

## Suppl 1. The case for urgent action

Whilst the political intent to protect 10% can be traced back to the early 1980s, the knowledge of ocean issues and increasingly large-scale changes to functions and processes due to human actions has rapidly expanded, particularly in the last two decades. Gone are simply the standard list of abatable impacts we have known for decades, such as pollution, fisheries, and mechanical habitat destruction, as these are now accompanied by whole-scale changes caused indirectly via breakdown of our greenhouse gas emissions.

There are now five major perturbations to the ocean beyond direct human impacts, significant at the Earth/ocean system scale, that demand urgent action.

- Significant and accelerating heating of the ocean and oxygen loss
- Significant alterations to wind regimes which shape ocean ecosystems and human societies
- Significant sea-level rise, and the worsening trend and displacement of peoples, nations, and associated losses of nature-based solutions
- Significant perturbation to the major ocean current and upwelling systems
- Significant regional acidification and persistent worsening trends

Urgency is related not only to the scale and speed of change now being observed, but also the realisation that the longer action is delayed the costlier and more challenging it will be to reverse. The trends do not favour human social, well-being, or economic values, and sit on top of a significant, sustained, and accelerating trend in loss of species and alterations and losses of ecosystem goods and services.

### Significant and accelerating heating of the ocean and oxygen loss

The ocean has warmed continuously to 2000 m since 1970 because of anthropogenic influence, with the rate of warming twice as fast since 1993 as from 1970-93. This warming and freshening at high latitudes is causing the surface waters to become less dense than deeper waters, enhancing stratification and reducing oxygenation of the interior ocean (ventilation). The effects of warming on solubility, ventilation, and respiration, caused an oxygen loss of 0.5-3.3% between 1979-2010 in the upper 1000 m of ocean, and expansion of the world's oxygen minimum zones by 3-8%, with some areas experiencing much higher oxygen loss. Marine heatwaves, periods of excessively high ocean temperatures, have likely doubled in frequency from 1982-2016, with major impacts on coral, seagrass and kelp ecosystems (IPCC, 2019).

### Significant alterations to wind regimes which shape ocean ecosystems and human societies

Tropical cyclones, also known as tornadoes and hurricanes have a particularly large impact and growing economic cost. The number of severe hurricanes that make landfall in the USA has increased (Hallam et al., 2019) with equivalent trends in cyclone damage in other regions of the world e.g. South East Asia (Park, Ho, & Kim, 2014). The cost for Small Island Developing States in the Pacific has been particularly high, averaging \$180 million per annum over the last 50 years, with

large environmental impacts especially on coral reefs, further limiting coastal protection (Thomas, Schleussner, & Kumar, 2018). At a global level, the frequency of tropical cyclones has been relatively stable, but the number growing to hurricane strength has significantly increased with considerable differences between ocean basins (Bhatia et al., 2019). There is also an increasing trend in the intensification of cyclones; this has reduced between 1986 and 2010 by 9 hours globally (Kishtawal, Jaiswal, Singh, & Niyogi, 2012). A consequence of the change in intensification is that there is less time to initiate warning and evacuation procedures. All these changes in cyclone occurrence are in line with observed increases in SST due to global warming.

To form, cyclones require SST of 26.5°C (>25.7°C in the Atlantic) plus especially low vertical wind shear. The strength of tropical cyclones increases with latitude and varies by ocean region e.g. cyclones at 30° latitude are double those at 15° latitude (Moon, Kim, & Chan, 2019). An increase in the occurrence of extreme rainfall and floods associated with cyclones has also been observed e.g. (Paerl et al., 2019; Patricola & Wehner, 2018; WMO, 2020), and has been attributed to higher water vapour in the atmosphere due to higher temperature and other factors (Liu, Vecchi, Smith, & Knutson, 2019). It is expected in a world that continues to warm that there is likely to be more flooding from associated storm surges, increases in rainfall, greater intensity to higher category hurricanes and cyclones with higher wind speeds.

#### Significant sea-level rise, and the worsening trend and displacement of peoples, nations, and associated losses of nature-based solutions

Global mean sea level is rising, with an acceleration in recent decades due to increasing rates of ice loss from the Greenland and Antarctic ice sheets, as well as continued glacier mass loss and ocean thermal expansion. In 1901-1990 the rise in sea level was 1.4 mm yr<sup>-1</sup> but in 2006-2015 this had accelerated to 3.6 mm per year and this trend is getting worse yearly. Antarctic ice mass loss over the period 2007–2016 tripled relative to 1997–2006. Despite significant uncertainties remaining, the IPCC (2019) predicts that sea level rise will continue for centuries, even if mitigation measures are put in place. Increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal hazards. The potential widespread collapse of ice shelves could lead to a twenty-first century sea level rise of up to several tenths of a metre, which will have drastic consequences both for people and marine life, particularly for low-lying nations IPCC (2019).

Local sea levels that historically occurred once per century are projected to become at least annual events at most locations during the 21st century. The human population exposed to extreme sea level events is growing significantly. Considering population growth and urbanisation, only 21 cm of global mean sea level rise by 2060 would increase the global population living below the hundred-year extreme sea level from about 189 million in 2000 to 316–411 million in 2060 (Neumann, Vafeidis, Zimmermann, & Nicholls, 2015). This will lead to mass human migration as the food growing areas of countries such as Bangladesh or even entire nations such as Mauritius are inundated by seawater. Coastal protection through dikes, seawalls, and surge barriers is widespread in many coastal cities and deltas. Hallegatte et al. (2015) conducted a global analysis of present and future losses in the 136 largest coastal cities. They predicted that global flood losses would increase from an average of six billion United States dollars per year in 2005 to one trillion US dollars by 2050, with projected socioeconomic change, climate breakdown and subsidence. Developing countries are particularly vulnerable to flood risk, with much lower investment in flood protection measures (Hallegatte et al., 2015).

### Significant perturbation to the major ocean current and upwelling systems

The ocean's large-scale vertical and horizontal Meridional Overturning Circulation (MOC), commonly known as the 'global conveyor belt' is primarily driven by winds at the surface and at depth by density differences from changes in temperature and salinity. Water heated in the tropics is moved towards the poles in the upper ocean by major ocean currents such as the Gulf Stream and Kuroshio Current with cold water sinking at the poles to the depths of the ocean returning south and northward to complete the conveyor by mixing and upwelling back to the surface.

Because of the formation of deep water in the North Atlantic this ocean has a key role in the MOC as the main conduit of heat towards the Arctic, also ensuring that Europe is warmer than elsewhere at similar latitudes (McCarthy et al., 2020). Modelling studies suggest that a decline in the overturning circulation and reduction of deep-water formation will lead to lower surface temperatures (McCarthy et al., 2020). The North Atlantic MOC (AMOC) is predicted to weaken substantially as the world gets warmer and there is already evidence that it has slowed down by about 13% since 2009 leading to lower temperature and salinity in the subpolar Atlantic and reduced transfer of heat to atmospheric westerlies (Bryden et al., 2019). Despite this Northwest Europe and the Arctic has continued to warm. Modelling by (Nummelin, Li, & Hezel, 2017) suggests that reduced loss of heat from subpolar latitudes can increase heat flow to the Arctic independently of changes in the AMOC. There is also evidence for pronounced changes in the deepest abyssal limb of the MOC, with increased heat content in Antarctic Bottom Water (AABW) to past the equator (Durack et al., 2018; Purkey & Johnson, 2010). At the same time the volume of AABW appears to be reducing as the melting of the Antarctic ice sheet and ice shelves increases. Silvano et al. (2018) show that increased stratification in polynyas, induced by input of glacial meltwater, is inhibiting the formation of AABW. The rapidly increasing input of meltwater to coastal waters of Antarctica is projected by (Lago & England 2019) for RCP 4.5 and 8.5 to cause a total collapse of AABW within only 30 to 60 years from present with grave consequences, if they are correct, for CO<sub>2</sub> sequestration and warming of the ocean. Forget and Ferreira (2019) challenges the traditional view of the MOC showing that most heat redistribution towards the poles takes place primarily within oceanic basins and is dominated by the Pacific with only minor exchanges between ocean basins.

In surface waters there has been an acceleration of warming in all western boundary currents (WBCs) that is 2 to 3 times faster than the global average (Beal & Elipot 2016). Hu et al. (2020) show that there has been a substantial acceleration in global mean ocean circulation (measured as globally integrated oceanic kinetic energy) caused by a global intensification of surface winds. All WBCs (except the Gulf Stream) are intensifying and their mid latitude extensions shifting toward the poles (Wu et al., 2012; Yang et al., 2016). These changes parallel evidence for a widening of the Hadley cells and an intensification and poleward shift of near-surface westerly winds and wind stress curl especially in the Southern Ocean (Wu et al., 2012) where there is also evidence for increased variability in winds more recently (Turney et al., 2017). The different pattern in the Gulf Stream is attributed to the evidence for a weakening of AMOC. The Gulf Stream appears to be weakening and broadening in its subpolar extension region with increased formation of eddies (McCarthy, Joyce, & Josey, 2018). A similar situation has been described for the Agulhas (Beal & Elipot, 2016) and the East Australian Current (Oke et al., 2019). It is suggested by (Nummelin et al., 2017) that recent cooling and reduced heat loss from the subpolar North Atlantic has enabled the Arctic to continue to warm. In the Arctic, winds have also accelerated leading to stronger currents and the increasing break-up and export of multiyear sea-ice through the Fram Strait between Greenland and Svalbard (Kwok, Spreen, & Pang, 2013). The scale of the changes in ocean circulation are so large and the

evidence already for major impacts on ecosystems so great that (van Gennip et al., 2017) recommend that it should have equal status to e.g. acidification and deoxygenation as a stressor of ecosystems.

Eastern Boundary Upwelling Systems (EBUS) represent only about 1% of the ocean surface but contribute more than 20% of the fish resources of the world. There are two main potentially competitive or complementary drivers of upwelling in these systems, wind forcing and stratification (thermocline depth) (Bonino, Di Lorenzo, Masina, & Iovino, 2019; García-Reyes et al., 2015). There is already good evidence for increased upwelling in most EBUS (except the Canaries), forced by stronger winds, and it is expected to accentuate and extend upwelling further towards the poles as the ocean warms (IPCC, 2019). A potential reduction of upwelling from increased water stability in a warmer ocean is less clear, but is expected from modelling results to reduce upwelling off Northwest Spain in the future (Sousa et al., 2020), with the opposite results for California (Arellano and Rivas 2019). Shoaling of the aragonite saturation horizon is already impacting East Pacific EBUS and is exacerbated by deoxygenation. Negrete-García, Lovenduski, Hauri, Krumhardt, and Lauvset (2019) predict that a shallow saturation horizon will occur over extensive area of the Southern Ocean with major impacts on plankton with aragonitic body parts, in only a few decades. Because of inherent variability between and within different EBUS it is difficult at present to predict the future effects of climate breakdown on these systems or the economic impact of a reduction in fish catches, which could have serious consequences for regional food security (IPCC, 2019). Major upwelling of deep water from the Atlantic, Indian and Pacific Oceans also occurs at five main topographic features in the Southern Ocean: Drake Passage, the Southwest Indian Ridge, Kerguelen Plateau, Macquarie Ridge and the Pacific–Antarctic Ridge (Tamsitt et al., 2017).

#### Significant regional acidification and persistent worsening trends

We are releasing around 1 million tons of CO<sub>2</sub> per hour into the Earth's atmosphere, of which about 25-30% is taken up by the ocean where it reacts with seawater causing surface ocean pH to fall by around 0.002 units per year (IPCC, 2019). This has triggered changes in ocean chemistry that have caused the depth at which seawater is corrosive to carbonate to shoal, threatening deep-water coral reefs worldwide through dissolution and intensified bio-erosion (Gómez, Wickes, Deega, Etnoyer, & Cordes, 2018). The COVID-19 pandemic in 2020 showed that humanity can make deep cuts in carbon emissions rapidly (Dutheil, Baker, & Navel, 2020). It is imperative to maintain lower emissions, since if we follow the IPCC representative concentration pathway 8.5, that will block the ability of tropical coral reefs to shift poleward whilst warming continues to kill them in the tropics (Albright et al., 2018) and would render the Arctic unsuitable for maerl habitats (Brodie et al., 2014).

Between 2005 and 2009, ocean acidification jeopardized a 270 million US dollar, 3,200 jobs per year, shellfish aquaculture industry in the USA. Billions of oysters were dying at hatcheries because seawater had become corrosive to larval shells and so the industry had to adapt by raising seawater pH in on-land hatcheries (Ekstrom et al., 2015). This region is especially vulnerable to ocean acidification as it is affected by naturally higher levels of seawater CO<sub>2</sub> due to deep water upwelling. Laboratory experiments have since shown that ocean acidification may affect all marine life, e.g. through changes in gene expression, physiology, reproduction and behaviour, and have adverse effects on the quality of seafood (IPCC, 2019). Work at marine CO<sub>2</sub> seeps shows that some groups of organisms do well in acidified conditions, but many taxa do not (Hall-Spencer & Harvey, 2019). Most macroalgae are resilient to ocean acidification as increased carbon availability stimulates primary production and can increase the toxicity of harmful phytoplankton (Cornwall et al. 2017; Riebesell et al., 2018). Yet there is around a 30% fall in macrofaunal biodiversity as average pH declines from 8.1

to 7.8 at CO<sub>2</sub> seeps (Agostini et al., 2018; Foo, Byrne, Ricevuto, & Gambi, 2018). Ocean acidification has direct effects on marine life, such as increased metabolic costs of coping with hypercapnia, and indirect effects such as increased susceptibility to predation (Sunday et al., 2017).

Ocean acidification results in less coastal protection and less habitat for biodiversity and fisheries. Live coral cover on tropical reefs has nearly halved in the past 150 years, the decline accelerating over the past two decades due to increased water temperature and ocean acidification exacerbating other drivers of coral loss. When combined with rising temperatures, sea level rise and increasing extreme climate events, ocean acidification further threatens the goods and services provided by coastal ecosystems (Hall-Spencer & Harvey, 2019).