

**A Scientific Assessment of Coastal Hazards
Subcommittee on Water, Oceans, and Wildlife
U.S. House Natural Resources Committee
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I am David R. Legates, professor and climatologist, at the University of Delaware. I also hold a joint appointment in the Department of Applied Economics and Statistics as well as in the Physical Ocean Science and Engineering program. I served as the Delaware State Climatologist from 2005 to 2011 and was a founder of the Delaware Environmental Observing System, a statewide network for environmental monitoring and analysis. I was part of the US delegation that negotiated a protocol for the first climate data exchange program with the Soviet Union in 1990. I am recognized as a Certified Consulting Meteorologist by the American Meteorological Society and was the recipient of the *2002 Boeing Autometric Award* in Image Analysis and Interpretation by the American Society of Photogrammetry and Remote Sensing. I would like to thank both the Chairman and the Committee for the opportunity to provide my perspective of forty years of experience on climate change and coastal communities.

It is a privilege for me to offer my views on the science involving sea level rise and coastal impacts due to weather and climate variability. I might best be described as a statistical hydroclimatologist – someone who researches the interactions between water and climate from an observational setting. I have investigated biases in our evaluation of precipitation owing to errors in precipitation gage measurement and how they influence satellite and radar estimates. I also have been involved with the analysis of hydrological data to assess the impact of climate variability and change.

INTRODUCTION

Living along the coasts and in low-lying areas can be hazardous. Coastal storms, such as hurricanes, tropical storms, and nor'easters, often batter the coast, producing high winds and waves. Heavy rainfall pools into low-lying areas, turning flood plains and the mouths of streams and rivers into flooded regions with possibly fast-moving water. Sea levels are rising, as they have been for the past 20,000 years, which encroaches upon the land. In addition, the land subsides in places due to channelization of the river system or the response of the Earth's mantle to glacial isostatic adjustment.

In Louisiana, for example, the land is subsiding at a considerable rate due to sediment compaction. The Mississippi River flood plain is naturally replenished by the sediment that is deposited during flood events. However, the Mississippi River has been channelized by the levee system such that it is like a "freeway with no on-ramp". Rivers such as the Amite and Comite no longer empty into the Mississippi. Thus, local flooding occurs in Baton Rouge and throughout much of southern Louisiana east of the Mississippi River because of the changed drainage patterns. Moreover, the flood waters of the Mississippi River, which used to bring sediments to replenish the land, are efficiently transported to the Gulf of Mexico. The land, therefore, subsides as the existing sediments compact, leaving areas such as New Orleans below sea level and resulting in an increased loss of wetland areas.

In the Mid-Atlantic region (*i.e.*, Delaware and New Jersey), the land also is subsiding at a rapid rate. At the maximum spatial extent of the Laurentide ice sheet (~21,500 years ago) that extended as far south as central Pennsylvania, the weight of the ice pressed down on the land surface causing it to subside, particularly over much of New England and eastern Canada. Consequently, the land along the peripheral forebulge of the Laurentide ice sheet (*i.e.*, in the Mid-Atlantic region) was forced upward due to the pressure placed on the land to the north. As the deglaciation of the Laurentide ice sheet occurred during the late

Holocene, the regions under the ice sheet, much of New England has seen relatively rapid uplift, while regions just to the south have experienced (and continue to experience) subsidence.

Barrier islands often block the effect of landfalling storms and mitigate the effect of these storms on inland areas. Storms often reshape the coastline by moving the sand that comprises barrier islands. Problems often arise when humans build upon these shifting sands and expect them to remain immobile. The fact is that barrier islands are constantly dynamic, and their shape and presence make living in coastal regions potentially hazardous.

SEA LEVEL RISE AND CLIMATE CHANGE

Globally, sea level began to rise after the demise of the last major glaciation approximately 20,000 years ago (Figure 1), rising nearly 400 feet (~120 m). As the glaciers covering much of the Northern Hemisphere land areas melted, sea level rose quite rapidly. Over the last 8,000 years or so, the rise has been much slower, and has occurred due to melting of land ice as well as the thermal expansion of sea

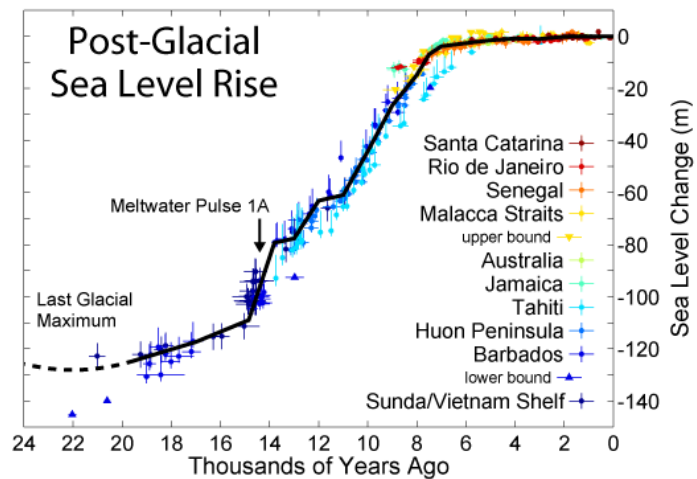


Figure 1: Sea level rise since the last glacial maximum (Wikipedia).

water. The rate over the last century has been about 7 to 8 inches (~2 mm yr⁻¹). However, the North Polar region has not yet reached equilibrium such that melting continues to occur. Locally, trends in sea levels may vary substantially from the global trend because of both tectonic activity and coastal subsidence or coastal isostatic rebound.

Consider a cube of ice placed into a room at 72°F. The ice will continue to melt, even though the room remains at a constant temperature. This is because the ice cube has not reached equilibrium with the temperature of the room and melt of the ice cube will continue to occur.

Our question today is whether rising concentrations of greenhouse gases are causing sea levels to rise dramatically. Specifically, are we seeing an increase in the rate of sea level rise? To address this question, we can examine historical observations of sea level as well as satellite-derived estimates.

The National Oceanographic and Atmospheric Administration (NOAA) regularly updates its coastal sea level tide gauge data which includes measurements at coastal locations along the East Coast, the Gulf Coast, the West Coast, the Pacific Ocean, the Atlantic Ocean, and the Gulf of Mexico. Their record covers more than 200 measurement stations.

The longest NOAA tide gauge record in the United States is located at the Battery in New York City. Its 160-year record (Figure 2, top) shows a steady rate of sea level rise of 11 inches per century, slightly higher than the current global average of about 7 to 8 inches per century (or about 0.075 inches per year) due to the coastal subsidence discussed earlier. Atlantic City NJ (Figure 2, bottom) illustrates a steady rise at a higher level – about 16 inches per century – due to its location near the peripheral forebulge of the Laurentide ice sheet.

Although the data from Kings Point is a much shorter record, both stations show that sea level rise over the past century (and since 1855 for The Battery) has been steadily increasing despite periods of relatively rapid air temperature increase and cooling that have occurred over the past century. Moreover, no correlation exists between atmospheric carbon dioxide concentrations and sea level rise – CO₂ has exhibited no apparent impact

on the rate of sea level rise despite the rise in atmospheric CO2 concentrations from 280 parts per million to 400 parts per million.

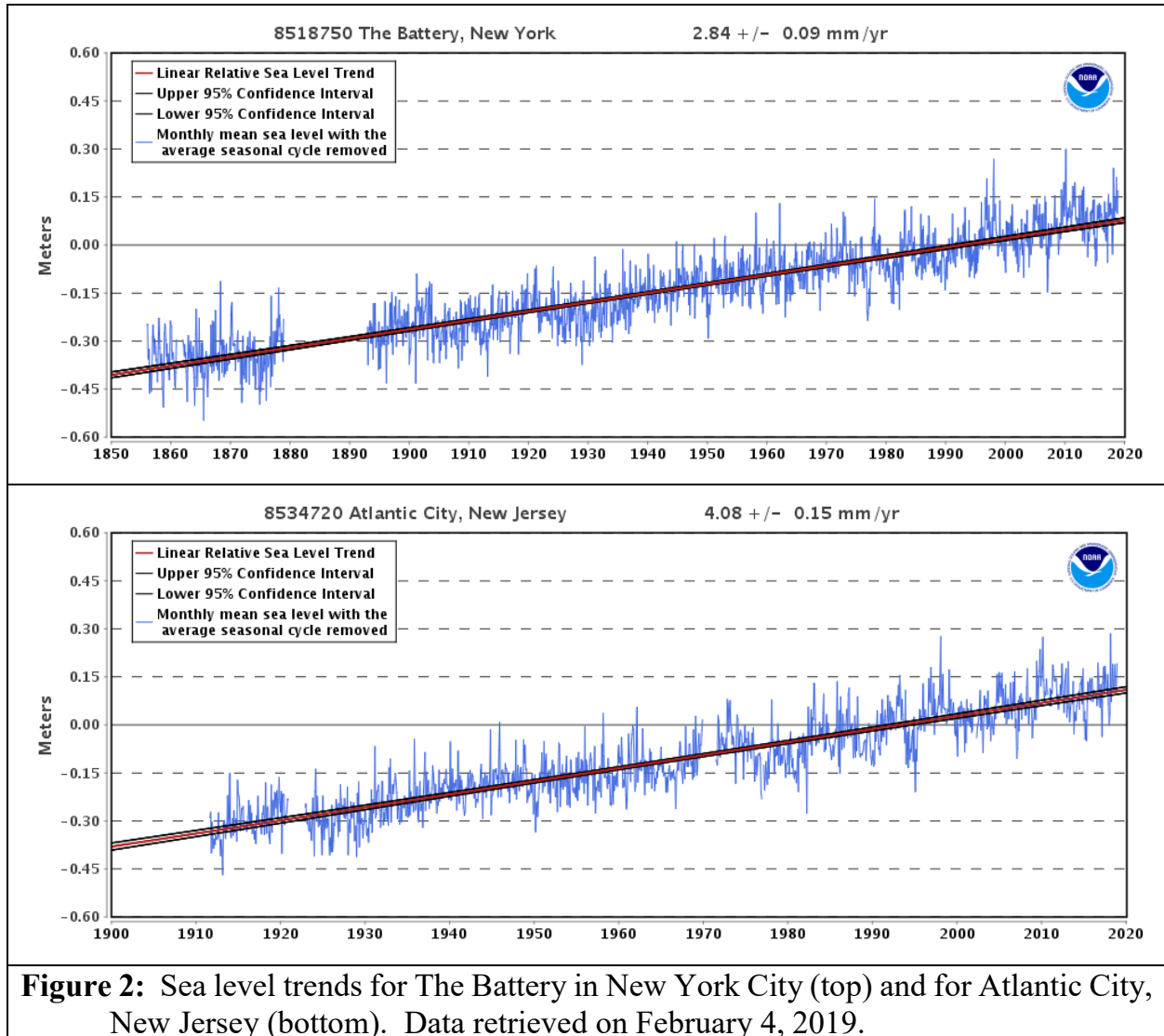
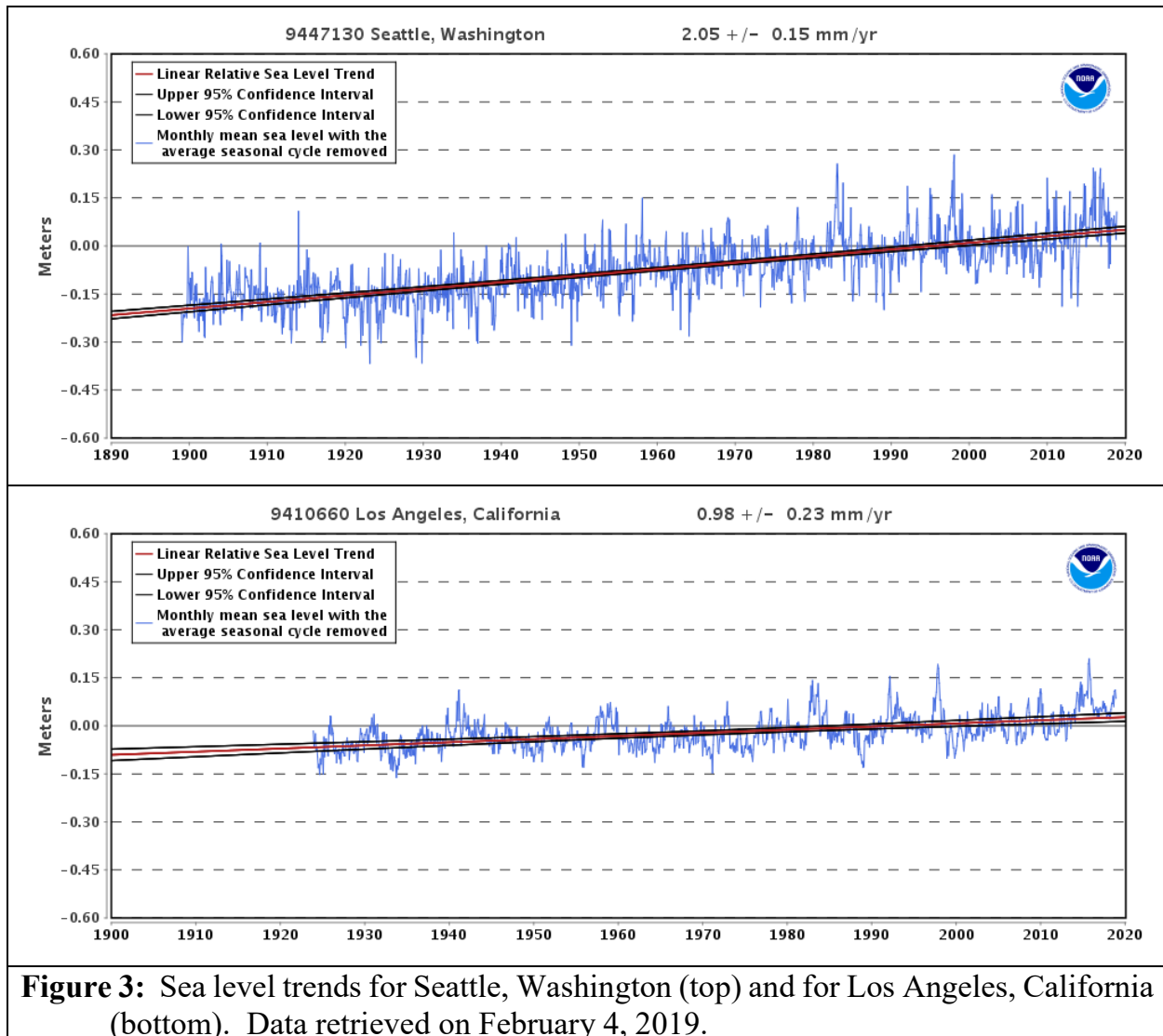


Figure 2: Sea level trends for The Battery in New York City (top) and for Atlantic City, New Jersey (bottom). Data retrieved on February 4, 2019.

Consider now the west coast of the United States. The 100+ year record in Seattle WA (Figure 3, top) shows a steady rate of sea level rise of about 8 inches per century, near the long-term global average. Although a shorter record at Los Angeles CA (Figure 3, bottom), Los Angeles has experienced a steady rate of sea level rise of about 4 inches per century, below the long-term global average.



Along the United States Gulf Coast, the 100+ year record at Grand Isle LA (Figure 4) also shows a steady rise in sea level of about 35.7 inches. Although the curve shows a very high rate of sea level rise, the increase is linear with little hint of an accelerating trend due to the possible impact of increases in anthropogenic greenhouse gases. Again, the culprit for this high rate of sea level rise is the compaction of sediments and the channelization of the Mississippi River.

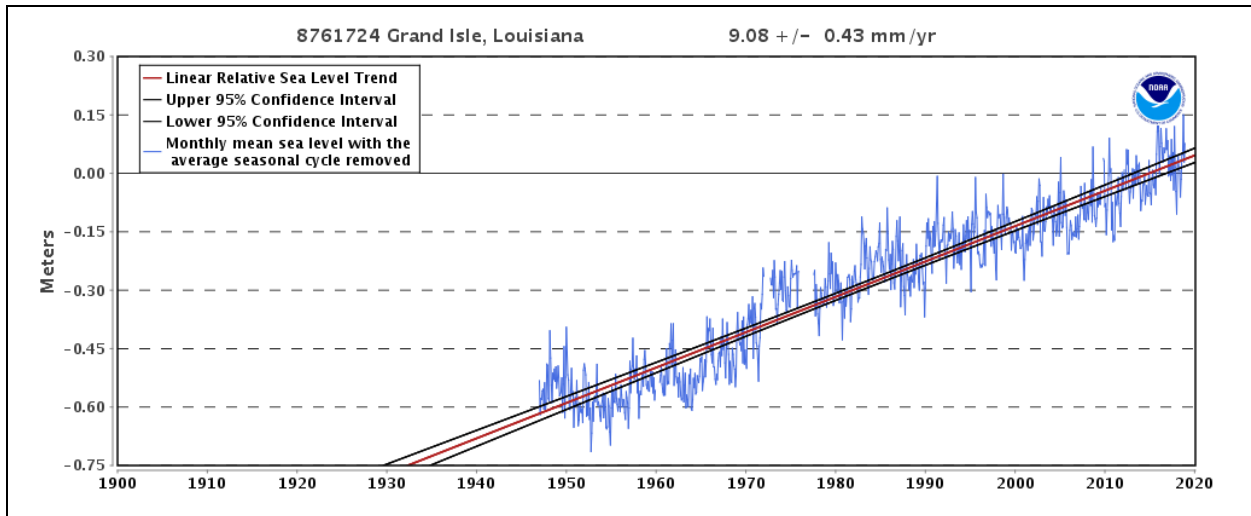


Figure 4: Sea level trends for Grand Isle, Louisiana. Data retrieved on February 4, 2019.

Honolulu HI (Figure 5), like many island stations, exhibits significant yearly fluctuations in sea level due to the impact of global ocean currents. However, sea level rise in Honolulu has been only about 5.8 inches per century, with virtually no correlation with global CO₂ levels.

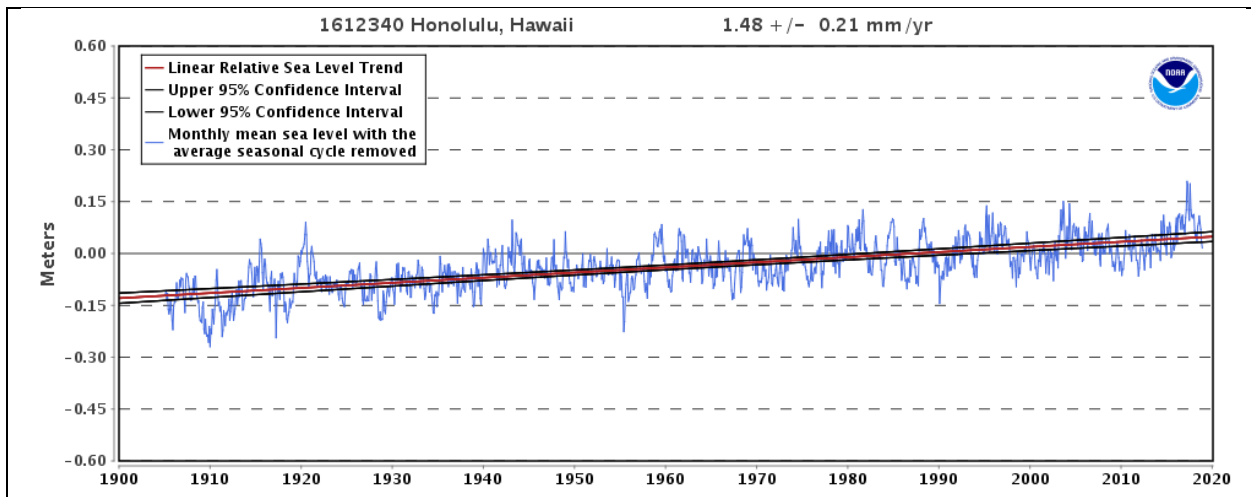
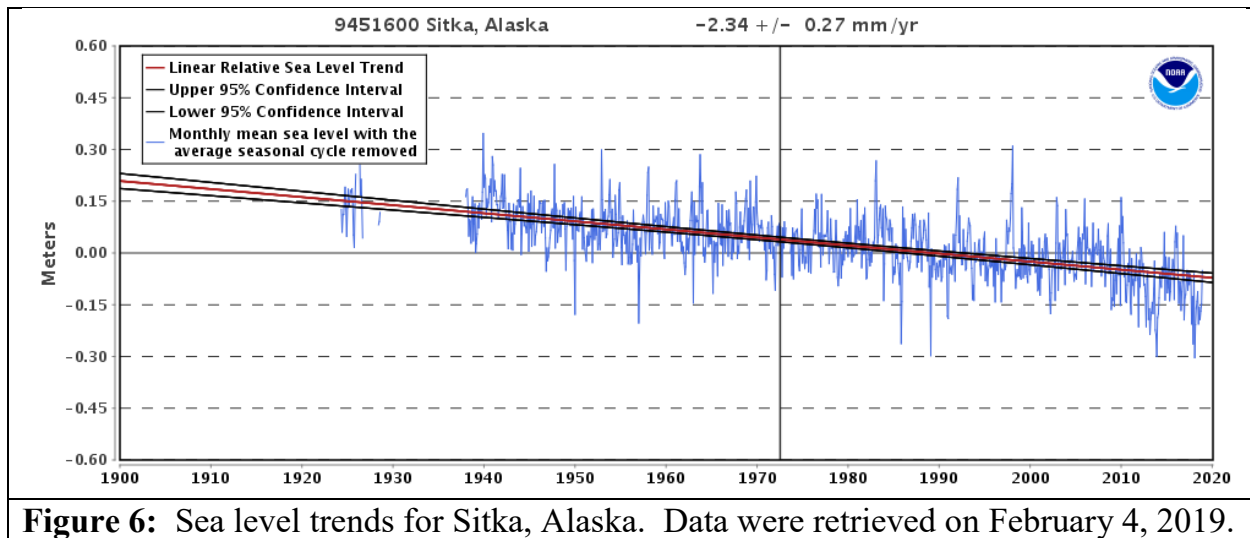


Figure 5: Sea level trends for Honolulu, Hawaii. Data were retrieved on February 4, 2019.

By contrast, sea level trends for Sitka AK (Figure 6) shows a *decrease* in sea level of about 9.2 inches per year. This illustrates the effect from both local tectonic activity as well as isostatic rebound effect of the unloading of the ice sheet during the last ice age.



The message of these and many other stations around the United States is that while sea level rise is not constant, its rate of change over time is *not* changing because of increasing concentrations of greenhouse gases. If CO₂ was an agent causing sea level rise to increase, the patterns should show an increasing trend in the rate of sea level rise over time. The records shown here (and at many other stations around the globe) do not exhibit a substantial increase in sea level over time. Local and regional changes in sea levels exhibit typical natural variability, relatively unrelated to changes in the global averaged sea level. Thus, atmospheric trace gas concentrations have no measurable impact on sea levels.

TROPICAL CYCLONES AND CLIMATE CHANGE

The impact of more frequent and intense hurricanes is important owing to the damage that may occur to coastal areas. However, much of the potential damage due to tropical cyclones along the coast is likely due to human settlement of low-lying and coastal areas.

In 2013, the Fifth Assessment report of the IPCC proclaimed “there is *low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities ... and there is *low confidence* in attribution of changes

in tropical cyclone activity to human influence owing to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings.”

Investigation of the trend in hurricanes making landfall in the continental United States since 1990 shows no significant trend in either landfalling hurricanes, major hurricanes (Category 3 or higher), or normalized damage (Figures 7 and 8). Although the data exhibit considerable variability, the long-term trend is fewer landfalling hurricanes and major hurricanes while the normalized damage (constant dollars) has remained unchanged.

In the 1990s, Dr. William Gray (Colorado State University) found that natural cycles in the Atlantic basin (sea surface temperatures) and air temperature variability drove variability in hurricane activity. Variability in the Atlantic Multidecadal Oscillation (fluctuations of sea surface temperature) may be related to changes in the thermohaline circulation. In its positive (warm) phase, hurricane formation is more likely while the converse is also true (Figure 9, blue line).

Accumulated Cyclone Energy (ACE) is the summation (every six hours) of the apparent wind energy produced by a tropical system over its lifetime. The three-year averaged ACE for the Atlantic Basin is shown (Figure 9, green line) and for the Northern Hemisphere and the globe (Figure 10). As with the Atlantic Multidecadal Oscillation, ACE shows much temporal variability but little by way of a trend.

Little-to-no observational evidence exists that tropical cyclone activity has worsened over the last 50+ years, let alone address the question of whether changes in hurricane activity could be affected by anthropogenic activities. None of these data demonstrate any obvious long-term trends, but they do exhibit large variability on yearly/decadal time scales.

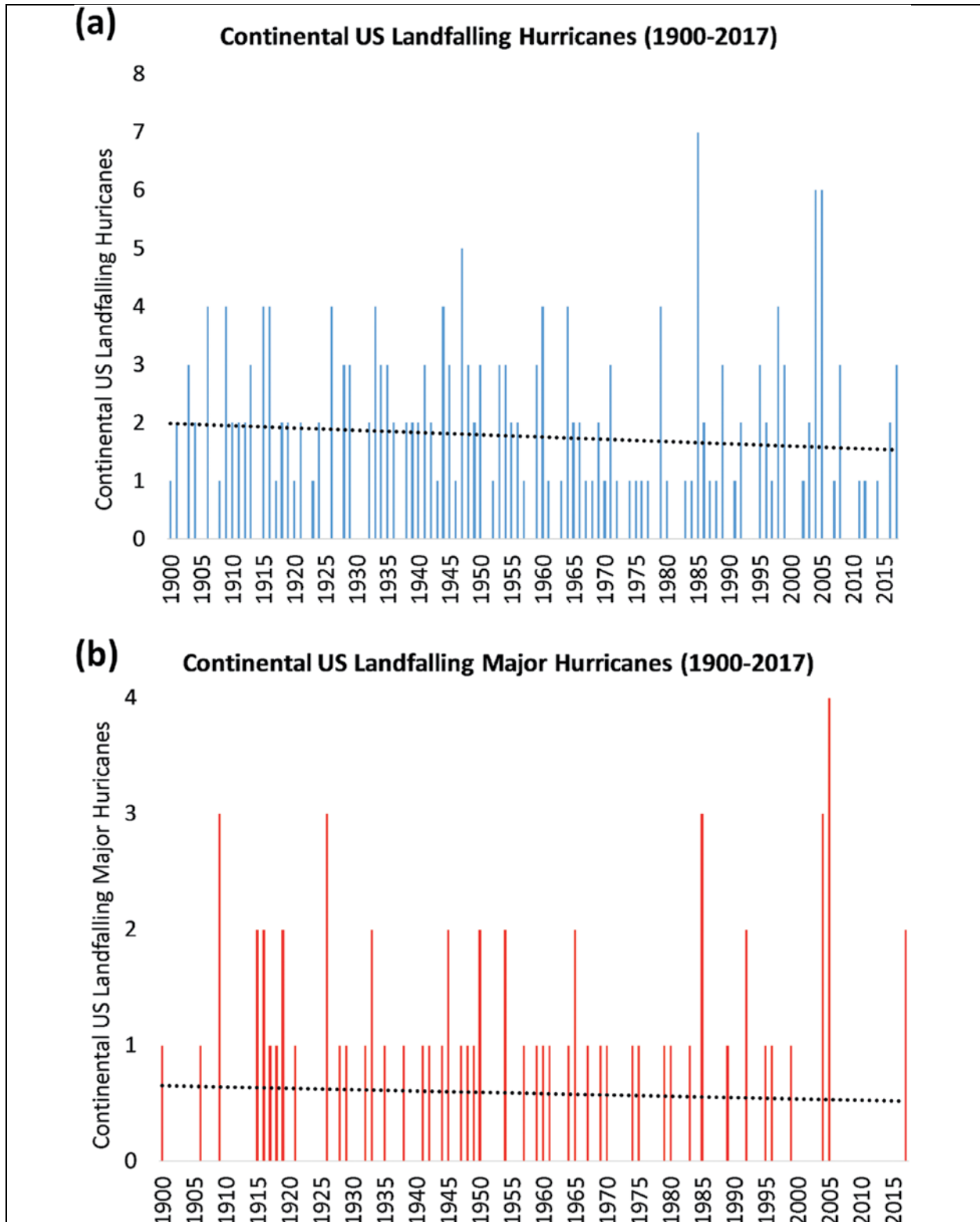


Figure 7: Landfalling hurricanes and major hurricanes for the continental United States since 1900. Figure from Klotzbach, P.J., S.G. Bowen, *et al.* (2018). “Continental U.S. hurricane landfall frequency and associated damage.” *Bull. Amer. Meteorol. Soc.* **99**(7): 1359-1377.

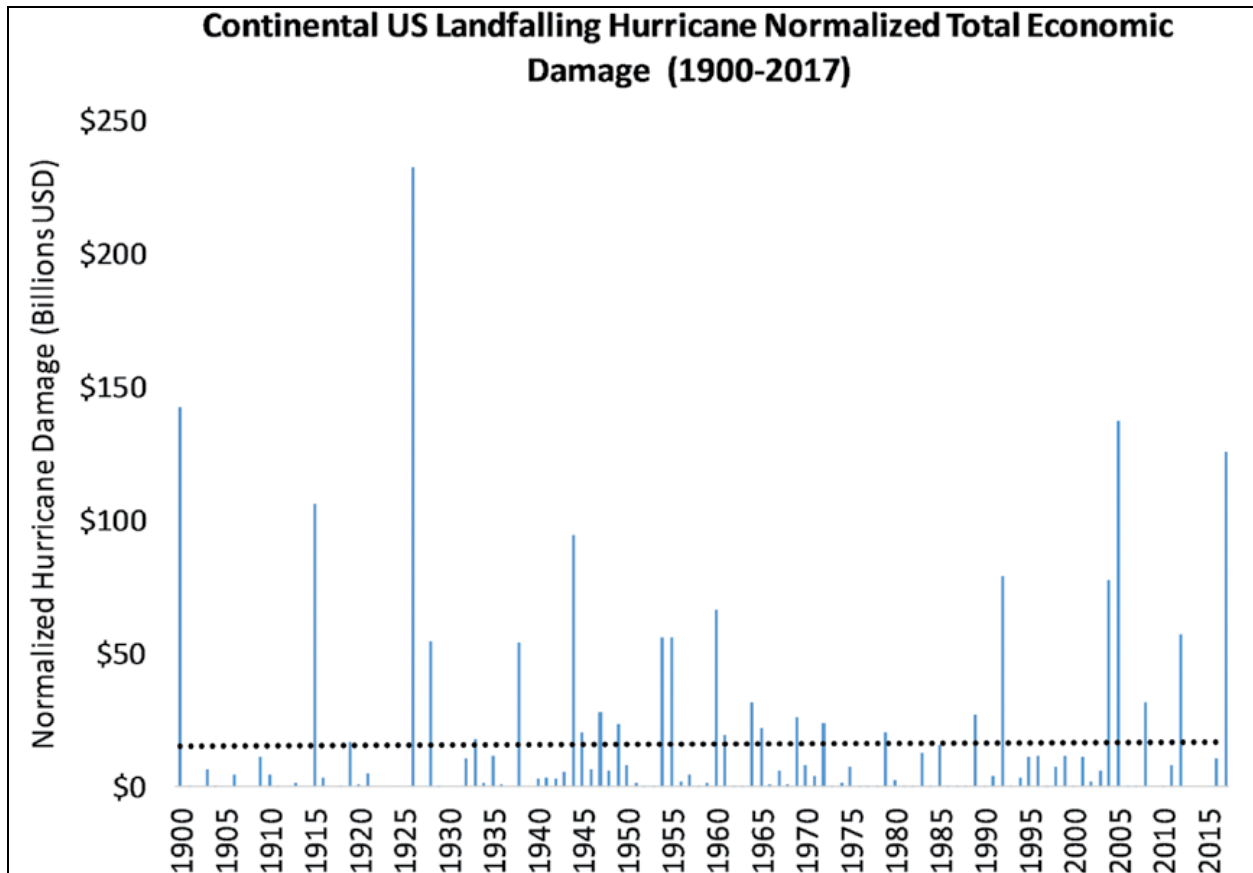


Figure 8: Normalized landfalling hurricane damage for the continental United States since 1900 in constant 2017 dollars. Figure from Klotzbach, P.J., S.G. Bowen, *et al.* (2018). “Continental U.S. hurricane landfall frequency and associated damage.” *Bull. Amer. Meteorol. Soc.* **99**(7): 1359-1377.

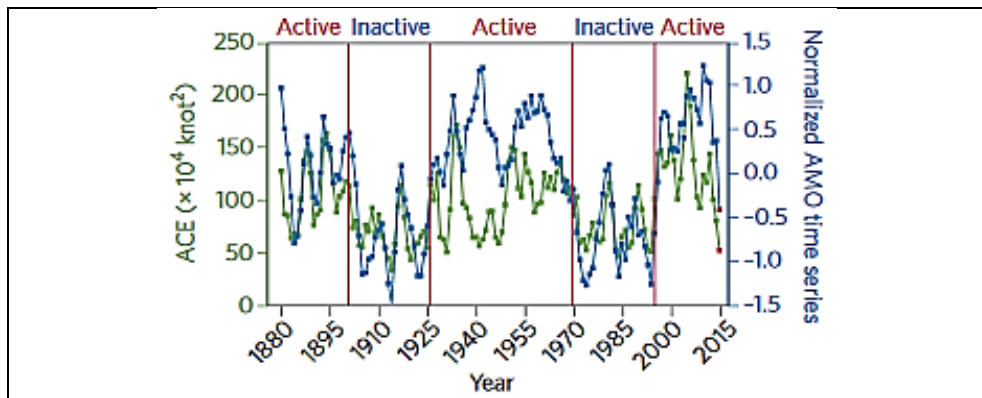
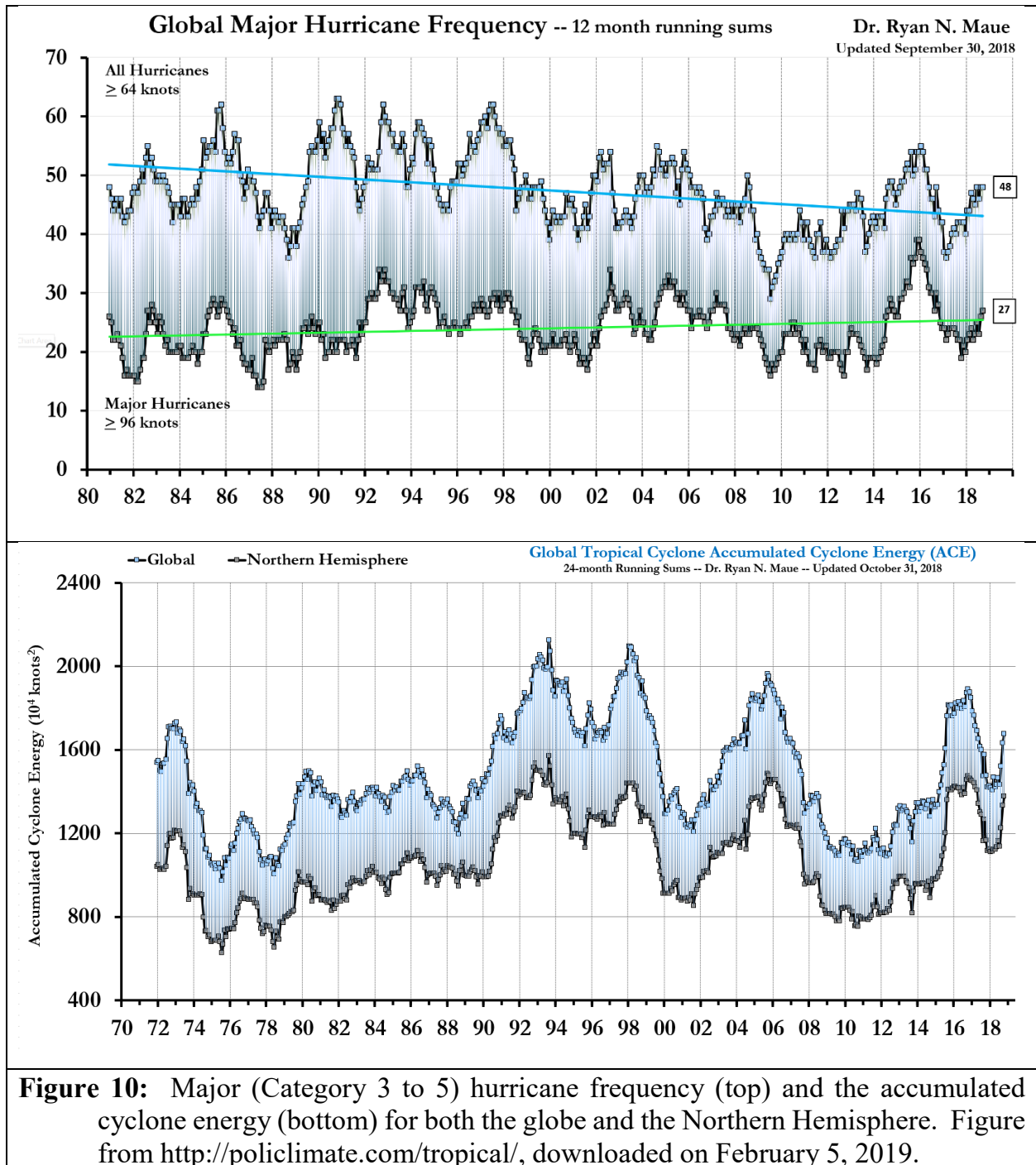


Figure 9: Accumulated cyclone energy (green) and the normalized Atlantic Multidecadal Oscillation (blue). Figure from Klotzbach, P.J., W.M. Gray, *et al.* (2015). “Active Atlantic hurricane era at its end?” *Nature Geoscience* **8**(10): 737-738.



While devastating, Hurricanes Katrina and Sandy were neither unusual nor unexpected. In the 1990s while at the University of Oklahoma, I taught that eventually a hurricane would pass New Orleans and the cyclonic winds would put stress on the levee system holding Lake Pontchartrain back. The pressure upon the levees may be enough to cause them to fail and water to flood portions of New Orleans. The normal FEMA response is to wait for the storm surge to recede and bring in mobile houses if the homes are uninhabitable. But since sediment compaction has caused portions of New Orleans to be below sea level. Thus, the water would not recede, and the normal FEMA response would be inappropriate. I was not a prophet; but rather, what I imparted to the students was simply a fact that climatologists knew was likely to occur.

Similarly, Hurricane Sandy was rare in that it turned west while in mid-latitudes. It is not surprising that weak storms (Hurricane Sandy was extratropical by the time it made landfall) would be affected by mid-latitude weather patterns. Hurricane Sandy, therefore, was not unexpected but the results were devastating because it made landfall at a highly populated location.

OCEAN ACIDIFICATION

Due to dissolved salts (primarily Na^+ and Cl^-), the pH of ocean seawater is primarily basic. With the inclusion of dissolved CO_2 , the pH of ocean seawater is decreasing (*i.e.*, becoming more acidic), which is termed “ocean acidification.” The question is whether this acidification is significant and whether it matters.

The addition of CO_2 to seawater increases carbonic acid which lowers the pH. However, the chemistry is more complex as chemical buffering by dissolved salts greatly affects the resulting pH. IPCC AR5 suggests that a doubling of atmospheric CO_2 might lower the pH by up to 0.2 – well within the normal seasonal/diurnal variation in seawater pH. Globally,

ocean surface pH varies considerably. Many factors affect local pH, including components of the ecosystem, underlying ocean depth, and dissolved parent material.

An argument has been made that lowering the oceanic pH due to the absorption of more CO₂ would likely destroy the CaCO₃ shells of various animals. Indeed, Dr. Jane Lubchenco testified on December 2, 2009 to a U.S. House subcommittee: “Who in the ocean is affected by this [‘Osteoporosis of the Sea’]? Any plant or animal that has a shell or skeleton made of calcium carbonate. The hard parts of many familiar animals such as oysters, clams, corals, lobsters, crabs, ... are made of calcium carbonate” and showed pictures from the National Geographic Society of the shell of a *Limacina helicina Antarctica*, a Pteropod, that had largely dissolved after about 45 days when subjected to decreased pH. But a study in 2008 (Iglesias-Rodriguez, M. D., P. R. Halloran, *et al.* 2008. “Phytoplankton calcification in a high-CO₂ world.” Science **320**: 336-340.) concluded that “Increased atmospheric CO₂ also enhances marine life, in contradiction to previous claims where lower pH in the ocean was said to be dissolving calcium material (i.e., CaCO₃) and therefore causing harm to marine life”. They go on to note that “most of these experiments [with lowered pH] used semi-continuous cultures, in which the carbonate system was modified by the addition of acid and/or base to control pH.” Indeed, some of these lab studies used hydrochloric acid, not carbon dioxide (*i.e.*, carbonic acid) to lower the pH of the seawater. While the change in pH may be similar, the chemistry involved with the chlorine ion is far different than that with the carbonate and bicarbonate ions.

Dr. Justin Ries of the University of North Carolina at Chapel Hill raised both lobsters and blue crabs in a CO₂-enriched environment (Figure 11) and demonstrated that under elevated CO₂ levels, both species grew faster. He has raised the concern that such rapid growth could disrupt the food chain but to simply assert that ocean acidification will necessarily diminish all life in the oceans is an extreme claim.



Figure 11: Lobster (top) and blue crab (bottom) grown under different levels of atmospheric CO₂. On the left are crustaceans grown under current (*i.e.*, 400 ppm) atmospheric CO₂ concentrations and under elevated CO₂ on the right (*i.e.*, ~2800 ppm). Figure from Dr. Justin Ries, marine researcher at the University of North Carolina-Chapel Hill.

SUMMARY

Coasts are naturally hazardous areas due to the impact of rising seas, coastal storms, shifting barrier islands, and flooding caused by rainfall into low-lying areas. Global sea levels have risen naturally at a rate of about 7 to 8 inches per century for at least several hundred years. Locally, this rate may be higher due to local land subsidence and/or compaction of sediments or lower due to isostatic rebound. Shifting sands on barrier islands change the local landscape and can affect life along coastal areas.

The question we wish to answer is whether anthropogenic increases in CO₂ concentrations exacerbate these coastal impacts. From the data shown above, sea level rise has been consistent linear at nearly all stations for which long-term measurements are made. This indicates that increasing CO₂ concentrations are not significantly affecting the rate of sea level rise. As these concentrations have increased from before the industrial age when atmospheric CO₂ levels were about 280 ppm to current conditions where they exceed 400 ppm, the lack of a significant change in the rate of increase implies that sea level rise is not responding to changes in greenhouse gas concentrations.

Severe weather events – most notably tropical cyclones/hurricanes – have not increased significantly over the last 60 or more years. No significant trend exists with either landfalling hurricanes in the United States, landfalling significant hurricanes (category 3 or higher), or with the accumulated cyclone energy; a measure of the energy associated with tropical cyclones integrated over all storms in the basin for a given season or month. In all cases, short-term trends exist but those reflect natural variability and do not contribute to the longer-term trend. Damage for the continental United States from landfalling tropical cyclones since 1900 also shows no increasing trend in constant dollars despite the increased development along our coastlines. Consequently, we can agree with the IPCC that low confidence exists in the attribution of changes in tropical cyclone activity to human influence.

Seawater is naturally alkaline, but the addition of dissolved CO₂ leads to acidification (*i.e.*, lowered pH) through the addition of carbonic acid. Rather than leading to the dissolution of CaCO₃-based shells of various animals in the oceans, many species will thrive on the addition of carbonate and bicarbonate ions and the slightly lowered pH content. Studies which have attempted to demonstrate that CaCO₃-based shells dissolve in lowered pH conditions often have used hydrochloric acid, rather than carbonic acid, which has a considerably different chemistry.

Coastal living is accompanied by additional hazards, although it is unlikely that these hazards will increase in the future due to increases in atmospheric concentrations of CO₂, in large part because concentrations have increased nearly 45% over pre-industrial levels and no significant impact on these hazards has been observed.