West Antarctic Ice Sheet (WAIS) Collapse and Future Impacts on Sea Level Rise – Driven Migration on the United States Atlantic Coast

Global mean sea level has increased approximately 8 to 9 inches since 1880; mostly due to a combination of glacier and ice sheet melt and thermal expansion of the ocean as it warms over time (NOAA Climate, 2022). According to the National Oceanic & Atmospheric Administration (NOAA), in 2021, global mean sea level was 3.8 inches above 1993 levels, which is the highest annual average in the satellite record. Mean sea level rose by 0.14 inches per year from 2006 to 2015, which was nearly 2.5 times the average rate of 0.06 inches per year throughout the majority of the twentieth century. By the end of this century, global mean sea level is predicted to rise at least 1 foot above 2000 levels (NOAA Climate, 2022). Based on this data, sea level is on the rise and shows no signs of slowing down in the future. Some of the most powerful impacts of increasing sea levels will be seen on flatter coastal land bordering large water bodies, and hotspots; this includes: the United States Atlantic Coast & Gulf Coast, Asia, and islands (NASA, n.d.).

Specifically, in the United States, nearly 30% of the population lives in coastal zones. In these regions, sea level plays a role in flooding, shoreline erosion, and storm hazards (NOAA Climate, 2022). In the "Sea Level Rise Technical Report" produced jointly by NOAA Ocean Service, NASA, the Environmental Protection Agency (EPA), the United States Geologic Survey (USGS), and a few other organizations, sea levels along the United States Atlantic Coastline will rise an additional 10 to 12 inches by 2050 with specific amounts varying regionally, mainly due to land height changes. Areas along the United States Atlantic Coast are most vulnerable to sea level rise due to the low-lying topography, high economic value, and relatively high storm frequency (Neumann, 2000). A drastic increase in sea level rise could cause extremely negative impacts in this region. As briefly mentioned, there are two major causes of global sea level rise; increased melting of land-based ice, such as glaciers and ice sheets, and thermal expansion caused by warming of the ocean. However, there is one specific event that poses the most immediate threat of a large sea level rise – the potential collapse of the West Antarctic Ice Sheet (WAIS).

Owing to its instability, the complete release of WAIS ice to the ocean would raise the global mean sea level by 4 to 6 meters, or approximately 13 to 19 feet, which would cause major coastal flooding across the globe (Oppenheimer et al. 1998). The Antarctic Ice Sheet is comprised of the West Antarctic Ice Sheet and the East Antarctic Ice Sheet, however, most of the WAIS is currently below sea level. Antarctica, surrounded by the Southern Ocean, holds 90% of the world's ice (World Economic Forum, 2023). The Antarctic Ice Sheet in general has been decreasing since 2016, and with the world heading towards a warming of 2.8 degrees Celsius (5 degrees Fahrenheit) by the end of the 21st century, the Antarctic Ice Sheet is predicted to continue to melt and contribute to global sea level rise (World Economic Forum, 2023). Feldmann et al. 2015 simulates the long-term evolution of the whole WAIS, and the results show that if the Amundsen Sea Embayment (ASE) is destabilized (Figure 1) the entire ice sheet will discharge into the ocean. The ASE, shown in Figure 2, accounts for the largest part of the ice loss in the WAIS, due to the thinning and grounding-line retreat of tributaries such as Pine Island Glacier and Thwaites Glacier during the last 4 decades.

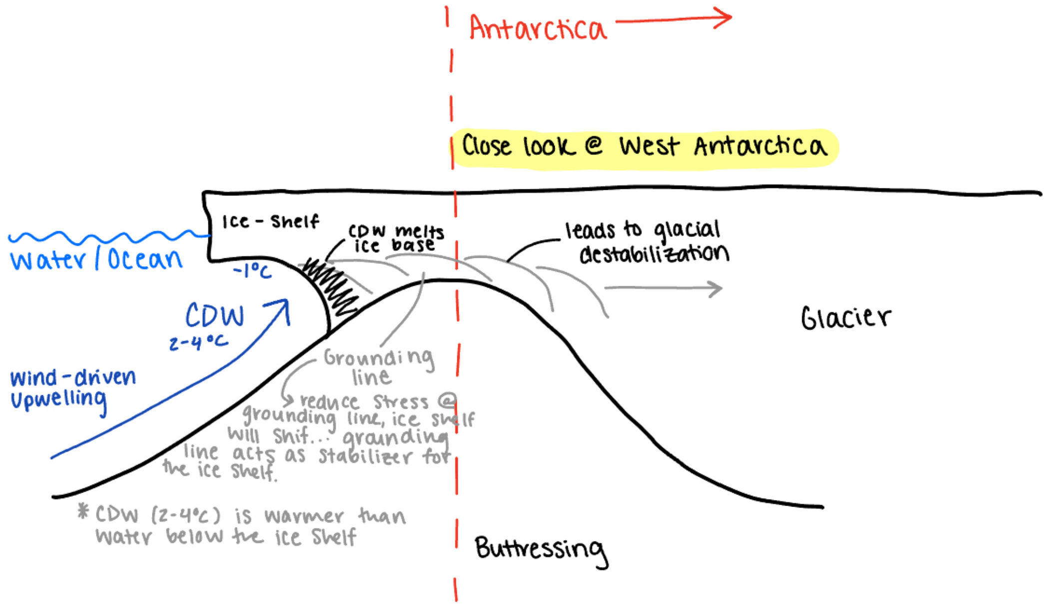

Figure 1 – Diagram of glacial destabilization in West Antarctica. Wind-driven upwelling of Circumpolar Deep Water (CDW) melts the ice base of the ice shelf. This causes the grounding line to shift which leads to destabilization.

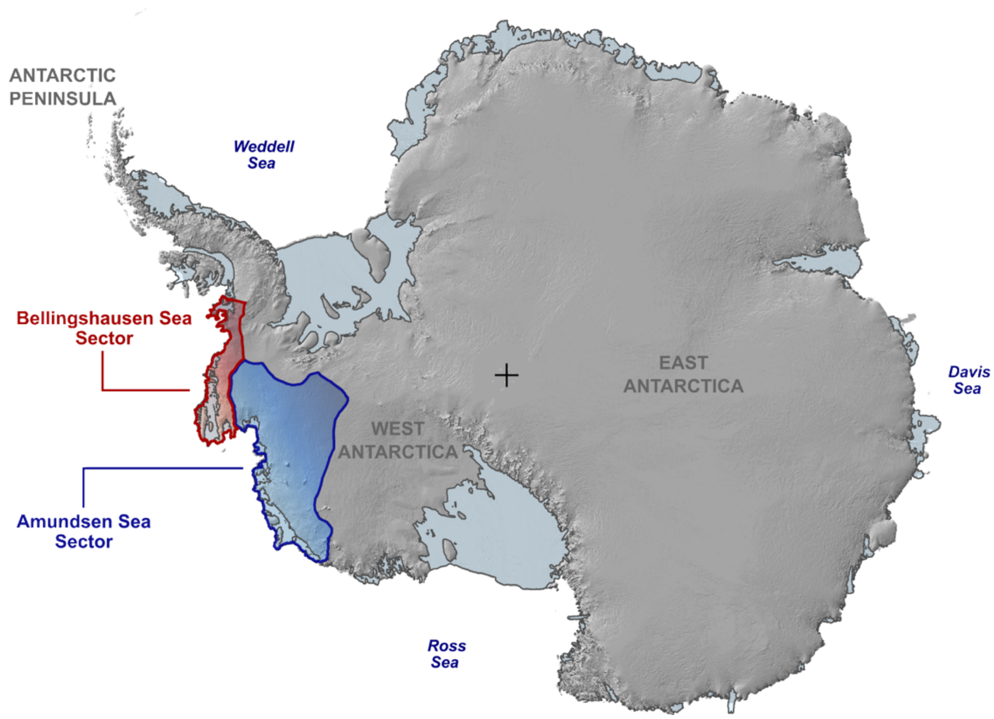

Figure 2 – Map showing location of West Antarctica, including the Amundsen Sea Embayment (blue) and the Bellingshausen Sea Embayment (red). Image courtesy of the University of Washington.

In the 6th Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) found that temperature will continue to increase, and the mass of the ice sheet will continue to decrease in the Antarctic. The growth of the Antarctic Ice Sheet is much slower than its retreat, meaning that if it continues to melt during this century, "this melting will not be reversible at a human time scale" (World Economic Forum, 2023). A sustained warming period of 2 degrees Celsius to 3 degrees Celsius (or 3.6 degrees Fahrenheit to 5.4 degrees Fahrenheit) would be enough to make the Antarctic Ice Sheet disappear completely, but this would take thousands of years to happen (World Economic Forum, 2023). In addition to this, in a recent study completed by international researchers in conjunction with the University of Washington shows the complexity of competing ice, ocean and atmosphere interactions driving shorter-term changes across West Antarctica and raises questions about how quickly Antarctica will evolve in an increasingly warm world. Either way, the melting of the Antarctic Ice Sheet, and the potential collapse of the West Antarctic Ice Sheet, will continue to contribute to sea level rise for a long period of time, and will test the adaptive capacity of humanity. Nichols et al. 2008 explores the global impact of extreme sea level rise, triggered by the hypothetical collapse of the WAIS. Based on 1995 data, it is estimated that roughly 400 million people are threatened by a 5-meter (or approximately a 16-foot) rise in sea level. The study found that much of the world's coasts would be abandoned given the extreme scenarios outlined in the paper. However, there is still uncertainty surrounding the response of polar ice sheets in the Antarctic to climate change limits and the ability to project sea level rise into the future.

Through analyzing ice cores, it can be revealed whether the WAIS melted fully the last time the Earth's climate warmed approximately 125,000 years ago – the same temperatures the planet is predicted to reach within the next 2 centuries (NOAA Climate, 2023). A research study could incorporate looking for patterns to track changes in the composition and temperature of Earth's atmosphere, and global events that may have shaped it. Some proxies that can be used to reveal past changes include oxygen–16 to oxygen–18 ratios, which can reveal the global temperature when ice was formed; and looking at gasses trapped in ice cores, which links carbon dioxide to changes in temperatures over time (NOAA Climate, 2023). To specifically observe and understand past sea-level changes, continuous and discontinuous ice cores can be analyzed. Continuous ice core records can be compared paleoclimate datasets to look at the relationship between past ice sheets and sea level up to 800,000 years ago, and discontinuous ice core records can be used to determine past ice-sheet arrangements (Christie et al. 2023). This can be used to make predictions about ice-sheet contributions to sea level during past time periods, which can be utilized to infer future ice-sheet contributions to sea level.

In addition to this, the information presented in Hillenbrand et al. 2017 is significant because it will aid in making "model-based predictions of future global sea level rise from Antarctic Ice Sheet melting more robust". This study looked at benthic and planktic $\delta^{13}C$ ratios, which indicated Circumpolar Deep Water (CDW) inflow onto the ASE shelf must have increased at sometime within the past millennium. Hillenbrand et al. 2017 also extends the record of CDW inflow onto the ASE shelf further back in time through a "period of significant ice sheet change and suggests early Holocene ice-shelf coverage of Pine Island Bay (PIB)".

Although there is uncertainty, scientists are generally certain that the collapse of the WAIS – whenever that might be – will contribute to significant sea level rise. This should be connected to areas that are most risk of sea level rise, such as the United States Atlantic Coast. To completely understand human migration responses to this environmental problem, Hauer et al. 2020 emphasizes that estimating the number of migrants due to sea level rise is difficult because "future exposure to sea level rise is dependent on the choices about carbon emissions today, as well as the coastal adaptation choices we make over time". Similarly, Oppenheimer et al. 1998 states, "human-induced climate change may play a significant role in controlling the long-term stability of the WAIS and in determining its contribution to sea level change in the near future".

In the modern age, flooding is becoming more frequent along the United States coastline. Nearly every site measured by the Environmental Protection Agency (EPA) in Figure 3 has had an increase in coastal flooding since the 1950s, specifically along the Atlantic Coast and the Gulf Coast. Sea level along the Atlantic coast (and other regions as well) can be measured using tide stations and satellite laser altimeters, which show what is happening at the local level and provide the average height of the entire ocean (NOAA's National Ocean Service, 2023). This technology can be used in conjunction with ice core data from Antarctica to assess the overall impact sea level rise due to WAIS melt has on the United States Atlantic Coast specifically.

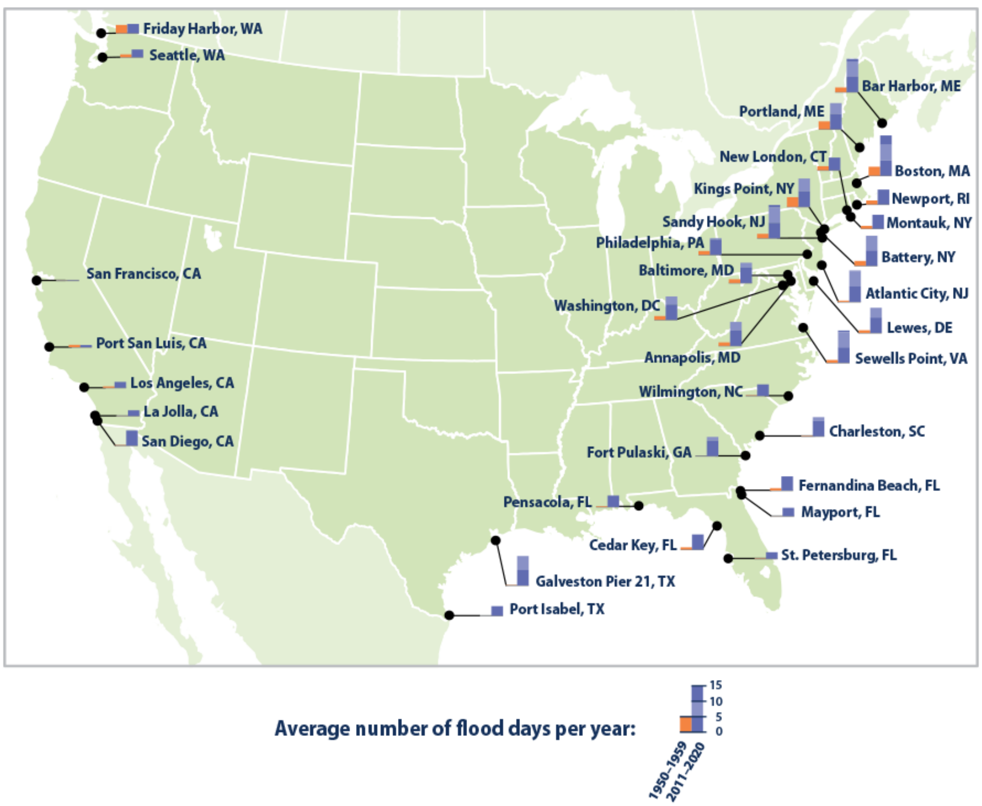

Figure 3 **–** Figure of flooding along United States Coasts, 2011–2020 versus 1950–1959. Image courtesy of the Environmental Protection Agency (n.d.).

As highlighted throughout this paper, with continued ocean and atmospheric warming, sea levels will most likely continue to rise for many centuries at rate higher than that of the current century. Beyond the United State Atlantic Coast, a large proportion of the global population presently reside in coastal regions where sea level rise impacts are expected and have, and will, influence the migration patterns of millions of people.

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