in observations) to 250 days per year by 2100 (SSP 8.5). The maximum intensity of marine heatwaves (i.e., SST anomaly exceeding the seasonally varying 90th percentile threshold) in the Indian Ocean is projected to increase from 0.60°C per year (in historical simulations, 0.96°C per year in observations) to 3.4°C per year by 2100 (Fig. 4, SSP 8.5).

Fig. 4a shows that for both the near and far future, SSP1-2.6 has an average number of marine heatwave days <200, while SSP2-4.5 and SSSP5-8.5 have higher values >250 days, indicating basin-wide near-permanent marine heatwave conditions (Fig. 4c). The maximum intensities also indicate a similar contrast, with the intensity projected below 1.2°C for the SSP1-2.6 while it is around 1.2–1.4°C for SSSP5-8.5 (Fig. 4b). In the far future, the entire Indian Ocean basin is projected to have marine heatwaves of above 1.8°C maximum intensity. The average cumulative intensity (sum of temperature anomalies over the duration of a marine heatwave, in °C) in SSP2-4.5 and SSP5-8.5 exceeds 480°C days in the near and far future for most of the tropical Indian Ocean (Fig. 4).

4 Projected changes in the biogeochemistry of the Indian Ocean

The western Indian Ocean, including the Arabian Sea, is one of the most prominent marine productivity hotspots within the tropical Indian Ocean, where upwelling of cold nutrient-rich water by the seasonally reversing monsoon winds promotes large phytoplankton blooms (Hood et al., 2024a; Prasanna Kumar et al., 2001; Wiggert et al., 2005). Ocean color measurements suggest that the surface chlorophyll—a proxy for estimating net primary productivity—has declined by up to 30% in the Arabian Sea during 1998–2013 (Roxy et al., 2016). Historical simulations from the CMIP5 Earth system models also agree with the observations, suggesting a 20% decline in this region, during 1950–2015 (Roxy et al., 2016). These strong declining trends in phytoplankton production are mainly due to the increased stratification of the oceanic water column caused by the warming of the ocean surface (Behrenfeld et al., 2006; Roxy et al., 2016). Global ocean salinity changes have contributed to enhanced ocean stratification in the high-latitude regions (Cheng et al., 2020), amplifying the effects of ocean warming, while such an impact is not evidenced for most of the tropical Indian Ocean (Li et al., 2020). In the low-latitude regions—that are primarily nutrient-limited as sunlight is abundant and temperature is high—an increase in ocean surface warming increases the water column stratification leading to reduced mixing and a reduced supply of nutrients from the subsurface into the surface (Behrenfeld et al., 2006; Boyce et al., 2010).

Earlier generations of Earth system models projected a mean global decline in the net primary productivity during the 21st century (Behrenfeld et al., 2006; Bopp et al., 2001, 2013; Boyce et al., 2010; Fung et al., 2005; Steinacher et al., 2010), associated with a net decrease in carbon export into the deeper ocean (Bopp et al., 2013). The CMIP6 models generally outperform the CMIP5 predecessors in simulating the observed ocean biogeochemistry (Séférian et al., 2020). The CMIP6 ensemble mean projects a further significant reduction in depth-integrated net primary production in the western Indian Ocean and Arabian Sea by the end of the 21st century (Kwiatkowski et al., 2020).

The CMIP6 projections indicate a reduction in surface chlorophyll concentrations in both the near-future (2041–2070) and far-future (2071–2100), with respect to the reference period (1976–2005) in most parts of the tropical Indian Ocean, particularly the western Arabian Sea and western Bay of Bengal (Fig. 5). Under medium-to-high emission scenarios, an 8%–10% decrease in surface chlorophyll is projected for the western Arabian Sea region (50–65°E, 5–25°N) by the end of

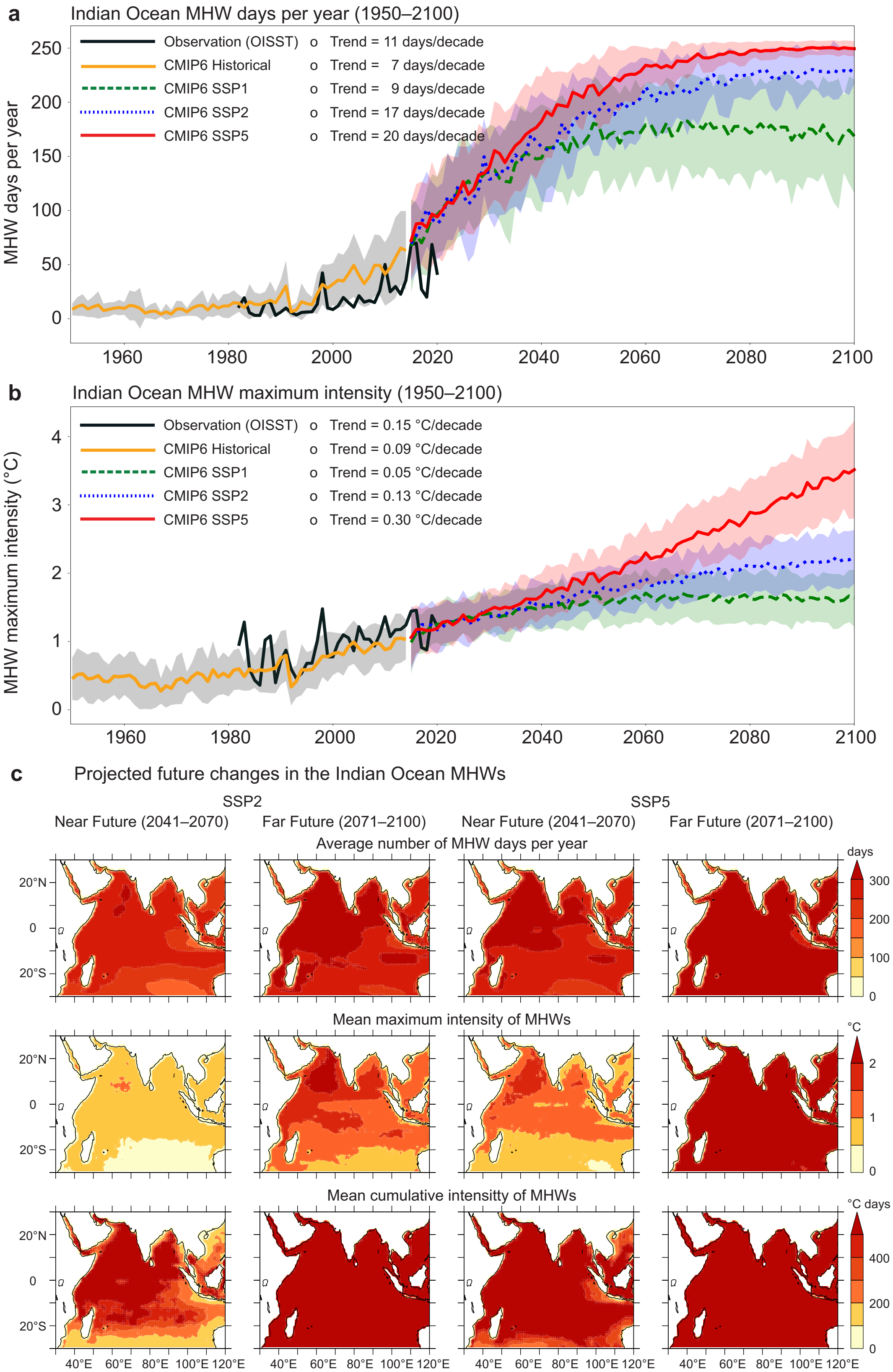

FIG. 4 (a) Marine heatwave (MHW) days and (b) maximum intensity (maximum temperature anomaly exceeding the seasonally-varying 90th percentile threshold during a marine heatwave, °C) in observations (National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature V2 data, NOAA OISST; Banzon et al., 2014), and CMIP6 simulations, for the tropical Indian Ocean. The baseline climatology for calculating the anomalies for historical and future simulations is based on the period 1970–2000. The trend (slope) is estimated for the period represented by the respective lines in the figure. (c) Future changes (with respect to 1970–2000) in the marine heatwave metrics—average number of marine heatwave days, mean maximum intensity, and mean cumulative intensity—using CMIP6 simulations (ensemble mean) under medium (SSP2-4.5) and high (SSP5-8.5) emission scenarios.

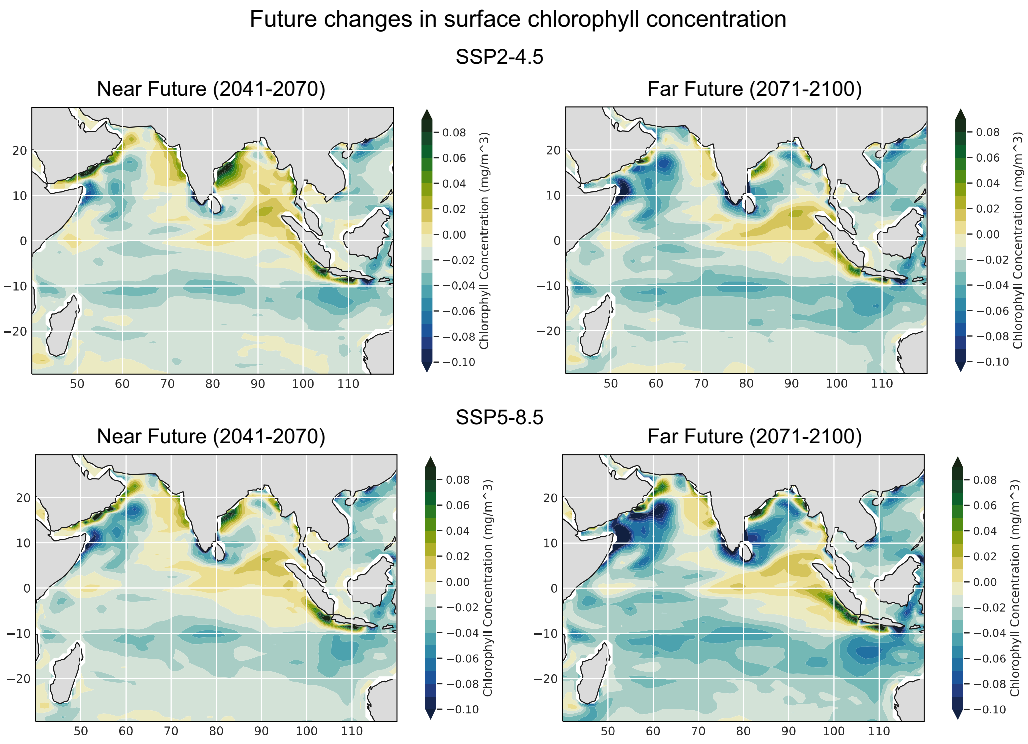

FIG. 5 Projected changes in ocean surface chlorophyll (in $mg\,m^{-3}$) during the summer monsoon (June–September) in (a) SSP2-4.5 for 2041–2070, (b) SSP2-4.5 for 2071–2100, (c) SSP5-8.5 for 2041–2070, and (d) SSP5-8.5 for 2071–2100, with respect to the reference period 1976–2005, in CMIP6 (ensemble mean) simulations.

the 21st century (Fig. 5). In contrast, the models project an increase in surface chlorophyll in the southeast Indian Ocean off the Sumatran and Java coasts and along most coastal regions in the northern Indian Ocean (Oman, western and eastern India, Myanmar).

This decline in chlorophyll is likely tied to the warming-driven increase in stratification (less-mixed), which limits the supply of subsurface nutrient-rich waters to the surface. Therefore, the tropical Indian Ocean may face a net negative impact on marine primary production (Marinov et al., 2010). Diatoms, which form a major component of the marine phytoplankton and account for more than 40% of the global CO_2 biological pump (Treguer & Pondaven, 2000), are projected to undergo a rapid decrease as compared to other phytoplankton types in the Indian Ocean, owing to stronger nitrate limitation (Bopp et al., 2005; Cermeño et al., 2008).

Although changes in stratification contribute to the observed and projected changes in marine primary production here, alterations to winds may also be crucial to understand. While the observed impacts of wind changes on the seasonal phytoplankton blooms are yet to be delineated (Roxy et al., 2016), the potential impact of future changes in monsoon winds on these blooms cannot be ruled out and requires an in-depth investigation (Parvathi et al., 2017; Praveen et al., 2016). As of now, the significant biases in CMIP6 models in representing the Indian Ocean variability and the monsoon system (Halder et al., 2021; Singh et al., 2019), and uncertainties and intermodel spread in the projections of biogeochemical changes limit a definitive understanding of future changes in marine primary production in the Indian Ocean (Tagliabue et al., 2021).

As the atmospheric carbon dioxide increases due to continued carbon emissions, the amount of carbon dioxide absorbed by the ocean also increases (IPCC Special Report on Ocean and Cryosphere in a Changing Climate), resulting in an increased concentration of hydrogen ions in the seawater, reducing its pH (Orr et al., 2005). The mean global ocean pH has already decreased from 8.16 to about 8.07 since the industrial revolution (Dore et al., 2009; Orr et al., 2005). Ocean biogeochemical model simulations show that the western Arabian Sea has undergone rapid acidification from 8.12 to 8.05 since 1961 (Sreeush et al., 2019). The western Arabian Sea has acidified more than the rest of the tropical Indian Ocean basin by drawing up anthropogenic CO_2 embedded into the deeper ocean during the process of upwelling, particularly during the southwest monsoon season.

The ocean acidity is projected (based on CMIP5 models) to increase, with the pH decreasing by an average of about −0.04 units per decade by the end of the 21st century (Dunne et al., 2013; Jiang et al., 2019; Kwiatkowski et al., 2020). Bopp

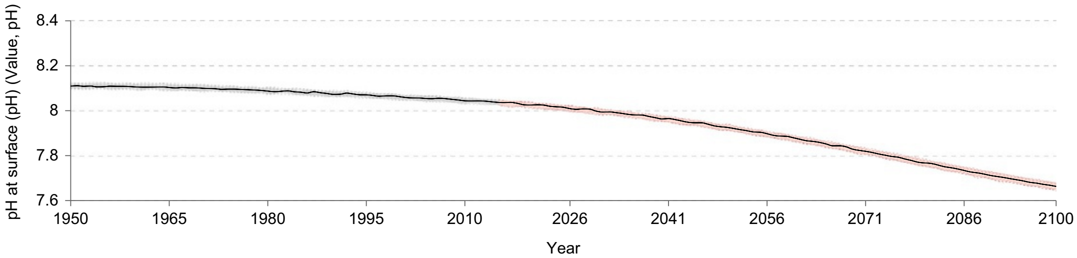

FIG. 6 Observed and projected surface pH in the tropical Indian Ocean under high emission scenario (SSP5-8.5), in CMIP6 (ensemble mean) simulations. The light shading indicates the spread between the 10th–90th percentiles. *(Adapted from the IPCC WGI Interactive Atlas (IPCC, 2021).)*

et al. (2013) and Frölicher et al. (2016) find a very low intermodel spread among the CMIP5 models and internal variability in their projections of a decline in pH over the course of the 21st century, increasing the confidence in these results. The projections of global mean surface pH suggest that it is likely to fall to around 7.67 by the year 2100, under a high-emissions scenario in case of no mitigation (Bernie et al., 2010). This would be likely five times the current amount of acidification. The projected change in surface pH over the Indian Ocean by CMIP6 models is on par with the globally projected change (Fig. 6). The corals that form reefs using aragonite and the phytoplankton, which requires calcites to form their shells, are projected to undergo a decline in the calcification rates in the low-latitude regions under reducing pH conditions (Feely et al., 2009). In the Arabian Sea, the planktonic foram *Globigerinoides ruber* already shows a significant reduction in the calcification rates used in their shell formation (de Moel et al., 2009).

The volume of oxygen minimum zones (OMZs) in the northern Indian Ocean has not dramatically changed over past decades, with observation suggesting that parts of the OMZ in the Arabian Sea have shrunk while others have expanded over this timeframe (Banse et al., 2014; Piontkovski & Al-Oufi, 2015; Queste et al., 2018). Yet there is growing observational evidence that oxygen concentrations are declining in most of the tropical Indian Ocean (e.g., Hood et al., 2024b; Lévy et al., 2021). In the northern Arabian Sea, dissolved oxygen concentrations measured during 1960–2010 show a decreasing trend in the surface mixed layer, potentially triggering large harmful algal (Noctiluca) winter blooms since the 2000s (do Rosário Gomes et al., 2014). Global ocean oxygen concentrations are very likely to decrease further in response to anthropogenic warming (IPCC SROCC), and this deoxygenation is expected to persist for thousands of years (Frölicher et al., 2020; IPCC, 2021; Oschlies, 2021). However, in contrast to the future projections of phytoplankton and pH, the future evolution of subsurface oxygen concentration in the tropical Indian Ocean is inconsistent across models from both the CMIP5 (Bopp et al., 2013; Busecke et al., 2019; Cabré et al., 2015; Lévy et al., 2021) and CMIP6 generations (Kwiatkowski et al., 2020). These projections are impeded by strong biases in oxygen distribution, with most Earth system models overestimating the oxygen concentration in the Arabian Sea and about half of them lacking an OMZ core in this region (Fig. 6, Rixen et al., 2020). Regional ocean model sensitivity experiments suggest, however, that the volume of the OMZ in the Arabian Sea could expand in response to anthropogenically-driven warming and wind intensification in the region (Lachkar et al., 2018, 2019). Recent work using Earth system models suggests that in response to the ocean warming, the outer OMZ expands while the OMZ core contracts, and in between the oxygen is redistributed with little effect on the OMZ volume (Ditkovsky et al., 2023).

5 Summary and discussion

The rapid warming of the Indian Ocean (at a rate of 0.12°C per decade between 1950 and 2020) has altered the weather and climate over the densely populated Indian Ocean rim nations, threatening the food, water, and energy security of the region (Anwar et al., 2023). Climate models project an increased basin-wide surface warming in the Indian Ocean, at the rate of 0.17–0.38°C per decade during 2020–2100, under medium-to-high greenhouse gas emission scenarios. The models project a large shift in the amplitude of the seasonal cycle, with the largest change during March–May, when the mean temperatures are also highest. The seasonal SST cycle ranging between 26°C and 28°C during 1980–2020 is projected to shift to 28.5–30.7°C by the end of the 21st century, under medium-to-high emission scenarios. The ocean heat content (OHC_{2000}) is also projected to consistently increase basin-wide in the future, at the rate of 16–22 zetta-joules per decade under mid-to-high emission scenarios. The frequency and intensity of future IOD events are projected to increase in the 21st century while the significant model bias and substantially large intermodel spread could be a factor potentially overestimating the projected increase in extremely positive IOD events.

The basin-wide warming in the Indian Ocean is a significant factor contributing to an increased frequency and intensity of marine heatwaves. The frequency, intensity, and the area covered by marine heatwaves are projected to increase substantially, driving a basin-wide near-permanent marine heatwave condition by the end of the 21st century, under medium and high emission scenarios. Rapid surface warming results in a stratified ocean, preventing the mixing of the surface with subsurface waters, which reduces the exchange of nutrients, oxygen, carbon, and heat. Under medium-to-high emission scenarios, an 8%–10% decrease in surface phytoplankton abundance is projected for the Arabian Sea region by the end of the 21st century (Fig. 5), potentially driven by enhanced thermal stratification. There is, however, a projected increase in surface phytoplankton in the southeast Indian Ocean off the Sumatran-Java coasts, and a few coastal regions in the north Indian Ocean.

With rising atmospheric CO_2 levels, ocean acidification is also increasing at a rapid pace. The surface pH of the tropical Indian Ocean is projected to decrease below 7.7 by the end of the 21st century, compared to a pH above 8.1 during the early 20th century. Since the pH scale is logarithmic, even a drop of 0.1 pH units represents approximately a 30% increase in the relative acidity of ocean water. The change may be easier to fathom when we realize that a 0.1 fall in human blood pH can result in rather profound health consequences and multiple-organ failure. The projected changes in pH may be detrimental to the marine ecosystem since many marine organisms—particularly corals and organisms that depend on calcification to build and maintain their shells—are sensitive to the change in ocean acidity (Doney et al., 2009).

Earth system models project inconsistent future changes in subsurface ocean oxygen concentrations in the tropical Indian Ocean. The high uncertainties in these projections are likely due to model limitations in simulating the biophysical processes that control oxygen concentrations in the Indian Ocean (Bopp et al., 2017; Lachkar et al., 2016; Resplandy et al., 2012; Rixen et al., 2020; Séférian et al., 2020). At the same time, gaps in high-quality long-term ocean observations limit our ability to separate multidecadal variability and anthropogenic warming in tropical oceans, particularly in terms of the observed changes in the biogeochemistry (Beal et al., 2020; Hermes et al., 2019; Hood et al., 2009; Stammer et al., 2019). Improved simulations of upper-ocean biophysical processes in Earth system models and urgent investment in high-resolution ocean observations are necessary to address the limitations of current projections, which exhibit high uncertainties in future changes in ocean biogeochemistry in the tropical Indian Ocean.

6 Educational resources

IPCC WGI Interactive Atlas: An interactive tool for spatial and temporal analyses of the observed and projected climate change information based on the IPCC Working Group I contribution to the Sixth Assessment Report (IPCC, 2021).

Website: https://interactive-atlas.ipcc.ch
Code with the data: https://github.com/IPCC-WG1/Atlas

Author contributions

MKR conceived and led the chapter. JSS and AA contributed to the analysis and figures in Sections 2 and 3, and AM contributed to Section 4. All authors contributed to the discussion of content and overall chapter structure and provided feedback on the entire chapter.

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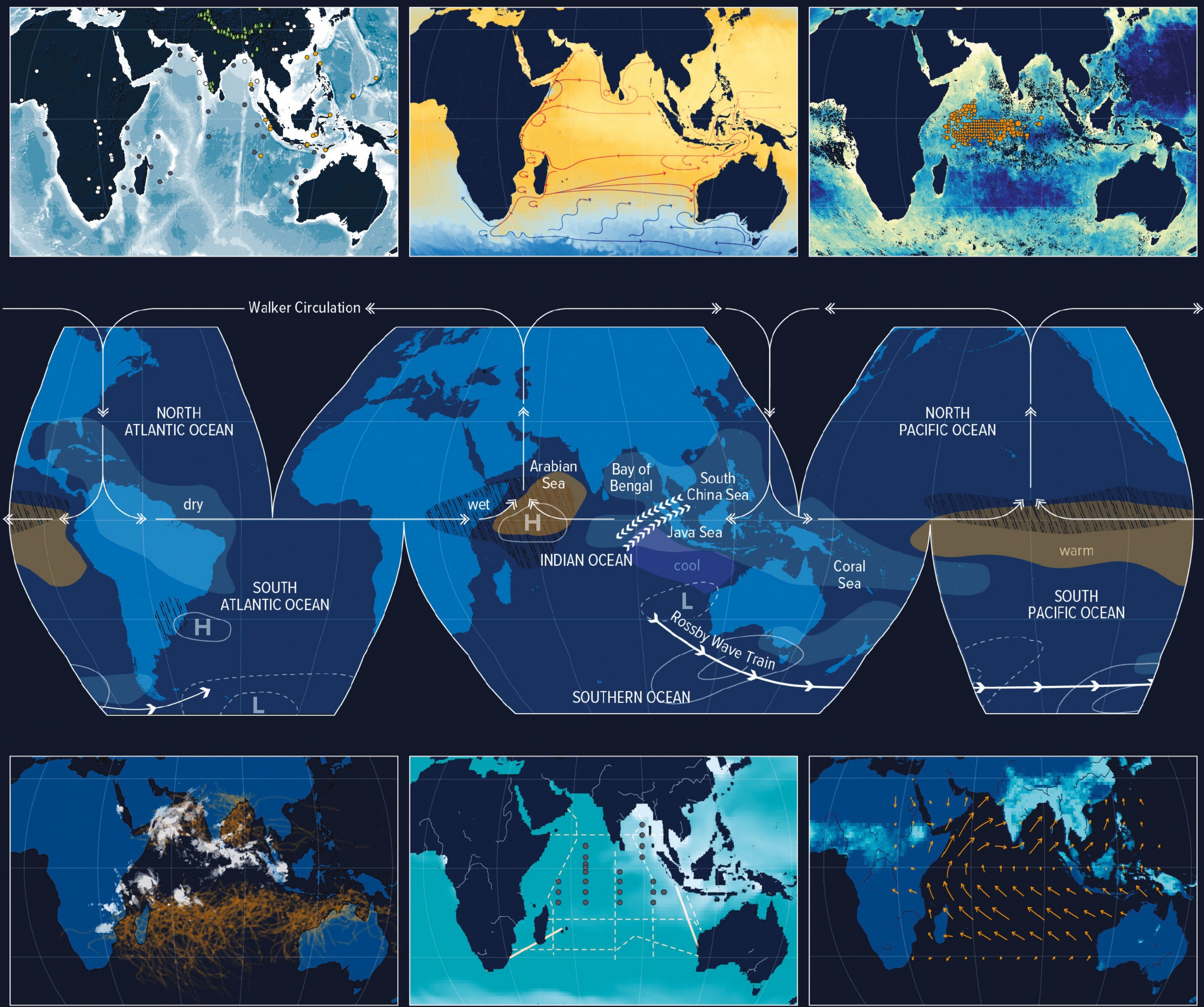

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