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Impacts of climate change on environment and human societies

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1 Introduction

This report is part of the first intellectual output (IO1) of the Erasmus Goes Green project. Its objective is to provide a general overview of the main current and potential future impacts of anthropogenic greenhouse gas emissions. It is based on the state-of-the art knowledge and builds on much of the previous synthesis reports provided by the Intergovernmental Panel of Climate Change (IPCC) and the European Environment Agency (EEA). The report is divided into four sections. Section 2 describes the functioning of the climate system and the basic principles of the greenhouse effect with a focus on the present-day anthropogenic emissions of the main greenhouse gases. Section 3 outlines the impact of these emissions on the different components of the climate system. The impacts of climatic change on the environment and on human societies are addressed in sections 4 and 5 respectively.

2 Human influence on the climate system

2.1 The climate system

Climate is usually defined as the long-term weather average. More rigorously, the IPCC defines the climate as a statistical description in terms of mean, trends and variability of meteorological variables (temperature, humidity, wind speed, atmospheric pressure and precipitation) over a long-time period, generally thirty years as recommended by the World Meteorological Organization. However, depending on the period under study, the reference period may range from months to thousands or even millions of years.

The climate system (also referred to as « the Earth system in the following ») includes five components: the atmosphere, the ocean, the cryosphere, the biosphere and the upper lithosphere. The driving force of the Earth system is the absorption of solar energy by the Earth’s surface. The excess energy received at the equator is redistributed towards the high latitudes through atmospheric and oceanic circulations. Incoming solar radiation is mainly concentrated in short wavelengths (i.e visible wavelengths). A part of this radiation does not reach the surface and is either absorbed by the atmosphere or directly reflected back to space. Around half ot the incoming shortwave radiation is absorbed by the Earth. To ensure the thermal equilibrium, the absorbed solar energy is compensated by a long wave energy flux (i.e. in the infrared wavelengths) emitted towards the atmosphere. This long wave radiation is partly reflected back to space, but the greater part is trapped by the atmospheric constituents, that are water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases (GHGs), clouds and aerosols. These constituents also emit long wave radiations in all directions, but ~95% are emitted downwards causing a further warming of the Earth’s surface and the lower layers of the atmosphere. This process is called the greenhouse effect.

2.2 Drivers of the climate system

The climate system is influenced by natural external forcings (e.g. changes in orbital parameters of the Earth, natural greenhouse gases, modulations of solar cycles, volcanic

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activity, tectonic changes) and by anthropogenic activities. Any change in these natural or anthropogenic forcings induces a change in the climate response. This response also depends on internal variability processes, such as the El Niño–Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Pacific Decadal Oscillation (PDO). In addition, climate changes may also be amplified (i.e. positive feedback) or mitigated (i.e. negative feedback) by the interactions between the different components of the Earth system.

Climate drivers act at different time scales. As an example, tectonic changes have affected the Earth's climate on time scales of a few tens to several hundred million years. Glacial-interglacial cycles have been driven by changes in orbital parameters of the Earth and variations of natural GHG in the atmosphere from around 180 ppm[1] to 280 ppm between glacial and interglacial periods respectively. Over the last millennium, it has been advanced that variations in solar and volcanic activities could have been responsible for climate fluctuations such as the Medieval Warm Period or the Little Ice Age. However, today, the effects of anthropogenic greenhouse gas emissions on the present-day climate greatly exceed the effects due to known changes in natural processes.

2.3 Greenhouse gas emissions

The main GHGs (H_2O, CO_2, CH_4 and N_2O) are naturally present in the atmosphere. They are emitted through evaporation (H_2O), volcanic eruptions and forest fires (CO_2), wetlands and various fermentation processes (CH_4), and from micro-organisms in soils and oceans (N_2O). All these GHG are responsible for the greenhouse effect which is a natural phenomenon without which the Earth’s surface temperature would be around -18°C. However, since the beginning of the industrial era in 1750, massive amounts of greenhouse gases (GHGs) have been discharged in the atmosphere through the combustion of fossil fuels (oil, gas, coal), deforestation, agriculture, intensive livestock breeding and fertilizer production. Besides water vapor (H_2O), the main GHGs are water carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) produced by the photodissociation of N_2O. Other GHGs, produced exclusively by human activities are fluorinated gases used in refrigeration and air conditioning systems, as well as in aerosol cans. According to the Intergovernmental Panel of Climate Change (IPCC, 2007), "*most of the observed increase in global mean surface temperature from 1951 to 2010 is very likely due to the observed increase in anthropogenic greenhouse gas concentrations*".

The anthropogenic contribution of water vapour is considerably much less than the natural evaporation. Moreover, water vapour is rapidly removed from the atmosphere (~10 days) through precipitation. Therefore, it is not considered as a primary driver for climate change. However, due to the increased water holding of warmer air, water vapour has the potential to amplify global warming. This process is known as the water vapour feedback. Carbon dioxide is the most abundant GHG after water vapor, and has the longest residence time in the atmosphere (several hundreds of years). Its atmospheric concentration increased by more

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[1] 1 ppm = One part per million. This unit is used to refer to as a mass fraction (1 ppm = 1 mg/kg =10^{-6}). In the same way, 1 ppb is defined as one part per billion (1 ppb = 1µg/kk = 10^{-9})

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than 46% between 1750 and 2019, rising from 277 ppm to 410 ppm, a level never attained over the last 800,000 years as indicated by Antarctic ice core records. Similarly, methane and nitrous oxide have experienced dramatic increases: 164 and 22% respectively in 2016-2017 relative to 1750.

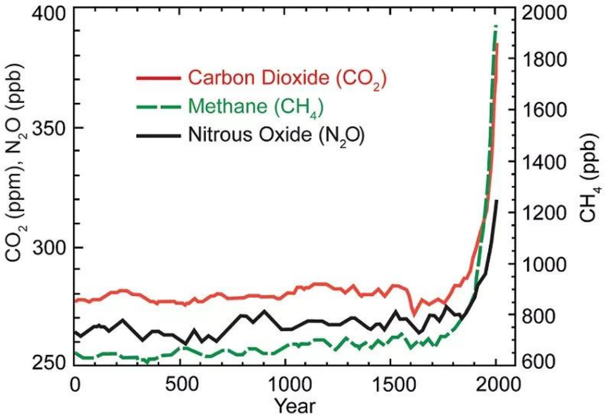

Figure 1 : *Evolution of the atmospheric concentrations of the three main greenhouse gases (CO_2, CH_4, N_2O) over the last two millennia (0-2000 years). This figure illustrates the sharp increase in GHG concentrations from the beginning of the industrial area. Source : IPCC (2007).*

Today, around 86 % of atmospheric CO_2 come from fossil fuel emissions and 14% from deforestation. Around 23% are dissolved in the ocean and 31% are buried in soils or used by vegetation for photosynthesis (Friedlingstein et al., 2020). These carbon sinks help to modulate global warming by removing carbon from the atmosphere. However, almost half of the CO2 emissions (46%) remain in the atmosphere. This fraction could be increased in the future. Indeed, as deforestation is becoming more and more widespread, there are less available plants to absorb CO_2. Moreover, oceans are not infinite reservoirs and may therefore no longer be able to absorb fossil emissions if they were keep on growing.

3 Observed and projected changes in the climate system

3.1 Changes in surface temperature

The effect of GHG increase in the atmosphere has been proved to be the dominant cause of the observed global warming since the second half of the 20th century. Increase in surface temperature was estimated in 2017 around 1.0°C above pre-industrial levels, with a likely range between 0.8°C and 1.2°C (Allen et al. 2018) and a warming trend of about 0.2°C per decade. According to the National Oceanic and Atmospheric Administration (NOAA, 2021), the last decade (2011-2020) was 0.82°C warmer than the 20th century (1901-2000) average, making it the warmest decade on record. This magnitude of warming is almost half of the 2°C warming that is compatible with the global climate stabilization target of the EU and the ultimate objective of the UNFCCC. The warming is generally greater than average over land areas while most ocean regions are warming at a slower rate.

The NOAA (2021) ranked the year 2020 as the second warmest year on record (+0.98°C compared to the pre-industrial reference period), just behind the year 2016 (+1.00°C). This makes 2020 the 44th consecutive year since 1977 with global land and ocean temperatures above the 20th century average. However, this warming was not uniform with differences from one continent to the other and between land and oceanic areas.

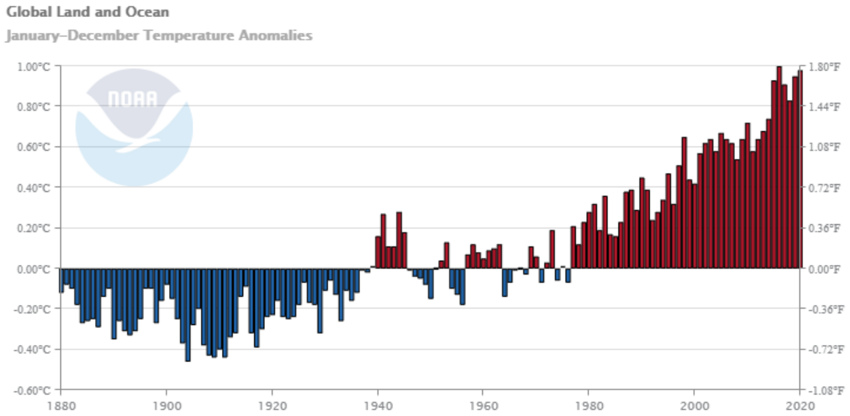

Figure 2: *Mean annual difference of surface air temperature relative to the 20th century average (1901-2000). Blue bars indicate colder than average temperatures and red bars indicate warmer temperatures (Source: NOAA).*

Over land areas, the 2020 warming (+1.59°C) even exceeded that of 2016 (+1.54°C). The largest continental warming in 2020 has been observed in Europe with 2.16°C above the 20th century average, surpassing the previous 2018 record by 0.28°C. It appears to be the 24th consecutive year having a near-surface temperature above the average. Reconstructions show that the recent decades in Europe are the warmest for at least 2 000 years and they lie significantly outside the range of natural variability. Over the period 2006-2015, the average annual temperature over land areas increased by 1.45 to 1.59°C with respect to pre-industrial times. This increase is larger than the increase in the global mean surface temperature. However, this masks large regional and seasonal disparities. In winter, the greatest warming is observed in northern and central Europe, where departures from the 1981-2010 climatological mean up to 3°C have been recorded. Conversely, the Iberian Peninsula warmed mostly in summer.

Climate models require information about future emissions or concentrations of GHGs and other climate drivers. For the fifth assessment report of the IPCC (IPCC, 2013), a set of four scenarios (the representative concentration pathways) has been defined by their approximate radiative forcing in 2100 relative to year 1750. These scenarios are labelled RCP2.6, RCP4.5, RCP6 and RCP8.5 and correspond to an additional radiative forcing in 2100 of 2.6, 4.5, 6 and 8.5 W/m^2 respectively[2]. They include economic, demographic, energy and climate considerations.

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[2] The RCP scenarios have been built with models including economic, demographic, energy and climate considerations. RCP2.6 is a mitigation scenario peaks at around 3W/m^2 before 2100 and then declines.

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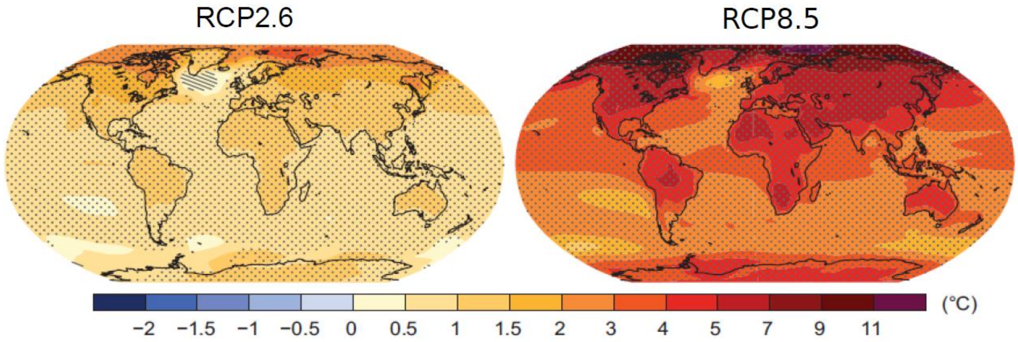

***Figure 3**: Annual mean surface temperature change in 2081-2100 (relative to 1986-2005) provided by the CMIP5 multi-model mean for the RCP2.6 (left) and RCP8.5 (right) scenarios. Black dots indicate regions where the temperature change greatly exceeds the internal variability and where at least 90% of the models agree on the sign of change. Hatched areas indicate regions where the mean is small compared to the internal variability. These maps indicate a greater warming for the Arctic region (up to 11°C) and a greater warming over the continents compared to the oceans. Adapted from IPCC 2013.*

Global climate models project further increases in the global mean surface air temperature over the 21st century (Hartmann et al., 2013). Until 2030-2040, the amplitude of warming does not differ so much between the scenarios. However, at longer time scales (from 2040 onwards), the warming rate becomes strongly dependent on the representative concentration pathways. According to the CMIP5[3] ensemble mean, the only scenario limiting the warming below 2°C within the 21st century (relative to 1850-1900) is the RCP2.6 scenario, illustrating the importance of climate policies. Compared to the climatological baseline reference period (1986-2005), the projected warming averaged over 2081-2100 is between 0.3 and 1.7°C with RCP2.6 and between 2.6 and 4.8°C with RCP8.5. These numbers represent the 5th and the 95th quantiles respectively. This means, for example, that 95% of the individual CMIP5 models project a warming 4.8°C with RCP8.5 and less than 5% simulate a warming below 2.6°C.

The EURO-CORDEX initiative (Jacob et al., 2014) provides high resolution (50 km and 12.5 km) regional climate simulations for Europe under the medium (RCP4.5) and the highest emission scenario (RCP8.5). The projected warmings in 2071-2100 (relative to 1971-2000)[4] obtained with these regional simulations are 1-4.5°C with RCP4.5 and 2.5-5.5°C with RCP8.5 (Fig. 4).

RCP4.5 and RCP6 stabilize after 2100 at 4.5 and 6.0 W/m^2 after 2100 and RCP8.5 reaches 8.5 W/m^2 in 2100 and continues to rise afterwards. The corresponding atmospheric GHG concentrations (in terms of CO2 equivalent) are respectively around 490, 650, 850 and 1390 ppm

[3] Climate Model Intercomparison Project, Phase 5 (Taylor et al., 2012).

[4] Note that the reference periods are different from those considered in the global mean CMIP5 ensemble

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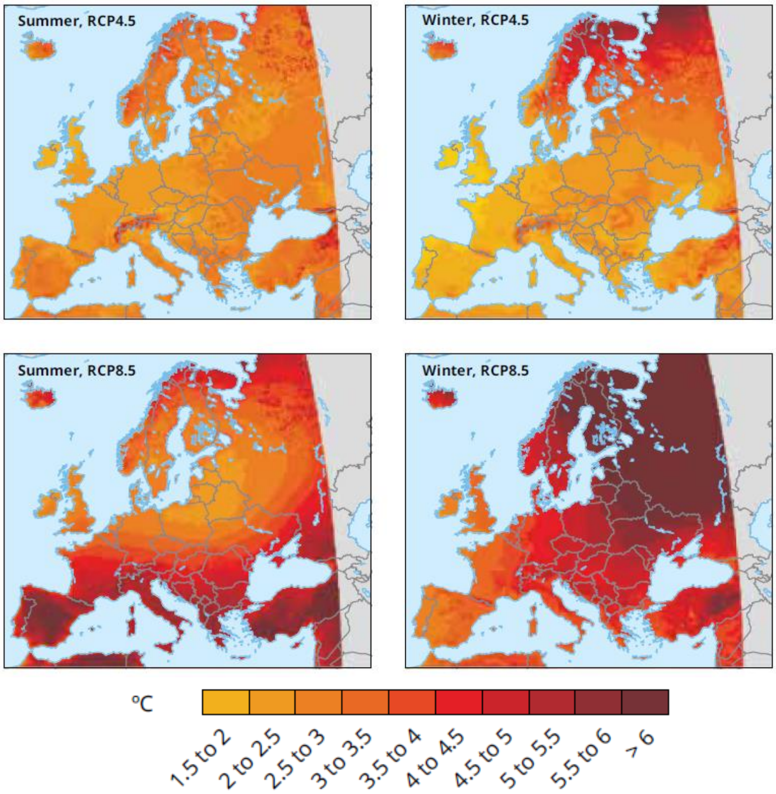

Figure 4: *Projected changes in Euopean summer (left) and winter (right) surface air temperature (in °C) for the RCP4.5 (top) and RCP8.5 (bottom) scenarios for the period 2071-2100 relative to 1971-2000.*
Model simulations are based on the multi-model ensemble average of the regional simulations from the EURO-CORDEX initiative. Adapted from EEA (2017).

For southern Europe, the strongest warming is projected to occur in summer, especially in the Iberian Peninsula where it could exceed 6°C. Conversely, these high warming amplitude could be seen in winter for northern and northeastern Europe (Jacob et al., 2014).

3.2 Changes in the hydrological cycle

Because increased temperatures favour evaporation, global warming has a direct influence on the hydrological cycle (precipitation, evaporation, runoff). Moreover, the water holding capacity of the air increases with temperature by about 7% per 1°C of warming, leading to a greater amount of water vapor content in the atmosphere. More intense precipitation is thus expected along with increased risks of flooding. However, there is no clear evidence of positive or negative trend in precipitation change averaged over global land areas, partly because of large interannual and decadal variability. In addition, large uncertainties exist regarding precipitation changes due to insufficient in situ measurements in some regions that are difficult to access and to uncertainties in algorithms used to convert direct spatial observations into precipitation rates. However, large scale patterns of precipitation change stand out, although they are only attributed with only low or medium confidence. Different data sets suggest that precipitation has increased in the tropics and subtropics (30°S-30°N), reversing the drying trend observed from the mod-1970s to the mid-1990s. The mid- and high-latitudes of the northern hemisphere also show an overall increase in precipitation, although, for the latter, the magnitude differ among datasets (Hartmann et al., 2013).

Average precipitation shows no significant change in Europe since the 1960s. However, at the sub-continental scales, large differences can be observed. In particular, there is a noticeable contrast between north and south. Observations indicate significant increases in annual precipitation in Scandinavia (up to 70 mm/decade in Norway) and the Baltic states, and strong decreases in southern regions, particularly in South of France and the Iberian Peninsula (up to 40 mm/decade). In central Portugal, the decrease is even more pronounced and reaches 90 mm/decade. In summer, drying extends over most parts of the Mediterranean Basin while increases have been reported in some northern regions (EEA, 2017 and references therein).

This north/south contrast is projected to be amplified in the future (Jacob et al., 2014). Results from the EURO-CORDEX consortium show that under the RCP8.5 scenario, annual precipitation rates in 2071-2100 are projected to decrease in the southernmost regions and increase in most northern and central Europe with the largest increase (relative to 1971-2000) occurring in Scandinavia and northeastern Europe (> 30%). In summer, regions of increased precipitation rates are less extended southwards and central Europe shows no significant change. By contrast, rainfall deficit extends over all the countries bordering the Mediterranean Sea and the North Sea with decreases ranging from 10-20% for UK, Belgium, Netherlands, west Germany to 30-40 % for the Iberian Peninsula, south France, western Italia coast and Greece (Fig. 5)

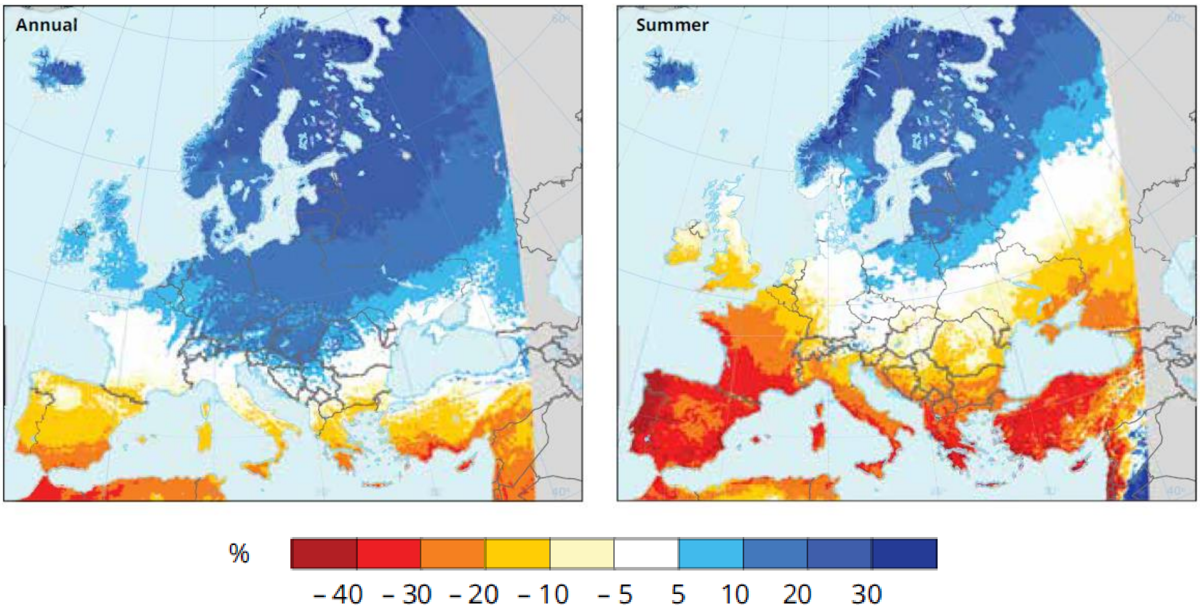

Figure 5: *Projected changes in annual (left) and summer (right) precipitation (%) in the period 2071-2100 compared to the baseline period 1971-2000 for the forcing scenario RCP8.5. Model simulations are based on the multi-model ensemble average of RCM simulations from the EURO-CORDEX initiative. Adapted from EEA (2017).*

3.3 Changes in extreme events

The increase in the global surface temperature and changes in the hydrological cycle are expected to affect the frequency and intensity of extreme events, such as heat waves, heavy precipitation, droughts, flooding cyclones and storms.

3.3.1 Hot extremes

Observations indicate a continued increase in heat extremes for land areas for the last three decades. These extremes are characterized by more frequent warm days and nights and more frequent heat waves. They also have strong direct impacts on human health and well-being, as well as on society (e.g. through decreased labour productivity), ecosystems (e.g. through forest fires) and agriculture. In particular, heat waves exacerbated by the urban heat island effect and air pollution can have devastating impacts on human health in urban areas.

In Europe, the maximum daily temperatures have shown significant upward trends and the number of unusually warm days has increased by up to 10 days per decade since 1960 in most of southern Europe and Scandinavia. Large areas have experienced intense and long heat waves since 1950, most of which occurred after 2000 (in 2003, 2006, 2007, 2010, 2014, 2015, 2018 and 2019). The severity of a heat wave depends on its duration, its relative intensity (how much hotter than the mean temperature at a given location) and its amplitude. The most severe European heat waves have been characterized by the persistence of extremely high temperatures at night (Russo et al. 2015). Summer 2003 was certainly one of the most striking examples with temperatures up to 40°C in some regions. However, in 2019, for example, two successive episodes occurred in June and July affecting the entire continent. But one of the most affected country was France where temperatures above 46°C were recorded.

Climate model projections performed under all RCP scenarios agree on increases in heat wave frequency and magnitude for most European regions in the course of the 21st century (Ouzeau et al. 2016). Temperatures, such as the ones experienced in different parts of Europe in 2003 and 2019 will become much more common in the future. Under the RCP8.5 scenario, very extreme heat waves are projected to occur every two years in the second half of the 21st century, with a greatest frequency in southern and south-eastern Europe (Russo et al. 2014). According to Ouzeau et al. (2016), the duration and intensity of the 2003 event could be much lower than the strongest heat waves that could occur over 2071-2100. Unless appropriate climate policies are adopted, 90% of the summers in southern, central and north-western Europe will be warmer than any summer in the 1920-2014 period under the RCP8.5 scenario (Lehner et al., 2018).

3.3.2 Heavy precipitation events

Despite uncertainties due to non-uniform data coverage, the majority of observation-based studies suggest that heavy precipitation events have become more intense and more frequent in Europe on average. However, there are large differences across regions and seasons. Studies generally agree that heavy precipitation has become more intense in northern and West Central Europe, although changes are not always statistically significant. In southern Europe, there is only low confidence for increasing trend of heavy precipitation, although sub-daily events are observed in regions where the mean precipitation decreases (Westra et al., 2014 and references therein).

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Global warming is projected to lead to a higher intensity of precipitation and longer dry periods in Europe (Hartmann et al., 2013). Projections show an increase in heavy daily precipitation in most parts of Europe in winter during the 21st century with increases of up to 30 % in north-eastern Europe. In summer, an increase is also projected in most parts of Europe, but decreases are projected for some regions in southern and south-western Europe (Jacob et al., 2014).

3.3.3 Wind storms

Storms may lead to significant damages on population, infrastructures and natural systems. In the North Atlantic and northwestern Europe, the most severe storms occur primarily in winter. They are characterized by high wind speeds and may be often accompanied by extremes of precipitation. In mid-latitudes, storms affecting large parts of land areas are referred to as extra-tropical cyclones. They develop from low-pressure weather systems that originate from the temperature gradient between the poles and the tropics. The storm tracks (i.e. the path of storms over time) depend on many factors such as land-sea contrasts, surface air temperature, topography and variability in the large-scale atmospheric circulation. The dominant mode of atmospheric variability in the North Atlantic is the North Atlantic Oscillation (NAO) defined as the pressure difference between the Icelandic low and the Azores high. When the pressure difference increases, more pronounced storms with high wind speeds are observed in northern Europe, while a weak pressure gradient leads to a displacement of the storms towards the Mediterranean basin.

Wind measurements are often inhomogeneous. This is due for example to instrumental changes, environmental influences, changes in the frequency of measurements and to various techniques of measurements. This leads to contradictory results and prevents from drawing robust conclusions about the trends of the intensity and the frequency of storms until the middle of the 20th century. Most models neither indicate a clear trend for the storm activity in the mid-latitude regions, but agree on an increase in northwestern Europe and the Baltic Sea (Hartmann et al., 2013, Feser et al., 2014). Despite large model uncertainties, it is now widely accepted that under gobal warming, the storm tracks shift poleward and eastwards (e.g. Ulbrich et al., 2009, Zappa et al., 2013, Yin et al., 2005). Moreover, modelling studies generally agrees on increase in the intensity of storms in northern, northwestern and Europe over the 21st century.

3.4 Impacts on cryosphere

The cryosphere includes snow, mountain glaciers and ice sheets, sea ice, permafrost, frozen lakes and rivers, and contains more than 70% of the Earth's freshwater reservoir. It is very sensitive to climate change and interacts in various ways with the other components of the climate system over a wide range of time (from seasonal to a hundred thousand years) and spatial scales. The extent of snow and ice surfaces has a direct influence on the energy balance of the Earth’s surface. Fresh snow reflects between 80 and 90% of incident solar radiation. The snow cover reduction due to warming decreases the fraction of solar energy reflected back to space, and thus, increases the absorption of incoming radiation, thereby increasing warming, which in turn accelerates snow melting. This effect is known as the albedo feedback. Another important aspect of snow cover is the role it plays in thermal insulation. In winter, snow covered ground cools much less quickly than bare ground, hence the importance of snow depth for plant and animal life. Finally, melting snow and/or ice in spring and summer requires a high latent heat of fusion, so that the snow cover represents a significant heat loss for the atmosphere during the melting season. Changes in sea ice thickness also modifies the energy exchanges at the air-sea interface and act on the strength of the thermohaline circulation by changing the density of sea waters (when sea ice is formed, salt is rejected and the water density increases).

The Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019) states that *“over the last decades, global warming has led to widespread shrinking of the cryosphere, with mass loss from ice sheets and glaciers, reduction in snow cover, and Arctic sea ice extent and thickness, and increased permafrost temperatures”.*

3.4.1 Snow cover

Observations reveal that snow cover has decreased in spring and summer since the 1920s, with an even more striking decrease since the end of the 1970s. According to the special IPCC report on Ocean and Cryosphere (IPCC, 2019), the snow season duration has declined in nearly all regions, especially at lower elevations by 5 days per decade on average. Over the period 1967-2015, snow cover extent has decreased by about 7% in the Northern hemisphere in March and April (47 % in June). In Europe, the observed reductions are even almost twice larger with13 % for March and April and 76 % for June between 1980 and 2015 (EEA 2017). Over the 21st century, these trends are projected to be enhanced in the Northern Hemisphere. In Europe, decreases in snow cover are projected to range from 4 to 12% for the low emission scenario (RCP2.6) to 20 to 35 % for the high emission scenario (RCP8.5). Snow cover duration will likely follow a similar trend with reductions of about 10 days for RCP2.6 and 40 days for RCP8.5 (Brutel-Vuilmet et al. 2013). In European mountains, decrease in snow mass could range from 30 to 95 % depending on the altitude and the emission scenario (Steger et al. 2013, Scmucki et al. 2015, Soncini and Bocchiola 2011, Lopez-Moreno et al. 2009, Frei et al., 2018).

3.4.2 Glaciers

Regional analyses have shown that, until around 2000, the average mass balance[5] cumulated over all European glaciers was close to zero, with significant mass losses for Alpine glaciers being compensated for by advances of glaciers in western Norway stemming from a sharp increase in precipitation. From the year 2000 onwards, the Norwegian glaciers began to retreat in response increase in temperature. Over the period 2003-2009, the most negative mass balances occurred for glaciers located in Central Europe and low latitude areas. In the Alps, glaciers have been retreating since the mid-nineteenth century. Projections suggest during the 21st century a substantial reduction of the ice volume of European glaciers located

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[5] The mass balance of a glacier is the difference between the mass gained by snow deposition and the mass lost by melting.

below 2000 m. In central Europe, Scandinavia and Caucasus glaciers will lose from 60% to 80% of their mass at the end of the 21st century depending on climate scenario (Hock et al., 2019).

3.4.3 Sea ice

The extent and thickness of sea ice are the two indicators of sea ice conditions. Typically, the average Arctic sea-ice extent ranges from 14 to 16 × 10^6 km^2 at the end of winter (7 to 9 × 10^6 km^2 at the end of summer). Over the last two decades, surface air temperatures in the Arctic region have increased by more than twice the global average. One striking result was the record reached in 2012 with a minimum sea ice coverage of 3.4 × 10^6 km^2 (i.e. 20% below the previous record of 2007). On September 15 in 2020, the annual minimum of Arctic sea ice was 3.74 × 10^6 km^2, making it the second lowest in the 42-year-old satellite record.

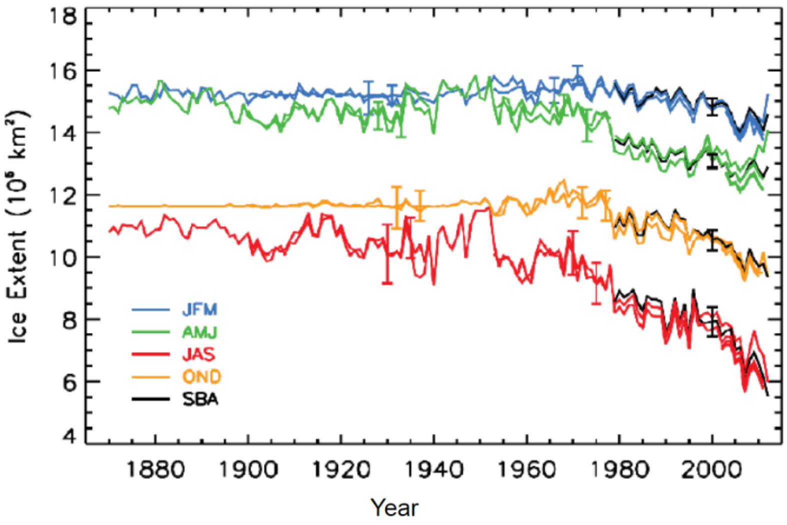

Figure 6: *Evolution of Arctic seasonal sea-ice extent from 1870 to 2011. Data from the different seasons are shown in different colors to illustrate variation between seasons (blue : January-February-March; green: April-May-June; red: July-August-September; orange: October-November-December). The black lines correspond to data coming from the Scanning Multichannel Microwave Radiometer and passive microwave data from the Special Sensor Microwave Imager (Source: IPCC, 2013).*

General circulation models clearly highlight a sea-ice decline in the course of the 21st century, the dominant factor being the rising summer temperatures (Notz and Stroeve, 2016). Projections of average reductions in Arctic sea ice extent for 2081–2100 compared to 1986–2005 range from 43% (RCP2.6) to 94% (RCP8.5) in September. For a 1.5°C global warming, sea ice in September is likely to be present at end of century with only ~1% chance of individual ice-free years (Jahn, 2018; Sigmond et al., 2018). After 10 years of 2°C warming, more frequent occurrence (10-35%) of an ice-free summer Arctic is expected (IPCC, 2019). However, there is a large spread between models in the timing at which these ice-free conditions will occur and their duration during the summer season (Notz and SIMIP community, 2020).

The evolution of sea ice around the Antarctic is more uncertain. Models project a decrease in sea ice extent ranging from 16% for RCP2.6 to 67% for RCP8.5 in austral summer for 2081–

2100 compared to 1986–2005. There is, however, low confidence in those values because of the wide inter-model spread and the inability of almost all of the available models to reproduce the mean annual cycle, the interannual variability and the overall increase of the Antarctic sea ice coverage observed during the satellite era (IPCC, 2013).

3.4.4 Polar ice sheets

The mass balance of the ice sheets[6] depend on changes in snowfall, atmospheric temperatures which act on surface melting, and ocean warming which enhances the basal melting under the ice-shelves. Eventually, this may lead to the dislocation of ice shelves and to iceberg calving. This causes an inland retreat of the grounding line (i.e. the limit beyond which ice starts to float), and subsequently, an acceleration of the upstream grounded ice[7]. Present-day ice sheets are important reservoirs of freshwater and have the potential to raise sea-level by ~ 60 m if they were to melt completely. In recent decades, the contribution of Greenland and Antarctic ice sheets to sea-level rise amounts to 18.2 mm (IMBIE team, 2018, 2019).

In the early years of the 1990s, the Greenland ice sheet gained mass in the interior because of increased snowfall. However, since the mid-1990s, in situ and remote sensing observations have clearly demonstrated that the ice sheet has been losing mass and that this process now affects all the sectors of the ice sheet. The mass loss is partitioned between surface melting due to increased temperatures (~52%) and increased ice discharge due to dynamic processes. (~48%). Between 1992-1997 and 2007-2012, the rate of mass loss has increased from -26 ± 27 Gt/yr to 275 ± 27 Gt/yr (IMBIE team, 2019). After a record mass loss in summer 2012 of more than 600 Gt (Nghiem et al. 2012), Greenland has seen a slight decrease in the short-term mass loss trend. However, in 2019, Greenland has experienced an exceptional melting season with a mass loss estimated to 560 Gt (Tedesco and Fettweis, 2020).

In the Antarctic ice sheet, surface melting is negligible and mass loss is mainly driven by dynamic ice discharges resulting from enhanced ice flow of marine-terminating glaciers. Over the period 1992-2017, the rate of mass loss has increased from 49 ± 67 Gt/yr to 219 ± 43 Gt/yr with contributions coming mainly from the West Antarctic ice sheet and, to a lesser extent, from the Antarctic Peninsula. It has long been considered that the East Antarctic ice sheet was gaining mass due to increased precipitation, despite no firm consensus being established (Velicogna and Wahr, 2006; Ramillien et al*.,* 2006). However, recent studies suggest that some sectors are also affected by mass loss. As a result, the rate of change in ice-sheet mass is estimated to be +11 ± 58 Gt/yr in 1992 (mass gain) and - 28 ± 30 Gt/yr (mass loss) in 2017 (IMBIE, 2018). Using a different technique, Rignot et al*.* (2019) estimate an even larger mass loss from EAIS with a strongly reduced uncertainty.

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[6] For ice sheets, an additional contribution of ice mass losses come from iceberg calving and from submarine melting of floating ice (also called ice-shelves).

[7] As opposed to floating ice, grounded ice is the ice resting on bedrock.

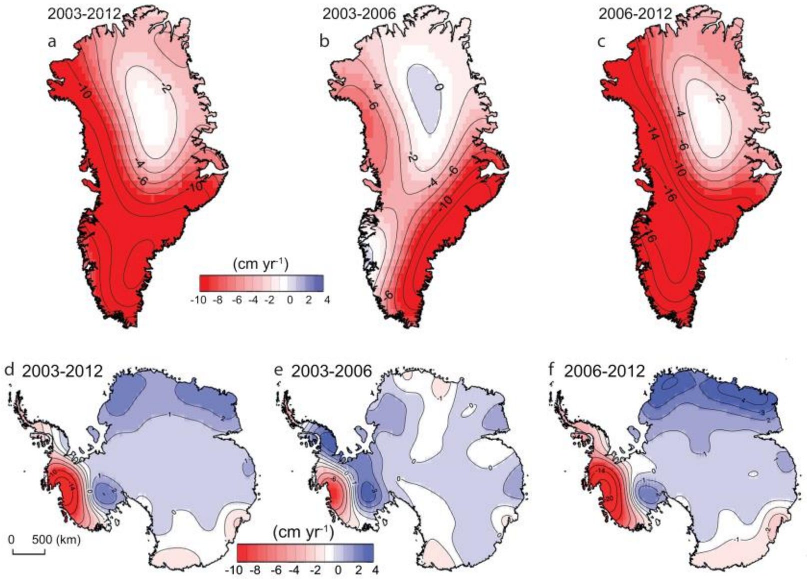

Figure7: *Temporal evolution of ice loss in Greenland (top) and Antarctica (bottom) determined from gravimetry observations from the GRACE satellite, shown in centimeters of water per year for the periods 2003–2012, 2003–2006 and 2006–2012, color coded red (loss) to blue (gain) (Source: IPCC, 2013).*

Ice sheet melting is accompanied by possible changes in albedo and therefore in the surface energy balance, which in turn can lead to changes in the mass balance of the ice sheets. Another consequence of the melting and/or mechanical destabilization of the ice sheets, concerns the freshwater flux released in the ocean. Locally, this release leads to a decrease in ocean surface temperatures, a change in sea ice cover and a reduction of ocean density in the vicinity of ice sheets. Density changes also cause a disruption of large-scale ocean circulation by altering deep-water convection. For example, meltwater from Greenland has the potential to weaken the Atlantic Meridional Overturning Circulation. These changes can have effects in regions far from the polar zones.

3.4.5 Permafrost

Permafrost is defined as soil that remains permanently frozen for at least two consecutive years. It is topped by a so-called ‘active layer’ that thaws each summer, and whose thickness can vary from a few centimeters to hundreds of meters, depending on altitude and latitude. At present, permafrost covers about 24% of the northern hemisphere continental areas. It is found mainly in polar and circumpolar areas and in mountain regions at lower latitudes (e.g. Chile, the Alps, the Himalayas). It can also be found in the seabed of the Arctic Ocean in the continental shelf areas.

In the Arctic region, measurements of ground temperatures indicate that permafrost temperatures have increased from mid-1970s to 2010 from 0.15 ± 0.03 to 0.82 ± 0.07 °C per decade. Over the last decade, data from various boreholes extending from Svalbard to the alps indicate a regional warming of permafrost of 0.5-1.0°C. Continuous monitoring over 5–7 years shows warming down to 60 m depth and current warming rates at the permafrost surface of 0.04–0.07 °C/year, with greatest warming in Svalbard and northern Sweden (EEA, 2017). One of the main consequences of permafrost warming is the increase in thickness of the active layer, although some permafrost areas exhibit only modest thickening or even a thinning. Indeed, a study based on the analysis of 169 circumpolar and mid-latitude sites revealed that only 43.2 % of them have experienced an increase of the active layer thickness since the 1990s (Luo *et al.,* 2016). In some European sites, increasing depth of the active layer has also been observed but there is great spatio-temporal variability from one site to the other ranging from a few tenths of cm/yr to more than 10 cm/yr.

Permafrost areas are very sensitive to the rate of warming and will very likely continue to thaw across Europe in the coming decades. Projections indicate substantial near-surface permafrost degradation and thaw depth deepening over much of the permafrost area. Projections based on the ensemble of CMIP5 climate models yield a reduction of near-surface permafrost area in the northern hemisphere between 37 ± 11% for RCP2.6 and 81±12% for RCP8.5 over the 21st century.

Thickening of the active layer is a matter of great concern since it may have large consequences on the stability of the surface due to the melting of shallow ice. Potential impacts include thaw settlement, soil creeps, slope failures and ponding of surface water. All these features can cause severe damages to infrastructures, such as roads, dams or structural building foundations but also to vegetation. In forested areas, thaw modifies the hydrological conditions and can lead, for example, to the destruction of tree roots, causing drastic changes in the ecosystems. Another consequence of permafrost degradation is the release of CO2 and CH4 gases to the atmosphere due to decomposition of organic matter by bacteria. The magnitude of the thaw related feedback is unknown but one study suggests that 232-380 billion tons of CO_2 equivalent could be emitting by 2100 (Schurr and Abbott, 2011), acting thereby as a strong positive feedback on global warming. The total amount of carbon stored in the permafrost has been estimated at 1 672 Gt, which is about twice the amount of carbon in the atmosphere.

3.5 Impact on the ocean

3.5.1 Oceanic heat content

In response to carbon emissions from human activities, ocean heat content has increased, at least since the 1950s. Oceanic warming represents approximately 93% of the Earth's warming and it has been estimated that ocean heat uptake has doubled since the 1970s with the two-thirds of the observed increase occurring in the upper layer (0 – 700 m). Over the 1971-2010 period, the ocean warmed at a rate of 0.11 ± 0.02°C per decade by 75 m, decreasing to 0.015°C per decade by 700 m. There are also evidences for warming in deeper layers (700 – 2000 m), but warming trends below 3000 m are not statistically significant. In Europe, remote sensing observations (since 1979) indicate that sea surface temperatures (SST) in North Atlantic and in the Baltic sea have respectively increased by 0.21°C and 0.40°C per decade. Increased SST influence the global oceanic circulation by modifying the density of water masses and therefore by altering the efficiency of the deep convection in high latitudes and the mixing between surface and deep-water masses. Moreover, higher SSTs can lead to a greater amount of water vapour in the atmosphere which has a direct influence on the weather patterns. As an example, the European climate in western Europe is strongly dependent on mass and energy exchanges between the atmosphere and the North Atlantic Ocean.

The ocean is likely to continue to warm throughout the 21st century. Projected ocean warming varies considerably across forcing scenarios. Globally averaged projected surface warming ranges from about 1 °C for RCP2.6 to more than 3 °C for RCP8.5 during the 21st century, and at a depth of 1 000 m ranges from 0.5 °C for RCP2.6 to 1.5 °C for RCP8.5.

3.5.2 Change in chemical properties

As GHG emissions increase, the dissolution of carbon in the ocean is more and more important leading to an acidification of ~30% which has affected ~95% of the near surface ocean. Since the 1980s, the pH value declines at a rate of 0.02-0.03 units per decade.

Moreover, warmer oceans cause deoxygenation, because oxygen is less soluble in warmer water, and because of stratification (i.e. less mixing between surface and deep waters) which inhibits the production of oxygen from photosynthesis. The likely range of oxygen loss is estimated at 0.5-3.3% between 1970 and 2010 from the surface to 1000 m (IPCC, 2019).

3.5.3 Changes in the oceanic circulation

The Atlantic Meridional overturning circulation (AMOC) is an important component of the Earth’s system as it is partly responsible (along with the atmosphere) of the heat transport from the tropics to the high latitude areas through a northward flow of warm and salty waters in the upper layer of the North Atlantic Ocean. Along its northward path, water cools down and becomes denser due to evaporation. In high latitude areas, cold and dense water sink down to the deep Atlantic Ocean and a southward flow takes place feeding the bottom layers of the different oceanic basins before coming back to the surface. The Gulf stream, which originates in the Gulf of Mexico is a branch of the AMOC. It follows the Florida coasts, crosses the Atlantic and reaches the western European coasts. As a result, it has a great influence on the North Atlantic weather patterns and on the western European climate. Global warming combined freshwater inputs from ice melting have the potential to reduce water density and thus, the strength of the AMOC, resulting in a cooling of western European areas.

However, despite considerable improvements in observations of the large-scale oceanic circulation, and thus of the AMOC since 2004, a long-term decline of the AMOC has not yet been detected because the record is not yet long enough (IPCC, 2019). However, reductions of 16 and 30% have been reported at 26°N for the 2008-2017 and 2009-2010 periods respectively (Smeed et al., 2018) and indirect measurements indicate that the AMOC has started to decline since the mid-20th century (Caesar et al., 2018) and is now at its weakest level (Caesar et al., 2021). There is also large spread in the 21st century projections of the AMOC among the CMIP5 models, but taking the model ensemble results in a decline of 11 ± 14% and 32 ± 14% for the RCP2.6 and RCP8.5 scenarios (IPCC, 2019). However, these results do not take into account the freshwater input from Greenland melting which is expected to amplify the decline of the AMOC (Rahmstorf et al., 2015). Accounting for this additional source of fresh water Bakker et al. (2016) estimate that the decline could be amplified by 5-10% by 2100 under the RCP8.5 scenario and could lead to a complete collapse by 2200-2300.

3.5.4 Sea-level rise

Changes in global mean sea-level results from changes in the volume of the oceans and oceanic basins as well as changes in the mass of water contained in the oceans. On time scales ranging from a few years to a few decades, variations in the mean sea level result from the increase of the ocean volume due to thermal expansion and from variations in the mass of water due to exchanges with continental reservoirs, such as rivers, lakes and inland seas, snowpack, ground water, but also mountain glaciers and polar ice sheets. While sea-level rise was primary due to the thermal expansion throughout the 20th century, the contribution from ice-sheet and glaciers has now become the dominant contribution. Altimetry observations provide estimates of the rate of sea level rise of 3.1 ± 0.3 mm/yr between 1993 and 2017 (WCRP Global Sea Level Budget Group, 2018) for a total sea level rise of 0.19 ± 0.02 m (IPCC, 2013).

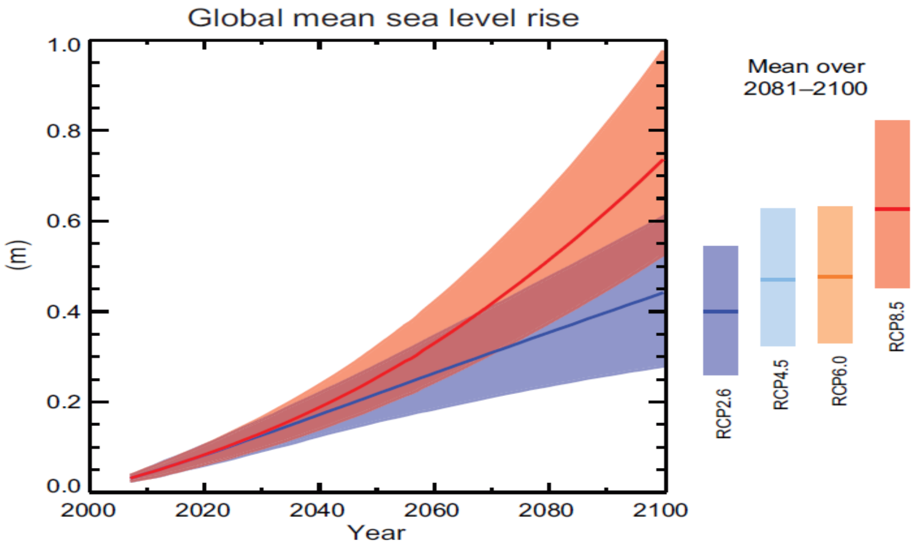

Figure 8: *Projections of sea level rise over the 21st century for the RCP2.6 and RCP8.5 scenarios (relative to 1986-2005) obtained from an ensemble of CMIP5 models. The assessed likely range (i.e. probability > 66%) is indicated by the shaded band. The vertical coloured bars indicate the assessed likely range of the mean for all the RCP scenarios for the period 2081-2100 and the median value is given as a horizontal bar (Source : IPCC, 2013).*

Global mean sea level rise (Fig. 8) is projected to increase in the future between 0.29-0.59 m for the RCP2.6 scenario and between 0.61-1.10 m for the RCP8.5 scenario (IPCC, 2013). However, the ice-sheet contribution still represents a major source of uncertainty because process-based models still lack realistic representations of physical mechanisms controlling

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the future ice shelf loss which could increase in Antarctica. As a result, higher sea-level rise estimates cannot be ruled out and a few studies and expert assessments indicate that the rise in sea level could be as high as 1.5-2.5 m by 2100 and 2.5-5.4 m by 2300 (Jevrejeva et al., 2014, IPCC, 2019).

The rise in sea-level varies regionally as a result of variations in ocean circulation, winds and atmospheric pressure, vertical land movements, and human interventions (e.g. dams, irrigation, urbanization, deforestation and water extraction from aquifers).

The global mean sea level has increased along most of the European coastlines and it will likely continue throughout the 21st century with regional deviations from the global average with exceptions in Scandinavia due to the post-glacial rebound following the disappearance of the Fennoscandian ice sheet during the last deglaciation and the subsequent land rise. Future sea-level rise will favour coastal flooding and coastal erosion. Unless appropriate adaptation measures are taken, this will have with major consequences on ecosystems, water resources, infrastructures and settlements, and human lives.

4 Impacts on the environment and ecosystems

4.1 Marine ecosystems

Changes in both the physical and chemical properties of the ocean alter the marine productivity and thus have substantial impacts on the health of marine ecosystems and the provision of seafood to society, such as through fisheries.

First, ocean acidification exerts a strong threat for coral reefs, by reducing the concentration of carbonate ions and therefore the material that corals need to build their skeleton. As coral reefs host numerous organisms, this negatively impacts the entire ecosystem.

Second, deoxygenation affects the metabolism of species by limiting the biological activity. In recent decades, oxygen-depleted areas have rapidly expanded leading to the so-called dead zones from which the organisms leave or in which they die. An outstanding example is the Baltic Sea in which the expansion of dead zones has experienced a 10-fold increase since 1900, but oxygen-depleted areas have also been observed in other European seas in recent decades.

Third, the increased stratification limits the transfer of nutrients to the surface lit-layer and thus limits the growth of phytoplankton. Ocean warming also contributes to modify the geographical range of habitat of marine organisms from phytoplankton to marine mammals. A northward expansion of warm water species and a northward retreat of cold-water species have been observed. As outlined in the IPCC Special Report on Ocean and Cryosphere (IPCC, 2019), this may change the community composition, alter the interactions between organisms and modifies the structure of the ecosystem.

Finally, agricultural fertilizers such N2O exert a strong negative influence on marine environment. Indeed, excessive nutrients favour the deoxygenation and lead to harmful algal blooms in estuaries and other coastal areas.

4.2 Coastal zones

European coastlines are expanded along more than 100,000 km with about 200 million people living in coastal areas, and host important economic activities, such as tourism, and various ecosystems. Therefore, a growing attention is being paid to the evolution of the littoral owing to the risks posed by climate change. Among the most important risks are coastal floods, saltwater intrusions, coastal erosion and submergence of low-lying areas. Under global warming, low-lying European areas (e.g. Belgium, Netherlands, Denmark, southern and western France…) could be permanently inundated in response to sea-level rise.

4.2.1 Coastal flooding

Coastal flooding result from a variety of causes including storm surges produced by wind storms and sea-level rise. When surges coincide with high tidal levels, extensive flooding may occur, threatening ecosystems, infrastructures and human lives. As an example, the coastal flooding which occurred in 1953 in the North Sea destroyed 40 000 buildings an caused 2000 deaths in Netherlands, Belgium and United Kingdom. This kind of flooding event occurs every hundred years on average, but could happen annually by the end of the 21st century, unless appropriate protection measures are taken. A recent study (Vousdakas et al. 2017) estimate that the North Sea is projected to face with the strongest increase in extreme sea level events (up to 1 m under the RCP8.5 scenario) followed by the Baltic Sea and the Atlantic coast, and 5 million of Europeans could be affected by coastal flooding. Moreover, flood damages could increase by 2 to 3 orders of magnitude in the absence of adaptation (IPCC, 2019).

4.2.2 Saltwater intrusions

Saltwater intrusions into aquifers come from sea level rise and overexploitation of groundwater resources. These intrusions have the potential to threaten water supply, agriculture and ecosystems in coastal regions.

4.2.3 Coastal areas

Coastal erosion is due to the imbalance between supply and export of sedimentary material to the coast. This results in the retreat of the coastline and threaten the sandy dunes which are a significant protection for the littoral and for the hosted flora and fauna species. It may also have huge economic impacts because of loss of land areas, and hence, because of the loss of properties and infrastructures. Coastal erosion is produced by strong winds, storm surges and high tidal levels and is amplified by sea level rise. It is also exacerbated human activities because the natural flow of sediments in river basins is obstructed by various infrastructures. Hence, highly urbanized coastal zones are more exposed to possible damages. Currently, almost one fifth of the European coastline are affected by costal erosion with retreats of 0.5 to 2 m/yr on average. Adaptation solution consisting of building natural or artificial barriers are therefore urgently needed. In the absence of appropriate adaptation measures, recent studies estimate that the coastline retreat could reach 65 m in southern Europe and 100 m in northern Europe (Athanasiou et al., 2019) for a 4°C warming but could be reduced by 50% if the warming was limited to 3°C (Vousdoukas et al., 2020).

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4.3 Freshwater systems

In addition to changes in rainfall patterns, changes in the hydrological cycle induced by climate change also affect river flows, and may also increase the severity and frequency of droughts or river flooding.

4.3.1 River flows

River flows are not only influenced by rainfall and runoff, but also by other human inferences such as land use or morphological changes or river regulation. In addition, there is a substantial interannual and decadal variability. It is therefore difficult to detect long-term trends. However, according to recent studies (Blöschl et al. 2019), observations suggest that river flows have i/ increased in northwestern Europe due to increased rainfall in autumn and winter, ii/ decreased in southern Europe due to decreased precipitation and increase evaporation, iii/ decreased in eastern European regions as a result of a decline in snow cover and an increased snow melting. These regional differences reflect the seasonal trend of precipitation patterns. The seasonality is projected to change across Europe. Summer flows are projected to decrease in most of Europe, while winter and spring flows are expected to increase due to the risk of heavy rainfall (Beniston et al. 2018). In snow-dominated regions, such as the Alps, Scandinavia and the Baltic countries, the peak flow will occur earlier in the year due to less snow mass and earlier snowmelt. In mountainous regions, this trend will be likely amplified in the course of the 21st century due to the glacier retreat.

4.3.2 River flood

River flood are caused by prolonged or heavy precipitation events, and they are the most important natural hazard in Europe in terms of economic losses. Direct economic impacts are related to damages to infrastructures (buildings, transports, roads) and agricultural areas. There are also indirect damages such as production losses due to damaging transports or energy infrastructures. Flooding has also negative effects on the environment and human health. Almost, 1500 floods have been reported in Europe since 1980 and more than half have occurred since 2000, but their occurrence result from several factors (land-use changes, expansion of urban areas, heavy precipitation) and it is therefore difficult to quantify the importance of each factor. As global warming is intensifying the hydrological cycle, more frequent heavy precipitation events are expected even in regions where the mean precipitation decreases) and more frequent flooding events could occur.

4.3.3 Droughts

Droughts are associated with rainfall deficits (meteorological droughts) or low-level water in lakes and natural reservoirs (hydrological droughts). The latter can be caused by prolonged rainfall deficit and by soil moisture deficit due to above- average evapotranspiration in response to high temperatures and hot extremes. They may have detrimental consequences on pant growth and crop yields, animal and vegetal ecosystems, water resource management (irrigation, power plant cooling) and on the availability of fresh water used for drinking.

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Since the second half of the 20th century, dry areas have expanded in Europe, and the frequency and severity of droughts have increased in the Mediterranean countries, Portugal and parts of central Europe. On the other hand, drought episodes have become less frequent in northern and parts of eastern Europe, but have become more severe in Scandinavia and southeastern Europe. In recent years (2006-2010), around 15% of the EU territory and 17% of the EU population have been affected by droughts occurring each year, mainly in Southern (Mediterranean basin and Portugal) and Central Europe, and more recent episodes (2003, 2010, 2015, 2018 and 2019) have mainly affected Central Europe, despite westward expansion in 2015 and 2019. At the global scale, simultaneous drying in Australia, Mexico and the Mediterranean region suggest that increasing frequency and severity of droughts can be attributed to climate change. However, at the regional scale, there is no clear evidence because the signal is masked by the natural interannual and decadal variability. Nevertheless, model simulations carried out within the framework of the EURO-CORDEX consortium projects that the frequency and duration of extreme meteorological droughts will significantly increase at the end of the 21st century with respect to the 1971-2000 reference period (Forzieri et al. 2014) in the Mediterranean region. In northern Europe, projections indicate that droughts will become less severe.

4.4 Terrestrial ecosystems

Climate change has also many impacts on terrestrial ecosystems. Firstly, it greatly affects biodiversity by modifying the phenology of plants (with longer growing seasons and earlier pollen seasons) and the life cycle of animals (e.g. earlier arrival of migrant birds, earlier onset of reproduction and longer breeding season of many thermophilic insects). These trends, primarily due to increased temperatures, are projected to persist in the future. Secondly, global warming modifies the geographical range of flora and fauna species. This may induce changes in the species composition and can cause in turn a change in their mutual interactions (e.g. Montoya and Raffaelli 2010). Migration of some species towards higher latitudes and/or higher elevations are observed (Chen et al., 2011), but local and regional extinctions also occur for other species. The species which are expected to be the most affected are small populations, those with restricted climatic envelopes (i.e. range of favourable climatic conditions), such as those living in high latitudes or high elevations (Engler et al. 2011) or those whose ability to migrate is limited by human-made barriers, such as land use change and deforestation or expanded urbanization (Pereira et al. 2012). As a result of habitat fragmentation acting against mobility, migration often lags the change in climate. This could lead to a progressive decline of biodiversity. In Europe, the northward and upward shift of many plants and animals is projected to continue throughout the 21st century. For example, a modelling study suggests that 20 to 60 % of Alpine plant species, depending on their living elevation and the climate scenario, could lose up to 80% of their suitable habitat (Engler et al. 2011), unless they take refuge in micro-climatic areas (Scherrer and Körner 2011).

Biodiversity and ecosystems provide important functions to human populations by sequestering carbon (see section 2), modulating the impacts of extreme events, maintaining soil moisture and air quality, acting as buffer for diseases, providing natural barriers against

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storm surges and flooding, and providing cultural services for recreation, mental and physical health. As an example, forests provide numerous ecosystems services by protecting soils from erosion, by regulating locally the climate through the evapotranspiration or globally by storing carbon. They are also important for biodiversity by providing habitats for numerous species, and for human societies by providing wood products or timber used for heating. They are also a source of food products and offer some services for tourism. However, forests are currently being threatened by several factors exacerbated by climate change, such as droughts, storms, atmospheric pollution, diseases and parasites. However, there are still many gaps in the knowledge of the impacts of human activities on forests. Recent studies suggest an upward shift of the tree line as well as a northward shift of boreal forests. Broadleaf trees are expected to expand throughout the 21st century, while the needleleaf cover is expected to decrease despite a northward expansion in northern Europe (EEA 2017). In southern Europe, forested areas are projected to decline.

Europe faces to increased risks of forest fires. These are due to many factors such as temperatures, land use, droughts, vegetation composition, wind speed and human behaviour. The Mediterranean region remains the most affected area because of noticeable warming, increased wind speed and more intense and frequent droughts (Turco et al. 2018), while fires in boreal forests are rather due to summer droughts (Drobyshev et al. 2015, 2016). The number of forest fires in the Mediterranean region increased from 1980 to 2000 but decreased thereafter. However, since the year 2017, unprecedented wildfires have occurred in many regions of the world, especially in Australia, South America, California and Europe. In Europe, these fires often coincided with record droughts and heatwaves. Such events are expected to become a key risk in the next decades, especially in southern Europe. However, a growing attention is now given to adaptation measures to reduce fire risk and fire damages. These include prescribed burnings, use of agricultural fields as fire breaks, behavioural changes, enhanced fire suppression and prevention activities (Khabarov et al. 2014). These measures have proven to be successful and despite a large number of fires in the Iberian Peninsula, the 2019 season was one of the best ever in terms of preventing accidents and loss of life, and there were also less devastating fires in Europe than those occurring in 2017 and 2018.

5 Impacts on human societies

Global warming and related changes in natural systems and have a strong influence on human societies, including water resources and food supplies, economic issues, health and well-being, energy production, migration of people and potentially geopolitical conflicts (Gemenne et al. 2014). There is a broad range of studies investigating the different aspects of these impacts and the potential adaptation strategies, synthesized in reports such as those provided by the IPCC (IPCC, 2014) or the European Environment Agency (EEA, 2017). The objective of this report is not to present an exhaustive review of all potential impacts but rather to give an overview of key changes that are affecting or are likely to affect European populations in the course of the 21st century.

5.1 Human health

Climate change also causes impacts on human health through warming temperatures, changes in precipitation, extreme events, degradation of the air quality and rising sea-levels. These impacts may directly affect the health of human beings (e.g. heat-related mortality or deaths and injuries from flooding or storms). There are also indirect effects from climate change, such as those acting on vector-borne diseases, food security and water quality. The severity of these risks is expected to increase in the future and will vary depending on where people live and to what extent they are exposed to climate risk, their economic status and how they are sensitive to health risks. It will also depend on the ability of public health and safety systems to address these new threats.

5.1.1 Extreme events

Extreme hot temperatures are associated with increases in mortality and morbidity. Exposure to extreme heat can lead to heat stroke and dehydration, as well as cardiovascular, respiratory, and cerebrovascular disease. In recent decades, the number of heat waves has increased across Europe and caused tens of thousands of premature deaths. An outstanding example is the heat wave in summer 2003 which caused at least 70 000 premature deaths (Robine et al. 2008). The most vulnerable populations include outdoor workers, homeless and low-income people, elderly persons, young children and people suffering from chronic diseases. In addition, people living in northern latitudes are more exposed because they are less prepared. Moreover, heat-related effects are exacerbated in urban areas because of the urban heat island effect and adverse heat impacts are often more frequent in cities than in the rural surroundings.

Heat waves are often accompanied by a degradation of the air quality because they favour wildfires, the stagnation of fine particulate matter and other air pollutants, and the formation of ground-level ozone. Particulate matter from wildfire smoke can often be carried over very long distances by winds, affecting people who live far from the source of this air pollutant (Ghorani-Azam et al. 2016). Worsened air quality is at the origin of respiratory, pulmonary and cardiovascular diseases. Warmer temperatures also favour the presence of allergens and asthma triggers due to the longer growing season for some plants having highly allergenic pollen. As the number and frequency of heat extremes is likely to increase in the future an excess of mortality is expected unless proper adaptation measures are taken.

Extreme low temperatures during cold spells also affect human health but cold-related mortality is projected to decrease owing to better social, economic and housing conditions in many European countries. However, whether or not global warming will lead to a further decrease in cold-related mortality remains an open question.

Increases in the frequency or severity of other extreme weather events, such as extreme precipitation, flooding, and storms, threaten the health of people during and after the event, through drowning, injuries, reducing the availability of safe food and drinking water, exposure to chemical risks, and creating or worsening mental health impacts such as depression and post-traumatic stress disorder. In addition, emergency evacuations can be difficult owing to damaging roads and bridges and disrupting access to hospitals. In most European regions an increasing trend of heavy precipitation has been observed in recent decades increasing the risk of river and coastal flooding. According to the World Health Organization, flooding has killed more than 1 000 people and affected 3.4 million over the period 2000-2011. Without adaptation, the number of people potentially affected by flooding every year by 2085 could increase from 775 000 to 5.5 million depending on the emission scenario, the western Europe being the most affected.

5.1.2 Vector borne diseases

Changes in temperature and precipitation increases the geographic range of vector-borne diseases and can lead to illnesses occurring earlier in the year or can bring non-endemic illnesses in the European areas. However, there are other factors favouring vector-borne diseases such as land use, travelling and human behaviour, vector control and public health capacities.

Lyme Borreliosis, transmitted by ticks, is the most common vector-borne disease in Europe, with more than 65 000 cases reported annually, despite no standard diagnosis of the Lyme disease in Europe. Ticks can also transmit tick-borne encephalitis and the mean annual cases reported in Europe has increased by ~400% over the past 30 years, although this can be due to a more robust detection. Global warming has increased the risk of tick-borne diseases in Europe by allowing ticks to survive at higher altitudes. The Asian tiger mosquito transmitting viral diseases (dengue, chikungunya, Zika) has been first recorded in Europe (Italy) in the 1990s. Since then, it has expanded its geographical range in several European countries and several cases of chikungunya have been reported in France and Italy (Rezza et al. 2007, Venturi et al 2017), and dengue in France and Croatia. Although malaria has been eradicated in Europe since the 1950s, several sporadic cases of local transmissions occur each year. In the United Kingdom it is estimated that, with temperature increases, the risk of local malaria transmission could increase by 8–15% by 2050. In Portugal, the number of days suitable for survival or malaria vectors is projected to increase. Malaria is unlikely to re-establish itself in Europe thanks to health systems in place and adequately functioning, but it might be introduced sporadically due to global travel and trade.

5.1.3 Food security and water quality

Warmer temperatures also favour the growth of bacteria in food, such as salmonella, or the exposure to chemical contaminants stemming from human activities. In the oceans, seafood is also impacted by toxins produced by harmful algae. For example, higher sea surface temperatures will lead to higher mercury concentrations in seafood. Increases in extreme weather event, such as heavy precipitation, will introduce contaminants into the food chain through water runoff. Moreover, crop yield (see Section 5.2) are also projected to decrease in southern Europe. While higher atmospheric CO_2 concentrations can act as a "fertilizer" for some plants, they also lower the amount of proteins and essential minerals in crops such as wheat, rice, and potatoes, making these foods less nutritious.

5.2 Agriculture and livestock

The agricultural sector is directly dependent on several climatic factors such as temperature, water availability and the occurrence of extreme climatic events. Crop yields and livestock production are therefore strongly influenced by climate change. On the other hand, increased CO_2 emissions favour fertilization and acts therefore as a positive impact. It is generally accepted that the productivity of crops will be positively impacted in northern Europe due to increased temperatures leading to a lengthened growing season (more than 10 days since 1992) and to a shortening of the frost-free period. Conversely, southern and central Europe are negatively impacted as a result of warmer temperatures, the occurrence of more frequent hot extremes and a decrease in precipitation. Since 1995, the water deficit has increased in large parts of southern and eastern Europe. This impact is expected to be most acute in the future, which may lead to an expansion of the irrigation systems. However, this expansion may be constrained by projected reductions in water availability and increased demand from other sectors and for other uses.

The extent to which climate change affects crop yields depends on the crop and type, the ability of the soil to store moisture and the climatic conditions in the region. For example, in north-east Spain, grape yield has been declining due to water deficits since the 1960s. Yields of several rainfed crops (e.g. wheat in France) are levelling off or decreasing (e.g. potato, wheat, maize and barley in Italy and southern-central Europe) because of increased temperatures. On the contrary longer growing seasons have increased the yield of wheat, maize and sugar beet in parts of northern-central Europe and of the United Kingdom. As a result, climate change will induce a reallocation of agricultural practices between European countries.

Future crop yield projections are subject to great uncertainty due to uncertainties in socio-economic scenarios, in climate projections and in the magnitude of the CO_2 fertilization effect. However, there are clear indications of a deteriorating agroclimatic conditions. Moreover, there is a risk of enhanced interannual variability in crop productivity and livestock production which constitutes a challenge for proper crop management and for adaptation strategies, but also for food security.

5.3 Fisheries

The effects of climate change on marine ecosystems lead to a modification of the entire seafood chain, by changing the primary production which affects the growth and survival of animals, by leading to the migration of certain species to higher latitudes, and by modifying the interactions between the different organisms. These effects have important socio-economic consequences, particularly in countries where fishing is the main activity. In many regions, the composition of fishing catches has been radically transformed and fish stocks have been reduced. For example, tropical areas experience the strongest decline, and by 2050, this decline is projected to be of ~40%. On the other hand, in regions at higher latitudes, such as the North Atlantic and North Pacific, there is an increase in the range of some fish species.

These changes pose challenges. In order to continue sustainable, fishing methods must be adopted, but the changes in spatial distribution and abundance of fish stocks have already challenged the management of some important fisheries and their economic benefits. The fishing industry and governments have found it difficult to agree on how to manage changing fish stocks, especially if fish cross international borders or if catches have to be significantly reduced.

5.4 Energy

The energy sector is responsible directly or indirectly for the majority of anthropogenic greenhouse gas emissions. Both energy supply and energy demand are highly sensitive to changes in climate conditions. Temperature is one of the major drivers of energy demand in Europe, affecting summer cooling and winter heating for residential properties and business/industry. Heating and cooling are responsible for a large fraction of the European energy use and for the electricity demand. Over the recent decades, heating has decreased, mainly in north-western Europe, and cooling has increased, particularly in southern and central countries.

The increased frequency of extreme weather events, including heat waves, droughts and storms, poses additional challenges for energy systems. Increases in temperatures and the occurrence of droughts may limit the availability of cooling water for thermal power generation in summer. However, the impacts of climate change on energy production depend on the energy mix and the geographical location. In particular, impacts on renewable energy generation is subject to strong regional variations. Hydropower production may experience significant risks due to the retreat of glaciers and the subsequent decrease of water availability. On the contrary, conditions in Scandinavia are expected to improve because of more abundant precipitation. The efficiency of fossil-powered generators and nuclear plants is sensitive to a reduced availability of cooling water due to increased temperatures and potential droughts. In this regard, France is the country facing the highest risks due to the great number of nuclear plants deployed on the territory. On the other hand, limited impacts on solar energy are expected. There is no general agreement concerning the impacts on wind power generation. Some studies project a limited effect of climate change (Tobin et al., 2015, 2016) despite a decrease of wind potential over Mediterranean areas and an increase over northern Europe, while others report a decline of the capacity of 6.9% and 9.7% under the RCP8.5 scenario by 2050 and 2070 respectively, with the highest decline in eastern and western Sweden, and in Andalusia. Finally, energy infrastructures installed in coastal zones are also exposed to the risk of sea-level rise.

5.5 Human migrations

Environmental changes have always been a key driver for population movements, even since the first hominids several million years ago. Today, climatic variations linked to human activities can occur on very short time scales (a few years to a few decades). The risk of climatic migrations is particularly exacerbated for populations already weakened by environmental conditions that are less favourable to the development of agriculture than in temperate latitudes, and by the fact that land use strategies do not always take into account all environmental risks. For example, in Africa and other parts of the world, there is a high population density around coastal areas and the risk of rising sea level is ignored. The current population movements related to the changing environmental conditions can be rapid in response to the occurrence of extreme events, or more gradual, such as those related to sea level rise. They can also be temporary or permanent. There is currently no consensus on the number of people displaced by climate change. This is because many factors leading to displacement are often intertwined, such as economic, political, social and demographic factors (Marotzke et al. 2020). Most displacement occurs preferentially within the country of origin, usually from rural to urban areas, but it can be expected that more and more people from North Africa or Sub-Saharan Africa will arrive in Europe, especially as decreasing rainfall and increasing temperatures (Gemenne. 2011, Defrance et al. 2017) have a deleterious effect on agricultural production. In addition to the disruption of ecosystem services, rising temperatures could lead to heat stress by exceeding the thermoregulatory capacities of the human body (Mora et al. 2017). Finally, populations from deltaic regions, where agricultural activities are often concentrated, or those living in low-lying areas are also expected to be more and more affected because of sea level rise, which could exceed 1 m by the end of the century. Non-linear phenomena such as changes in the oceanic circulation or the melting of the polar ice sheets, with still uncertain consequences on the climate and the environment, must also be taken into account in the migration forecasts of the coming decades (Defrance et al. 2017).

Year after year, climate-related disasters are displacing more people than conflicts and violence, although the climate-related problems, such as dwindling access to water and food resources, are themselves also sources of armed conflicts.

Given the scale of the migration risk, political measures are needed to ensure the rights of displaced persons. But the implementation of these measures is made difficult by conflicting narratives in international negotiations. For example, some see migration as a way to reduce population pressure on certain natural resources and recommend that migration be facilitated and financed (Black et al. 2011). Others, on the contrary, present migration as a failure of adaptation and a humanitarian tragedy to be avoided at all costs (Anik M. and Simsek R, 2018). Following an initiative by the Swiss and Norwegian governments (Nansen initiative) launched in 2012[8], a protection agenda containing innovative solutions has been established to uphold the rights of displaced people (Gemenne and Brücker 2015), a new international

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[8] The Nansen Initiative is a was a consultative process intended to build consensus among states on on key principles and elements to protect people displaced across borders in the context of disasters caused by natural hazards, including those linked to climate change. Among other things, better disaster preparedness should prevent such forced displacements and better protect those affected This agenda has been adopted by 109 states in Geneva in October 2015.

organization (the Platform on Disaster Displacement) was set up to ensure the implementation of these solutions.

6 Conclusions

In this report, we have provided key examples of how climate change due to human activities may impact our environment and thereby human societies. There is a wide range of other possible consequences that have not been addressed here including the new challenges facing the tourism industry owing to deteriorating climatic conditions in some regions, or the economic costs that will be induced by the damages to infrastructures. Moreover, exposure to natural disasters can result in mental health consequences such as anxiety, depression and post-traumatic stress disorders. Although, there are still uncertainties associated with the magnitude of the different climate-related impacts at the local and regional scales, most of them have now become a reality. Our future will therefore depend on our willingness to reduce our greenhouse gas emissions and on the future socio-economic pathways. The implementation of appropriate adaptation and mitigation measures by policy-makers to meet the commitments made in the Paris Agreement in 2015 is therefore urgently needed.

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