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Climate Change Science Review 2018 and Associated Social and Economic Impacts

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ABSTRACT

Climate change and its impacts on average temperature, water supply, agriculture, coastal flooding, biodiversity, social and economic stability, human migration, and overall global stability is one of the leading threats emerging for humanity, and is likely to increase as a threat for decades to come. This report represents a snapshot of climate change data, information, and understanding, as of 2018, and can serve as a kind of benchmark for changes going forward in time.

This report covers temperature change and heat effects, atmospheric and ocean circulation, freshwater supply changes, sea level rise and flooding, extreme climate events, oceanic deoxygenation, land degredation, social and economic changes, migration, and food. Data and information on all these issues represent a compelling body of knowledge supporting the scientific hypothesis describing climate change, and an important mile marker in our effort to track the unfolding nature of the problem.

A slide presentation that summarizes the content of this report is in Appendix A and can serve as an executive summary for the report.

ACKNOWLEDGMENTS

We gratefully acknowledge Dr. Tom Nelson of Sandia National Labs who provided funding and leadership for this study.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ALT	Active Layer Thickness
AMOC	Atlantic Meridional Overturning Circulation
cm	centimeter(s)
CMIP5	Coupled Model Intercomparison Project Phase 5
CV	coefficient of variation
EAIS	East Antarctic Ice Sheet
EU	European Union
FAO	Food & Agriculture Organization
GHG	greenhouse gases
GIA	glacial isostatic adjustment
GRACE	Gravity Recovery & Climate Experiment
GrIS	Greenland Ice Sheet
HCVI	Hunger & Climate Vulnerability Index
IMBIE	Ice Sheet Mass Balance Intercomparison Exercise
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
km	kilometer(s)
MAGT	Mean Annual Ground Temperature
mm	millimeter(s)
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmospheric Administration
NRC	National Resources Council (?)
PET	potential evapotranspiration
RCP	Representative Concentration Pathway
SNL	Sandia National Laboratories
TAC	Tropical Atmospheric Circulation
UN DESA	United Nations Department of Social and Economic Affairs
USD	United States Dollar
USGCRP	U.S. Global Change Research Program
WAIS	Western Antarctic Ice Sheet

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1. INTRODUCTION

"Flooding in Lynchburg Virginia, prompts fears of dam failure, leads to evacuations" was the title of an NBC News article on August 4, 2018 (Chuck, 2018). Observed as an isolated incident, this is just one tragedy facing one community. This represents one event in a larger series that tell the story of climate change and the consequences for human social and economic systems.

Section 2 of this report addresses how climate change is a complex, global process that plays out in regional settings. To understand the current science, this section reviews the most recent trends in climatic observations, change drivers, and impending effects mostly using the four Representative Concentration Pathways (RCPs). RCPs are the standard recognized by the Intergovernmental Panel on Climate Change (IPCC) used in climate science research. The four RCPs (RCP 2.6, RCP 4.5, RCP 6, and RCP 8.5) define climatic outcomes associated with radiative forcing conditions (measured in watts per square meter) from anthropogenic greenhouse gas (GHG) emissions by 2100 (Moss et al., 2010).

Section 3 addresses how physical climate change affects social and economic conditions. This section breaks down how new understandings in climate science research translate to impacts on regional and global human systems. The studies presented in this section analyze how certain regions are already being impacted while other studies model, project, and forecast social and economic outcomes of changing physical environments.

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2. A BROAD SUMMER 2018 REVIEW OF CLIMATE SCIENCE RESEARCH

According to trends in recent publications from the past year, here is a small selection of how physical environments are changing in significant ways: temperature changes and heat effects, atmospheric and oceanic circulation changes, freshwater supply changes, sea level rise and flooding, extreme climate events, oceanic deoxygenation, and land degradation.

2.1. Temperature Changes and Heat Effects

According to atmospheric, land, and sea-based measurements, Earth's global mean temperature has increased by 0.7° to 1.0°C since 1901, indicating that the planet is warming (USGCRP, 2017). It is this change in global temperature that results in the cascading effects both quantified and qualified as climate change. These cascading effects are driven by thermodynamic processes that allow the atmosphere and oceans to hold more heat (Figure 2-1).

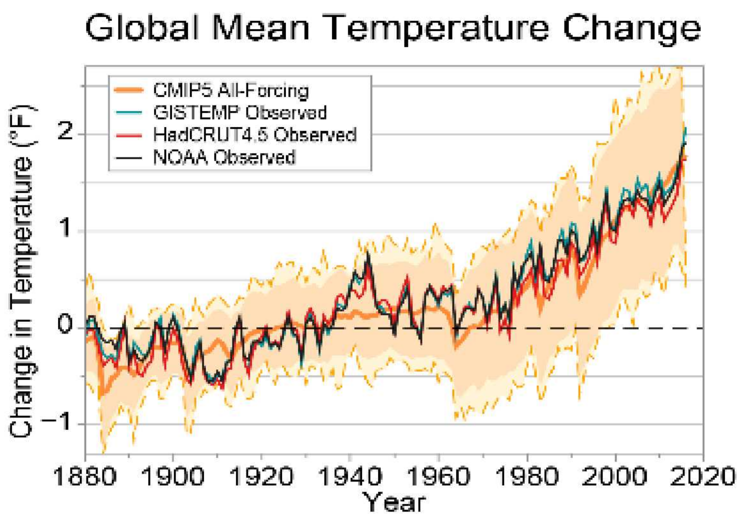

Figure 2-1. Graph of Increases in Global Mean Temperature (USGCRP 2017)

2.1.1. The Arctic

The region that best captures the effects of global temperature and heat change is the Arctic (Figure 2-2 and Figure 2-3). The Arctic is experiencing the fastest and most intense warming in the world – more than twice the rate of global mean temperature – causing extreme, unprecedented ice mass loss in recent decades (USGCRP, 2017; Carmack et al., 2015).

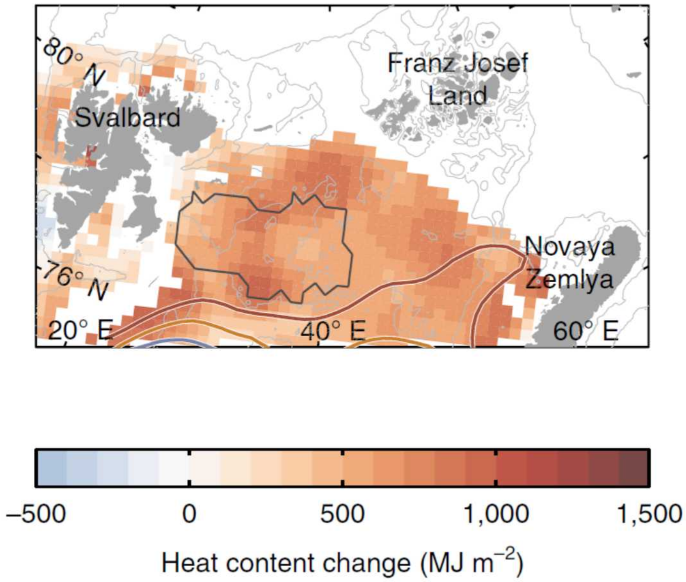

Figure 2-2. Changes in Heat Content of the Northern Barents Sea from 1970 – 2016 (Lind et al., 2018)

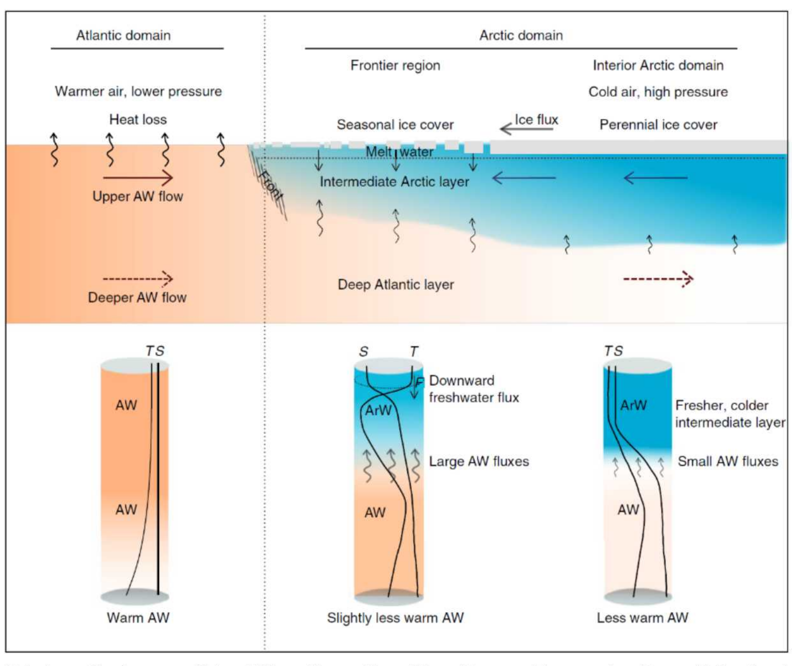

Figure 2-3. Water Column Stratification the Northern Barents Sea (Lind et al., 2018)

A few studies published this year provide better insight as to what is currently taking place in the Arctic. Scientists identified what they described to be a warming hotspot in the northern Barents Sea where the greatest temperature increase in the region is observed (Lind et al., 2018). Through different hydrographic observations, they identified processes by which rapid warming inhibits the formation of sea ice. This process is causing the northern Barents to become more Atlantic and less Arctic in nature, decreasing the geographic buffer between the Arctic and Atlantic climate regimes.

As of the time this paper was written, these active changes have undetermined ecological and commercial consequences.

A recent study produced by Graeter et al. (2018) confirmed that the Greenland Ice Sheet (GrIS) is melting at an unprecedented rate using ice cores as an in-situ observation tool. Ice cores contain records of a region's historical melting patterns. The study analyzed and compared the distribution of layers between ice cores of different lengths. Their analysis determined that melt rates in western Greenland are highest since at least 1550, and responsible for the massive losses in the GrIS. The scientists involved in the study concluded that the rapid melting is due to Greenland being 1.2°C warmer than it was in the 1800s, most likely a result of climate change caused by human activity.

The future of the Arctic as far as mean annual ground temperature and active layer thickness – both of which affect permafrost, surface hydrology, and vegetation – are captured in newly developed, high resolution statistical model that uses ground thermal observations and global spatial data (Aalto et al., 2018). Their results forecast significant increases in Arctic ground temperature and subsequent changes in active layer thickness, as shown in Figure 2-4.

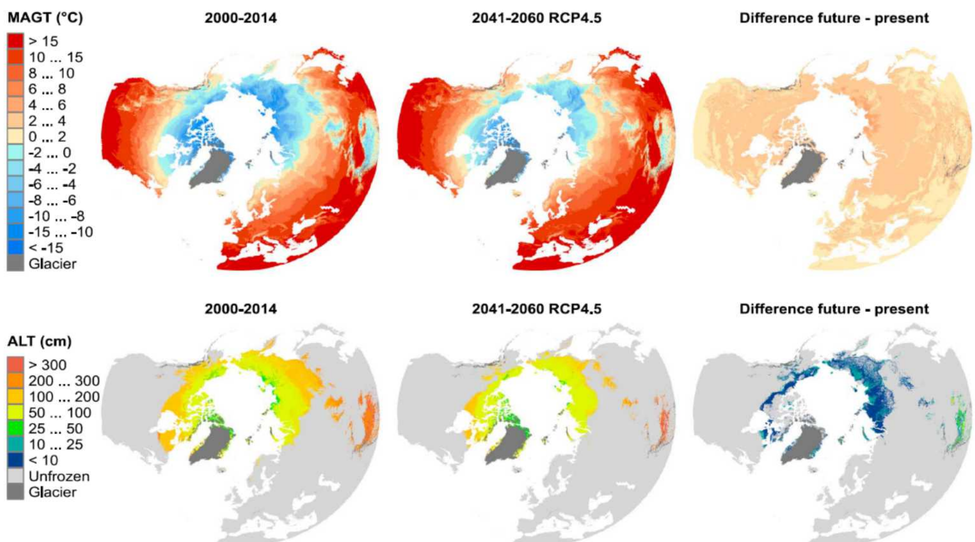

Figure 2-4. Changes in Mean Annual Ground Temperature (MAGT) and Active Layer Thickness (ALT) (Aalto et al., 2018).

2.1.2. The Antarctic

The Antarctic is also changing with rises in global temperature, but with considerable uncertainty compared to the Arctic (Barletta et al., 2018). The National Aeronautics and Space Administration's (NASA) Ice Sheet Mass Balance Intercomparison Exercise (IMBIE) Team's recent analysis, using satellite observations and mass balance modeling, determined that Antarctica has lost 2720 ± 1390 billion tons of ice between 1992 and 2017 equating to a sea level rise of 7.6 ± 3.9 millimeters (IMBIE Team, 2018). The scientists attribute most of this ice loss to the reduction of the Western Antarctic Ice Sheet (WAIS). The scientists assert that the mechanism driving the loss is the warming of surrounding oceanic waters, which confirms the findings of a melting feedback loop recently published by Silvano et al. (2018). They concluded that an influx of melted glacial freshwater drives an oceanic mixing mechanism causing cold Antarctic water to become warmer. This process results in an increased spreading of warm water across the Antarctic continental shelf, supplying heat to melt Antarctica's ice sheets.

The East Antarctic Ice Sheet (EAIS) tells a different, more uncertain story that contributes to the large standard error (IMBIE Team, 2018). The IMBIE Team reported EAIS ice mass changes to be 5±4.6 billion tons between 1992 and 2017. The uncertainty stems from accounting for glacial isostatic adjustment (GIA) – a process by which the land underneath the ice rises and falls in reaction to the mass above it – and how this process affects ice sheet stability (NOAA, 2015). Barletta et al. (2018) found that bedrock underneath the ice sheets is rising, more quickly than previously believed, at approximately 41 millimeters per year due to a much lower than global average viscosity found in the upper mantle. The scientists reported that as the earth rises, sea levels subsequently fall due to GIA and in return help promote ice sheet stability. They concluded that this new finding is significant enough to affect how accurately Antarctica's ice sheets model over time. They determined these findings should be better accounted for in projecting sea level rise.

2.2. Atmospheric and Ocean Circulation Changes

Atmospheric and oceanic circulations and climate are inextricably linked through various hydrological and heat exchange processes that also act as feedback loops. These circulations determine climate trends for decades and even centuries to come. Increases in global mean temperature create new thermal conditions for circulatory heat exchange processes. Circulations respond and adjust to these new conditions by driving thermodynamic and hydrological processes that alter regional precipitation and climate events (Ma et al., 2018). However, a great amount of uncertainty still surrounds how much anthropogenic emissions affect atmospheric and oceanic circulation (USGCRP, 2017). Studies published in the past year document observed changes in the Tropical Atmospheric Circulation (TAC) and the Atlantic Meridional Overturning Circulation (AMOC).

2.2.1. Tropical Atmospheric Circulation Weakening

Ma et al. (2018) determined TAC is weakening in response to global temperature increases. However, the scientists are unclear about what mechanisms are behind this weakening. They do understand that the weakening presents itself as changes in large-scale and regional responses. Large-scale responses include observed changes in the overall amount of atmospheric water vapor, lapse rate, precipitation, and radiative cooling whereas regional responses are the tropics getting wetter and the subtropics getting drier.

2.2.2. Atlantic Meridional Overturning Circulation Weakening

AMOC is a major oceanic circulation that plays an important role in the planet's heat distribution (Caesar et al., 2018). The AMOC is controlled by temperature and salinity (Caesar et al., 2018). Paleoclimates revealed that historical changes in the AMOC resulted in fast and dramatic shifts in climate across the world (Masson-Delmotte et al., 2013).

Direct continuous measurements of the AMOC are relatively new with data only available from the past 10 years, but a recent study by Caesar et al. (2018) managed to identify a weakening in AMOC since the mid-1900s. The scientists did so by establishing a characteristic spatial and sea surface temperature fingerprint (Caesar et al., 2018). The study establishes that the fingerprint is defined by a cooling pattern in the subpolar Atlantic and warming in the Gulf Stream. They concluded that this is likely in response to increasing anthropogenic emissions, global warming, and increasing flows of cold, fresh water from the Arctic into the warmer, saline waters of the Atlantic.

A weakening AMOC implicates climate in Europe, causing intense heat waves in the past and is likely to cause more changes in European atmospheric circulations (Caesar et al., 2018). Some scientists also associate a weakening AMOC with sea level rise along the east coast of the United States and drought in the African Sahel (Defrance et al., 2017; Sallenger et al., 2012). Those scientists also assert that further increases in global mean temperature will further weaken the AMOC due to altered hydrological cycles, more sea ice loss, and more GrIS melt freshening of the northern portion of the Atlantic Ocean (Bakker, et al., 2016; Böning et al., 2016).

2.3. Freshwater Supply Changes

A major security implication in large-scale circulation changes is altered regional precipitation and terrestrial water storage sources such as groundwater, aquifers, and lakes (Rodell et al., 2018). This section discusses global trends in precipitation, freshwater, and terrestrial water storage.

2.3.1. Global Freshwater Availability

Rodell et al. (2018) utilized Gravity Recovery & Climate Experiment (GRACE) satellite date from 2002 to 2016 to analyze emerging trends in global freshwater availability and terrestrial water storage (Figure 2-5). The most notable global trends are decreases in terrestrial water storage due to ice sheet loss and glacial melting in Antarctica (−127.6 ± 39.9 gigatons/year), Greenland (−279.0 ± 23.2 gigatons/year), the Gulf of Alaska (−62.6 ± 8.2 gigatons/year), and the Canadian Archipelago (−74.6 ± 4.1 gigatons/year).

Oppositely, the study found that there is an accumulation of freshwater in northern North America, northern Eurasia, and the wet tropics that correlate with increasing amounts of precipitation in the high latitudes and in the tropics (Syed et al., 2010). These trends are consistent with increasing global mean temperatures, but human consumption also influences global trends. The study reveals that available freshwater is decreasing in the world's regions that primarily use irrigation agriculture (Rodell et al., 2018). And lastly the study confirms that the majority of other changes trend consistent with natural climate variability between wet and dry oscillations such as El Niño and La Niña (Humphrey et al., 2016).

The regions exhibiting the greatest decreases in freshwater availability through terrestrial water storage depletion are northern India (-19.2 ± 1.1 gigatons/year), China's Xinjiang province (−5.5 ± 0.5 gigatons/year), the China's agricultural region surrounding Beijing (−11.3 ± 1.3 gigatons/year), East India-Bangladesh-Burma-southern China (−23.3 ± 1.9 gigatons/year), the north Middle East of Turkey-Syria-Iraq-Iran (−32.1 ± 1.5 gigatons/year), and the Ukraine-western Russia-Kazakhstan region (−18.1 ± 1.3 gigatons/year) (Rodell et al., 2018). The Ukraine-western Russia-Kazakhstan region in particular is responsible for the −2.2 ± 0.1 gigaton/year depletion in the disastrous Aral Sea and the −23.7 ± 4.2 gigaton/year decrease in the Caspian Sea (Rodell et al., 2018). The depletion of terrestrial water storage in each of these regions is heavily due to groundwater consumption for irrigational agriculture, with depletive conditions in Turkey-Syria-Iran-Iraq region and the Ukraine-western Russia-Kazakhstan region exacerbated by intensifying drought conditions (Voss et al., 2013).

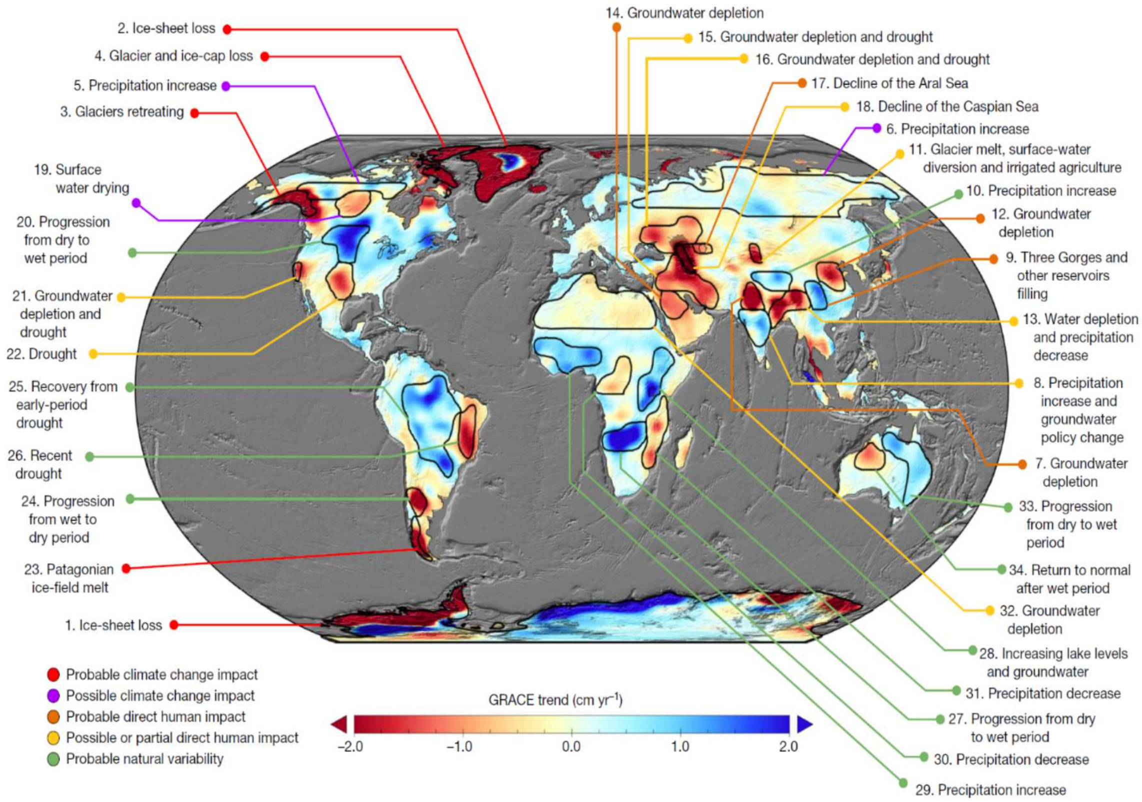

Figure 2-5. Changes in Global Freshwater Availability (Rodell et al., 2018)

2.3.2. Aridification

The demand of water, known potential evapotranspiration (PET), is projected to increase beyond the atmospheric water supply as a result of increases in global temperature, leading to increased land degradation and desertification (Park et al., 2018). Park et al.'s (2018) study analyzed how aridification emerges under different emission scenarios using 27 different global climate models (Figure 2-6). They managed to identify the percentage of total land surface that would undergo aridification in each scenario by 2100: 42% for RCP 4.5 and 49% for RCP 8.5. They concluded that nonlinear response mechanisms in hydrological processes per degree of warming in addition to regional aerosol forcing should be better understood to improve climate model predictions.

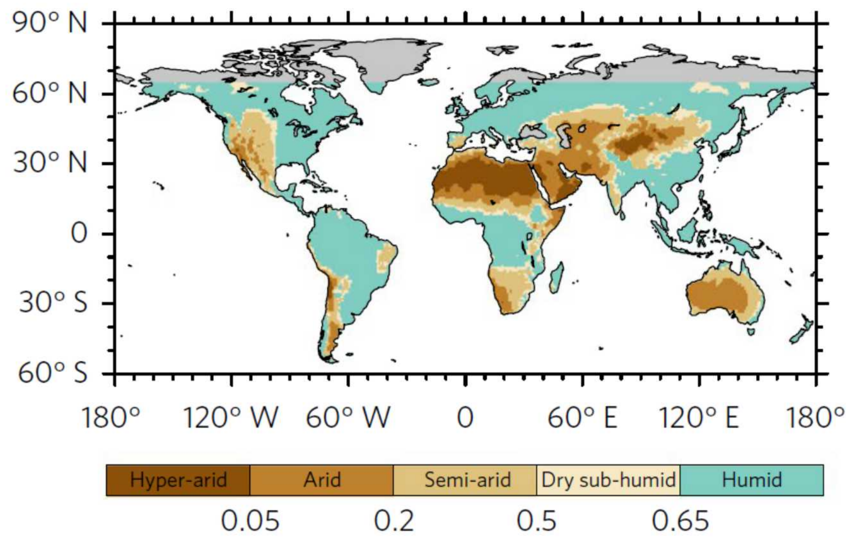

Figure 2-6. Spatial Distribution of the World's Arid Regions (Park et al., 2018)

2.4. Sea Level Rise & Flooding

The physical mechanisms driving sea level rise occur at differing spatial and temporal scales, but are primarily driven by water volume increasing due to thermal expansion and an overall increase in liquid water mass due to melting of glaciers and ice sheets (USGCRP, 2017). The USGCRP states with high confidence that anthropogenic emissions fueled rises in sea level of approximately 20 to 23 cm since 1880. Recent observations and new measurement technology show that sea level is rising even faster than previous decades (accelerating at a rate of 0.084 ± 0.025 mm/year), resulting in an 8 cm rise since the early 1990s (Nerem et al., 2018; USGCRP 2017) (Figure 2-7). However, sea level changes vary across the globe due to atmospheric and oceanic circulation. One such example is Gulf Stream weakening in the early 2000s leading to rapid and intense sea level rise along the northeastern coast of the U.S. (USGCRP, 2017).

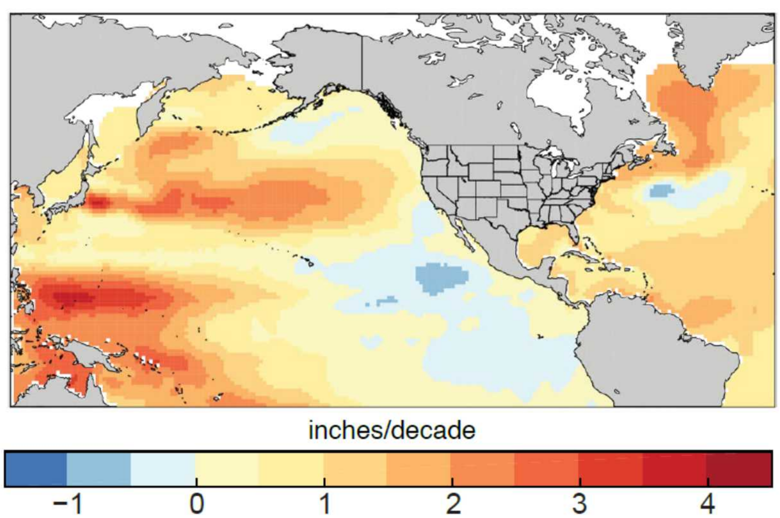

Figure 2-7. Changes in Sea Surface Height from 1993 – 2015 (USGCRP, 2017)

2.4.1. U.S. High Tide Flooding

This rise in global sea level has come with notable consequences in the form of more frequent and more intense nuisance high tide flooding in U.S. coastal cities since 1965 (an increase anywhere from 300% to 900%), with cities along the Atlantic and Gulf coasts experiencing the greatest impact (NOAA, 2015; USGCRP, 2017). Last year saw U.S. high tide flooding hit a record high of six flooding days (NOAA, 2015). The northeast Atlantic Coast and western Gulf of Mexico experienced the worst of it due to nor'easter and hurricane seasons. This is not the only form of flooding to buffet coastal cities, higher sea levels have resulted in deadlier and more destructive storm surges that go farther inland than they did before in previous decades (NOAA, 2015) (Figure 2-8.

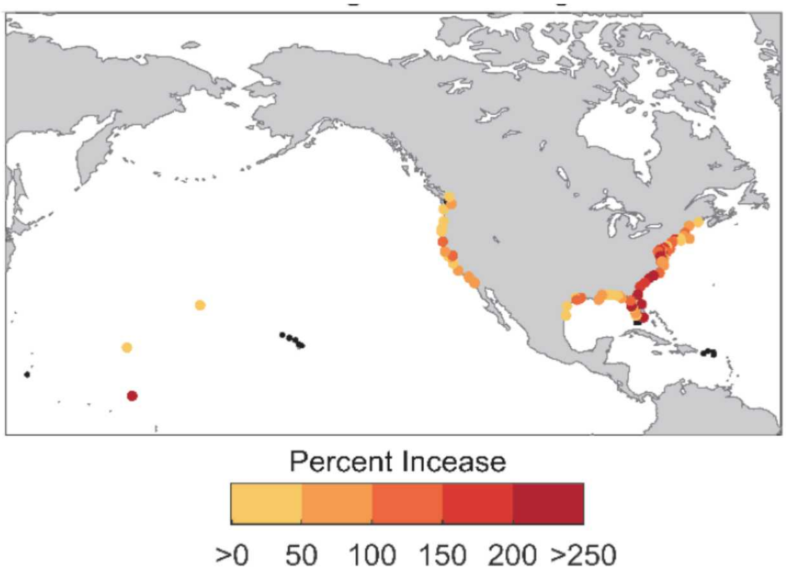

Figure 2-8. Percent Increase in U.S. High Tide Flooding since 2000 (NOAA, 2015)

2.4.2. Extreme Sea Level Rise

Extreme sea levels arise due to a combination of high tides and extreme weather events (Wahl et al., 2017). With warming continuing to drive sea level rise at an even faster rate, Vousdoukas et al. (2018) published a paper quantifying how future extreme sea levels will change using mean sea level, wind-waves, and storm surges (drivers of extreme sea level) under different emission scenarios (Figure 2-9). Their results show that extreme sea level events that usually only occur every 100 years would start occurring every year along global coastlines by 2100, increasing the frequency of catastrophic flooding for coastal cities (Figure 2-10). Under RCP 4.5, they project an increase in extreme sea levels of 34 to 76 cm by 2100. Under RCP 8.5, they project an increase in extreme sea levels of 58 to 172 cm. Their study concludes that the changes in extreme sea level are driven most by thermal expansion, loss in ice mass from glaciers, and reduction in Greenland and Antarctic ice sheets. A notable finding is that the tropics are projected to see 100-year extreme sea level events become annual events by 2050 under both emission scenarios RCP 4.5 and RCP 8.5.

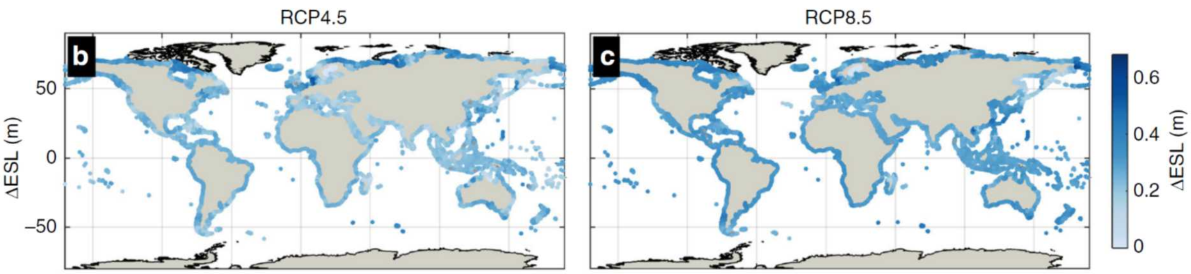

Figure 2-9. Projected Changes in Extreme Sea Level Height under Different Emission Scenarios (Vousdoukas et al., 2018)

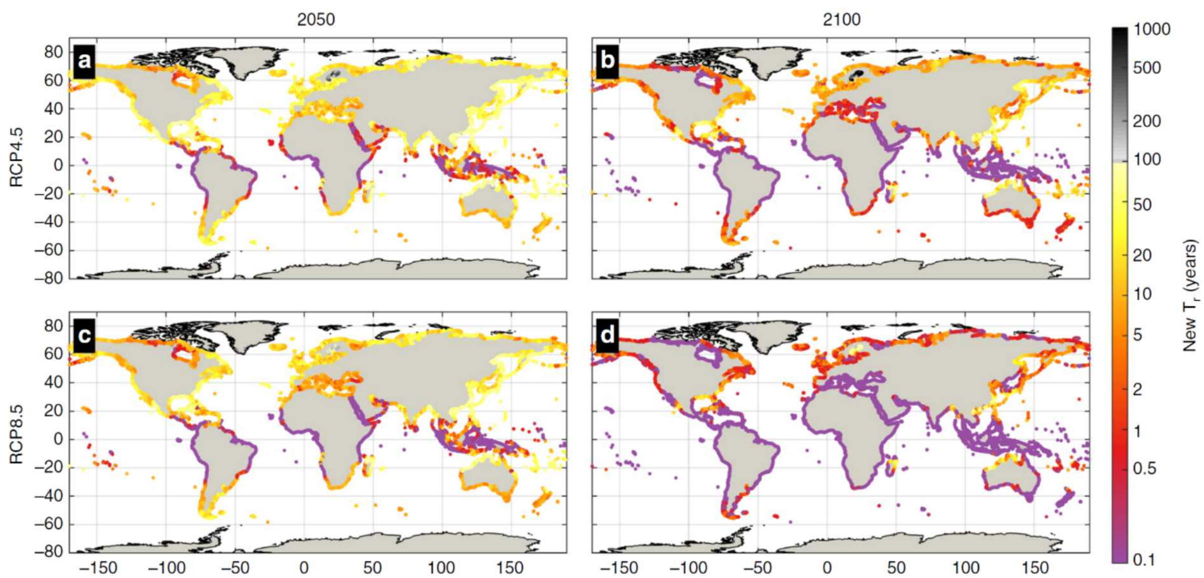

Figure 2-10. Changes in Frequency of Return for What Were Considered 100-year Extreme Sea Levels under Different Radiative Forcing Scenarios (Vousdoukas et al., 2018)

2.5. Extreme Climate Events

Changes in extreme weather and climate events, including hot events, cold events, precipitation events, tornadoes, thunderstorms, winter storms, and tropical cyclones, are considered to be one of the most important impacts of climate change (USGCRP, 2017). A small change in the mean of any single weather factor can result in a large change in the threshold of extreme event probability (IPCC, 2013). Determining how these events might be changing with climate has been challenging in the past (USGCRP, 2017). But now the science of understanding what mechanisms attribute to extreme events is developing quickly (USGCRP, 2017).

As climate changes due to the enhanced radiative forcing caused by carbon emissions, the frequency and intensity of heatwaves (both in number of days and maximum temperature at day and night) has increased around the world (IPCC, 2013). As mentioned before, a thermodynamic consequence of a warmer atmosphere is an increase in atmospheric water, which has increased the number of extreme precipitation events globally (USGCRP, 2017). The risk of extreme convection also rises with increased atmospheric temperature and water vapor, influencing the global frequency of severe thunderstorm conditions (USGCRP, 2017). As for tropical cyclones, the research is still developing and is a highly debated topic (UGCRP, 2017). There is consensus that increased warming increases the intensity of tropical cyclones beyond the intensity of any extreme storms on record (USGCRP, 2017). The debate and uncertainty lie in how frequent tropical cyclones develop in a warmer climate (USGCRP, 2017).

Diffenbaugh et al. (2018) conducted a study to understand the consequences of a world 1.5° to 3°C warmer using different RCPs. Their research is the first to assess the specific quantitative probability of unprecedented climate events using cumulative emission windows that correspond to warming scenarios, past climate data, the targets of the Paris Agreements, and national pledge commitments. If cumulative emissions remain within a range that creates a planet 1° to 2°C warmer, their study finds that approximately 25% of the area in their observed regions, including North America, Europe, East Asia, South America, and Australia, are 5 times more likely to experience extreme and unprecedented hot, cold, wet, and dry events.

A study performed by Cohen at al. (2018) found a link between intense warming in the Arctic and extreme winter weather in the United States. The study acknowledges that the mechanisms that drive the relationship between Arctic variability and weather in the Northern Hemisphere is still being researched and not definitively understood. However, the study finds that whenever the Arctic warming trend is greatest, the mid-latitudes see an increase in frequency of severe winter weather, noting that this holds particularly true for the eastern United States.

2.5.1. Heatwaves

Using data from documented lethal heatwaves between 1980 and 2014, Mora et al. (2017) determined the threshold where climatic conditions of surface air temperature and relative humidity become deadly. They found that approximately 30% of the world's population experiences what constitutes as lethal heatwave conditions for at least 20 days a year. To understand how these conditions might change over time, the Mora et al. (2017) modeled how the geographic distribution of these climatic conditions change depending on different emission scenarios. Even with significant GHG emission reduction under RCP 2.6, results show 47.6% ± 9.6% of the world's population being exposed to deadly combinations of surface air temperature and relative humidity for at least 20 days a year by 2100. Under higher emission scenarios of RCP 4.5 and RCP 8.5, that percentage increases to 53.7% + 8.7% and 73.9% ± 6.6% respectively. The duration in number of deadly condition days also changes with different emission scenarios, with higher emission scenarios yielding a larger number of days with lethal climate conditions. These changes are illustrated in Figure 2-11.

Taking a more regional focus on how the intensity and frequency of heat waves will change under different emission scenarios, Guerreiro et al. (2018) at Newcastle University in England determine that under low, medium, and high emission scenarios the number of heatwave days increases for 571 European cities, with the greatest increases occurring in southern Europe (Figure 2-12). They also find that maximum heat wave temperatures increase most across central European cities.

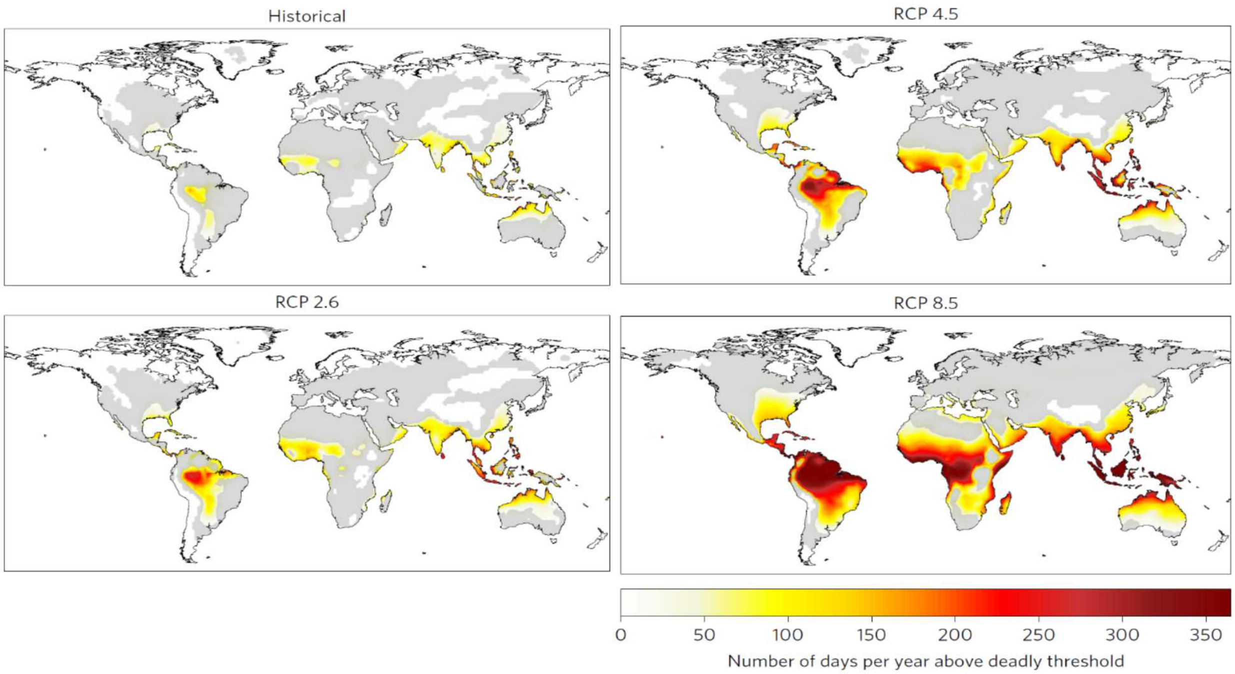

Figure 2-11. Changes in Number of Days of Exposure to Lethal Climatic Conditions under Different Emission Scenarios (Guerreiro et al., 2018)

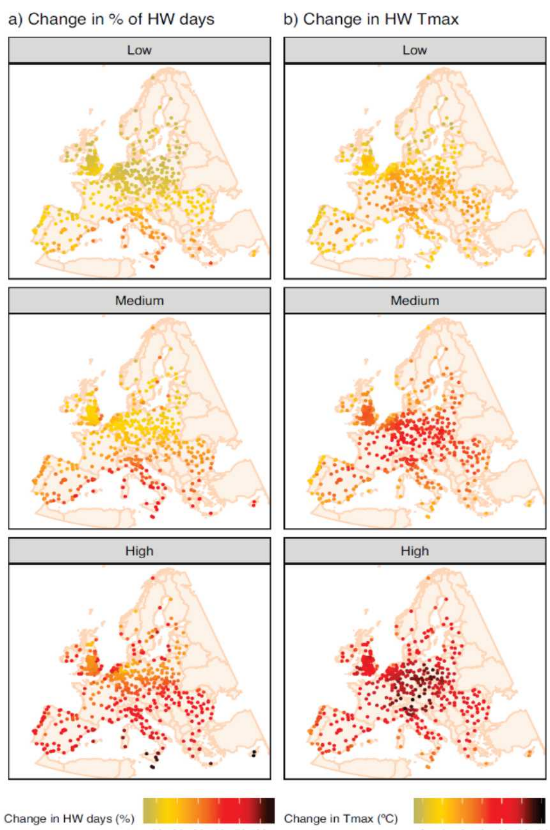

Figure 2-12. Changes in Number of Days of Heatwave Days and Max Heatwave Temperatures under Different Emission Scenarios (Guerreiro et al., 2018)

2.5.2. Atmospheric Rivers

Atmospheric rivers are long, horizontal water vapor transport and make up 90% of the poleward water vapor transport across the mid-latitudes (Espinoza et al., 2018). Atmospheric rivers are important to future climate events because they contribute to extreme precipitation events that can lead to flooding and cause high winds (Espinoza et al., 2018). While there are projected to be 10% fewer atmospheric rivers, atmospheric rivers will be 25% longer, 25% wider, and cause stronger integrated water vapor transport under emissions scenario RCP 8.5 (Espinoza et al., 2018). The study identifies that there may be implications for North America, South America, and western Europe extreme precipitation events, but further study is necessary to fully understand impacts.

2.6. Oceanic Deoxygenation

According to Breitburg et al. (2018), oxygen content in open oceans and coastal waters has been declining since the mid-1900s. The ocean is losing its oxygen due to human activities, both anthropogenic emissions increasing global temperatures and nutrients being discharged into coastal waters from agricultural runoff.

2.6.1. Warming & Nutrient Driven Oceanic Deoxygenation

The available amount of oxygen in the open ocean has decreased by 77 billion metric tons (Breitburg et al., 2018) (Figure 2-13). As far as coastal waters, there are more than 500 sites across the United States. that report hypoxia conditions where oxygen concentrations are less than 2 mg/l (Breitburg et al., 2018). Warming contributes to oceanic oxygenation mostly in the open ocean by reducing the solubility of oxygen in water, increasing metabolic rates that consume oxygen, directly intensifying thermal stratification and therefore slowing deep overturning circulation, and indirectly intensifying saline-based stratification through melting ice sheets and precipitation (Breitburg et al., 2018).

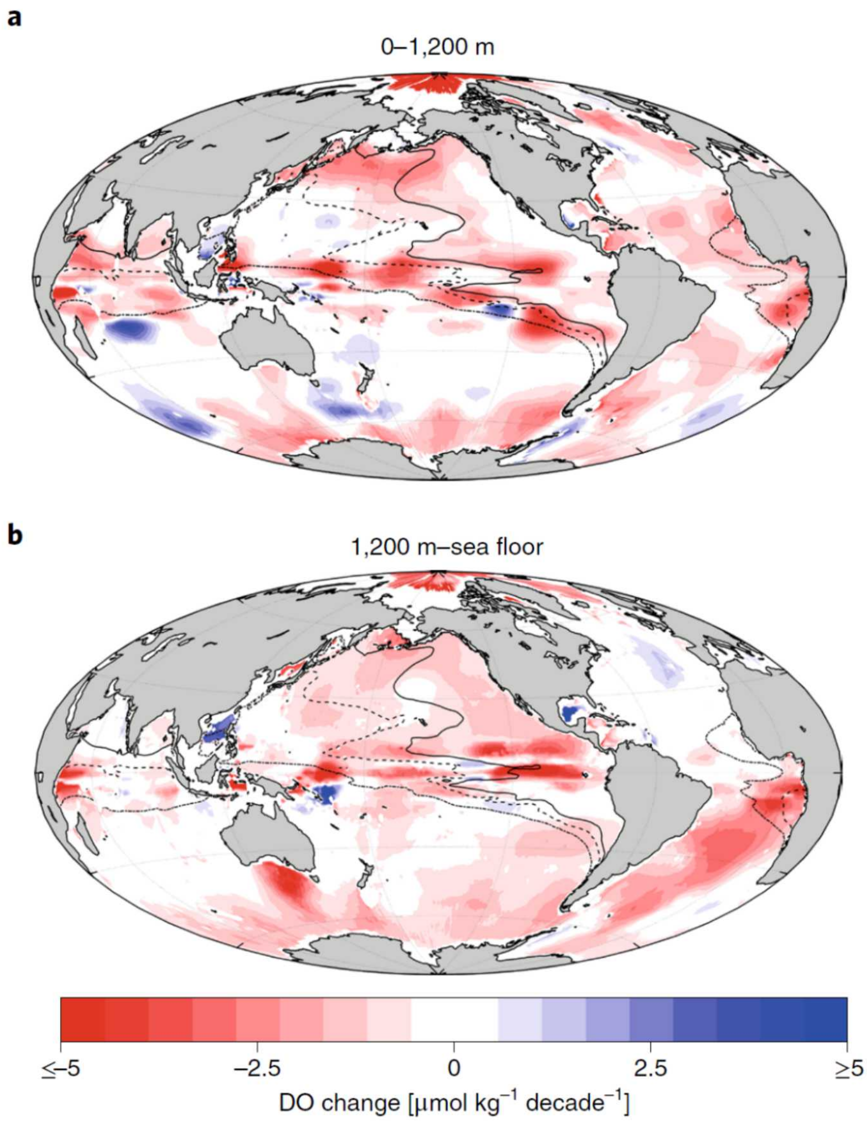

Figure 2-13. Changes in Dissolved Oxygen (DO) Content in the Ocean at Different Levels (Breitburg et al., 2018)

Nutrient enrichment by means of discharge contributes to oceanic deoxygenation mostly in coastal waters through eutrophication – a process induced when nutrients from agricultural runoff and sewage spur blooms algae growth, which in turn causes a surge in aerobic respiration that consumes dissolved oxygen (Breitburg et al., 2018) (Figure 2-14). In addition to eutrophication, warming increases deoxygenation in coastal waters by mechanisms similar to what is occurring in open ocean settings, creating a faster deoxygenation environment in coastal waters than in the open ocean because of this combined warming and eutrophication effect (Breitburg et al., 2018).

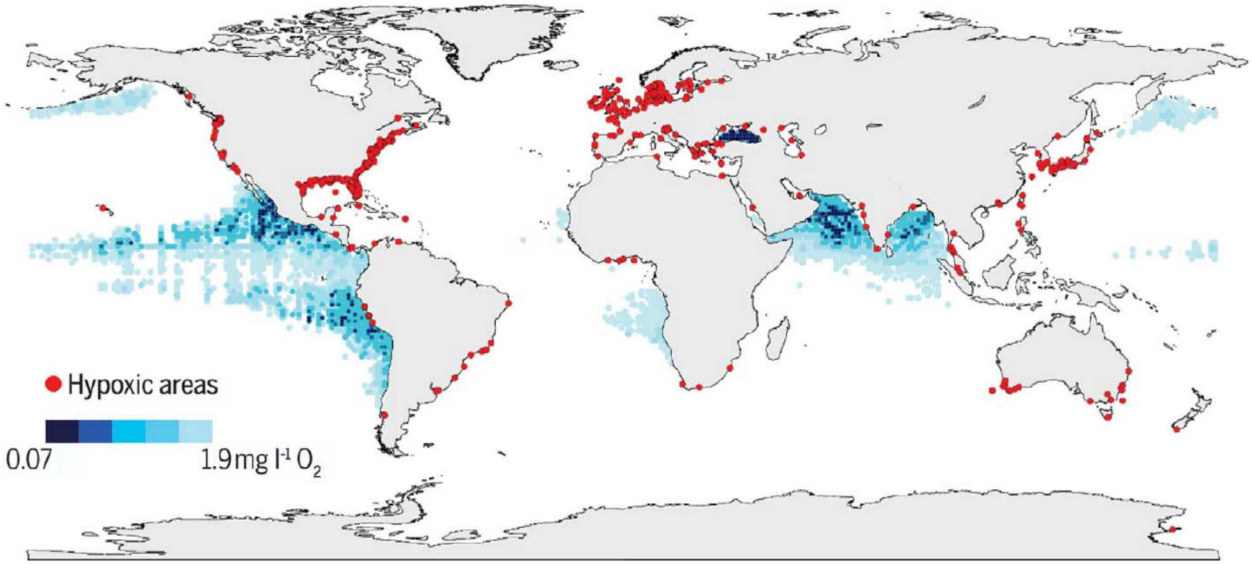

Figure 2-14. Coastal Areas Deprived of Adequate Oxygen Supply (hypoxic meaning concentration less than 2 micrograms/liter represented by red dots) and Oxygen Minimum Concentration Represented by the Shaded Areas (Breitburg et al., 2018)

There are gaps in understanding and modeling of future oceanic deoxygenation (Oschlies et al., 2018). Current ocean models can neither reproduce changes in oxygen content throughout the ocean's thermocline nor accurately estimate how oxygen concentration changes with air-sea mixture though time. Thus, ocean models severely underestimate observed oceanic deoxygenation when integrated over the entire global ocean system (Oschlies et al., 2018). The scientists who were part of the study determined that the mechanisms driving oxygen transport need to be better understood to develop more accurate ocean models. Variations in biological oxygen demand need to be more accurately represented in addition to identifying other biogeochemical feedbacks (Oschlies et al., 2018).

2.7. Land Degradation

Forest land cover plays a significant role in processing carbon in the atmosphere. Therefore, changes to forest land cover affects climatic conditions by altering the earth's global carbon sink system. Understanding how forest land cover is changing, especially tropical forest land cover, is essential to understanding how climate is and will continue to change.

2.7.1. Southeast Asia Forest Loss

Zeng et al. (2018) discovered tropical deforestation is occurring in Southeast Asia due to agricultural intensification. Using multiple satellite imagery streams, they found huge increases in undocumented cropland expansion equating to an estimated 82 billion square meters of new forest loss (Figure 2-15). This estimate is in stark contrast with the current land cover data being used to understand climate change as it relates to future warming, and its relationship between carbon processing and land degradation (Zeng at al. 2018). The scientists note the expansion of cropland continues to occur despite governing entities working to increase the number of protected forest areas.

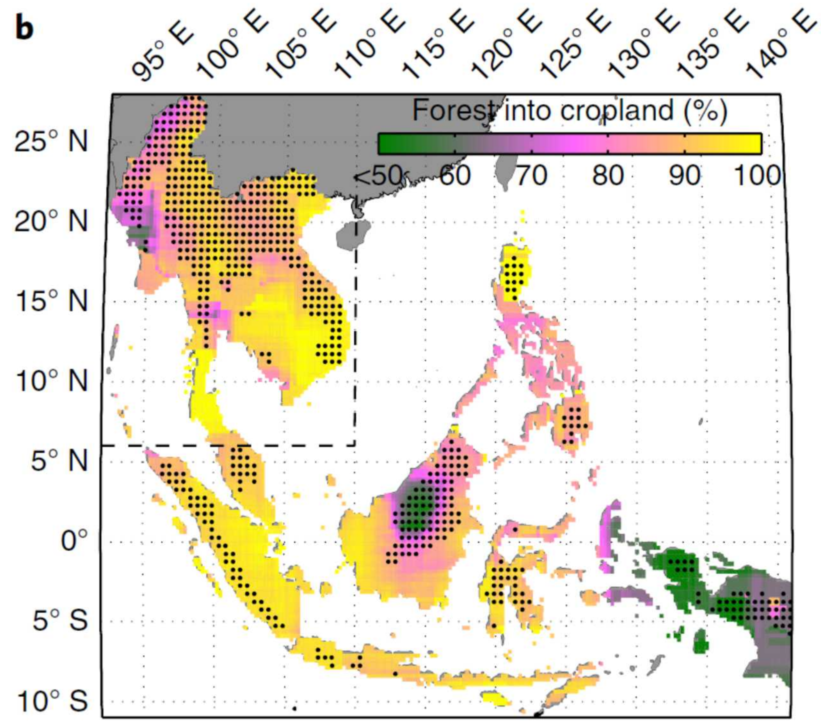

Figure 2-15. Percentage of Forest Transitioned into Cropland (Zeng et al., 2018)

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3. SOCIAL AND ECONOMIC CHANGES & RISKS ASSOCIATED WITH CLIMATE CHANGE

3.1. Climate Change and Social Stress

Climatic changes are of enough concern to draw the attention of the U.S. intelligence community (National Academies NRC, 2013). The greatest concerns surround rising seas; melting glaciers; superstorms; and more intense droughts, floods, and heat waves (National Academies NRC, 2013). The study performed by the National Academies determined that climate events, due to both climate change and climate variability, have the potential to disrupt and overwhelm social and economic systems. They determined human-based support systems inability to cope well under increased distress created by these climate events is the most pressing vulnerability. This vulnerability could lead to destabilization and unrest threatening regional stability and U.S. national security in the form of disrupting water resources, forcing migration, interrupting food supply, and crippling infrastructure. Thus, the relationship between climate and security is one of nuance and complexity as climate events create second- and third-order security implications for social and economic conditions.

3.2. Inequity and Inequality of a Warming Climate

Climate change contributes to inequity and inequality by acting as a multiplier of disadvantageous circumstances, increasing adversity for already marginalized groups. Inequity and inequality exist as a byproduct of disproportionately distributed negative consequences to marginalized groups due to a lack of fairness and justice in human developed systems. According to the United Nations Department of Social and Economic Affairs (UN DESA), climate change increases inequity and inequality by increasing exposure to adverse outcomes, increasing susceptibility to damaging climate events, and decreasing the ability to cope and recover from damaging climate events (Islam and Winkel, 2017). The World Bank identifies the following regions at greatest risk to the effects of climate change due to their social, economic, and environmental conditions: Sub-Saharan Africa, East Asia and the Pacific, Eastern Europe and Central Asia, Latin America and the Caribbean, Middle East and North Africa, and South Asia (World Bank, 2016).

Climate in the world's poorest countries will experience the greatest local changes if global warming is not kept to the aspirational target of 1.5°C below the preindustrial era, exacerbating the impacts of poverty in these nations (King and Harrington, 2018). During the Paris Agreements, poor small island nations pushed for adoption of the 1.5°C target because of their concerns about sea level rise (King and Harrington, 2018). Recently published studies also show that climate models project the greatest increases in temperature variability to occur in poor tropical countries (Bathiany et al., 2018). These changes in variability are quantified as 10% to 15% increases in temperature variability for regions surrounding the Amazon, Southern Africa, the Sahel, India, and Southeast India (Bathiany et al., 2018). Poorer countries are already more socially and economically susceptible to extreme weather and climate events. And inevitably, the poor countries that contributed the least to climate change will end up suffering the most severe climatic consequences in the form of disruption to crop yield, productivity, and long-term economic growth rate (Bathiany et al., 2018).

3.3. Water

Section 2.3 of this paper introduced how climate change and human activity are changing the world's available water resources. The convergence of climate change and consumption habits have started to further strain freshwater resources in regions where water is already considered extremely scarce. As populations in these regions grow while the world gets warmer, freshwater resources face unprecedented strain with simultaneous increases in water demand and decreases in water supply reliability (World Bank, 2016).

The World Bank projects the following increases in water demand by 2050: 50% increase in demand for agricultural purposes, 50% to 70% increase in demand for urban population growth, and 85% increase in demand for energy purposes by 2035. These increases in demand by different sectors of society will create conflict among water use and conflate risk in unprecedented ways. The global agriculture sector uses 70% of the world's available freshwater resources, as made clear by the extensive use for irrigated agriculture in the world's dry regions (Rodell et al., 2018; World Bank, 2016). As the world's cities grow, the urban regions will become more vulnerable to water-related climate shocks (such as flooding reducing the quality of surface and groundwater, rising seas resulting in salt water intrusion on groundwater, permanent damage to water-related infrastructure) with 25% of the world's cities already facing water insecurity (World Bank, 2016). Cities are also expected to be impacted by an increase in intensity and frequency of slow onset droughts driven by climate change, causing strain on municipal and industrial use. (World Bank, 2016).

3.4. Migration

Van Schaik et al. (2018) illustrated how multiple international organizations have published reports about how climate change is affecting migration patterns through stressed scarce resource pathways. The report cites papers from the World Bank, the Food & Agriculture Organization (FAO), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) that address trending migration patterns as a consequence of decreases in arable land and increases in water scarcity and food insecurity. This section discusses the current state of climate change-influenced migration and some modeled projections, in addition to presenting them through regional examples.

3.4.1. Internal Climate Migration

The World Bank's Groundswell report offers a comprehensive analysis of internal climate migration, defined to be migration that occurs within a nation's borders and a pressing development issue for policymakers (World Bank, 2018). The report models three regions, including Sub-Saharan Africa, South Asia, and Latin America by projecting the number of people that will be displaced and migrate within their country's borders due to slowly physically changing environments (Figure 3-1). The findings conclude that the migration in these regions will stress infrastructure and social support systems. The report makes use of utilizing demographic and socioeconomic data and models it with slow-onset environmental changes, such as water scarcity, crop failure, and sea level rise (not including extreme climate events such as flooding and superstorms). The model is integrated over 14 km^2 grid cells to simulate and understand population trends over the next 30 years.

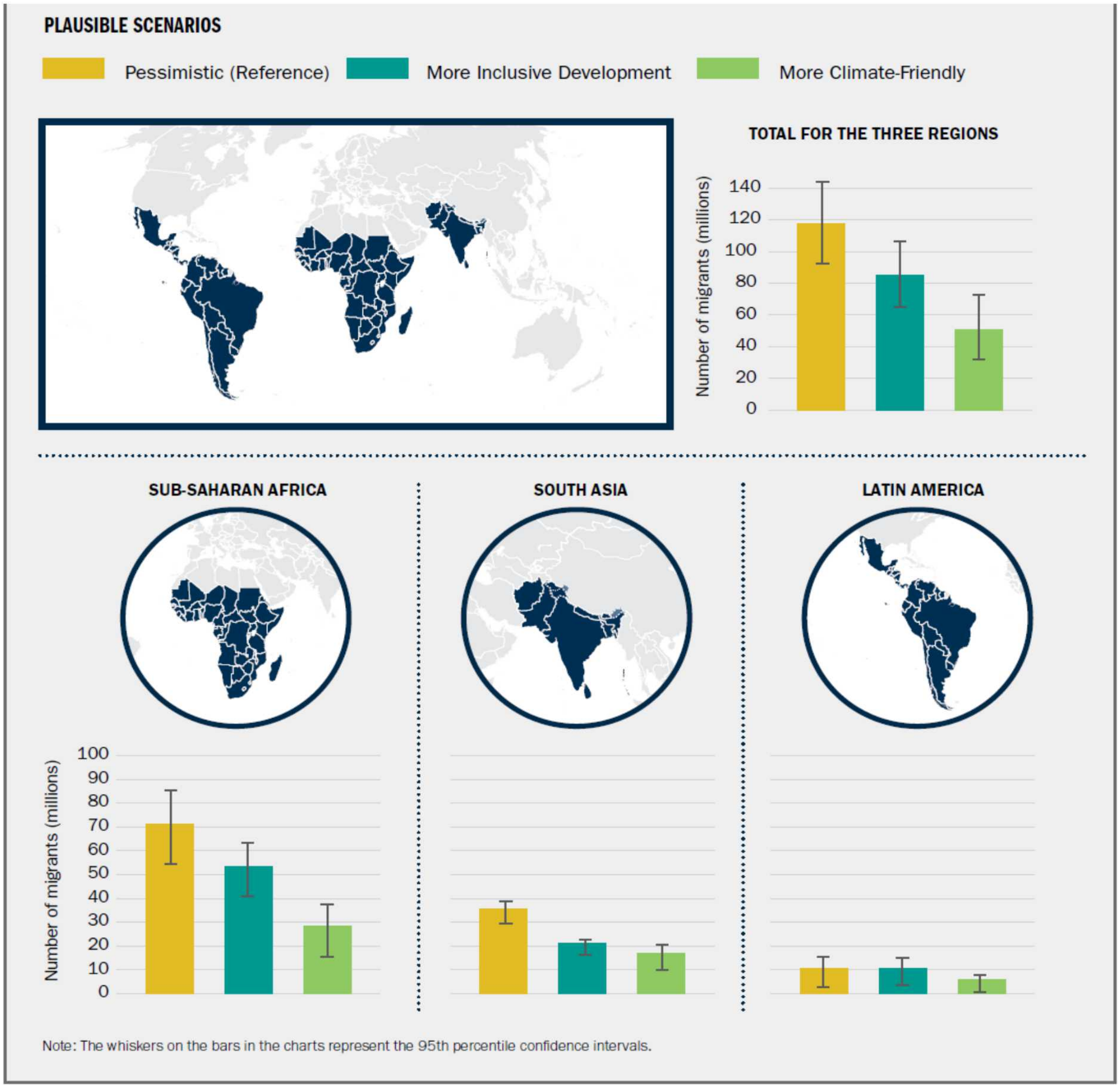


Figure 3-1. Projections of Internal Migration under Different Warming Scenarios by 2050 with 95% Confidence Intervals (World Bank, 2018)

To mitigate uncertainty, the model is run within defined climate and development parameters represented by three scenarios. These include a worst-case reference scenario, a development-focused scenario, and an optimistic climate scenario. In each modeled scenario, there is an increase of internal climate migration rate in each region by 2050. The worst-case scenario projects 143 million climate migrants with 86 million in Sub-Saharan Africa, 40 million in South Asia, and 17 million in Latin America if global carbon emissions remain high with poor development policies. The development-focused scenario projects the number of climate migrants within the three regions to be between 65 and 105 million if global emissions remain high but there is holistic development of infrastructure and support systems to meet the needs of climate migrants. The optimistic climate scenario projects 31 to 72 million climate migrants within the three regions if global emissions are abated and development remains business as usual. Each scenario projects the poorest countries seeing the highest migration numbers with migrants moving from areas vulnerable to climatic stress into areas well suited for agricultural development and urban environments, with these defined "in and out" areas emerging by 2030 and significantly increasing by 2050.

3.4.2. External Climate Migration – Asylum Applications

With immigrants seeking refuge from war torn counties, the European Union (EU) saw a surge in immigration during 2015. Missirian and Schlenker (2018) started investigating how climatic conditions might stress migration flows. Their motivation comes from trying to understand the relationship among severe drought, poor crop yields, and stressfully migrated farmers prior to the Syrian conflict (Missirian and Schlenker, 2018). Using data from 2000 to 2014, Missirian and Schlenker (2018) analyzed how climate in 103 countries contributed to the 351,000 asylum applications per year to the EU. They found a nonlinear relationship between temperature and EU asylum applications, noting that the deviation from the optimum temperature of 20°C resulted in an increase in asylum applications. They then modeled how asylum applications might change under future warming and emissions scenarios. Their results indicate a 28% increase (98,000 more) in asylum applications under RCP 4.5 and a 188% increase in (660,000 more) asylum applications under RCP 8.5.

3.5. Food

Betts et al. (2018) conducted a study using a modified version of the Hunger & Climate Vulnerability Index (HCVI), a tool developed by the UN World Food Program to understand a country's vulnerability to food insecurity as a function of climate events. The utilized a gridded climate model projection to better understand how physically changing environments impact food insecurity under the parameters of different scenarios. However, this iteration of the HCVI only considers food produced within a country's borders, and excludes food trade. With this constraint, Betts et al. (2018) examines the HCVI for 122 developing and least-developing nations defined by their lack of membership in the Office for Economic Cooperation and Development or the EU.

Using this modified HCVI and using data from the World Bank, the World Resources Institute, the UN Food & Agriculture Organization, the UN Development Program, and the UN Population Fund, the study quantifies food insecurity as a function of a nation's exposure to hazardous climate events, a nation's agriculture production sensitivity to hazardous climate events, and a nation's ability to cope with food shocks caused by climate-related events. They find that the HCVI's greatest geographic variation is due to social and economic conditions. Notable findings include the greatest increases in vulnerability to food insecurity for Oman, India, Bangladesh, Saudi Arabia, Mauritania, and Yemen. Southeastern Africa also saw significant increases in vulnerability to food insecurity due to increased length of drought. However, vulnerability to food insecurity decreases for three African countries including Mali, Burkina Faso, and Sudan (Figure 3-2). The researchers attribute this to the recovery period in rainfall that this region is generally believed to be experiencing. They also note that India's projected increase in vulnerability is due to the increase in flooding outweighing the decrease in episodic droughts.

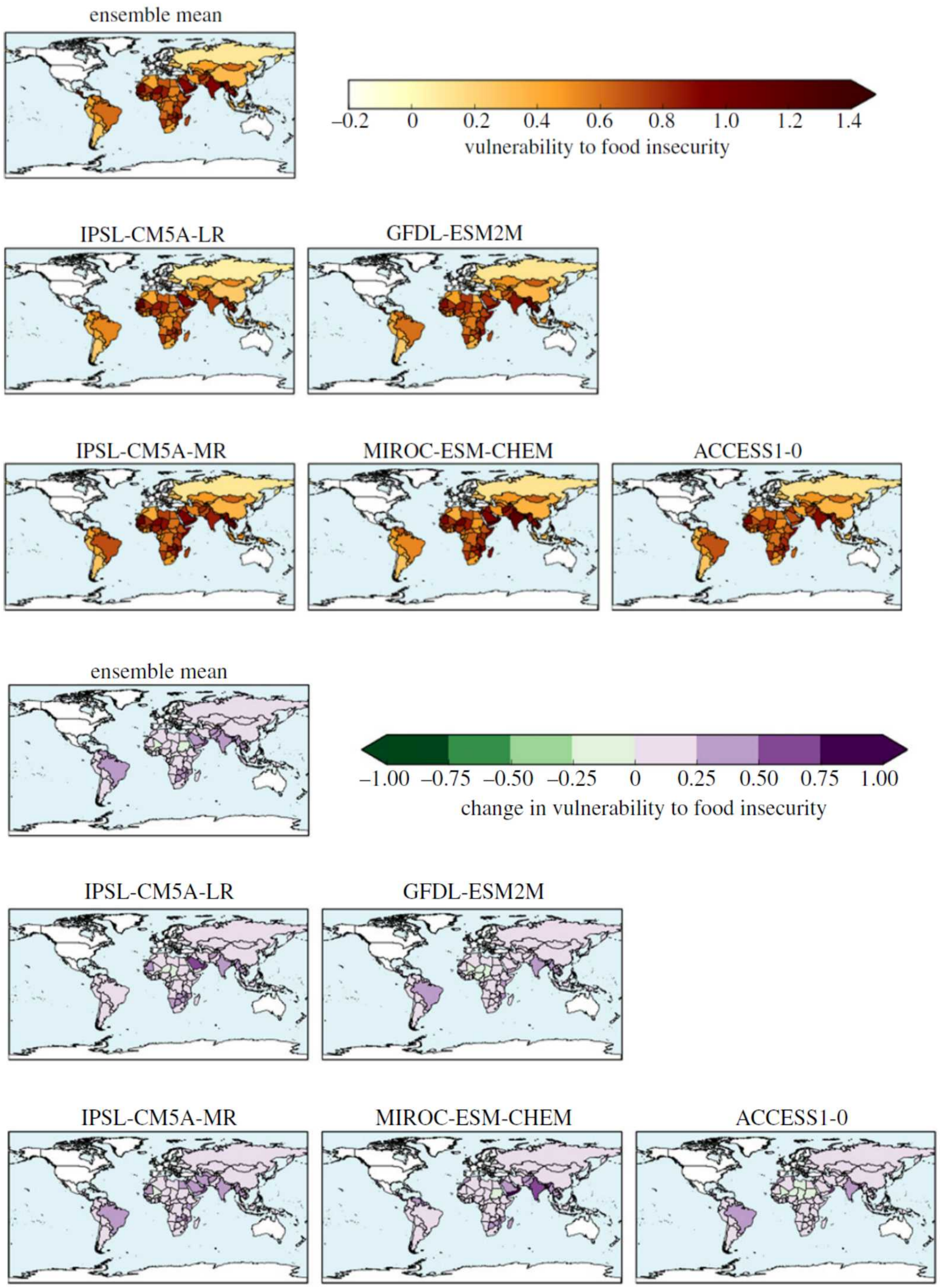
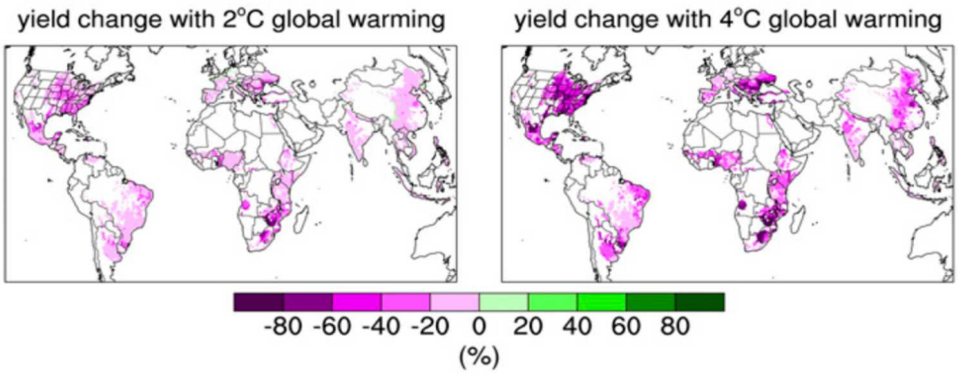


Figure 3-2. Changes in UN World Food Program Hunger and Climate Vulnerability Index under 2°C of Warming (Betts et al., 2018)

3.5.1. Corn Production Shocks

Volatility in cereal markets is not new, with the peak monthly nominal prices of corn, wheat, and rice being anywhere from 200-300% higher than low monthly prices between 2007 and 2017 (Tigchelaar et al., 2018). As global mean temperature rises, climate change impacts are added to the list of factors that contribute to market volatility, such as biofuel production, available inventory, trade agreements, and the status of international financial institutions (Tigchelaar et al., 2018). They project that continued warming will disrupt mean crop yields by 2050, with the tropics suffering the most due to their vulnerability to food insecurity (Tigchelaar et al., 2018).



Country	Present-day climate, %		2 °C warming, %		4 °C warming, %	
	>10	>20	>10	>20	>10%	>20
United States	3.8	0.0	68.6	29.5	100.0	96.9
China	6.6	0.0	46.2	16.8	98.8	89.2
Brazil	1.4	0.0	38.7	9.4	90.5	64.1
Argentina	3.4	0.1	50.0	9.9	96.9	86.9
Ukraine	2.5	0.3	51.8	19.2	98.2	85.0
Mexico	1.0	0.0	18.5	1.7	79.6	44.0
India	0.8	0.0	7.4	1.6	50.9	10.4
France	0.9	0.0	21.1	2.3	81.7	52.3
Canada	0.3	0.0	12.0	1.1	70.0	40.6
South Africa	16.6	6.9	79.2	59.8	97.5	94.5
Top four producing*	0.0	0.0	6.1	0.0	86.6	48.1
Top four exporting†	0.0	0.0	6.9	0.1	86.1	45.8
Top export + import‡	0.0	0.0	1.1	0.0	68.9	21.2

Figure 3-3. How Temperature Changes Are Affecting Corn Yield (Tigchelaar et al., 2018)

Tigchelaar et al. (2018) also considered the impact of physically changing environments on mean corn yields and the variability in corn yields (Figure 3-3). Using the constraint of a 2°C increase in global mean temperature above the preindustrial era, the scientists model and analyze the effect of this Paris Agreements target on crop yields using Coupled Model Intercomparison Project Phase 5 (CMIP5) pathway simulations. The modeling efforts do not include the effects of precipitation changes. The study concludes that corn crop yields will decrease globally with the exception of some areas in western Europe and China. Their results reveal particularly strong corn production decreases in the southeastern United States, eastern Europe, and southeastern Africa, aligning with previous model predictions using empirical data in Tigchelaar et al. (2018). In numbers, mean total corn production is projected to decrease for the United States by 18%, 10% for China, 8% for

Brazil, and 12% for Argentina – the four largest producers of corn – under a 2°C warming scenario. This equates to a decline in global exports of 53 million tons of corn or 43% volume decrease of corn currently exported in the world (Tigchelaar et al., 2018).

The study also quantifies how warming will affect yield variability by analyzing the commonly used coefficient of variation (CV) to model crop yield variability. Their results show CV increases globally, with notable variability increases in the United States, eastern Europe, and southern Africa. Within a 2°C warming scenario, the chances of a >10% crop loss in a given year increases to 69% for the United States, 46% for China, 39% for Brazil, and 50% for Argentina. With the world's population expected to increase to approximately 10 billion by 2050, these circumstances create food security implications by redefining the ability to supply the global market with sufficient and affordable food. It should be noted that the study does not estimate how mean total corn production will increase in countries that could become the bread baskets of the world.

3.6. Flood Damage Costs

With rises in global mean sea level, the associated costs of flood damage are projected to be $1.4 trillion USD/year by 2100 under an RCP 4.5 emissions scenario (Jevrejeva et al., 2018). Under RCP 8.5, the scientists in Jevrejeva et al. (2018) discover costs that could increase to at least 10 times that amount, equaling $14 trillion to $27 trillion USD/year by 2100. Their study finds that upper middle income countries experience the largest increase in year to year flood damage costs, with China experiencing the greatest costs. High income countries with better present-day infrastructure are projected to experience the lowest costs.

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4. CONCLUSION

This report gives a brief overview of climate change science and its current and impending consequences, both in physical environments and on socioeconomic systems. After reviewing the science and the consequences, there is a clear difference between what is happening and what is going to happen. Although there is tangible evidence of climate change having current impacts, its effects are a slow onset, stressing environmental, social, and economic systems and threatening security and stability regionally and globally. The material in this report serves as evidence of that climate change and its associated social and economic impacts are a futures problem unless technology, mitigation, development and policy address the gaps and provide solutions to abate the effects of global human activity.

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APPENDIX A. CLIMATE CHANGE SCIENCE IN 2018 & ASSOCIATED SOCIAL AND ECONOMIC IMPACTS – A BRIEF OVERVIEW

climate change science in 2018 & associated social and economic impacts

- a brief overview -

presentation outline

climate change science review 2018

currently changing environments

what has changed? what is changing?

climate projections & predictions

what will change?

temperature, atmospheric & oceanic circulation, freshwater supply, sea level rise & flooding, extreme climate events, oceanic deoxygenation, land degradation

associated social & economic impacts

economic impacts

what are some associated costs with change?

social stressors

how will humans and human developed systems be affected by change?

inequity, inequality, water, migration, food, flood damage costs

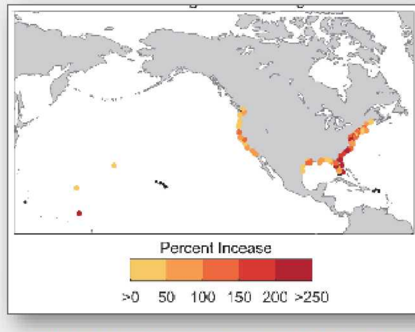
2

rain and flooding in lynchburg, virginia

an incident:

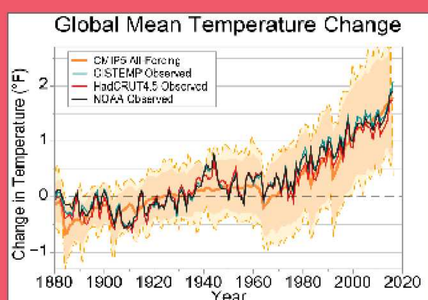
"Flooding in Lynchburg, Virginia prompts fears of dam failure, leads to evacuations" was the title of an NBC News article on August 4, 2018

greater context:

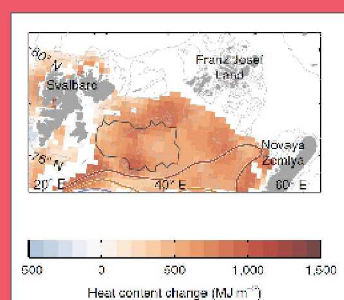


% Increase in U.S. High Tide Flooding since 2000 (NOAA, 2018)

3



Graph of increases in global mean temperature (USGCRP 2017)



Displays the changes in heat content of the northern Barents Sea from 1970 – 2016 (Lind et al., 2018).

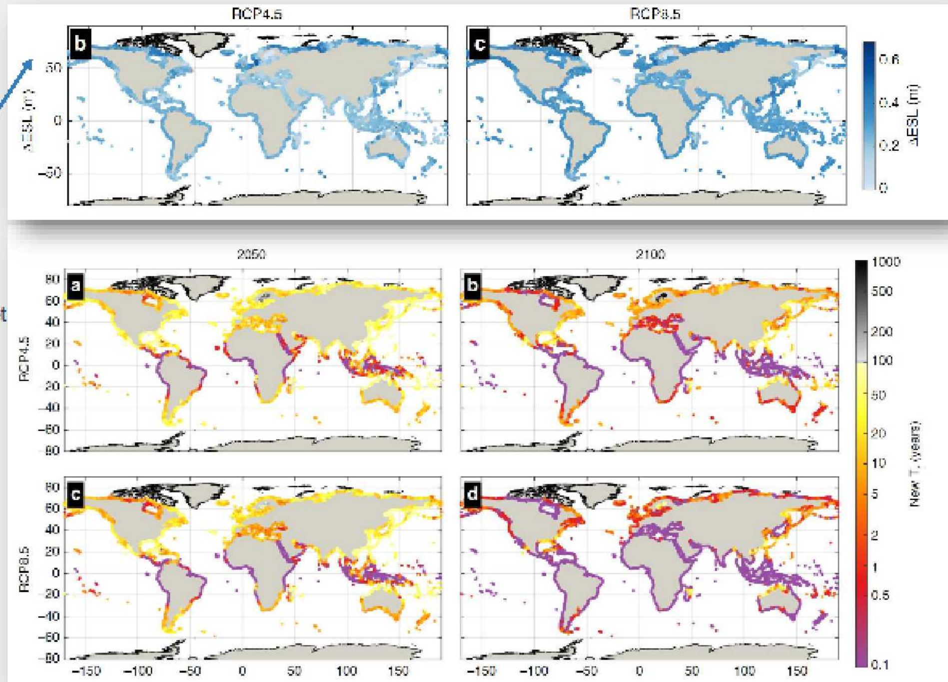
it's getting hot

- Ice cores in Greenland reveal unprecedented summer melting
- The IMBIE Team at NASA reveal 2,720 ± 1,390 billion tons of ice loss from Antarctic Ice Sheets between 1992 and 2017
- Warming hotspot shows northern Barents Sea becoming more Atlantic and less Arctic

4

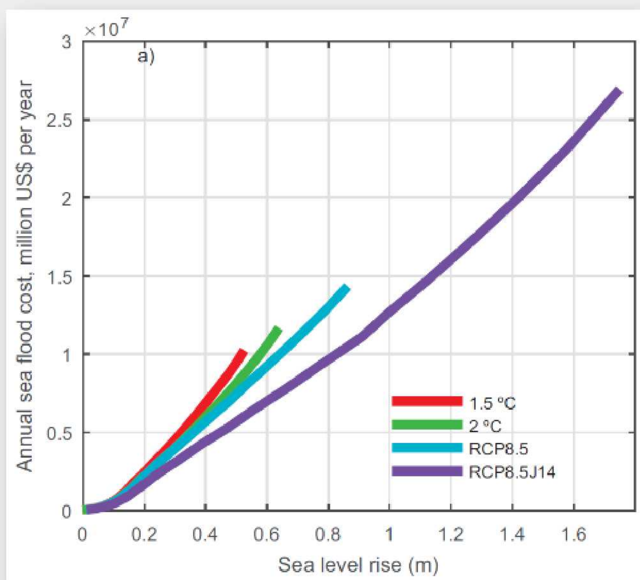
some environmental consequences

Projected changes in extreme sea level height under different emission scenarios (Vousdoukas et al., 2018)

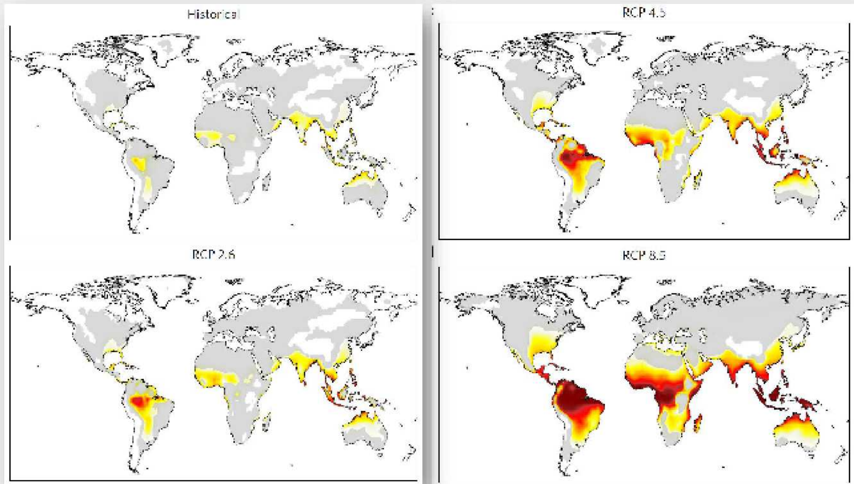


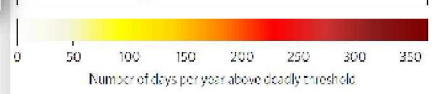
Changes in frequency of return for what were considered 100 year extreme sea levels under different radiative forcing scenarios (Vousdoukas et al., 2018)

Global costs associated with annual coastal flooding under different radiative forcing scenarios (Jevrejeva et al., 2018)



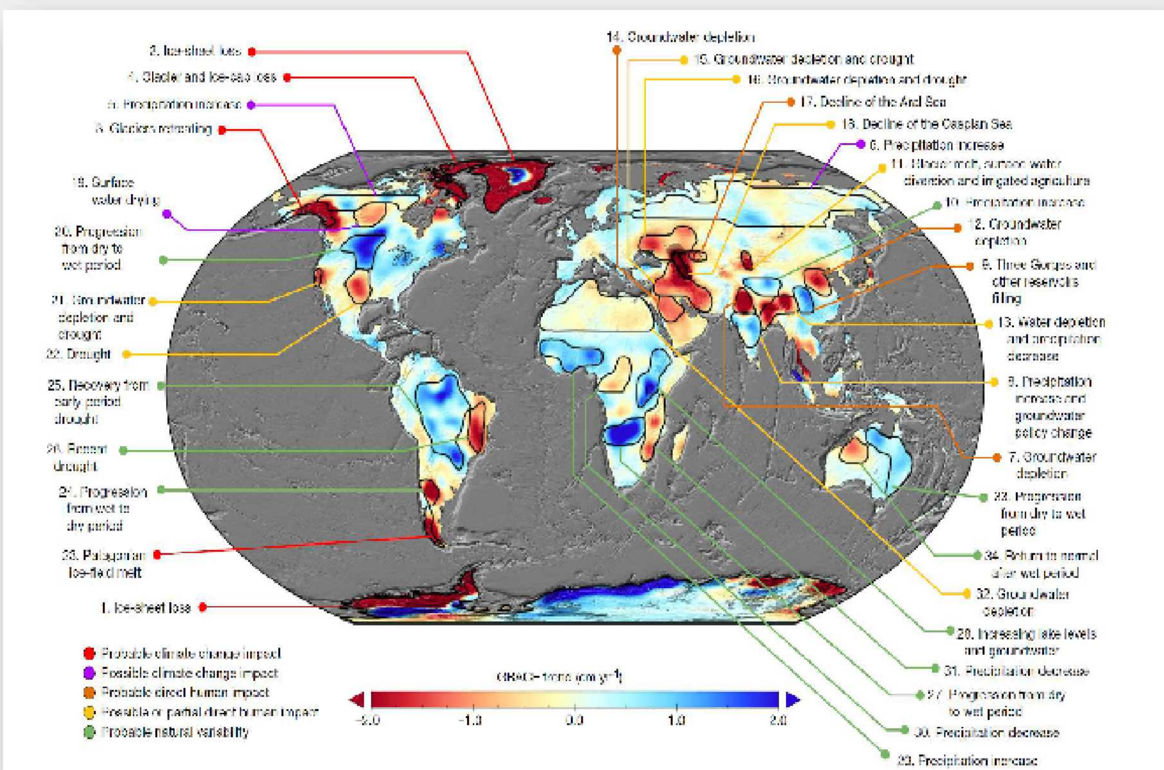
which will cost





Displays number of days of exposure to lethal climatic conditions under different radiative forcing scenarios (Guerreiro et al., 2018).

other environmental consequences will be



Displays the changes in global freshwater availability from 2002 to 2016 (Rodell et al., 2018).

but this is also happening

50%

Demand increase in water for agriculture by 2050

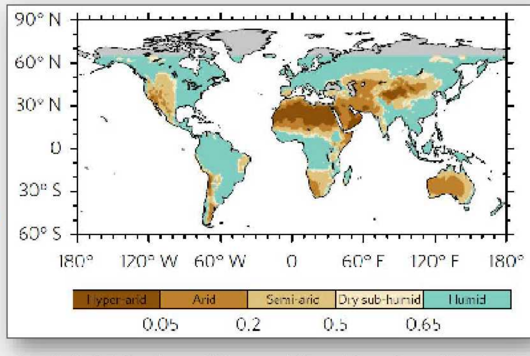
50% - 70%

Demand increase in water for cities by 2050

85%

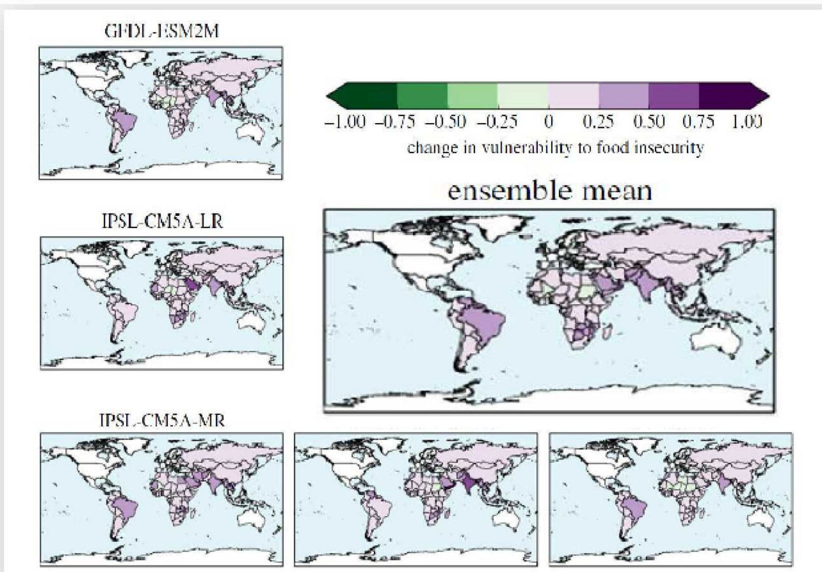
Demand increase in water for energy sector by 2035

Projections of increase in demand due to population growth, climate change and human consumption (World Bank, 2016)



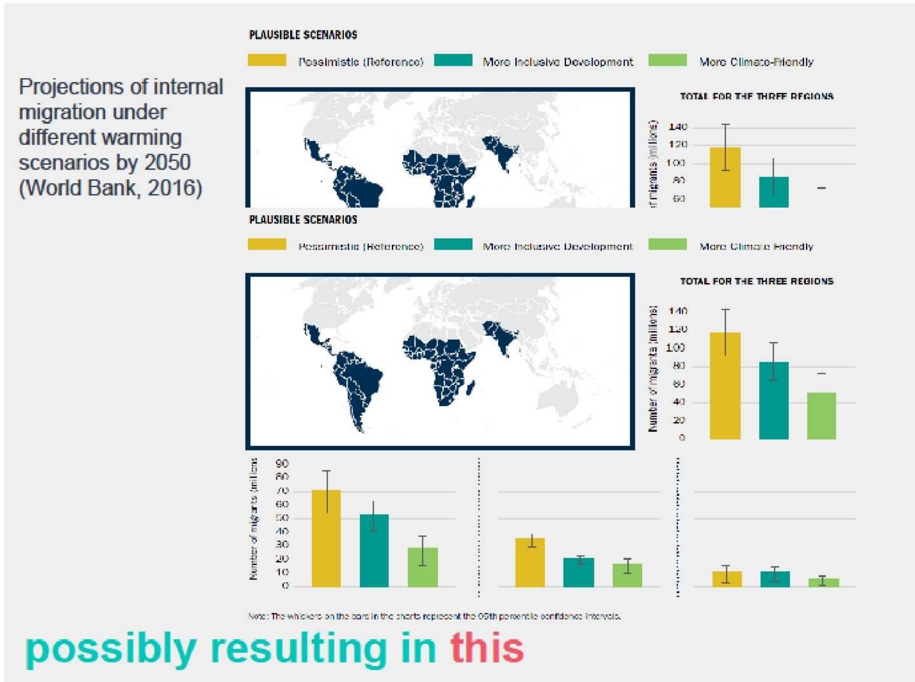
Spatial distribution of the world's arid regions (Park et al., 2018)

with this on the horizon



Changes in UN World Food Program Hunger & Climate Vulnerability Index under 2° C of warming (Betts et al., 2018

creating scenarios like this


Projections of internal migration under different warming scenarios by 2050 (World Bank, 2016)
PLAUSIBLE SCENARIOS
Pessimistic (Reference)
More Inclusive Development
More Climate-Friendly
TOTAL FOR THE THREE REGIONS
Number of migrants (millions)
Note: The whiskers on the bars in the charts represent the 95th percentile confidence intervals.
possibly resulting in this


areas considered to be at greatest socioeconomic risk due to climate change
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