9 Ocean, Cryosphere and Sea Level Change

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Executive Summary

This chapter assesses past and projected changes in the ocean, cryosphere and sea level using paleoreconstructions, instrumental observations and model simulations. In the following summary, we update and expand the related assessments from the IPCC Fifth Assessment Report (AR5), the Special Report on Global Warming of 1.5°C (SR1.5) and the Special Report on Ocean and Cryosphere in a Changing Climate (SROCC). This chapter covers major advances since SROCC, including the synthesis of extended and new observations. These advances allow for improved assessment of past change, processes and budgets for the last century, and the use of a hierarchy of models and emulators, which provide improved projections and uncertainty estimates of future change. In addition, the systematic use of model emulators makes our projections of ocean heat content, land ice loss and sea level rise fully consistent with each other and with the assessed equilibrium climate sensitivity and projections of global surface air temperature across the entire report. In this executive summary, uncertainty ranges are reported as *very likely* ranges and expressed by square brackets, unless otherwise noted.

Ocean Heat and Salinity

At the ocean surface, temperature has, on average, increased by 0.88 [0.68 to 1.01] °C between 1850–1900 and 2011–2020, with 0.60 [0.44 to 0.74] °C of this warming having occurred since 1980. The ocean surface temperature is projected to increase between 1995 to 2014 and 2081 to 2100 on average by 0.86 [0.43 to 1.47, *likely* range] °C in SSP1-2.6 and by 2.89 [2.01 to 4.07, *likely* range] °C in SSP5-8.5. Since the 1950s, the fastest surface warming has occurred in the Indian Ocean and in western boundary currents, while ocean circulation has caused slow warming or surface cooling in the Southern Ocean, equatorial Pacific, North Atlantic, and coastal upwelling systems (*very high confidence*). At least 83% of the ocean surface will *very likely* warm over the 21st century in all Shared Socio-economic Pathways (SSP) scenarios. {2.3.3, 9.2.1}

The heat content of the global ocean has increased since at least 1970, and will continue to increase over the 21st century (*virtually certain*). The associated warming will *likely* continue until at least 2300, even for low-emissions scenarios, because of the slow circulation of the deep ocean. Ocean heat content has increased from 1971 to 2018 by 0.396 [0.329 to 0.463, *likely* range] yottajoules and will *likely* increase until 2100 by two to four times that amount under SSP1-2.6 and four to eight times that amount under SSP5-8.5. The long time scale also implies that the amount of deep-ocean warming will only become scenario-dependent after about 2040 (*medium confidence*), and that the warming is irreversible over centuries to millennia (*very high confidence*). On annual to decadal time scales, the redistribution of heat by the ocean circulation dominates spatial patterns of temperature change (*high confidence*). At longer time scales, the spatial patterns are dominated by additional heat, primarily stored in water masses formed in the Southern Ocean, and by weaker warming in the North Atlantic where heat redistribution caused by changing circulation counteracts the additional heat input through the surface (*high confidence*). {9.2.2, 9.2.4, 9.6.1, Cross-Chapter Box 9.1}

Marine heatwaves – sustained periods of anomalously high near-surface temperatures that can lead to severe and persistent impacts on marine ecosystems – have become more frequent over the 20th century (*high confidence*). Since the 1980s, they have approximately doubled in frequency (*high confidence*) and have become more intense and longer (*medium confidence*). This trend will continue, with marine heatwaves at global scale becoming four times [2 to 9, *likely* range] more frequent in 2081–2100 compared to 1995–2014 under SSP1-2.6, and eight times [3 to 15, *likely* range] more frequent under SSP5-8.5. The largest changes will occur in the tropical ocean and the Arctic (*medium confidence*). {Box 9.2}

The upper ocean has become more stably stratified since at least 1970 over the vast majority of the globe (*virtually certain*), primarily due to surface-intensified warming and high-latitude surface freshening (*very high confidence*). Changes in ocean stability affect vertical exchanges of surface waters with the deep ocean and large-scale ocean circulation. Based on recent refined analyses of the available observations, the global 0–200 m stratification is now assessed to have increased about twice as much as reported by SROCC, with a 4.9 ± 1.5% increase from 1970 to 2018 (*high confidence*) and even higher increases at the base of the surface mixed layer. Upper-ocean stratification will continue to increase throughout the 21st century (*virtually certain*). {9.2.1}

Ocean Circulation

The Atlantic Meridional Overturning Circulation (AMOC) will *very likely* decline over the 21st century for all SSP scenarios. There is *medium confidence* that the decline will not involve an abrupt collapse before 2100. For the 20th century, there is *low confidence* in reconstructed and modelled AMOC changes because of their *low agreement* in quantitative trends. The *low confidence* also arises from new observations that indicate missing key processes in both models and measurements used for formulating proxies and from new evaluations of modelled AMOC variability. This results in *low confidence* in quantitative projections of AMOC decline in the 21st century, despite the *high confidence* in the future decline as a qualitative feature based on process understanding. {9.2.3}

Southern Ocean circulation and associated temperature changes in Antarctic ice-shelf cavities are sensitive to changes in wind patterns and increased ice shelf melt (*high confidence*). However, limitations in understanding feedback mechanisms involving the ocean, atmosphere and cryosphere, which are not fully represented in the current generation of climate models, generally limit our confidence in future projections of the Southern Ocean and of its forcing on Antarctic sea ice and ice shelves. {9.2.3, 9.3.2, 9.4.2}

Many ocean currents will change in the 21st century as a response to changes in wind stress associated with anthropogenic warming (*high confidence*). Western boundary currents have shifted poleward since 1993 (*medium confidence*), consistent with a poleward shift of the subtropical gyres. Of the four eastern boundary upwelling systems, only the California Current system has experienced some large-scale upwelling-favourable

wind intensification since the 1980s (*medium confidence*). In the 21st century, consistent with projected changes in the surface winds, the East Australian Current Extension and Agulhas Current Extension will intensify, while the Gulf Stream and Indonesian Throughflow will weaken (*medium confidence*). Eastern boundary upwelling systems will change, with a dipole spatial pattern within each system of reduction at low latitude and enhancement at high latitude (*high confidence*). {9.2.1, 9.2.3}

Sea Ice

The Arctic Ocean will *likely* become practically sea ice free[1] during the seasonal sea ice minimum for the first time before 2050 in all considered SSP scenarios. There is no tipping point for this loss of Arctic summer sea ice (*high confidence*). The practically ice-free state is projected to occur more often with higher greenhouse gas concentrations, and it will become the new normal for high-emissions scenarios by the end of this century (*high confidence*). Based on observational evidence, Coupled Model Intercomparison Project Phase 6 (CMIP6) models and conceptual understanding, the substantial satellite-observed decrease of Arctic sea ice area over the period 1979–2019 is well described as a linear function of global mean surface temperature, and thus of cumulative anthropogenic carbon dioxide (CO_2) emissions, with superimposed internal variability (*high confidence*). According to both process understanding and CMIP6 simulations, a practically sea ice-free state will *likely* be observed some years before additional (post-2020) cumulative anthropogenic CO_2 emissions reach 1000 $GtCO_2$. {4.3.2, 9.3.1}

For Antarctic sea ice, regionally opposing trends and large interannual variability result in no significant trend in satellite-observed sea ice area from 1979 to 2020 in both winter and summer (*high confidence*). The regionally opposing trends result primarily from changing regional wind forcing (*medium confidence*). There is *low confidence* in model simulations of future Antarctic sea ice decrease, and lack of decrease, due to deficiencies of process representation, in particular at the regional level. {2.3.2, 9.2.3, 9.3.2}

Ice Sheets

The Greenland Ice Sheet has lost 4890 [4140 to 5640] Gt mass over the period 1992–2020, equivalent to 13.5 [11.4 to 15.6] mm global mean sea level rise. The mass-loss rate was on average 39 [–3 to +80] Gt yr^{-1} over the period 1992–1999, 175 [131 to 220] Gt yr^{-1} over the period 2000–2009 and 243 [197 to 290] Gt yr^{-1} over the period 2010–2019. This mass loss is driven by both discharge and surface melt, with the latter increasingly becoming the dominating component of mass loss with high interannual variability in the last decade (*high confidence*). The largest mass losses occurred in the north-west and the south-east of Greenland (*high confidence*). {2.3.2, 9.4.1}

The Antarctic Ice Sheet has lost 2670 [1800 to 3540] Gt mass over the period 1992–2020, equivalent to 7.4 [5.0 to 9.8] mm global mean sea level rise. The mass-loss rate was, on average, 49 [–2 to +100] Gt yr^{-1} over the period 1992–1999, 70 [22 to 119] Gt yr^{-1} over the period 2000–2009 and 148 [94 to 202] Gt yr^{-1} over the period 2010–2019. Mass losses from West Antarctic outlet glaciers outpaced mass gain from increased snow accumulation on the continent and dominated the ice-sheet mass losses since 1992 (*very high confidence*). These mass losses from the West Antarctic outlet glaciers were mainly induced by ice-shelf basal melt (*high confidence*) and locally by ice-shelf disintegration preceded by strong surface melt (*high confidence*). Parts of the East Antarctic Ice Sheet have lost mass in the last two decades (*high confidence*). {2.3.2, 9.4.2, Atlas.11.1}

Both the Greenland Ice Sheet (*virtually certain*) and the Antarctic Ice Sheet (*likely*) will continue to lose mass throughout this century under all considered SSP scenarios. The related contribution to global mean sea level rise until 2100 from the Greenland Ice Sheet will *likely* be 0.01 to 0.10 m under SSP1-2.6, 0.04 to 0.13 m under SSP2-4.5 and 0.09–0.18 m under SSP5-8.5, while the Antarctic Ice Sheet will *likely* contribute 0.03 to 0.27 m under SSP1-2.6, 0.03 to 0.29 m under SSP2-4.5, and 0.03 to 0.34 m under SSP5-8.5. The loss of ice from Greenland will become increasingly dominated by surface melt, as marine margins retreat and the ocean-forced dynamic response of ice-sheet margins diminishes (*high confidence*). In the Antarctic, dynamic losses driven by ocean warming and ice-shelf disintegration will *likely* continue to outpace increasing snowfall this century (*medium confidence*). Beyond 2100, total mass loss from both ice sheets will be greater under high-emissions scenarios than under low-emissions scenarios (*high confidence*). The assessed *likely* ranges consider those ice-sheet processes in whose representation in current models we have at least *medium confidence*, including surface mass balance and grounding-line retreat in the absence of instabilities. Under high-emissions scenarios, poorly understood processes related to marine ice sheet instability and marine ice cliff instability, characterized by deep uncertainty, have the potential to strongly increase Antarctic mass loss on century to multi-century time scales. {9.4.1, 9.4.2, 9.6.3, Box 9.3, Box 9.4}

Glaciers

Glaciers lost 6200 [4600 to 7800] Gt of mass (17.1 [12.7 to 21.5] mm global mean sea level equivalent) over the period 1993–2019 and will continue losing mass under all SSP scenarios (*very high confidence*). During the decade 2010–2019, glaciers lost more mass than in any other decade since the beginning of the observational record (*very high confidence*). For all regions with long-term observations, glacier mass in the decade 2010–2019 is the smallest since at least the beginning of the 20th century (*medium confidence*). Because of their lagged response, glaciers will continue to lose mass at least for several decades even if global temperature is stabilized (*very high confidence*). Glaciers will lose

1 Sea ice area below 1 million km^2.

29,000 [9000 to 49,000] Gt and 58,000 [28,000 to 88,000] Gt over the period 2015–2100 for RCP2.6 and RCP8.5, respectively (*medium confidence*), which represents 18 [5 to 31] % and 36 [16 to 56] % of their early-21st-century mass, respectively. {2.3.2, 9.5.1, 9.6.1, 9.6.3, 12.4}

Permafrost

Increases in permafrost temperature have been observed over the past three to four decades throughout the permafrost regions (*high confidence*), and further global warming will lead to near-surface permafrost volume loss (*high confidence*). Complete permafrost thaw in recent decades is a common phenomenon in discontinuous and sporadic permafrost regions (*medium confidence*). Permafrost warmed globally by 0.29 [0.17 to 0.41, *likely* range] °C between 2007 and 2016 (*medium confidence*). An increase in the active layer thickness is a pan-Arctic phenomenon (*medium confidence*), subject to strong heterogeneity in surface conditions. The volume of perennially frozen soil within the upper 3 m of the ground will decrease by about 25% per 1°C of global surface air temperature change (up to 4°C above pre-industrial temperature) (*medium confidence*). {9.5.2}

Snow

Northern Hemisphere spring snow cover extent has been decreasing since 1978 (*very high confidence*), and there is *high confidence* that this trend extends back to 1950. Further decrease of Northern Hemisphere seasonal snow cover extent is *virtually certain* under further global warming. The observed sensitivity of Northern Hemisphere snow cover extent to Northern Hemisphere land surface air temperature for 1981–2010 is –1.9 [–2.8 to –1.0, *likely* range] million km^2 per 1°C throughout the snow season. It is *virtually certain* that Northern Hemisphere snow cover extent will continue to decrease as global climate continues to warm, and process understanding strongly suggests that this also applies to Southern Hemisphere seasonal snow cover (*high confidence*). Northern Hemisphere spring snow cover extent will decrease by about 8% per 1°C of global surface air temperature change (up to 4°C above pre-industrial temperature) (*medium confidence*). {9.5.3}

Sea Level

Global mean sea level (GMSL) rose faster in the 20th century than in any prior century over the last three millennia (*high confidence*), with a 0.20 [0.15 to 0.25] m rise over the period 1901–2018 (*high confidence*). GMSL rise has accelerated since the late 1960s, with an average rate of 2.3 [1.6 to 3.1] mm yr^{-1} over the period 1971–2018 increasing to 3.7 [3.2 to 4.2] mm yr^{-1} over the period 2006–2018 (*high confidence*). New observation-based estimates published since SROCC lead to an assessed sea level rise over the period 1901–2018 that is consistent with the sum of individual components. Ocean thermal expansion (38%) and mass loss from glaciers (41%) dominate the total change from 1901 to 2018. The contribution of Greenland and Antarctica to GMSL rise was four times larger during 2010–2019 than during 1992–1999 (*high confidence*). Because of the increased ice-sheet mass loss, the total loss of land ice (glaciers and ice sheets) was the largest contributor to global mean sea level rise over the period 2006–2018 (*high confidence*). {2.3.3, 9.6.1, 9.6.2, Cross-Chapter Box 9.1, Table 9.A.1, Box 7.2}

At the basin scale, sea levels rose fastest in the Western Pacific and slowest in the Eastern Pacific over the period 1993–2018 (*medium confidence*). Regional differences in sea level arise from: ocean dynamics; changes in Earth gravity, rotation and deformation due to land ice and land-water changes; and vertical land motion. Temporal variability in ocean dynamics dominates regional patterns on annual to decadal time scales (*high confidence*). The anthropogenic signal in regional sea level change will emerge in most regions by 2100 (*medium confidence*). {9.2.4, 9.6.1}

Regional sea level change has been the main driver of changes in extreme still water levels across the quasi-global tide gauge network over the 20th century (*high confidence*) and will be the main driver of a substantial increase in the frequency of extreme still water levels over the next century (*medium confidence*). Observations show that high-tide flooding events that occurred five times per year during the period 1960–1980 occurred, on average, more than eight times per year during the period 1995–2014 (*high confidence*). Under the assumption that other contributors to extreme sea levels remain constant (e.g., stationary tides, storm-surge, and wave climate), extreme sea levels that occurred once per century in the recent past will occur annually or more frequently at about 19–31% of tide gauges by 2050 and at about 60% (SSP1-2.6) to 82% (SSP5-8.5) of tide gauges by 2100 (*medium confidence*). In total, such extreme sea levels will occur about 20 to 30 times more frequently by 2050 and 160 to 530 times more frequently by 2100 compared to the recent past, as inferred from the median amplification factors for SSP1-2.6, SSP2-4.5, and SSP5-8.5 (*medium confidence*). Over the 21st century, the majority of coastal locations will experience a median projected regional sea level rise within ±20% of the median projected GMSL change (*medium confidence*). {9.6.3, 9.6.4}

It is *virtually certain* that GMSL will continue to rise until at least 2100, because all assessed contributors to GMSL are *likely* to *virtually certain* to continue contributing throughout this century. Considering only processes for which projections can be made with at least *medium confidence*, relative to the period 1995–2014, GMSL will rise by 2050 between 0.18 [0.15 to 0.23, *likely* range] m (SSP1-1.9) and 0.23 [0.20 to 0.29, *likely* range] m (SSP5-8.5), and by 2100 between 0.38 [0.28 to 0.55, *likely* range] m (SSP1-1.9) and 0.77 [0.63 to 1.01, *likely* range] m (SSP5-8.5). This GMSL rise is primarily caused by thermal expansion and mass loss from glaciers and ice sheets, with minor contributions from changes in land-water storage. These *likely* range projections do not include those ice-sheet-related processes that are characterized by deep uncertainty. {9.6.3}

Higher amounts of GMSL rise before 2100 could be caused by earlier-than-projected disintegration of marine ice shelves, the abrupt, widespread onset of marine ice sheet instability and marine ice cliff instability around Antarctica, and faster-than-projected changes in the surface mass balance and discharge from Greenland. These processes are characterized by deep uncertainty arising from limited process understanding, limited availability of evaluation data, uncertainties in their external forcing and high sensitivity to uncertain boundary conditions and parameters. In a low-likelihood, high-impact storyline, under high emissions such processes could in combination contribute more than one additional metre of sea level rise by 2100. {9.6.3, Box 9.4}

Beyond 2100, GMSL will continue to rise for centuries due to continuing deep-ocean heat uptake and mass loss of the Greenland and Antarctic ice sheets, and will remain elevated for thousands of years (*high confidence*). Considering only processes for which projections can be made with at least *medium confidence* and assuming no increase in ice-mass flux after 2100, relative to the period 1995–2014, by 2150, GMSL will rise between 0.6 [0.4 to 0.9, *likely* range] m (SSP1-1.9) and 1.4 [1.0 to 1.9, *likely* range] m (SSP5-8.5). By 2300, GMSL will rise between 0.3 m and 3.1 m under SSP1-2.6, between 1.7 m and 6.8 m under SSP5-8.5 in the absence of marine ice cliff instability, and by up to 16 m under SSP5-8.5 considering marine ice cliff instability (*low confidence*). {9.6.3}

Cryospheric Changes and Sea Level Rise at Specific Levels of Global Warming

At sustained warming levels between 1.5°C and 2°C, the Arctic Ocean will become practically sea ice-free in September in some years (*medium confidence*); the ice sheets will continue to lose mass (*high confidence*), but will not fully disintegrate on time scales of multiple centuries (*medium confidence*); there is *limited evidence* that the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia; about 50 to 60% of current glacier mass excluding the two ice sheets and the glaciers peripheral to the Antarctic Ice Sheet will remain, predominantly in the polar regions (*low confidence*); Northern Hemisphere spring snow cover extent will decrease by up to 20% relative to 1995–2014 (*medium confidence*); the permafrost volume in the top 3 m will decrease by up to 50% relative to 1995–2014 (*medium confidence*). Committed GMSL rise over 2000 years will be about 2 to 6 m with 2°C of peak warming (*medium agreement, limited evidence*). {9.3.1, 9.4.1, 9.4.2, 9.5.1, 9.5.2, 9.5.3, 9.6.3}

At sustained warming levels between 2°C and 3°C, the Arctic Ocean will be practically sea ice free throughout September in most years (*medium confidence*); there is *limited evidence* that the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss will increase with higher temperatures (*high confidence*); about 50 to 60% of current glacier mass outside Antarctica will be lost (*low confidence*); Northern Hemisphere spring snow cover extent will decrease by up to 30% relative to 1995–2014 (*medium confidence*); permafrost volume in the top 3 m will decrease by up to 75% relative to 1995–2014 (*medium confidence*). Committed GMSL rise over 2000 years will be about 4 to 10 m with 3°C of peak warming (*medium agreement, limited evidence*). {9.3.1, 9.4.1, 9.4.2, 9.5.1, 9.5.2, 9.5.3, 9.6.3}

At sustained warming levels between 3°C and 5°C, the Arctic Ocean will become practically sea ice free throughout several months in most years (*high confidence*); near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet will occur irreversibly over multiple millennia (*medium confidence*); substantial parts or all of Wilkes Subglacial Basin in East Antarctica will be lost over multiple millennia (*low confidence*); 60 to 75% of current glacier mass outside Antarctica will disappear (*low confidence*); nearly all glacier mass in low latitudes, Central Europe, Caucasus, western Canada and the USA, North Asia, Scandinavia and New Zealand will *likely* disappear; Northern Hemisphere spring snow cover extent will decrease by up to 50% relative to 1995–2014 (*medium confidence*); permafrost volume in the top 3 m will decrease by up to 90% compared to 1995–2014 (*medium confidence*). Committed GMSL rise over 2000 years will be about 12 to 16 m with 4°C of peak warming and 19 to 22 m with 5°C of peak warming (*medium agreement, limited evidence*). {9.3.1, 9.4.1, 9.4.2, 9.5.1, 9.5.2, 9.5.3, 9.6.3}