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Review

The ocean response to climate change guides both adaptation and mitigation efforts

John Abraham[a,*], Lijing Cheng[b,c,*], Michael E. Mann[d], Kevin Trenberth[e,g], Karina von Schuckmann[f]

[a] University of St. Thomas, School of Engineering, Minnesota, USA
[b] Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
[c] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China
[d] Department of Meteorology and Atmospheric Science, Penn State, Pennsylvania, USA
[e] National Center for Atmospheric Research, Boulder, CO, USA
[f] Mercator Ocean International, Toulouse, France
[g] University of Auckland, Auckland, New Zealand

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ABSTRACT

The ocean's thermal inertia is a major contributor to irreversible ocean changes exceeding time scales that matter to human society. This fact is a challenge to societies as they prepare for the consequences of climate change, especially with respect to the ocean. Here the authors review the requirements for human actions from the ocean's perspective. In the near term (~2030), goals such as the United Nations Sustainable Development Goals (SDGs) will be critical. Over longer times (~2050–2060 and beyond), global carbon neutrality targets may be met as countries continue to work toward reducing emissions. Both adaptation and mitigation plans need to be fully implemented in the interim, and the Global Ocean Observation System should be sustained so that changes can be continuously monitored. In the longer-term (after ~2060), slow emerging changes such as deep ocean warming and sea level rise are committed to continue even in the scenario where net zero emissions are reached. Thus, climate actions have to extend to time scales of hundreds of years. At these time scales, preparation for "high impact, low probability" risks — such as an abrupt showdown of Atlantic Meridional Overturning Circulation, ecosystem change, or irreversible ice sheet loss — should be fully integrated into long-term planning.

摘要
在全球变化背景下, 海洋的很多变化在人类社会发展的时间尺度上 (百年至千年) 具有不可逆转性, 海洋巨大的热惯性是造成该不可逆性的主要原因. 这个特征为人类和生态系统应对海洋变化提出一系列挑战. 本文从海洋变化的角度总结了人类应对气候变化的要求, 提出需要进行多时间尺度的规划和统筹. 在近期 (到2030年) , 实现联合国可持续发展目标至关重要. 在中期 (2050–2060年前后) , 全球需要逐步减排并实现碳中和目标. 同时, 适应和减缓气候变化的行动和措施必须同步施行; 全球海洋观测系统需要得以维持并完善以持续监测海洋变化. 在远期 (在2060年之后) , 即使全球达到净零排放, 包括深海变暖和海平面上升在内的海洋变化都将持续, 因此应对全球变化的行动需持续数百年之久. 在该时间尺度, 应对"低概率, 高影响"气候风险 (即发生的可能性较低, 但一旦发生影响极大的事件带来的风险, 例如: 大西洋经圈反转环流突然减弱, 海洋生态系统跨过临界点, 无可挽回的冰盖质量损失等) 的准备应充分纳入长期规划.

1. Thermal inertia of the ocean and its responses to greenhouse gas emissions

The global ocean covers ~70% of Earth's surface with a total area of ~3.61 × 10^{14} km^2; ~40% of the ocean is located in the Northern Hemisphere and ~60% in the Southern Hemisphere. The average density of seawater is ~1025 kg m^{-3} (~1000 times larger than air, 1~4 times larger than soil) and the specific heat of seawater is ~4200 J/kg K (more than 4 times larger than the air). The average depth of the ocean is 3,800 m a depth that far exceeds the active thermal layer of land. The large mass and heat capacity means the ocean is much more capable of storing heat than air or land and the ocean is hence the most important controlling component of the Earth's climate. For example, the ocean is responsible for the uptake of heat and gaseous atmospheric components; the ocean also exchanges heat and moisture with the atmosphere thus affecting weather. This manuscript updates current ocean warming,

* Corresponding authors.
E-mail addresses: JPABRAHAM@stthomas.edu (J. Abraham), chenglij@mail.iap.ac.cn (L. Cheng).

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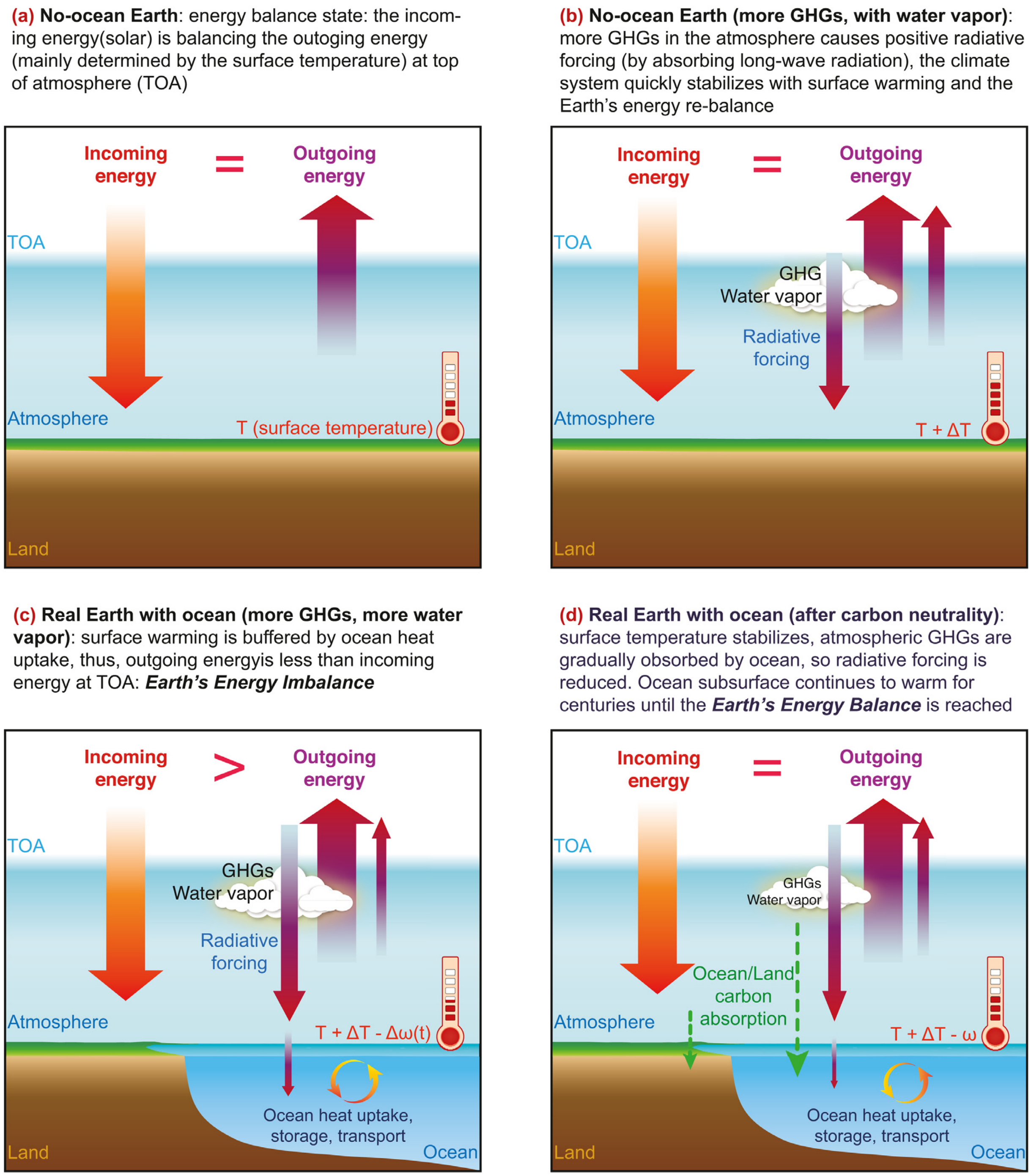

Fig. 1. An idealised schematic illustrating the ocean's role in climate change from the energy budget perspective.

discusses connections between warming oceans and impacts to human society and biological systems, and notes the importance of adaptation and mitigation strategies in the context of a changing climate.

Fig. 1 provides a highly idealized illustration highlighting the ocean's role in climate change from an energy budget perspective. As a starting point, if there is no ocean on Earth and no changing atmosphere, the incoming and outgoing energy is balanced in a stable climate, when averaged over the entire globe. As humans emit greenhouse gasses (GHGs) into the atmosphere, a radiative forcing (denoted as F) develops that traps heat inside the climate system. The atmospheric and land responses and feedbacks are relatively fast (within several years). The Earth's surface temperature T (in this case, only land) increases from T to $T+\Delta T$ in a short time and the climate system stabilizes again (Fig. 1(b)), where ΔT is the temperature increment of the Earth surface temperature. The magnitude of ΔT is also determined by many feedback processes in the climate system (e.g. from changing albedo, cloud, and atmospheric structure) which can be represented as $F = \lambda_0 \Delta T$ where λ_0 accounts for all climate feedbacks. Here the response also includes the water vapor increase in the atmosphere as it is a critical GHG. In this idealized no-ocean case, the long-wavelength radiation leaving the Earth increases as the Earth's temperature rises—thus restoring the energy balance within several years.

The Earth's response is different when one considers the ocean and its heat uptake and transport capacities (Fig. 1(c)). The surface warming is transported into the ocean interior, and surface warming is blunted. This damping effect slows down the surface warming and delays the time it takes to reach the equilibrium. In this case, surface warming can be expressed as $T+\Delta T-\Delta\omega_{(t)}$, where $\Delta\omega$ is a function of time that reflects the ocean's damping effect. Other effects are involved, for example, the ocean circulation may change in response to climate forcing and thus further impact the surface temperature. In this case, the associated outgoing radiation energy is not strong enough to offset the positive radiative forcing imposed by GHGs before the equilibrium, leading to a persistent imbalance of Earth's energy budget (denoted as $N_{(t)}$ which varies with time). Thus, the actual climate system response can be written as: $N_{(t)} = F-\lambda\,(\Delta T-\Delta\omega_{(t)})$. Here we use a different response coefficient λ rather than λ_0 to reflect climate feedback processes in this case. According to Trenberth (2022), the net Earth's Energy Imbalance (EEI) is ~0.9±0.15 W m^{-2} for 2005–2019.

When (or if) societies reach net-zero emissions, or carbon neutrality (global carbon emitted is balanced by the carbon absorbed from the atmosphere by carbon sinks), the Earth surface temperature can be approximately stabilized at $T+\Delta T-\omega$, however, the climate system will still be in an imbalanced state for a long time because 1) outgoing radiative energy at the TOA (mainly determined by temperature structure within the troposphere, convection, weather systems, and other processes) is still not sufficient to balance the net incoming energy at the top of atmosphere (TOA) and 2) the deep ocean continues to warm as heat is transported downwards into deeper ocean waters. However, after achieving global net-zero emissions, CO_2 in the atmosphere will be partly absorbed by the ocean (in the upper ~100 m of ocean waters) with a small additional absorption in terrestrial regions (IPCC, 2021). As a result, CO_2 concentrations and radiative forcing will decrease over time. This process can be expressed as $N_{(t)} = F_{(t)}-\lambda\,(\Delta T-\omega)$, where both $N_{(t)}$ and $F_{(t)}$ decrease with time but approximately balance each other. The climate system re-stabilizes (i.e. when $N_{(t)} = F_{(t)} = 0$) when the deep ocean stops warming and it reaches thermal equilibrium with balanced in-flow and out-flow of heat. In equilibrium, the incoming solar energy balances the outgoing energy at TOA (Fig. 1(d), $N_{(t)} = 0$). This process takes at least thousands of years, a duration that reflects the thermal inertia of the ocean (Golledge et al., 2015; IPCC, 2019). Finally, 3) ice sheets also react slowly as they re-establish equilibrium conditions to a change in energy balance.

Three relevant points to reinforce are:

1) While surface warming may stop when global emissions reach net-zero (i.e. "carbon-neutrality") sub-surface ocean warming will continue for at least thousands of years (IPCC, 2019, 2021).
2) The changes in the world's ocean and their impacts mean urgent actions are required to deal with climate change; more attention should be given to the ocean if we want to achieve the United Nations Sustainable Development Goals (SDGs), for example. While the ocean has played a mitigating role by absorbing both heat and CO_2, they have also played an aggravating role in climate awareness and policy action by locking in long-term committed changes that have not been fully appreciated in the public discourse over climate action.
3) The changes to the ocean are slowly emerging. Fig. 2 shows the multi-decadal changes to both surface temperatures and ocean heat content. This figure includes data from multiple research teams and will be discussed in more detail later. While these changes may be slow compared to human experience, they are very fast on a geological time scale. In addition, some geographical areas are being significantly affected by changes to the ocean (coastal and low-lying areas, areas susceptible to coastal flooding and storms, and areas that are experiencing notable changes to weather extremes, for example). Some geographical regions have experienced significant effects due to oceanic changes. There is a conspiracy with these two factors that makes action more difficult. The perceived slowness of unfolding climate change make people think that climate change is not the clear and present danger that it is. The geographic non-uniformity in the impacts of climate change make it hard to motivate societies that have not yet felt the brunt of global warming enough to take action.

2. Ocean Monitoring System Development

Measuring climate change is a challenging task. Ocean climatic trends, by their nature, are long-term rates of change in quantities such as ocean heat content (OHC), salinity, sea level, stratification, dissolved oxygen, ocean chemistry/acidity, the biological flora and fauna, and others. While data from a particular year, or even a particular decade, may be useful snapshots in time; multiple years or decades of information must be obtained for climate trend analysis. Consequently, climate trends generally require long-duration consistent and calibrated measurements. The methods used to extract OHC changes are discussed and applied in (Cheng et al., 2017, 2021, 2022; Abraham et al., 2013; Meyssignac et al., 2019).

The ocean subsurface temperature observing system is an integration of multiple complementary instruments (Fig. 3) including eXpendable Bathy Thermographs (XBTs), Conductivity-Temperature-Depth devices (CTDs), moored arrays, gliders, Autonomous Pinniped Bathythermographs (APBs), Drifting Buoys (DRBs), Argo, etc. (Abraham et al., 2013; Garci-Soto et al., 2021; Legler et al., 2015; for example). These *in situ* observations are now complemented by many remote sensing measurements from satellites, including altimetry (sea level), passive and active sea surface temperature sensors, ocean color, and scatterometry (surface wind stress).

The Argo network, which came online in the early 2000s, is formed by more than 3000 autonomous profiling buoyant probes that periodically rise and fall in the ocean waters (down to depths of ~ 2000 m). Argo revolutionized global OHC by providing a near-global open ocean coverage of the upper 2000 m. APBs and DRBs provide critical measurements for polar regions; CTDs and XBTs fill the data gaps in the coastal regions and major channels (Indonesian Throughflow region for example). Moored arrays provide continuous data in the tropics and other locations. Learning from the synthesis from the data-rich Argo era, Cheng et al. (2017) were able to better analyse the data back to the International Geophysical Year (IGY, 1958). Hence, taken together, these instruments provide accurate OHC information for the last 60 years, thus enabling climatic trends to be obtained.

Fig. 2 shows both global Sea Surface Temperature (SST) anomalies as well as OHC trends down to a depth of 2000 m over seven decades. Both SST and OHC display a long-term persistent increase, consistent with a warming planet. It is noteworthy that both SST and OHC have been measured by multiple research groups and the results are in excellent agreement. SSTs are provided back to the mid 1800s, however with time, the coverage of observations decreases and uncertainty increases.

The effort set forth by the Global Ocean Observing System (GOOS, www.goosocean.org) has identified Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs) as critical measures of the state of the ocean. ECVs are variables for all parts of the climate system while EOVs are specifically related to climate change in the ocean (GCOS, 2016; WMO, 2017; von Schuckmann et al., 2020). Interested readers are directed to these references for a listing of the ECVs and a very detailed discussion linking various ocean metrics to specific SDGs. Compared with temperature, other ocean ECVs are much less observed, for example ocean surface heat flux, currents, salinity, surface stress, inorganic carbon, nitrous oxide, nutrients, oxygen, transient tracers, marine habitat properties, and plankton. To address some of these measurements and their coverage, the Argo community is currently planning to: i) improve the current data coverage to under-ice regions, coastal regions, and other areas that are under-sampled, (ii) achieve better coordination across nations to facilitate the data sharing, integration, and analyses in the coastal regions, (iii) add biogeochemical sensors for improved understanding of oceanic cycles of carbon, nutrients, and ecosystems, and (iv) explore new sensors that might be included in the future,

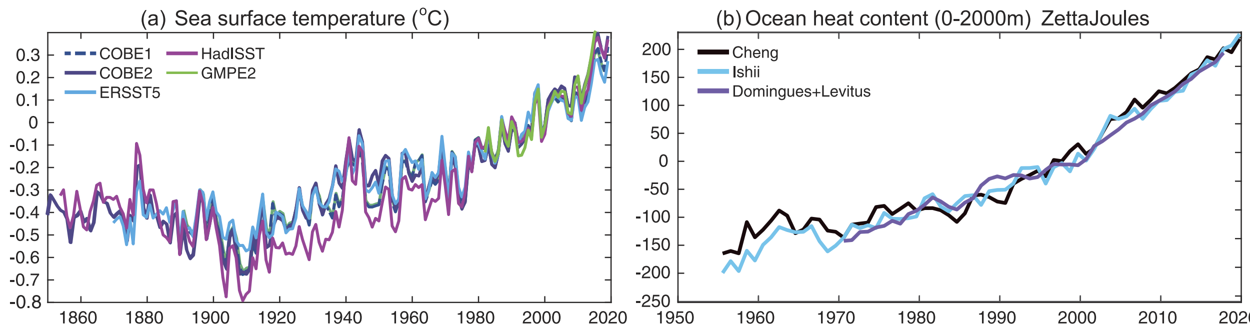

Fig. 2. (a) Global mean SST and (b) OHC time series from the 1950s to 2020. The figure is updated from Garcia-Soto et al. (2021).

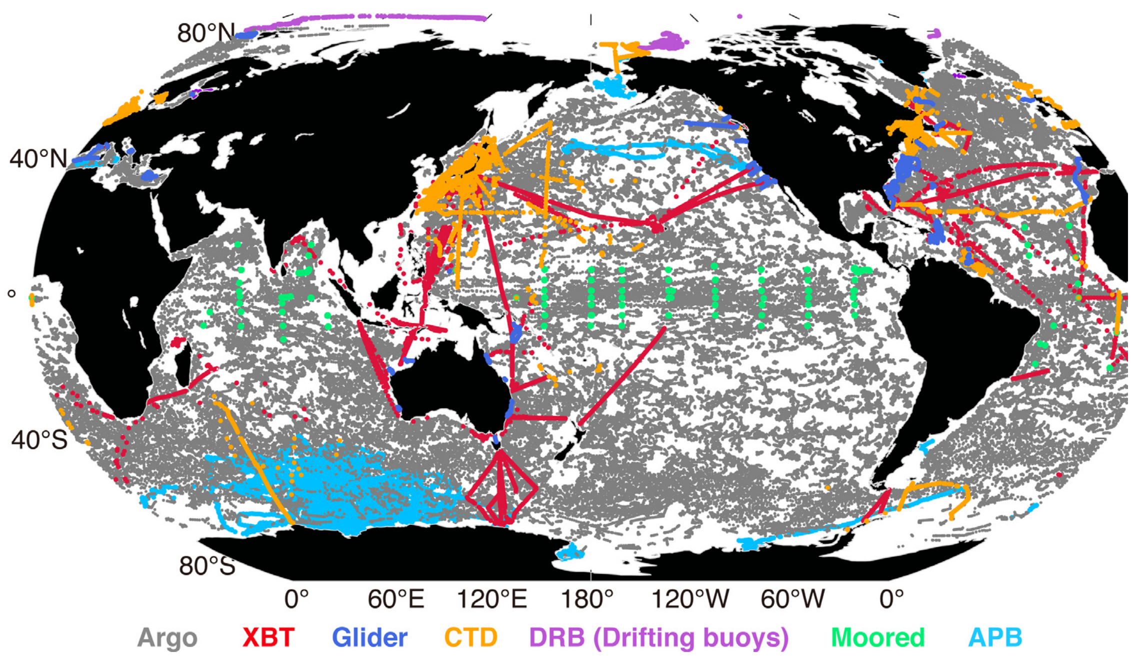

Fig. 3. Geographic coverage of the 2020 ocean in situ temperature observing system: the dots are the temperature profiles observed by Argo (grey), CTDs (orange), XBTs (red), moored stations (light green), Gliders (blue), pinnipeds (light blue), and ice-tethered profilers (purple). Data are sourced from World Ocean Database (Boyer et al., 2018).

for example to document the spatial and temporal patterns of ocean mixing.

Fig. 3 shows the geographical distribution of *in situ* ocean temperature measurements and their associated measurement method. With the current state of the GOOS now discussed, and the past and future ocean warming rates provided, we turn our attention to the intersection of ocean health and its impacts on human society and biosystem health.

3. Sustainable Development Goals

One critical issue is how our knowledge of climate change in general, and ocean warming in particular, can be used to inform social decisions of adaptation and mitigation. To connect the climate with issues that affect human society, it is helpful to identify goals that guide us, collectively, toward a healthier and more sustainable future. One such framework that has been developed is the Sustainable Development Goals of the United Nations (SDGs) as discussed in von Schuckmann et al. (2020). These SDGs are critical for achieving a sustainable advancement in both the world economy and environment Achieving the SDGs will certainly be a challenge; effective decisions need to be guided by knowledge of past climate change as well as estimates of future changes.

The health of the ocean is vital to the SDGs, and to health/society/economics in general (Clar and Steurer, 2019; IPCC, 2019; von Schuckmann et al., 2020). The influence of oceanic changes on social and economic systems depends on the physical state of the ocean and the local vulnerability to changes, as well as worldwide efforts to both mitigate future climate change and to adapt to current and forthcoming changes.

The United Nations has proposed 17 goals and 169 targets that are focused on maintaining the health and vitality of human societies and natural ecosystems around the world (https://sdgs.un.org/goals).

Some goals are directly related to the health of the world's oceans (SDGs 13 and 14). SDG 13 (Climate Action) explicitly addresses climate change, including the ocean changes and their impacts. Ocean warming, salinity, stratification, and pH changes directly impact SDG 14 (Life Below Water). The productivity and distributions of some marine species are changing in ways that alter the health and availability of marine species and impact fishery production, (e.g., Diz et al., 2017; Serpetti et al., 2017; Blasiak et al., 2020).

In addition to the above, many other goals are connected to the ocean. For example, insofar as the ocean and changes to ocean temperatures influence weather systems and the hydrological cycle, the effects of these changes extend well beyond the confines of the ocean. Such changes directly impact both terrestrial and ocean-based food production and thus impact societies and human well-being in a myriad of ways. Consequently, at least SDGs 1, 2, 3, 6, 10, 12, 15, and 16 are indirectly impacted by the world's oceans. Furthermore, since changes to the

Fig. 4. UN Sustainable Development Goals that are directly related (red line) or indirectly related (blue line) to the world's oceans.

ocean also impact extreme weather (Yang et al., 2016; Trenberth et al., 2018; Kruhoeffer, 2022), SDGs 9 and 11 are also indirectly affected by ocean health. The health of the ocean touches on most of the SDGs either directly or indirectly—emphasizing the incredible significance of the ocean on our future (von Schuckmann et al., 2020). The SDGs (Fig. 4) are directly affected (red lines) or indirectly affected (blue lines) by the ocean.

A few examples connecting ocean changes to SDGs will now be provided for context. For example, infiltration of sea water into fresh water supplies can affect coastal food supplies, aquifers, and local economies (Sherif and Singh, 1999; Barlow, 2003; Nicholls and Cazenave, 2010; White and Kaplan, 2017; Klassen and Allen, 2017; Rao and Chandur, 2021; Guimond and Michael, 2020) (related to SDGs 1, 2, 6, 9, 10, 11, 15, and 16). This issue threatens populations that rely upon coastal food production for their sustenance; food production impacts the health and well-being of persons who rely upon coastal food production (SDGs 1 and 2). Infiltration of sea water also inhibits economic growth, makes coastal activities less sustainable (SDGs 6, 9, 11, and 15) and disproportionately threatens the health and livelihood of vulnerable communities (SDGs 10 and 16) (Tosi et al., 2022; Bene et al., 2015; IPCC, 2019).

Under a warming climate, the global precipitation amount changes are governed by energy changes and evaporation (Trenberth, 2011). Given upward motion in the atmosphere, the intensity of precipitation depends upon the amount of moisture available. As temperatures rise with global warming by 1°C, the average near surface moisture holding capacity goes up by about 7%. This increases atmospheric demand for moisture from the surface and dries the land and vegetation. In most places where moisture availability is not an issue, such as the ocean and near coastal regions, the actual atmospheric moisture is apt to go up, thereby feeding 7% more moisture into any storms or weather systems, and hence it rains harder, as is observed. Or it snows harder, provided that temperatures are low enough. The availability of moisture from the surface is largest where sea surface temperatures are highest, while interiors of continents are prone to be dry (Feng and Zhang, 2016; Myrhe et al., 2019; Hu et al., 2018; Donat et al., 2019; Byrne and O'Gorman, 2015; Westra et al., 2013; Kharin et al., 2013).

The extra evaporation in dry regions, where it is sunny, means the locally evaporated moisture is carried away by winds to places where it is precipitating. Higher temperatures mean increased atmospheric demand for moisture, and increased evapotranspiration in the dry areas exacerbates aridity and droughts. Meanwhile, in precipitation locations, it rains (or snows) harder and there is an increased risk of flooding. Because, with warming, more precipitation occurs as rain instead of snow and snow melts earlier, there is increased runoff and risk of flooding in early spring, but increased risk of drought in summer, especially over continental areas.

As another example, observed and projected increases in intensity of tropical cyclones (and increased associated precipitation totals) are connected to ocean warming (e.g., Emanuel, 2013; Trenberth et al., 2018). More damaging storm surges are expected from a combination of sea level rise and increased storm intensities (Garner et al., 2017; Kruhoeffer, 2022; Studholme et al., 2022), both of which are favored by ocean warming. Other impacts include marine heatwaves (Marx et al., 2021), and a more intense hydrological cycle (Cheng et al., 2020; Liu et al., 2021). These factors will impact SDGs related to human health and food/water security (SDGs 1 and 2), issues of equity and economics (SDGs 6, 7, 10, 11, and 16) and viability of infrastructure (SDGs 9 and 11).

4. Ocean changes and mid-term (2050–2060) climate actions

In the middle term (~2050–2060), if the nations commit to their climate targets, the global carbon neutrality target will hopefully be reached and the global surface temperature will stabilize (1.5~2°C above the pre-industrial level), With this warming, there will be more significant climate risks than today.

A recent and comprehensive review of climate risks that are expected to occur, with confidence levels included, is provided by the IPCC sixth assessment (IPCC, 2021). Climate impacts are grouped into seven categories (heat and cold, wet and dry, wind, snow and ice, coastal, open ocean, and other). These risks are termed "climate impact drivers" (CIDs). They are climatic conditions that can be measured (mean and

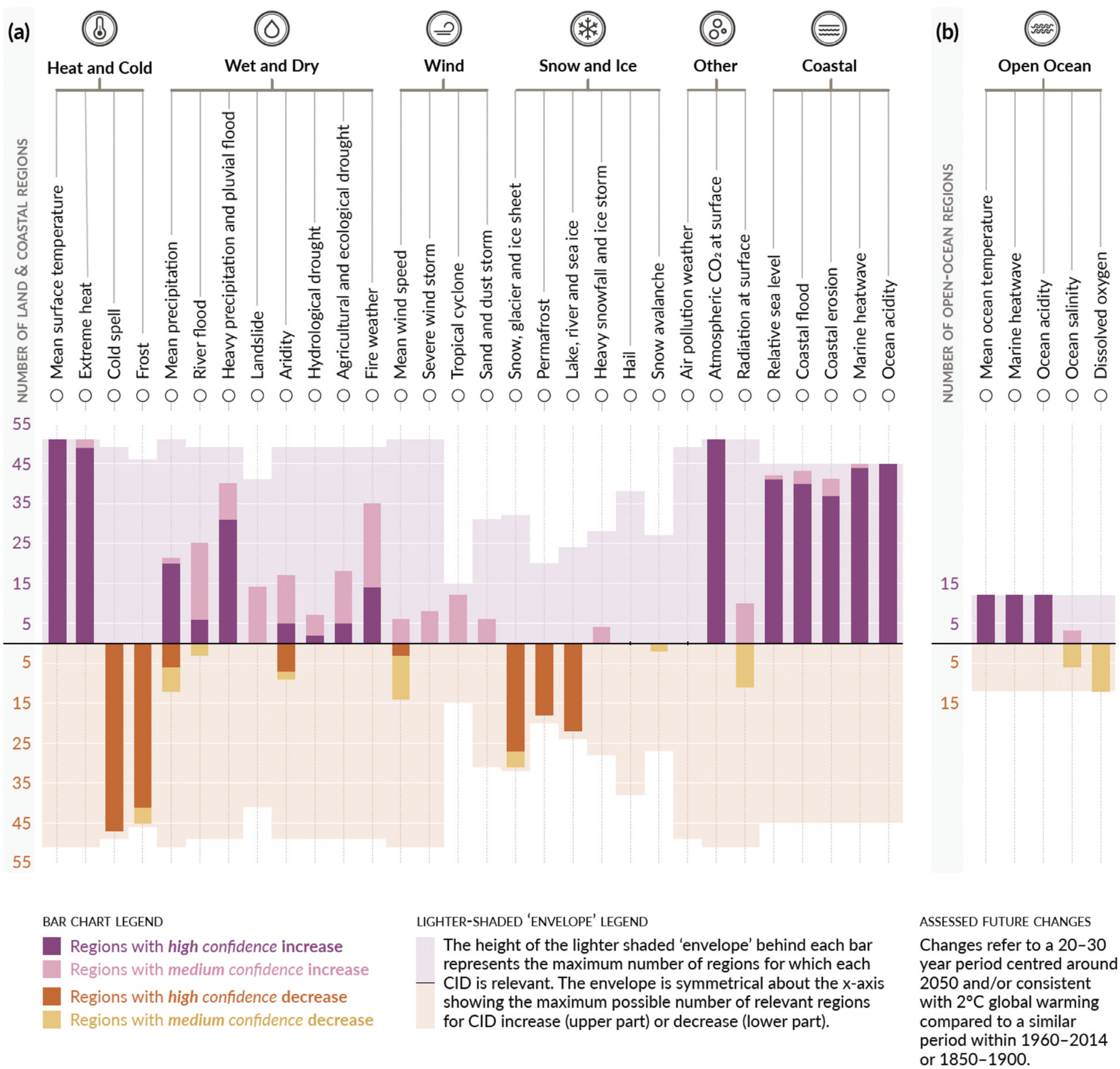

Fig. 5. IPCC AR6 WG1, SPM image 9 (IPCC, 2021).

extreme values of parameters and extreme events) and changes are expressed in terms of the confidence in those changes (Fig. 5). With respect to the ocean, the CIDs relate to ocean temperatures, sea ice, chemical composition, sea levels and their changes, and erosion.

Of course, the ocean also contributes to other CIDs through its interaction with the atmosphere and the consequent changes to the hydrologic cycle, atmospheric temperatures, weather, and extreme events.

Generally speaking, a changing climate prevents planning based on past experience. The new and evolving climate will be different to the climates of the past, and there has not been enough time or effort to adapt to these new conditions. Numerous recent scientific publications have provided guidance for social (and coastal) development in a changing climate (especially IPCC, reports). Toimil et al. (2020) reviewed the challenges that coastal areas will be subjected to as climate change continues and proposed a refocusing of traditional development practices to more "climate-aware" approaches. There is a need to embrace uncertainty (challenging for designers planning infrastructure that has a lifetime of many decades). Of course, there is uncertainty both in the future rate of climate change but also in the influence of climate change on coastal regions. Other studies, such as Abraham et al. (2015, 2017) focused on the connection between infrastructure and future climate resiliency and planning. So too, engineers are optimizing municipal infrastructure, especially water management systems, to function efficiently in a changing climate (Ghaderi et al., 2020). These references provide insight into how civil engineers view climate change in the context of long-term infrastructure planning. While there is some optimism, the world's countries have not yet demonstrated a commitment to combating climate change that will achieve these goals. A much more pessimistic view is that societies will continue with business as usual for the indefinite future.

Similar warnings are also expressed in large international cooperative scientific reports. For example, IPCC (2014) identified a number of different ways human society will experience a changing climate, including risks associated with the ocean, ocean temperatures, and ocean levels. For example:

- Many marine species have shifted their geographical range (high confidence)
- Impacts from climate-related extreme weather (heat waves, droughts, floods, cyclones, wild fires, etc.) are changing (very high confidence)

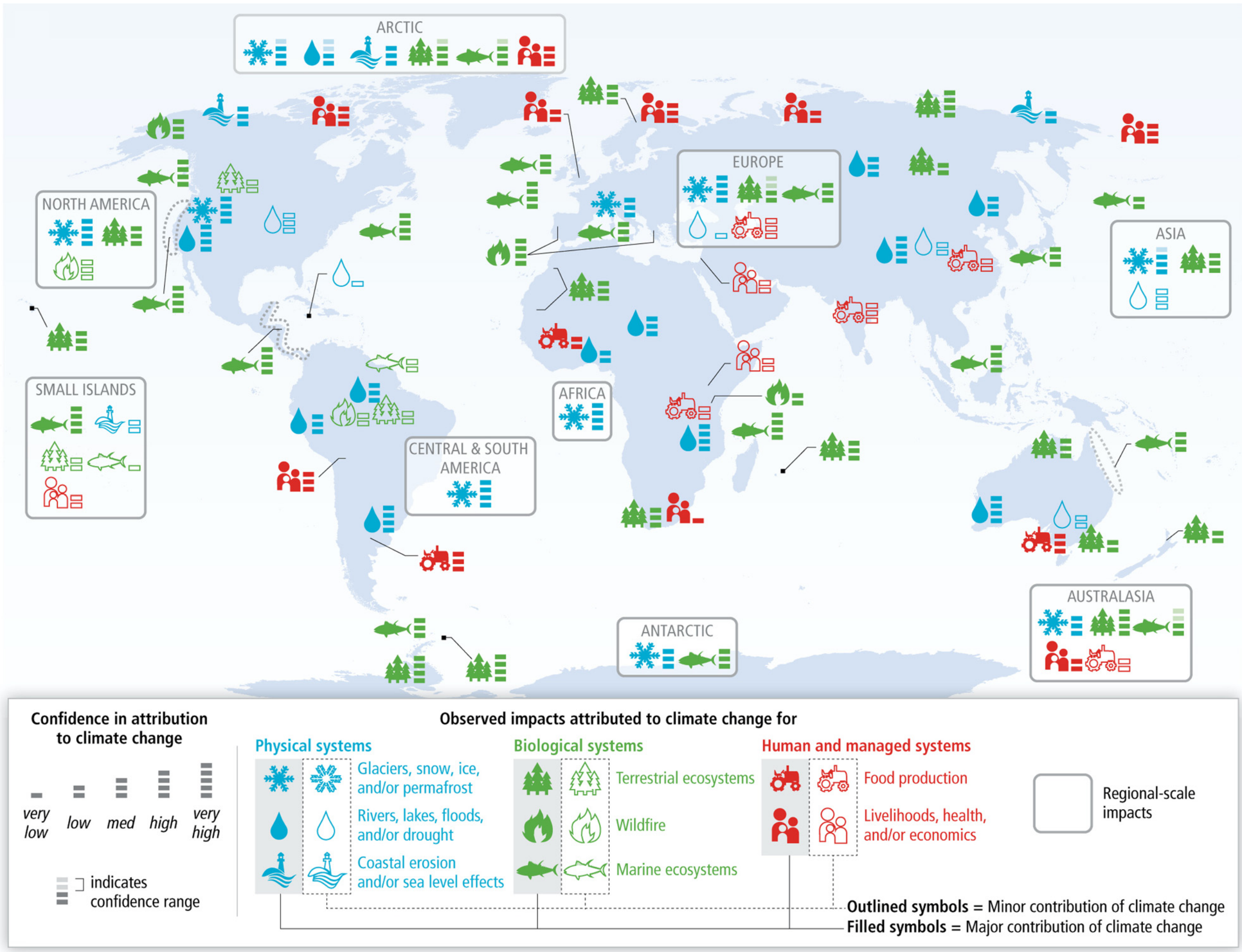

Fig. 6. IPCC WG2, SPM image 2 (IPCC, 2014).

- Climate related impacts make other stressors more challenging, particularly for populations in poverty (high confidence)
- Violent conflict increases vulnerability to climate change (medium evidence)
- Sea-level rise will increase adverse impacts on coastal communities (e.g., submergence, coastal flooding, coastal erosion) (very high confidence)
- Spatial shits of marine-species habitation will challenge fishery production and other bio-system services (high confidence)
- Ocean acidification risks marine ecosystems, particularly in polar regions and coral reefs (medium to high confidence)
- Agricultural production will be negatively impacted for global temperature increases in excess of 2°C (medium confidence)
- Decreases in fishery yields, particularly at low latitudes (high confidence)
- Reduced biodiversity and coastal protection afforded by coral reefs, increased coral bleaching and mortality (high confidence)
- Coastal inundation and habitat loss due to sea level rise, extreme weather, and changes to precipitation (medium to high confidence)

These and other projections are provided in the IPCC AR5 report from Working Group II, see Fig. 6.

5. Long-term (>2060) climate actions

Throughout the 21st century and the following several centuries, the ocean changes will impact both coastal areas as well as non-coastal areas—however the types of impacts will differ for these regions. For example (Chapter 12 in IPCC, 2021), coastal areas are subjected to rising sea levels, coastal flooding, coastal erosion, more intense storm precipitation, marine heat waves, ocean acidification, oxygen depletion, among others. Climate change is particularly important for these reasons both because of the concentration of people and infrastructure near coasts as well as the proximity of the coastal areas to the warming ocean waters (Gargiulo et al., 2020). On the other hand, even regions far from coasts are also experiencing climate impacts, often through intensification of the hydrological cycles and changes to weather patterns, as previously discussed.

Recently, an assessment of different coastal adaptation strategies was provided by Baills et al. (2020) for cases along the French coast. The results, generalized to be applicable to other regions, assessed the potential for success for various adaptation strategies. Among some of the shortest decision timelines, the authors suggest steps such as the creation of sand fences, cliff foot palisades, beach and dune restoration, improved drainage, geotextiles, and sealed buildings. Longer-term adaptation measures include flood-proof buildings, floating or amphibious buildings and residences, elevated buildings and residences, movable structures, raising coastal grounds for buildings, roads, bridges, and other infrastructure. Clearly this later group of measures will take a much longer time to implement but will also provide much longer lasting benefits. Multi-scale adaptation practices like this should be considered throughout the globe.

Also, cross-chapter box 9 in IPCC (2019) discusses the already-occurring changes that are experienced by islands and coastal regions and identifies Small Island Developing States (SIDS) and the differential impact that will occur in this century. Societies in coral reef or polar regions will first exceed their ability to adapt to climate change—before the end of the century—and that most low-lying areas will exceed adaptation by 2100, or even by mid-century, because of sea-level rise. These projections affect a large portion of the Earth's human population (11%) and a significant portion of the economic production.

Of course, the susceptibility of a particular coastal city is dictated not only by global climate change but also on local factors (such as city elevation and global location—sea level rise is not uniform across the globe (Scambos and Abraham, 2015; IPCC, 2019). Globally, the number of people whose lives are impacted by coastal flooding will increase dramatically (Wahl, 2017; IPCC, 2019; McMichael et al., 2020) — with hundreds of millions of people living within a few meters of sea level rise. Some coastal communities can adapt to reduce the threat from climate change by building sea walls or raising the height of infrastructure, for example, or communities can lower the costs when climate change does occur (and reduce the costs of recovery). All of these adaptation measures required time, resources, and planning: three commodities that are in short supply (Solecki et al., 2011; Abraham et al., 2015, 2017).

Some urban areas are adapting by building more robust coastal infrastructure that is able to withstand short but intense storm surges and precipitation. Many urban areas have adopted storm proofing of buildings, residences, and infrastructure to reduce future repair costs. Examples of these adoptions are improved building standards to resist high-winds and the water proofing of infrastructure. As adaptation measures are taken, a cost-benefit analysis should be used to drive the balance between adaptation and mitigation (Stone et al., 2010; Araos et al., 2016; Chen et al., 2018; Cardona et al., 2020; Foti et al., 2020).

In less developed or less urban environments, research paints a similar picture. However, often there is increased risk of displacement. For example, Chowdhury et al. (2020) attempted to understand the causes and impacts of displacement of coastal residents in Bangladesh, and the climatic effects which primarily led to displacement were coastal erosion and storms. Climate-related displacement exceeded displacements associated with political strife or conflict. Climate-migration is clearly an issue that will require international cooperation, discussions of national security, robust cost-benefit analyses, and equitable distribution of resources (Oloruntoba and Banomyong, 2018; Ahmed, 2018; Brzoska and Frohlich, 2016).

While beyond the scope of this brief review, other research has elucidated the global climate change effects on food production through agricultural stress (Dasgupta et al., 2018; Clapp et al., 2018; Venkatramana et al., 2020, as examples). Collectively, prior research has detailed methods to characterize the vulnerability of different systems to climate change (Kantamaneni et al., 2020) or the impacts on ocean-food production (Brander, 2010; Harrod, 2015; Savo et al., 2017). A comprehensive assessment of climate impacts was discussed in the Fourth National Climate Assessment (Chapter 8 in NCA, 2018); while focused on the United States, it has applications for other locations as well.

Finally, there could be "high impact, low probability" events (an unlikely event that would have significant consequences if it happens), such as an abrupt showdown of Atlantic Meridional Overturning Circulation, large methane emissions from thawing permafrost or clathrates, passing a tipping point for losing a major ice sheet, or an abrupt shift and transition of ocean ecosystem including massive extinction (Chapter 9 in IPCC, 2021).

6. Concluding Remarks

We started from the ocean role in climate and its changes as a basis to discuss the relationship between ocean heat content, temperatures and climate, and the need for climate adaptation and mitigation at several different time scales. Using the UN Sustainable Development Goals as a basis for relating climate change to its impacts on the health and vitality of human and biological systems in near-term (~2030), it is clear that global warming in general, and ocean warming in particular, is a very important issue for achievements of SDGs. Rising ocean temperatures and sea level are having negative consequences on coastal societies, and those consequences will grow inexorably as time passes. There are still excellent opportunities to both reduce future warming and make our societies less vulnerable to changes when they occur. The opportunities should be subject to cost-benefit analyses to ensure resources are well spent. In addition, the implementation of both mitigation and adaptation sustainable strategies should be performed with due consideration of the various timelines for them to be realized. The scientific community is helping develop plans for future monitoring, management, and protection of the world's oceans while supporting the UN Decade of ocean science for sustainable development (Ryabinin et al., 2019; https://www.oceandecade.org/). These efforts will hopefully bear fruit as we collectively work to sustain the hospitableness of Earth.

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References

Abraham, J.P., Baringer, M., Bindoff, N.L., Boyer, T., Cheng, L.J., Church, J.A., Conroy, J.L., et al., 2013. A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. Rev. Geophys. 51, 450–483. doi:10.1002/rog.20022.

Abraham, J., Stark, J., Minkowycz, W., 2015. Extreme weather: Observations of precipitation changes in the USA. Proc. Inst. Civ. Eng. Forensic Eng. 168, 68–70. doi:10.1680/feng.14.00015.

Abraham, J., Cheng, L., Mann, M.E., 2017. Future climate projections allow engineering planning. Proc. Inst. Civ. Eng. Forensic Eng. 170, 54–57. doi:10.1680/jfoen.17.00002.

Ahmed, B., 2018. Who takes responsibility for the climate refugees? Int. J. Clim. Chang. Str. 10, 5–26. doi:10.1108/IJCCSM-10-2016-0149.

Araos, M., Berrang-Ford, L., Ford, J., Austin, S., Biesbroek, R., Lesnikowski, A., 2016. Climate change adaptation planning in large cities: A systematic global assessment. Environ. Sci. Policy 66, 375–382. doi:10.1016/j.envsci.2016.06.009.

Barlow, P.M., 2003. Ground water in freshwater-saltwater environments of the Atlantic coast. Circular 1262, USGS. doi: 10.3133/cir1262.

Baills, A., Garcin, M., Bulteau, T., 2020. Assessment of selected climate change adaptation measures for coast areas. Ocean Coast Manage. 185, 105059. doi:10.1016/j.ocecoaman.2019.105059.

Bene, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G., Williams, M., 2015. Feeding 9 billion by 2050−Putting fish back on the menu. Food Secur. 7, 261–274. doi:10.1007/s12571-015=0427-z.

Blasiak, R., Wynberg, R., Grorud-Colvert, K., Thambisetty, S., Bandarra, N.M., Canario, A.V.M., da Silva, J., et al., 2020. The ocean genome and future prospects for conservation and equity. Nature Sustainability 3, 588–596. doi:10.1038/s41893-020-0522-9.

Boyer, T. P., Baranova, O.K., Coleman, C., Garcia, H.E., Grodsky, A., Locarnini, R.A., Mishonov, A.V., et al., 2018. World Ocean Database 2018. A. V. Mishonov, Technical Editor, NOAA Atlas NESDIS. 87. https://www.ncei.noaa.gov/sites/default/files/2020-04/wod_intro_0.pdf.

Brander, K., 2010. Impacts of climate change on fisheries. J. Mar. Syst. 79, 389–403. doi:10.1016/j.marsys.2008.12.015.

Brzoska, M., Frohlich, C., 2016. Climate change, migration, and violent conflict: Vulnerabilities, pathways, and adaptation strategies. Migr. Dev. 5, 190–210. doi:10.1080/21632324.2015.1022973.

Byrne, M.P., O'Gorman, P.A., 2015. The response of precipitation minus evapotranspiration to climate warming: why the "wet-get-wetter, dry-get-drier" scaling does not hold over land. J. Clim. 28, 8078–8092. doi:10.1175/jclim-d-15-0369.1.

Cardona, F., Ferreira, J., Lopes, A., 2020. Cost and benefit analysis of climate change adaptation strategies in coastal areas at risk. J. Coastal Res. 95, 764–768. doi:10.2112/SI95-149.1.

Chen, R., Zhang, Y., Xu, D., Liu, M., 2018. Climate change and coastal megacities: Disaster risk assessment and responses in Shanghai city. In: Mal, S., Singh, R., Huggel, C. (Eds.), Climate Change, Extreme Events and Disaster Risk Reduction. Sustainable Development Goals Series. Springer, Cham, pp. 203–216. doi:10.1007/978.-3-319-56469-2_14.

Cheng, L.J., Trenberth, K.E., Faullo, J., Boyer, T., Abraham, J.P., Zhu, J., 2017. Improved estimates of ocean heat content from 1960-2015. Sci. Adv. 4, e1601545. doi:10.1126/sciadv.1601545.

Cheng, L., Trenberth, K.E., Gruber, N., Abraham, J.P., Fasullo, J.T., Li, G., Mann, M.E., Zhao, X., Zhu, J., 2020. Improved estimates of changes in upper ocean salinity and the hydrological cycle. J. Clim. 33, 10357–10381. doi:10.1175/jcli-d-20-0366.1.

Cheng, L., Abraham, J.P., Trenberth, K.E., Fasullo, J.T., Boyer, T., Locarnini, R., Zhang, B., et al., 2021. Upper Ocean temperatures hit record high in 2020. Adv. Atmos. Sci. 38, 523–530. doi:10.1007/s00376-021-0447-x.

Cheng, L., Abraham, J.P., Trenberth, K.E., Fasullo, J.T., Boyer, T., Mann, M.E., Zhu, J., et al., 2022. Another record: Ocean warming continues through 2021 despite La Nina Conditions. Adv. Atmos. Sci. 39, 373–385. doi:10.1007/s00376-022-14671-3.

Chowdhury, M., Hasan, M., Younos, T., 2020. Climate change impacts and adaptation on health of internally displaced people (IDP): An exploratory study on coastal areas of Bangladesh. Heliyon 6, e05018. doi:10.1016/j.heliyon.2020.e05018.

Clapp, J., Newell, P., Brent, Z., 2018. The global political economy of climate change, agriculture, and food systems. J. Peasant Stud. 45, 80–89. doi:10.1080/03066150.2017.1381602.

Clar, C., Steurer, R., 2019. Climate change adaptation strategies at different levels of government. Nat. Resour. Forum 43 (2), 121–131. doi:10.1111/1477-8947.12168.

Dasgupta, S., Hossain, M., Huq, M., Wheeler, D., 2018. Climate change, salinization, and high-yield rice production in coastal Bangladesh. Econ. Rev. 47 (1), 66–89. doi:10.1017/age.2017.14.

Diz, D., Morgera, E., Wilson, M., 2017. Marine policy special issue SDG synergies for sustainable fisheries and poverty alleviation. Mar. Policy 110, 102860. doi:10.1016/j.marpol.2017.08.020.

Donat, M.G., Angelil, O., Ukkola, A.M., 2019. Intensification of precipitation extremes in the world's humid and water-limited regions. Environ. Res. Lett. 14 (6), 065003. doi:10.1088/1748-9326/ab1c8e.

Emanuel, K., 2013. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. Proc. Natl. Acad. Sci. U. S. A. 110, 12219–12224. doi:10.1073/pnas.1301293110.

Feng, H., Zhang, M., 2016. Global land moisture trends: drier in dry and wetter in wet over land. Sci. Rep. 5, 18018. doi:10.1038/srep18018.

Foti, E., Musumeci, R., Stagnitti, M., 2020. Coastal defence techniques and climate change: A review. Coastal Prot. 31, 123–128. doi:10.1007/s12210-020-00877-y.

Garcia-Soto, C., Cheng, L., Caeser, L., Schmidtko, S., Jewett, E.B., Cheripka, A., Rigor, I., et al., 2021. An overview of ocean climate change indicators: sea surface temperature, ocean heat content, ocean Ph, dissolved oxygen concentration, artic ice extent, thickness, and volume. Front. Mar. Sci. 8, 642372. doi:10.3389/fmars.2021.642372.

Gargiulo, C., Battarra, R., Tremiterra, M., 2020. Coastal areas and climate change: A decision support tool for implementing adaptation measures. Land Use Pol. 91, 104413. doi:10.1016/j.landusepol.2018.104413.

Garner, A.J., Mann, M.E., Emanuel, K.A., Kopp, R.E., Lin, N., Alley, R.B., Horton, B.P., et al., 2017. The impact of climate change on New York city's coastal flood hazard: increasing flood heights from the pre-industrial to 2300 CE. Proc. Natl. Acad. Sci. 114, 11861–11866. doi:10.1073/pnas.1703568114.

Ghaderi, A., Shokri, M., Abraham, J.P., 2020. Estimation of actual evapotranspiration using remote sensing method and SEBAL algorithm: A case study in Ein Khosh Plain, Iran. Hydrology 7, 36. doi:10.3390/hydrology7020036.

GCOS (Global Climate Observing System), 2016. The global observing system for climate, implementation needs. No. 200. https://public.wmo.int/en/programmes/global-climate-observing-system.

Golledge, N.R., Kowalewski, D.E., Naish, T.R., Levy, R.H., Fogwill, C.J., Gasson, E.G.W., 2015. The multi-millennial Antarctic commitment to future sea-level rise. Nature 526, 421–425. doi:10.1038/nature15706.

Guimond, J.A., Michael, H.A., 2020. Effects of marsh migration on flooding, saltwater intrusion, and crop yield in coastal agricultural land subject to storm surge inundation. Water Resour. Res. 57, e2020WR028326. doi:10.1029/2020WR028326.

Harrod, C., 2015. Climate change and freshwater fisheries. Chap. 7.3 in Freshwater Fisheries Ecology. John Wiley & Sons, Ltd, Chichester, pp. 641–694. doi:10.1002/9781118394380.ch50.

Hu, Z., Chen, X., Cheng, D., Li, J., Wang, S., Zhou, Q., Yin, G., Guo, M., 2018. Dry gets drier, wet gets wetter: A case study over the arid regions of central Asia. Int. J. Climatol. 39, 1072–1091. doi:10.1002/joc.5863.

IPCC (Intergovernmental Panel on Climate Change), 2014. Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the 5th Assessment Report of the Intergovernmental Panel on Climate Change. Field, C.B., Barros,V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, USA, pp. 1–32.

IPCC (Intergovernmental Panel on Climate Change), 2019. Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., et al. (eds.). Cambridge University Press, Cambridge, UK and New York, USA, pp.3-35. doi:10.1017/9781009157964.001.

IPCC (Intergovernmental Panel on Climate Change), 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group 1 to the sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, USA, In press. doi:10.1017/9781009157896.

Kantamaneni, K., Rice, L., Yenneti, Y., Campos, L., 2020. Assessing the vulnerability of agricultural systems to climate change in coastal areas: A novel index. Sustainability 12 (11), 4471. doi:10.3390/su12114771.

Kharin, V.V., Zwiers, F.W., Zhang, X., Wehner, M., 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Clim. Chang. 19, 345–357. doi:10.1007/s10584-013-0705-8.

Klassen, J., Allen, D.M., 2017. Assessing the risk of saltwater intrusion in coastal aquifers. J. Hydrol. 551, 730–745. doi:10.1016/j.hydrol.2017.02.044.

Kruhoeffer, D., 2022. A "climate index" sets better expectations for future extreme weather events. AMS Annual Meeting January 23-27, 2022.

Legler, D.M., Freeland, H.J., Lumpkin, R., Ball, G., McPhaden, M.J., North, S., Cowley, R., et al., 2015. The current status of the real-time in situ Global Ocean Observing System for operational oceanography. J. Oper. Oceanogr. 8, s189–s200. doi:10.1080/1755876x.2015.1049883.

Liu, M., Vecchi, G., Soden, B., Yang, W., Zhang, B., 2021. Enhanced hydrological cycle increases ocean heat uptake and moderates transient climate change. Nat. Clim. Chang. 11, 848–853. doi:10.1038/s41558-021-01152-0.

Marx, W., Haunschild, R., Bornmann, L., 2021. Heat waves: A hot topic in climate change research. Theor. Appl. Climatol. 146, 781–800. doi:10.1007/s00704-021-03758-y.

McMichael, C., Dasgupta, S., Ayeb-Karlsson, S., 2020. A review of estimating population exposure to sea-level rise and the relevance for migration. Environ. Res. Lett. 15, 123005. doi:10.1088/1748-9326/abb398.

Meyssignac, B., Boyer, T., Zhao, Z., Hakuba, M.Z., Landerer, F.W., Stammer, D., Kohl, A., et al., 2019. Measuring global ocean heat content to estimate the earth energy imbalance. Front. Mar. Sci. 6, 198–228. doi:10.3389/fmars.2019.00432.

Myrhe, G., Alterskjar, K., Stjern, C.W., Hodnebrog, O., Marelle, L., Samset, B.H., Sillman, J., et al., 2019. Frequency of extreme precipitation increases extensively. Sci. Rep. 9, 16063. doi:10.1038/s412598-019-52277-4.

NCA (National Climate Assessment), 2018. U.S. Global Change Research Program, 4th Edition. Washington DC, USA, https://nca2018.globalchange.gov/credits/.

Nicholes, R.J., Casenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517–1520. doi:10.1126/science.1185782.

Oloruntoba, R., Banomyong, R., 2018. Humanitarian logistics research for the care of refugees and internally displaced persons: A new area of research and a research agenda. J. Humanitarian Logist. Supply Chain Manage. 8, 282–294. doi:10.1108/JHLSCM-02-2018-0015.

Rao, S., Chandur, S., 2021. "Moving the topic of climate change from politics to economics". In Theories of Change, edited by Wendt, K.,. Springer, Heidelberg, pp. 487–500.

Ryabinin, V., Barbiere, J., Haugan, P., Kullenberg, G., Smith, N., McLean, C., et al., 2019. The UN decade of ocean science for sustainable development. Front. Mar. Sci. 6, 470. doi:10.3389/fmars.2019.00470.

Savo, V., Morton, C., Lepofsky, D., 2017. Impacts of climate change for coastal fishers and implications for fisheries. Fish Fish. 18, 877–889. doi:10.1111/faf.12212.

Scambos, T., Abraham, J., 2015. Briefing: Antarctic ice sheet mass loss and future sea-level rise, Forensic Engineering. Proc. Inst. Civ. Eng. 168, 68–70. doi:10.1680/feng.14.00014.

Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouet, P., Fernandes, P.G., Heymans, J.J., 2017. Impact of ocean warming on sustainable fisheries management informs the ecosystem approach to fisheries. Sci. Rep. 7, 13438. doi:10.1038/s31598-017-13220-7.

Sherif, M.M., Singh, V.P., 1999. Effect of climate change on sea water intrusion in coastal aquifers. Hydrol. Processes 13 (8), 1277–1287. doi:10.1002/(SICI)1099-1085(19990615)13:8<1277::AID-HYP765>3.0.CO;2-W.

Solecki, W., Leichenko, R., O'Brian, K., 2011. Climate change adaptation strategies and disaster reduction in cities connections, contentions, and synergies. Curr. Opin. Environ. Sustainability 3 (3), 135–141. doi:10.1016/j.cosust.2011.03.001.

Stone, B., Hess, J.J., Frumkin, H., 2010. Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact ones? Environ. Health Perspect. 118, 1425–1428. doi:10.1289/ehp.0901879.

Studholme, J., Federov, A.V., Gulev, S.K., Emanuel, K., Hodges, K., 2022. Poleward expansion of tropical cyclone latitudes in warming climates. Nat. Geosci. 15, 14–28. doi:10.1038/s41561-021-00859-1.

Toimil, A., Losada, I.J., Nicholls, R.J., Dalrymple, R.A., Stive, M.J.F., 2020. Addressing the challenges of climate change risks and adaptation in coast areas: A review. Coastal Eng. 156, 103611. doi:10.1016/j.coastaleng.2019.103611.

Tosi, L., Lio, C.D., Bergamasco, A., Cosma, M., Cavallina, C., Fasson, A., Viezzoli, A., Zaggia, L., Donnici, S., 2022. Sensitivity, hazards, and vulnerability of farmlands to saltwater intrusion in low-lying coastal areas of Venice, Italy. Water 14, 64. doi:10.3390/w14010064.

Trenberth, K.E., 2011. Changes in precipitation with climate change. Clim. Res. 47, 123–138. doi:10.3354/cr00953.

Trenberth, K.E., 2022. The changing flow of energy through the climate system. In: The changing flow of energy through the climate system. Cambridge University Press, Cambridge, UK and New York, USA, p. 319. doi:10.1017/9781108979030.

Trenberth, K. E., Cheng, L., Zhang, Y., Fasullo, J., 2018. Hurricane Harvey links to ocean heat content and climate change adaptation. Earth's Future 6, 730–744. doi:10.1029/2018EF000825.

Venkatramanan, V., Shah, S., Prasad, R., 2020. Global climate change: Resilient and smart agriculture. Springer, Singapore, pp.1-358 doi:10.1007/978-981-32-9856-9.

von Schuckmann, K., Holland, E., Haugan, P., Thompson, P., 2020. Ocean science, data, and services for the UN 2030 Sustainable Development Goals. Mar. Policy 121, 104154. doi:10.1016/j.marpol.2020.104154.

Wahl, T., 2017. Sea-level rise and storm surges, relationship status: complicated!. Environ. Res. Lett. 12, 111001. doi:10.1088/1748-9326/aa8eba.

Westra, S., Alexander, L.V., Zwiers, F.W., 2013. Global increasing trends in annual maximum daily precipitation. J. Clim. 26, 3904–3918. doi:10.1175/jcli-D-12-00502.1.

White, E., Kaplan, D., 2017. Restore or retreat? Saltwater intrusion and water management in coastal wetlands. Ecosyst. Health Sustainability 3, e01258. doi:10.1002/ehs2.1258.

WMO (World Meteorological Organization), 2017. Weather ready, Climate smart - Supporting the 2030 Agenda for Sustainable Development. WMO Bulletin 66 (2), 1–57. https://public.wmo.int/en/resources/bulletin?tid-type-bulletin=425.

Yang, Q., Dixon, T.H., Myers, P.G., Bonin, J., Chambers, D., van den Broeke, M.R., Ribegaard, M.H., Mortensen, J., 2016. Recent increase in Arctic freshwater flux affects Labrador Sea convection and overturning circulation. Nature Commun. 7, 10525. doi:10.1038/ncomms10525.