Venice in a Changing Climate: Literature Review

Report

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Venice in a Changing Climate
Literature Review

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1. Introduction

Venice, with its rich cultural heritage and unique lagoon ecosystem, faces increasing risks from climate change. This literature review examines the city's most pressing environmental challenges, particularly increasing temperatures, rising sea levels, and extreme flooding events. It also assesses the effectiveness and limitations of current adaptation measures, such as the MoSE barriers and cooling solutions.

The goal of this review is to synthesize recent research on Venice's vulnerability to climate change impacts and possible local and global strategies for mitigation and adaptation. By contextualizing Venice's challenges within global climate trends, this review underscores the urgent need for coordinated action to safeguard the city's future.

2. Some Terminology

- **Climate**: Climate refers to the long-term patterns and variability of atmospheric conditions in a specific region, typically averaged over 30 years. In a broader sense, it represents the overall state of the Earth system, encompassing interactions between the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. These complex interactions shape regional and global climates over timescales ranging from months to hundreds of years, influencing ecosystems, weather patterns, and human societies.

- **Climate projection**: While weather can be predicted on timescales from days to weeks, the climate over a period of 10 years or more is influenced by anthropogenic emissions and other factors. Consequently, climate projections are conditional on assumptions about future emissions and socio-economic scenarios. Thus, it is important to note that climate cannot be predicted in the same deterministic manner as weather; rather, it is projected based on plausible scenarios.

- **Climate scenario**: A climate scenario describes a possible and realistic future state of the climate system. It is typically presented for a specific region and time frame (e.g., "by 2050") or in terms of a global warming level (e.g., "3-degree world"). These scenarios are based on projections of potential greenhouse gas emissions, which are influenced by factors such as population growth, economic development, and technological change (IPCC, 2023).

  The possible future trajectories as used by the last assessment report by the Intergovernmental Panel on Climate Change (IPCC) are based on five narratives describing alternative socio-economic developments, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development (O'Neill et al., 2016; Riahi et al., 2017). These are usually combined with greenhouse gas emission scenarios. For example:

– Sustainability and low-emission scenario (SSP 1-1.9), inclusive development path that respects perceived environmental boundaries, leading to 1.6 degrees of warming by 2050;
– Fossil-fueled Development and high-emission scenario (SSP 5-8.5), path relying on rapid technological progress and development of human capital, leading to 2.5 degrees of global warming by 2050.

The different effects of scenarios on global temperature can be seen in Fig. A.1.

For the most comprehensive scientific assessments on climate change, its implications and potential future risks, see the IPCC reports (https://www.ipcc.ch/).

3. Temperature, Humidity, and Precipitation Trends

Climate change is intensifying the frequency and severity of extreme events worldwide (Seneviratne et al., 2021; Seneviratne & Hauser, 2020). On a local scale, this leads to a complex interplay of climate risks, creating new challenges for already vulnerable places like Venice.

From a global perspective, mean temperatures are expected to rise by approximately +4.4°C (likely range +3.3°C to +5.7°C (IPCC, 2021a), (Fig. A.1) in the high emission scenario by the end of the century. Temperature extremes that occurred once every decade in the preindustrial period (1850–1900) may occur 9.4 times more often and be 5.1°C hotter in a +4°C world (Fig. A.6). Similarly, heavy one-day precipitation events could happen 2.7 times more frequently and be 30.2 % wetter (Fig. A.7). It is virtually certain that human-caused greenhouse gas emissions are the main driver of observed changes in global hot and cold extremes. They are also likely responsible for the intensification of heavy rainfall over land (Seneviratne et al., 2021).

Over the past two decades, Italy's temperature has been rising slightly faster than the global average (International Energy Agency, 2022; Spano et al., 2020). More specifically, in Northern Italy, projections for 2080–2100 relative to 1995–2014 show a rise in the annual maximum temperature by approximately +5.4°C in a high-emission scenario, as seen in Fig. 1. This includes around 35 additional days above 35°C, with maximum temperatures in August climbing from an average of 33°C to 41.3°C (Fig. 2 left).

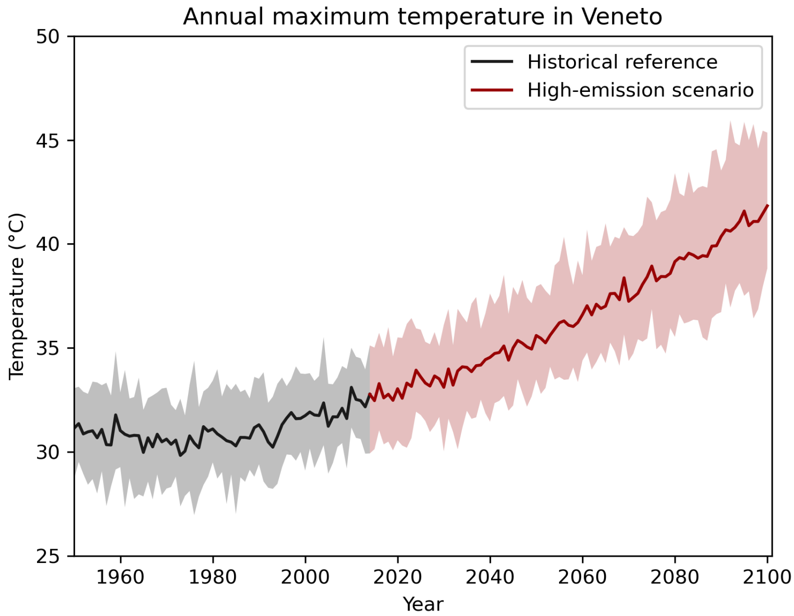

Figure 1: *Projected trend of Maximum daily maximum temperature for Veneto Region, based on analysis conducted by ETH Zurich for this report. In black the historical reference period, and in red the projected future under a high emission scenario (IPCC, 2023). Shaded areas, corresponding to the 10th to 90th percentile range, represent the uncertainty in the trend. Computed using downscaled CMIP6 data (Eyring et al., 2016; O'Neill et al., 2016), bias corrected with the ERA5 reanalysis data (Hersbach et al., 2020) in the time period 1995-2014.*

Although relative humidity is expected to decrease during the hottest months (Fig. 2 Center), the overall moisture quantity in the air is projected to increase. The combined effect of higher temperatures and water vapor content will significantly increase the heat stress. When humidity is very high, even a temperature of 32°C can lead to strong heat stress, while 35°C has the potential to trigger lethal consequences (Asseng et al., 2021) (Fig. 2 Right).

Using the Universal Thermal Climate Index (Fig. A.4), a physiologically accurate measure of human outdoor temperature sensation that combines temperature, humidity, wind speed, and radiation, one finds that people in Venice will likely experience strong and very strong heat stress in July and August approximately two weeks more than in the past [1] (Nam et al., 2024).

While low and medium precipitation events have become less frequent, the number of heavy rainfall episodes per year has increased across Italy. Precipitation trends in Northern Italy are less certain, but indicate an average decrease in mean precipitation by 4.5%, alongside an 11% increase in annual maximum daily precipitation (Baronetti et al., 2022; Gutiérrez et al., 2021).

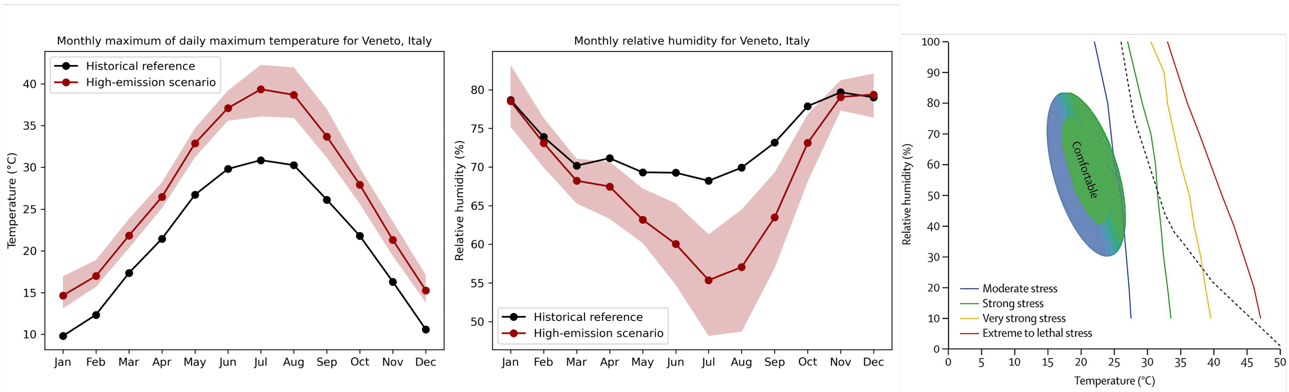

Figure 2: *Left: Monthly maximum temperature for Veneto Region for a historical reference period (1995-2014, black), and as projected under a high emission scenario (red) by the end of the century (2080-2099). Center: Average surface relative humidity projections for historical conditions (black) and projected for a high emission future scenario (red). The left and center panels are based on ETH Zurich analysis, computed using CMIP6 data (Eyring et al., 2016), bias corrected with ERA5 reanalysis (Hersbach et al., 2020). Right: Preferable temperature zones are shown with gradients from cool (blue shading) to warm (green shading) temperatures. Lines represent the average levels of heat stress in humans, based on the Universal Thermal Climate Index. The dotted black line indicates the single lethal temperature threshold: prolonged exposure to this environment becomes dangerously unsustainable for human survival (Asseng et al., 2021).*

3.1. Adapting to Rising Temperatures: The Role of Cooling

In a warming climate, cooling has become increasingly vital in protecting people from rising temperatures, preserving the quality and safety of food and pharmaceuticals, and supporting economic productivity. In fact, labor supply (the number of working hours) and labor productivity (output during those hours) are extremely vulnerable to heat stress (Dasgupta & Robinson, 2023). Given these challenges, sustainable and efficient cooling practices are essential for achieving the sustainable development goals (Mazzone & Khosla, 2021; Mazzone et al., 2023).

The flip side is that cooling growth, under business as usual, would lead to a doubling of the its greenhouse gas emissions by 2050 (UN Environment Programme, 2023). Unless rapid actions are taken to transition to sustainable cooling and to lower cooling demand, cooling will play a growing role in accelerating climate change (Khosla et al., 2022).

While decentralized cooling units decrease indoor temperatures, they can increase night temperature in urban contexts by up to 1.5° Celsius and aggravate the heat island effect (International Energy Agency, 2018; Lee & Oh, 2018; Salamanca et al., 2014; Stewart & Oke, 2012). There is substantial amplification of future energy demand growth due to climate change (van Ruijven et al., 2019), not least due to cooling needs. While cooling does emit CO_2, the main issue is that it adds strain to the energy infrastructure. While peak cooling demand

[1] It is worth noting the Universal Thermal Climate Index provides an objective estimate of heat stress based on physiological parameters, but specific differences might still emerge depending on demographics, social, cultural and health characteristics of individuals.

often coincides with peak solar energy production, emissions remain significant when power is generated from fossil fuels. In this case, decentralized cooling units lead to a global emission of 1.5 billion metric tons of CO2 equivalent, about 3% of global emissions (International Energy Agency, 2018). Still, in most countries, CO2 emissions from air conditioning already account for approximately 25% of emissions from residential electricity. In Italy, they amount to 11% today and are expected to increase to 15% by 2050 (The Cooling Solution, 2023). Today, there are around 2 billion air conditioning units in the world. The International Energy Agency (IEA) projects that this could almost triple to over 5.5 billion by 2050. Around 39% of Italian households currently use air conditioning, and this share could rise by 28% by 2050 as increasing average temperatures across the Mediterranean is expected to drive up demand.

Deploying passive cooling measures, such as insulation, natural shading and ventilation, would dramatically reduce cooling loads. Higher efficiency standards could triple the global average efficiency of cooling equipment by 2050. A faster phase down of climate-warming hydrofluorocarbon (HFC) refrigerants would also make a huge difference (UN Environment Programme, 2023).

4. Sea Level Rise in Venice

The Venice lagoon exemplifies the vulnerability of coastal zones to rising sea levels, standing out as one of the most affected regions globally. The mean sea level in Venice closely mirrors the trend of the Subpolar North Atlantic (Fig. A.2), with an increase projected to reach approximately 10cm by the end of the century (Anzidei et al., 2024; Lionello, Barriopedro, et al., 2021; Lionello, Nicholls, et al., 2021). However, the city is also burdened by considerable vertical downward land movement (Carbognin et al., 2010; Vecchio et al., 2024). This subsidence exacerbates the relative sea level rise — meaning measured relative to a fixed land point — making it considerably higher than the mean sea level rise alone (Fig. 3 Left).

In Venice, the reference point is the Zero Mareografico di Punta della Salute (ZMPS), a conventional level established in 1897. In San Marco's Square, one of the lowest parts of the city, the water reaches walking level when the sea level is 82 cm above the ZMPS, which is a quite common occurrence[2].

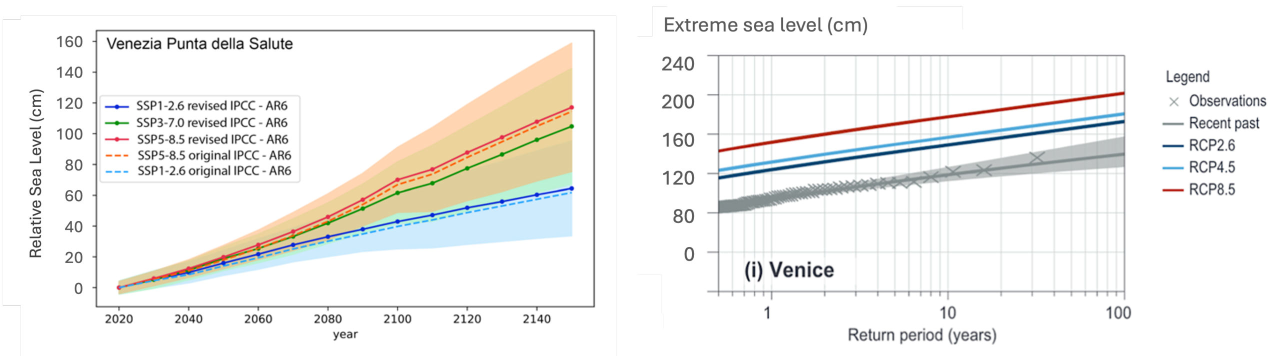

Figure 3: *Left: Relative Sea Level Rise projections for Venice with respect to 2020, based on revised IPCC data (Bednar-Friedl et al., 2022) to account for tectonic effects in the Mediterranean Sea (Anzidei et al., 2024). In blue the low emission scenario, in green intermediate scenario, and in red the high emission scenario. Right: Extreme Sea Level events in Venice, including observations from the past (grey) and future projections (blue lower emission scenario, red higher emission scenario). The return period characterizes the average time between two extreme events with a certain intensity (IPCC, 2019).*

However, as the average Relative Sea Level increases, rare and destructive events, referred to as Extreme Sea Level (ESL) events that substantially flood the city, will become more frequent, intense, and persistent. The interplay of various processes, such as astronomical tides, seiches, and atmospheric forcings including strong winds, depressions, storm surges, and meteotsunamis[3], complicates precise forecasting of such extreme events (Ferrarin et al., 2022; Umgiesser et al., 2021).

[2] https://www.comune.venezia.it/it/content/venezia-e-lacqua-alta

[3] tsunami-like waves of an atmospheric origin typically smaller and less destructive than those of seismic origin, but that can still contribute significantly to flooding (Ferrarin et al., 2023).

The interaction of these processes, combined with a higher Relative Sea Level baseline, is expected to increase the likelihood and severity of flooding throughout the century (Lionello, Barriopedro, et al., 2021; Lionello, Nicholls, et al., 2021; Zanchettin et al., 2007, 2021). For example, a one-in-ten year Extreme Sea Level event led to a water height of 1.2 m in the recent past, but could reach 1.8 m in a high-emission scenario (Fig. 3 Right). In particular, water heights of 1.10 m flood about 12% of Venice's historic center, while 1.40 m submerge 59% of the city (Fig. 4). These projections do not account for recent adaptation measures such as MoSE barriers (Anzidei et al., 2024).

Severe flooding led to exceptional events in Venice: on November 12, 2019, the city experienced its second highest water level in 53 years (1.87 m), inundating over 80% of the historic city. Saint Mark's Square was submerged by more than a meter, and Saint Mark's Basilica was flooded for the sixth time in 1200 years, with four of these floods occurring in the past two decades. Additional storms in the following days brought the seventh and ninth highest water levels on record (1.54 m and 1.50 m, respectively). Modern records date back to 1897 (Masters, 2019), however, proxies, such as algae belts in historical paintings and submerged water stairs, can extend these records back to 1350 (Camuffo et al., 2017).

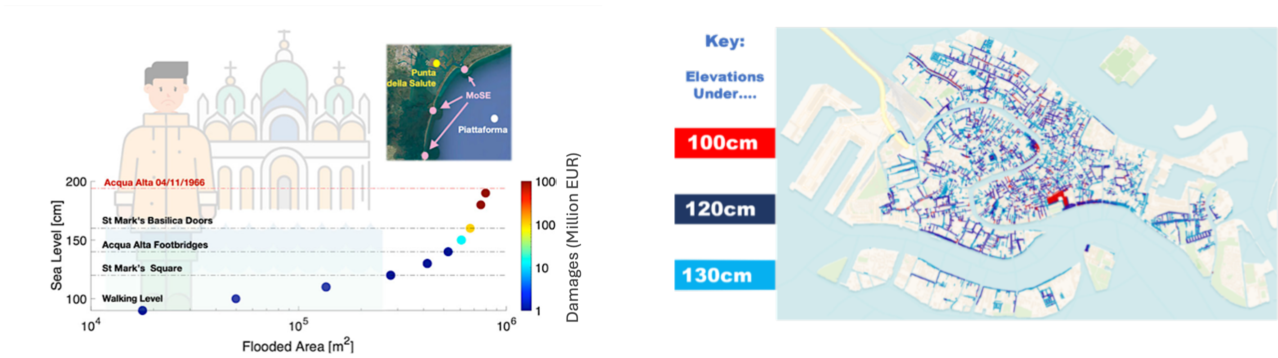

Figure 4: *Left: Relation between water height, flooded area, and estimated damages. The horizontal lines represent substantial flooding levels for St. Mark's square (120 cm), the level at which footbridges are needed to walk across the square (140 cm), and the level at which water will enter the St. Mark's Basilica (160 cm). The yellow and white dots represent the stations where sea level is measured, while the pink dots represent the location of the flood protection system for the lagoon, the MoSE barriers. (Faranda et al., 2023). Right: Areas that will flood at indicated water levels (Silvernail et al., 2022).*

4.1. Adapting to Sea Level Rise: The Case of the MoSE Barriers

Venice has a long history of adapting to the rise of sea level. Since the 1966 floods, adaptation measures have included raising parts of the historic center and, recently, the construction of MoSE (*MOdulo Sperimentale Elettromeccanico*) (Mel et al., 2021), a system of mobile barriers designed to protect Venice and its lagoon from flooding. However, in a high-emission scenario, these defenses may be inadequate by the end of the century, potentially requiring the barriers to remain closed for six months each year (Faranda et al., 2023; Lionello, Barriopedro, et al., 2021; Tomasicchio et al., 2022). It is predicted that MoSE can keep water levels below 110 cm if sea level rise remains under 50 cm, but at this threshold, closures would occur on average once a day (Umgiesser, 2020). With a Sea Level Rise of 75 cm, the lagoon would be closed more often than kept open, effectively separating it from the sea.

Despite the ecological, socio-cultural, and political challenges, "these dramatic interventions may also provide some opportunities such as, for example on a local scale, the management of sea level within the city and, on a regional scale, the optimization of ecological functions and ecosystem services provided by the nascent lagoons through an oriented and adaptive design" (Giupponi et al., 2024; Tagliapietra & Umgiesser, 2023).

5. Venice in the Global Context

Venice stands as a model of pedestrian urbanism, showcasing the concept of "Isobenefit urbanism" — an approach that aims at equal access to workplaces, amenities, and green spaces within a walkable distance, promoting sustainability and well-being (D'Acci et al., 2024). Residents can access cultural, educational, and recreational centers by foot, regardless of their location, highlighting the city's unique resilience and interconnectedness amid mounting environmental challenges.

Most ongoing and future climate-induced sea level rise, as well as temperature and precipitation extremes, are strongly affected by global actions on greenhouse gas emissions. Although local adaptation strategies can soften climate impacts in Venice, addressing the primary drivers of these environmental changes and mitigating their effects requires collective global cooperation to reduce emissions. These efforts would benefit Venice and other coastal cities facing severe climate risks while adapting to inevitable changes.

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A. Appendix: Additional Figures

This appendix contains additional figures that support the main text.

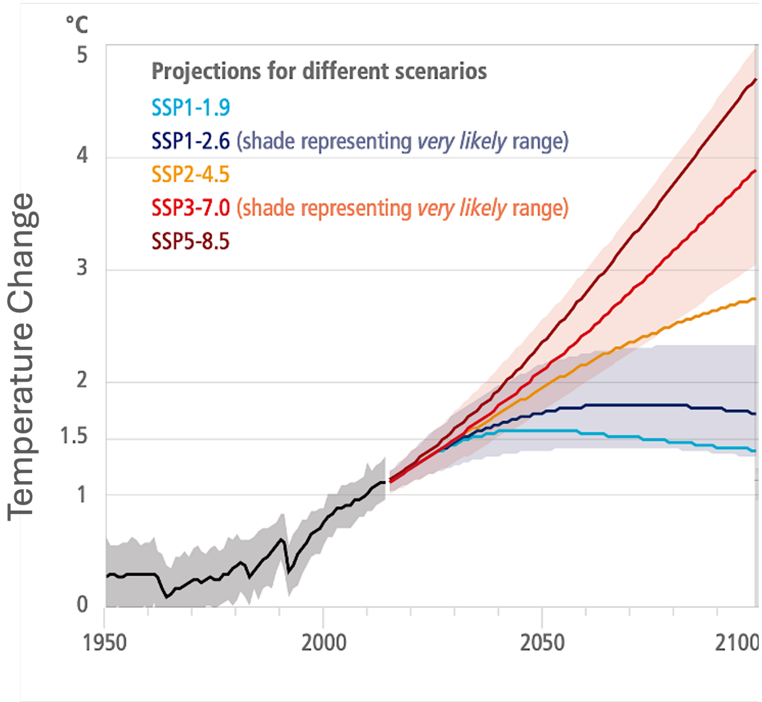

Figure A.1: *Projections for global mean surface temperature in different shared socioeconomic pathways, ranging from a sustainable and low-emission scenario (SSP1-1.9) to a fossil-fuel-driven and high-emission scenario (SSP5-8.5). Increase relative to the period 1850-1900 (IPCC, 2021a)*

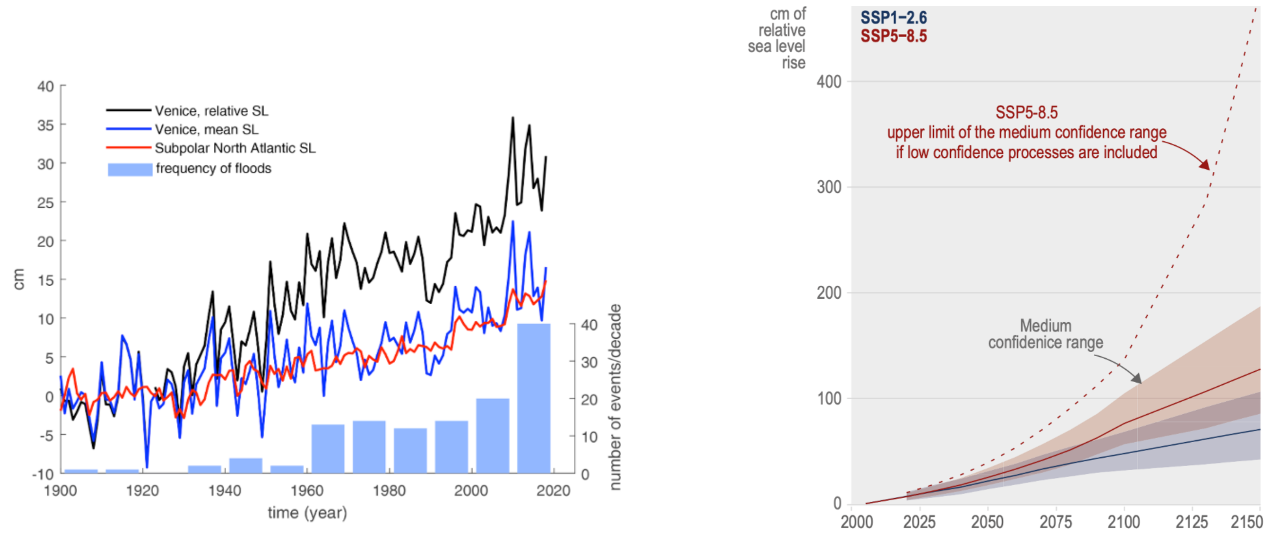

Figure A.2: *Left: Historical Sea Level Trend for Venice (blue) and the Subpolar North Atlantic (red). In black the same trend as shown in blue but accounting for land subsidence in Venice (Lionello, Nicholls, et al., 2021). Right: Projections for relative sea level rise in Venice, taking into account the local land subsidence (Bednar-Friedl et al., 2022)*

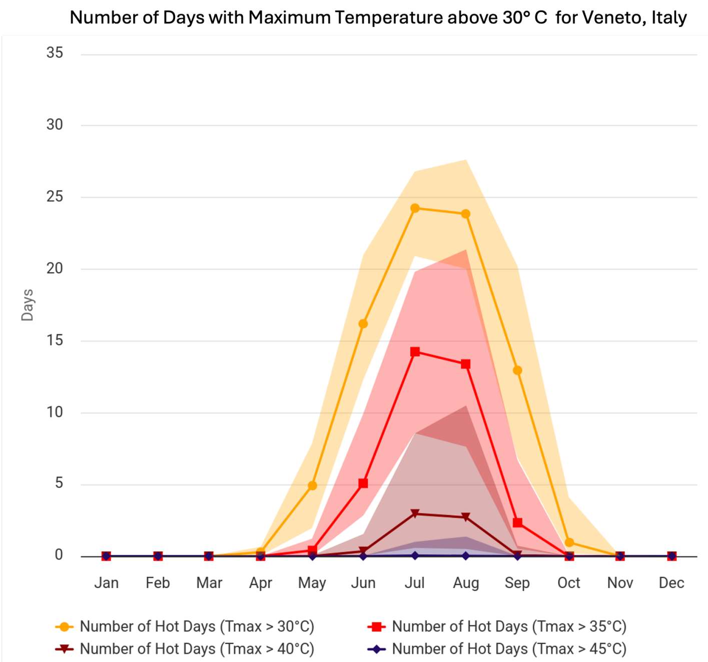

Figure A.3: *Number of days in 2080-2099 with a maximum temperature exceeding a certain threshold in the high emission scenario. In the historical reference (1995-2014), there were on average only up to 5 days above 30 degrees, and only 1 above 35 degrees. Obtained from (Climate Change Knowledge Portal, 2023)*

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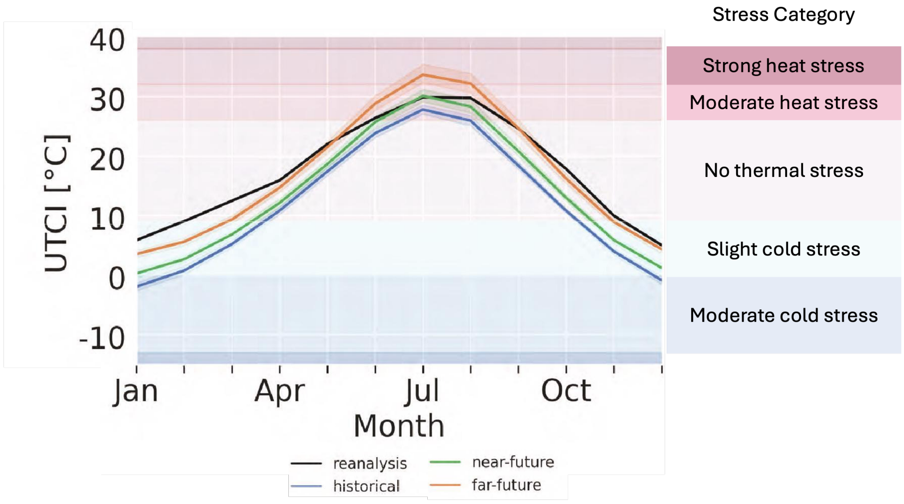

Figure A.4: *Average Universal Thermal Climate Index (UTCI) for the area of Venice. In black data that takes into account observations, while blue lines denote the Historical trend for the 1971–2000 period, green lines denote the high-emission scenario for the 2021–2050 period, and orange lines denote the high-emission scenario for the 2070–2099 period. The background color denotes Thermal Stress categories: from 26 to 32 degrees is moderate heat stress, 32-38 degrees is strong heat stress. Adapted from Nam et al. (2024) and Krüger and Di Napoli (2022)*

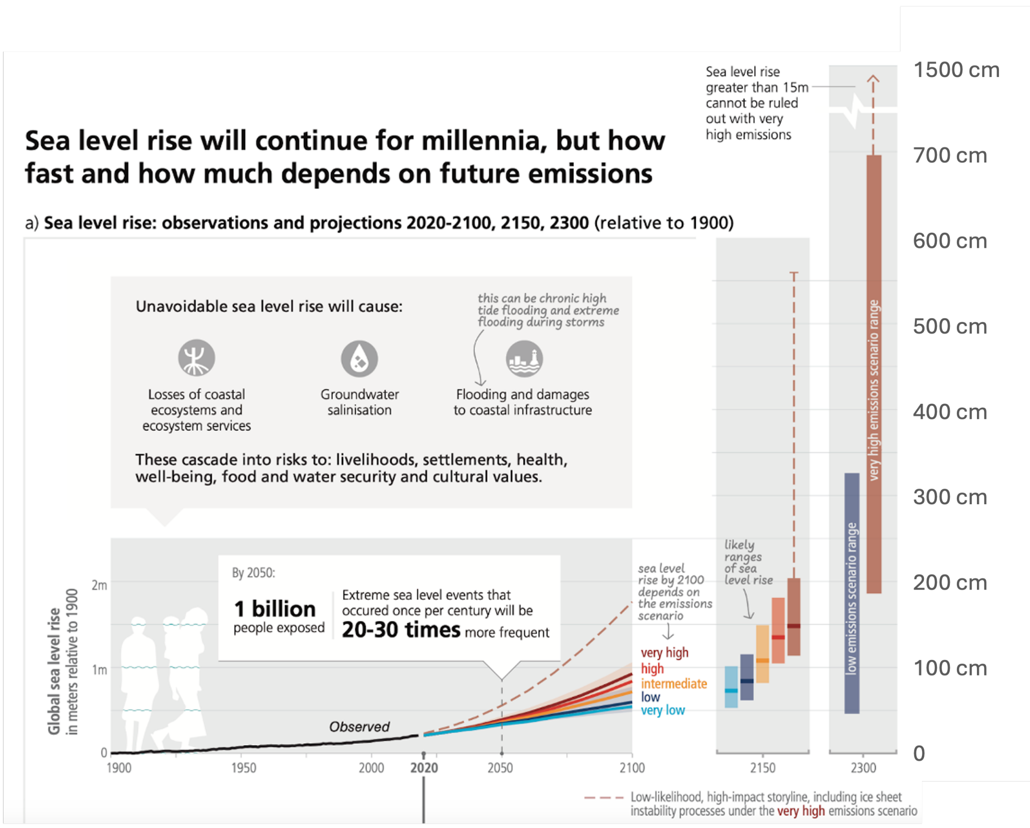

Figure A.5: *Global sea level rise trends (IPCC, 2023).*

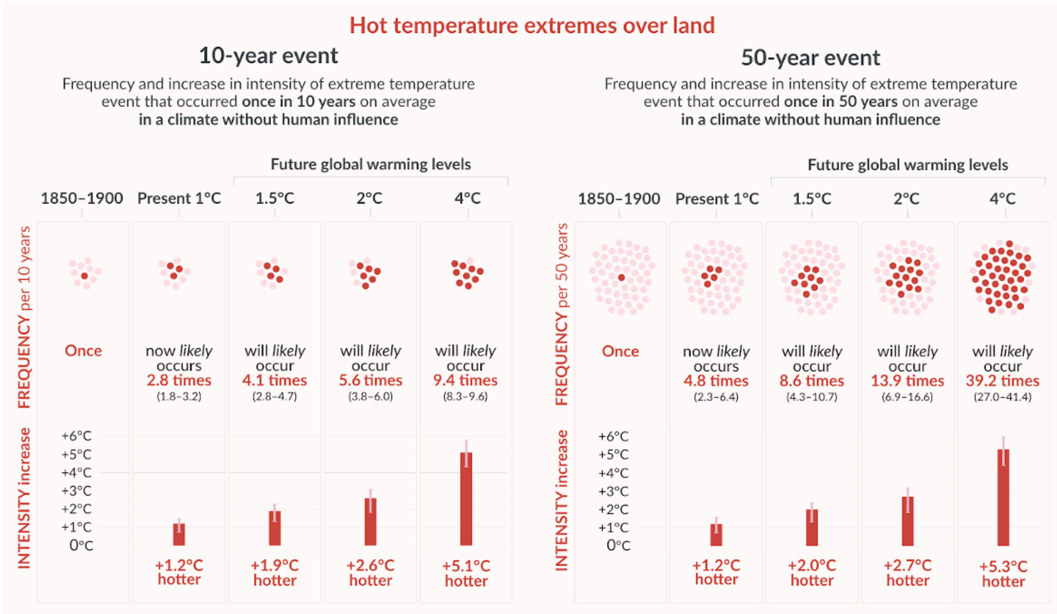

Figure A.6: *Global Evolution of hot temperature extremes (IPCC, 2021b).*

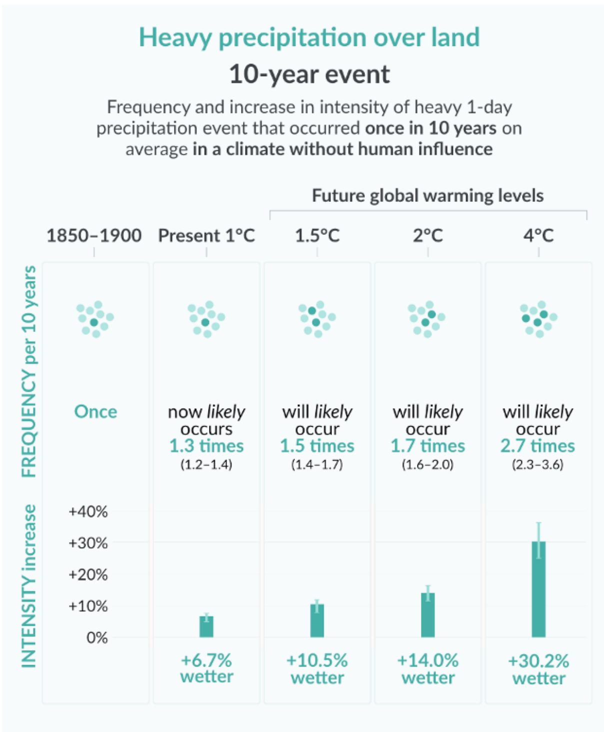

Figure A.7: *Global Evolution of precipitation extremes (IPCC, 2021b).*