



Sea Level Rise & Tree Damage

Dr. Kim D. Coder, Professor of Tree Biology & Health Care / University Hill Fellow
University of Georgia Warnell School of Forestry & Natural Resources

Coastal communities and their community forests, as well as maritime forests, are under mounting stress from sea level rise. Coupled with predicted hurricane intensity increases and associated storm surge heights, sea level rise is causing, and will cause, increased tree mortality and tree site losses. Understanding the history of sea level rise, and future trends, can help tree health care providers and community forest managers better prepare for risks.

Change Engine

Sea level rise can be caused by a number of things. Land height changes relative to ocean levels due to glacial rebound, tectonic movements, geologic time-scale erosion, and volcanism can all be a component of sea level rise. Sea level changes of the last few decades are directly correlated with ocean water warming at various depths, due to general atmospheric warming from greenhouse gases, which disrupt energy reflection and transmission. (IPCC, 2018)

Greenhouse gases drive changing energy balance within and between atmosphere and ocean. Figure 1 shows greenhouse gases cited as generating global warming in 2016. The largest proportion of impact (42%) comes from carbon-dioxide, although many other gases contribute to this energy balance change. (IPCC, 2018)

Expanding Water

The cause of global energy balance changes have been a combination of natural processes, and since just before 1900, human impacts. Figure 2 demonstrates the amount and relative proportion of atmospheric temperature change caused by natural and human processes. The human impacts have greatly accelerated over the 105 years between 1900 and 2005. (IPCC, 2018)

As the atmosphere temperature rises, so does the temperature of ocean water. As water warms, it increases in volume slightly. This water expansion with increasing temperature is little noticed in small shallow lakes or in a tank of water. Within a deep ocean volume covering a majority of the globe, small amounts of water expansion within each small volume is magnified by the whole mass of water present in the oceans. (NOAA 2012)

Rising Components

With small increases in atmospheric and ocean water temperatures, sea levels rise. The components of sea level rise cited from 1994 to 2012 is given in Figure 3. Land mass ice melt from mountain glaciers, Greenland, and Antarctica comprise roughly 55% of sea level rise. Thermal

expansion of seawater is 27% of sea level rise. Combined ~83% of sea level rise is generated by land ice melt and thermal expansion. (NOAA 2012)

In a more recent examination, sea level rise components (from 2002 – 2014) demonstrate thermal expansion of the oceans accounting for 50% of sea level rise, and land ice loss accounting for the remaining 50%. Figure 4. (NOAA 2015) As energy balance changes in both the atmosphere and oceans continue, generating overall warmer planetary temperatures, sea level will continue to rise.

Time Passages

Over the last 550 million years, sea level has changed constantly. The “normal” pattern of sea level change is constant, both rising and falling with planetary changes. Figure 5 shows average sea level changes derived from three different studies. On average, sea level has changed in height approximately 1,400 feet over about the last one-half billion years. Sea level has been greater than 800 feet higher and up to 460 feet lower than today. (Hine et.al. 2016)

For example in Georgia, the Coastal plain was a shallow sea approximately 100 million years ago. Figure 6. Seawater came up to the taller hills termed the Fall line, cutting the land area of modern Georgia roughly in half. (Hine et.al. 2016)

More Recent

Examining sea level rise and fall in more recent times shows wide variation. Figure 7 provides a change path for sea level rise and fall over the last 160,000 years, compared with today’s sea level. Note, there have been two low and two high sea levels periods. Over the last 15,000 years, as the planet moved out of an ice age, sea level has risen about 380 feet from its lowest point during the most recent ice age maximum. (Hine et.al. 2016)

Figure 8 shows sea level rise over the last 24,000 years. As the last ice age period ends and a rapid warming period occurs, sea level rises almost 400 feet, with roughly 220 feet of rise over a 6,000 year period. This sea level rise represents the most recent period of great natural variation which can occur with planetary changes. (Englander 2014)

Modern Measures

Sea level rises vary greatly from moment to moment, month to month and year to year. It is difficult at times to glean long term trends from short term variation. Beginning in the 1880’s, the trend in sea level rise begins to climb. Figure 9. Over the last 130 years, average annual sea levels have risen ~8 inches. (Hine et.al. 2016)

The relationship between ocean warming and thermal expansion, and associated sea level rise, is demonstrated in Figure 10. This figure shows the relationship between tide gauges on the coast and thermal expansion within the top 2,300 feet of ocean. Average annual sea level rise over 60 years increased by roughly +2.7 inches at the tide gauges associated with increasing thermal expansion of the top layer of ocean. (Hine et.al. 2016)

Sea level is currently continuing to rise. Figure 11 shows sea level rise since 1994. The amount of sea level rise has averaged roughly 0.13 inches per year globally. For example, the daily tide range at the Ft. Pulaski, Georgia station has ranged from 4.3 feet (neap tides) to 9.8 feet (Spring or King tides) total distance up and down. (Conrads et.al. 2013). Within these variable tide ranges has been a steady sea level rise of 0.12 inches per year. (Conrads et.al. 2013; Williams et.al. 2009)

Future Seawater

There have been a number of scientific sea level rise predictions based upon climate change models. Figure 12 demonstrates the uncertainty and range in six common models for sea level rise. Note no model shows less than a 1 foot rise in sea level over the next decades. Some models suggest a sea level rise range to as much as 6-7 feet. (Englander 2014)

Figure 13 demonstrates the projected average sea level increase in feet over the next 80 years. Sea level rise is based upon high emissions of greenhouse gases, and intermediate emission levels impacting global average temperatures. Both high and medium greenhouse emissions are expected to raise sea levels by about 2 feet. (Hine et.al. 2016)

In another view, NOAA has projected average sea level increases for the next 80 years in order to better help regional planning for management of risks. Figure 14 shows two expectations of sea level rise based upon an intermediate high and an intermediate low greenhouse gas emission level. Sea level rise could range from 2 feet to 4 feet. (Hine et.al. 2016)

Impact Projections

Given middle / intermediate levels of sea level rise projections, the Union of Concerned Scientist organization issued some moderate (i.e. not high or low, but intermediate) probability predictions. For example, at St. Simons Island, Georgia the current population of the island with homes at risk from rising sea level is almost 23%. Currently liveable land area on the island submerged by seawater is estimated as 26.4% by 2060, and 60.1% by 2100. Property values at risk by 2060 is estimated to be \$1.75 billion.

A second example of impacts from sea level rise is for Tybee and Wilmington Islands, Georgia. The current population of these islands with homes at risk from rising sea level is almost 17.4%. Currently liveable land area on the islands which will be submerged by seawater is estimated as 32.9% by 2060, and 70.4% by 2100. Property values at risk by 2060 is estimated to be \$915 million.

Rise Expectations

Sea level rise will impact many maritime forests and community forest landscapes. Expectations of intermediate sea level rise over the next 50 years due to ocean warming include: more intense storm surge; more flooding; more freshwater / seawater inundation; taller wave heights; severe coastal erosion of barrier islands; and, beach dune systems moving landward falling back from current beach positions. (Hine et.al. 2016)

Fresh / Salt

Coastal estuary rivers will see a change in extent and location of the freshwater / seawater interface. During freshwater flooding moving downstream, or during neap tides, freshwater pushes over the top of underlying denser seawater, and the interface moves downstream. With lower stream flows, higher sea levels, and greater Spring tide heights, the freshwater / seawater interface is pushed farther upstream, and this interface zone with freshwater occurs over a shorter distance. Seawater pushed farther inland along rivers can compromise community water intakes and affect wells. Figure 15. (Conrads et.al. 2013)

Growing Space

Figure 16 shows a normal below ground freshwater / seawater interface zone in a landscape beneath trees. Close to the coast, deep well intakes could be close to or below the freshwater / seawater interface, and deliver brackish water. Note the amount of ecological viable volume available to trees above the freshwater table where good soil drainage and aeration occur, and tree roots can thrive. (Hine et.al. 2016)

With sea level rise, the freshwater / seawater interface moves inland and upward. Figure 17 demonstrates sea level rise impacts on tree sites. As sea level rises, the freshwater table rises, the freshwater / seawater interface moves inland and upward, waterway flows increase, and ecological viable volume decline greatly. The result is tree stress and mortality. (Hine et.al. 2016)

Figure 18 demonstrates results from a sea level rise along the ocean front. More and more tree and forest landscapes are inundated periodically, or flooded for extended times with brackish or seawater. As a result, trees die and the tree mortality line moves inland.

Island Problems

Barrier islands generate many problems for trees as sea levels rise. Figure 19 shows a normal barrier island tree system. Beneath the island is a floating freshwater lens or pocket derived from accumulated precipitation. Trees grow in ecological viable volumes of aerated, drained, and freshwater dominated soils. (Hine et.al. 2016)

With sea level rise, the freshwater lens shrinks and becomes more shallow and closer to the surface. The result, shown in Figure 20, is a great loss of ecological viable space and a diminishment of tree covered areas and freshwater dominated soils. Many trees die. (Hine et.al. 2016)

Figure 21 lists the barrier island tree impacts as sea levels rise and the ecological system is more physically and chemically controlled by seawater. The first visible result is increasing erosion. Erosion leads to beach and bluff retreat and shoreline recession. Next, barrier islands thin and are washed over more often during storms. The freshwater wetlands are quickly converted to higher salinity systems, and saltwater marshes expand farther inland. The major impacts for trees and maritime forests are die-off and tree site losses. (Hine et.al. 2016)

Tree Impacts

The symptoms of sea level rise, and associated upstream and inland shift of the freshwater / seawater interface (i.e. increase in salinity), include noticeable tree crown dieback around the outside or one major branch at a time, depending upon the tree species. As trees succumb and die, more of the understory is converted to tidal marsh species. (Jones et.al. 2009)

A key impact on trees is soil drainage and aeration to maintain a healthy and ecologically viable soil volume. With rising sea level, coastal drainage systems, both normally or after a storm surge or flooding, could be compromised. Figure 22 shows the slowed or stopped drainage, with potential of reversing flow, within drainage systems. Tree landscapes could be severely damaged depending upon short-term water saturation or flooding, and long-term soil changes occurring, associated with poorly draining flood water. (Hine et.al. 2016)

Shrinking Responsibilities

One aspect of tree and landscape ownership with rising sea levels is public access and public ownership / control of beach areas. Figure 23 shows the beach zones of dune vegetation, dry beach, wet

beach, and open water edge. Generally, public access and ownership is considered to be up to the average high water level, or the top of the wet beach. (Titus 2009)

With increased sea levels, both storm waters and Spring high tides will be greater and move farther up the beach, contributing to many tree and land-use issues. With increased sea level, the average high water mark delineating the wet beach extent (and land ownership) will be much farther up the beach. (Titus 2009)

One Type of Summary

As maritime forests and community trees are challenged by seawater rise and associated changes in storm surges, flooding, and loss of ecological viable space, two primary management responses are presented: protect trees and sites, or retreat from the ocean. Some communities and nations have made investments in protecting their forested coastal assets. Other communities have decided to have a managed retreat against rising seas.

Still other communities have not decided to do anything yet, as they review and evaluate the risks trees and their sites face. For these communities, the dominant choices are three: anticipate change and actively begin formulating sustainable responses; wait to react as changes become too great; or, do nothing. Historic community forest management activities have demonstrated the latter two choices tend to have greater overall costs in the long-run and generate great damage to the tree / forest resources.

Citation:

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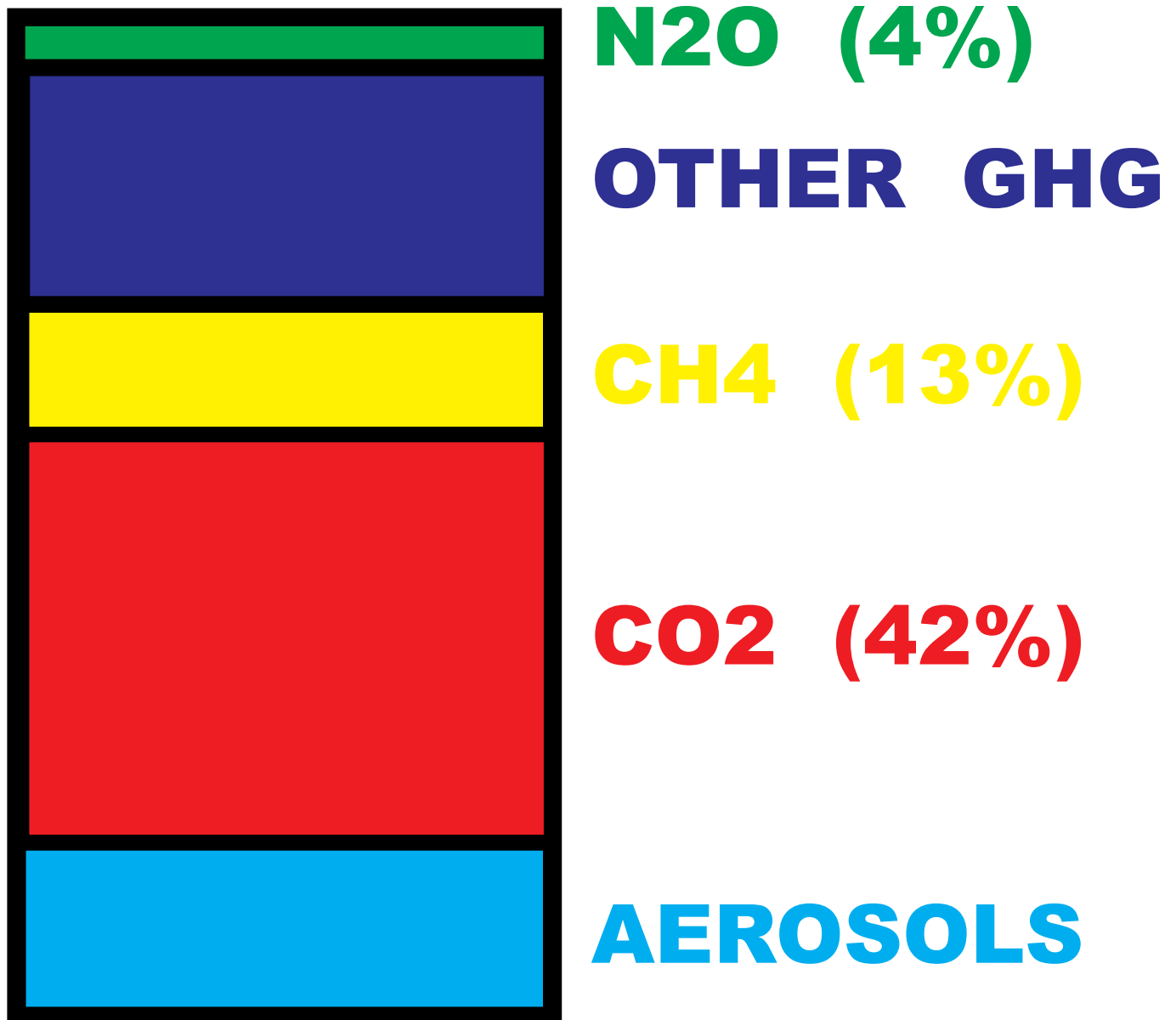


Figure 1: Proportions of greenhouse gases (GHG) generating global warming in 2016. (from IPCC-SR1.5-ISM-21, 2018)

temperature change (°F)

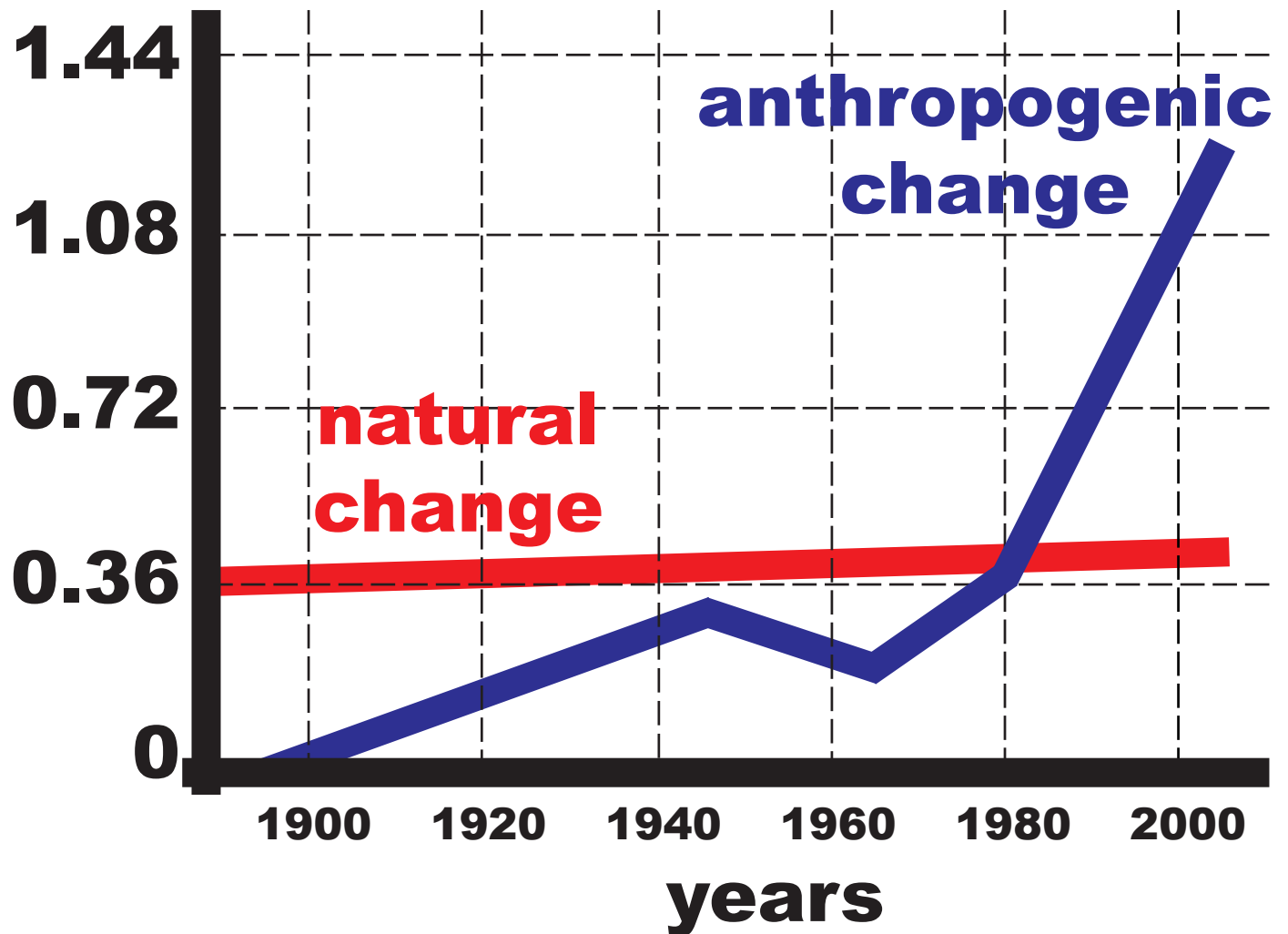


Figure 2: Proportion of natural and human caused temperature change over a 55 year period ending in 2005.

(from IPCC-SR1.5-1SM-21, 2018)

1994 -- 2012 SEA RISE Components

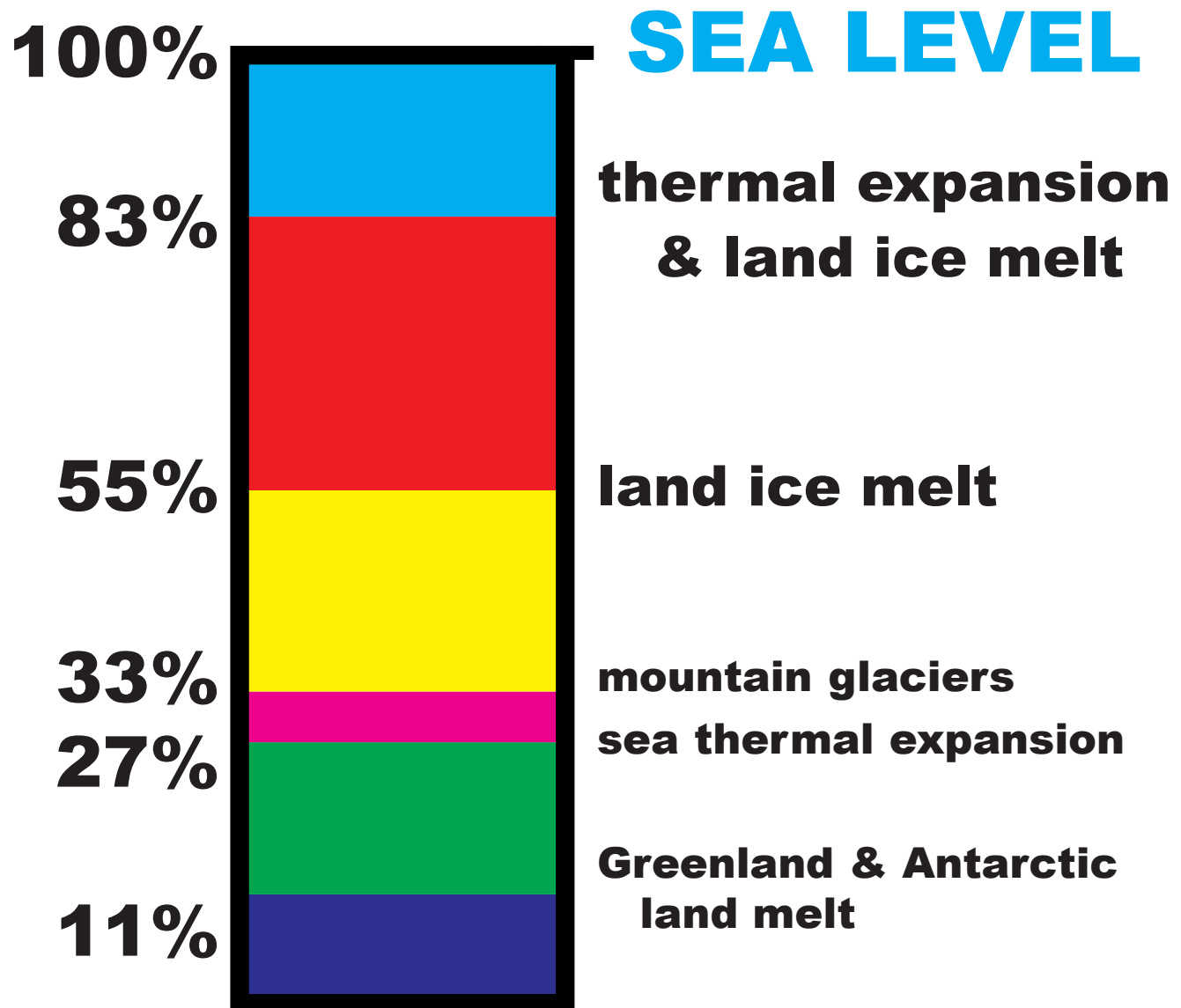


Figure 3: Components of sea level rise from 1994-2012.
(NOAA 2012)

2002 -- 2014

SEA LEVEL RISE COMPONENTS

thermal expansion	50%
Greenland ice melt	27%
mountain glacier melt	14%
Antarctic ice melt	9%

Figure 4: Components of sea level rise from 2002-2014.
(NOAA 2015)

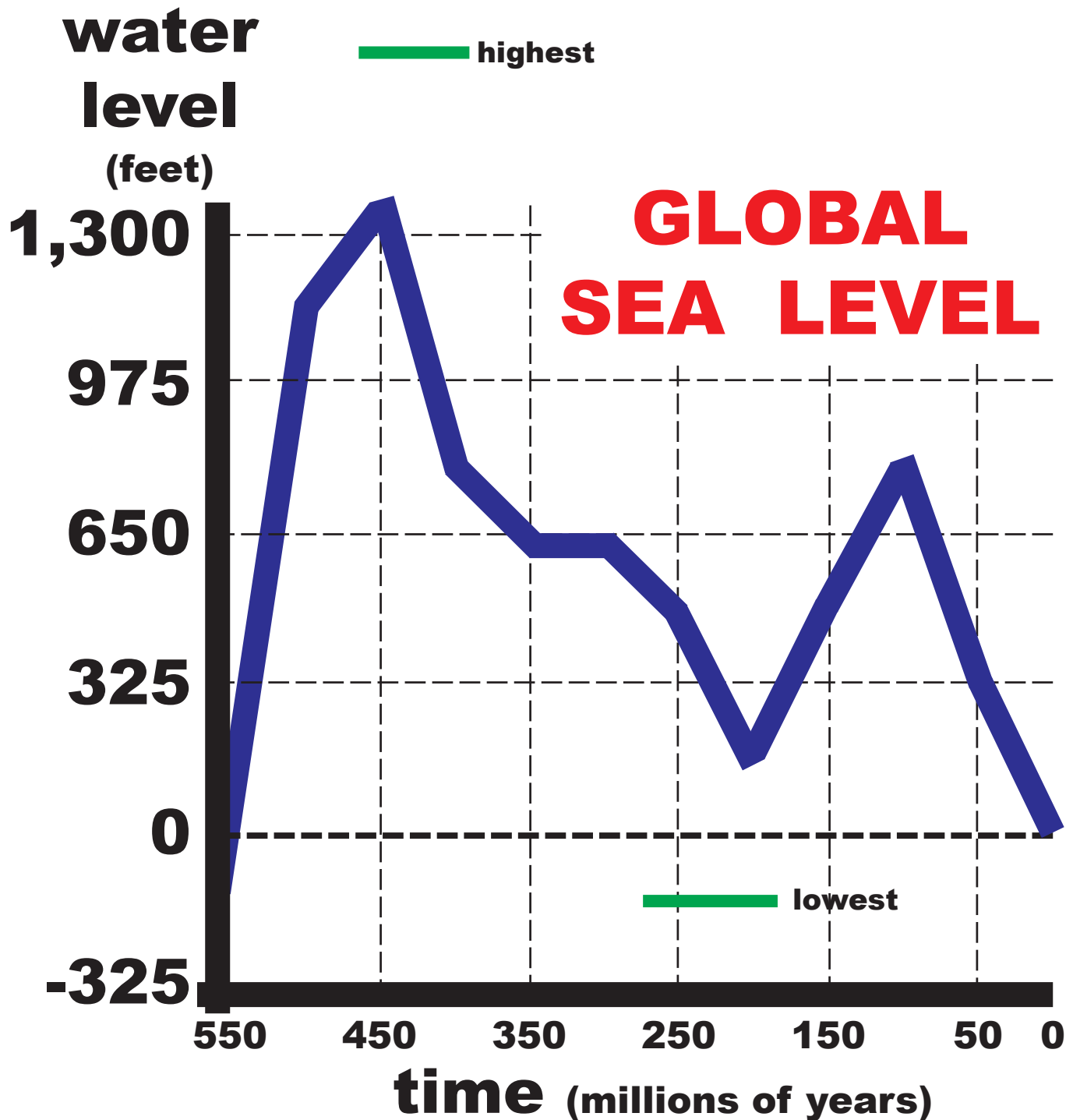


Figure 5: Sea level changes in feet estimated over last 550 million years from three different studies. (after Hine et.al. 2016)

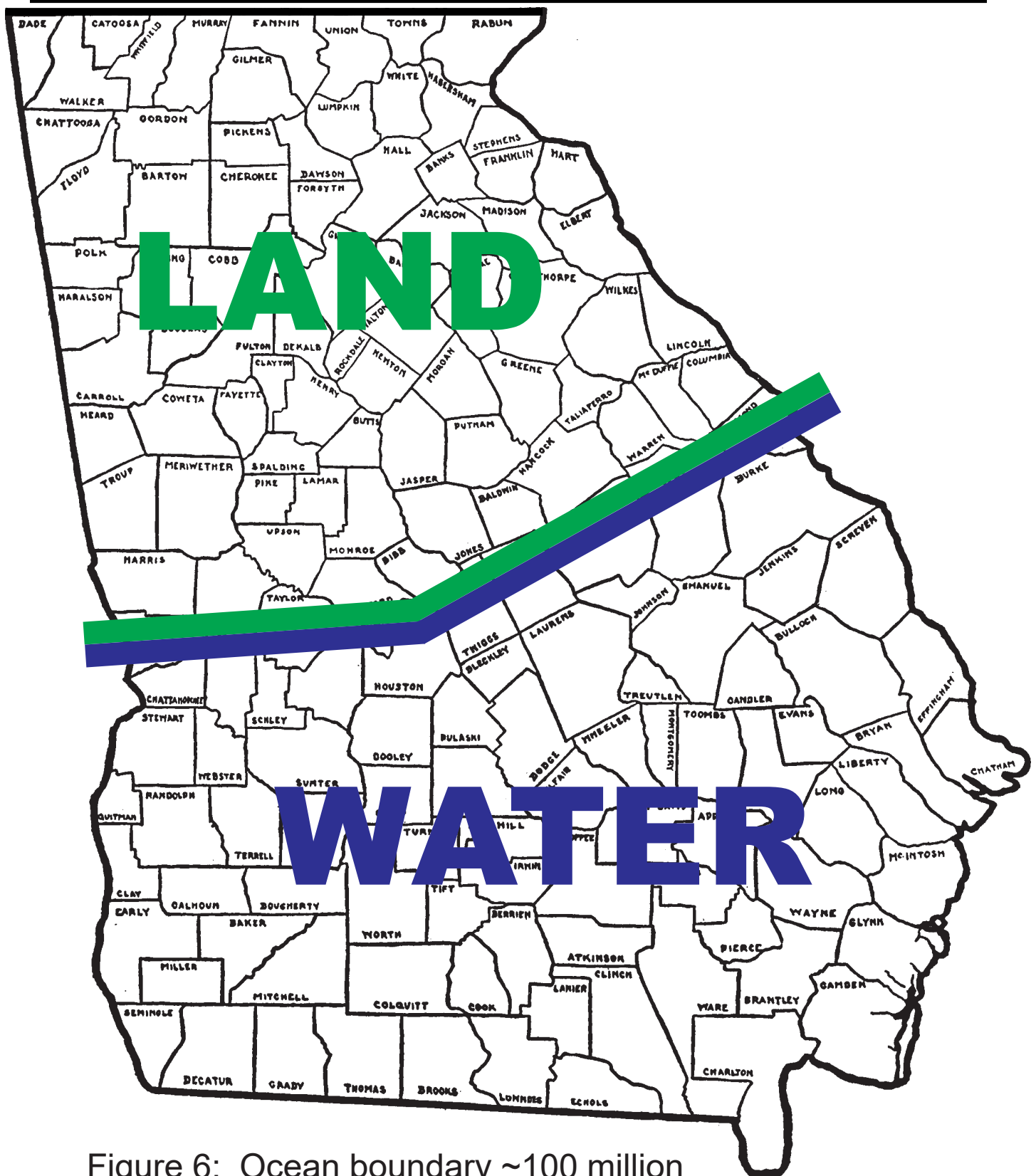


Figure 6: Ocean boundary ~100 million years ago (Cretaceous). (after Hine et.al. 2016)

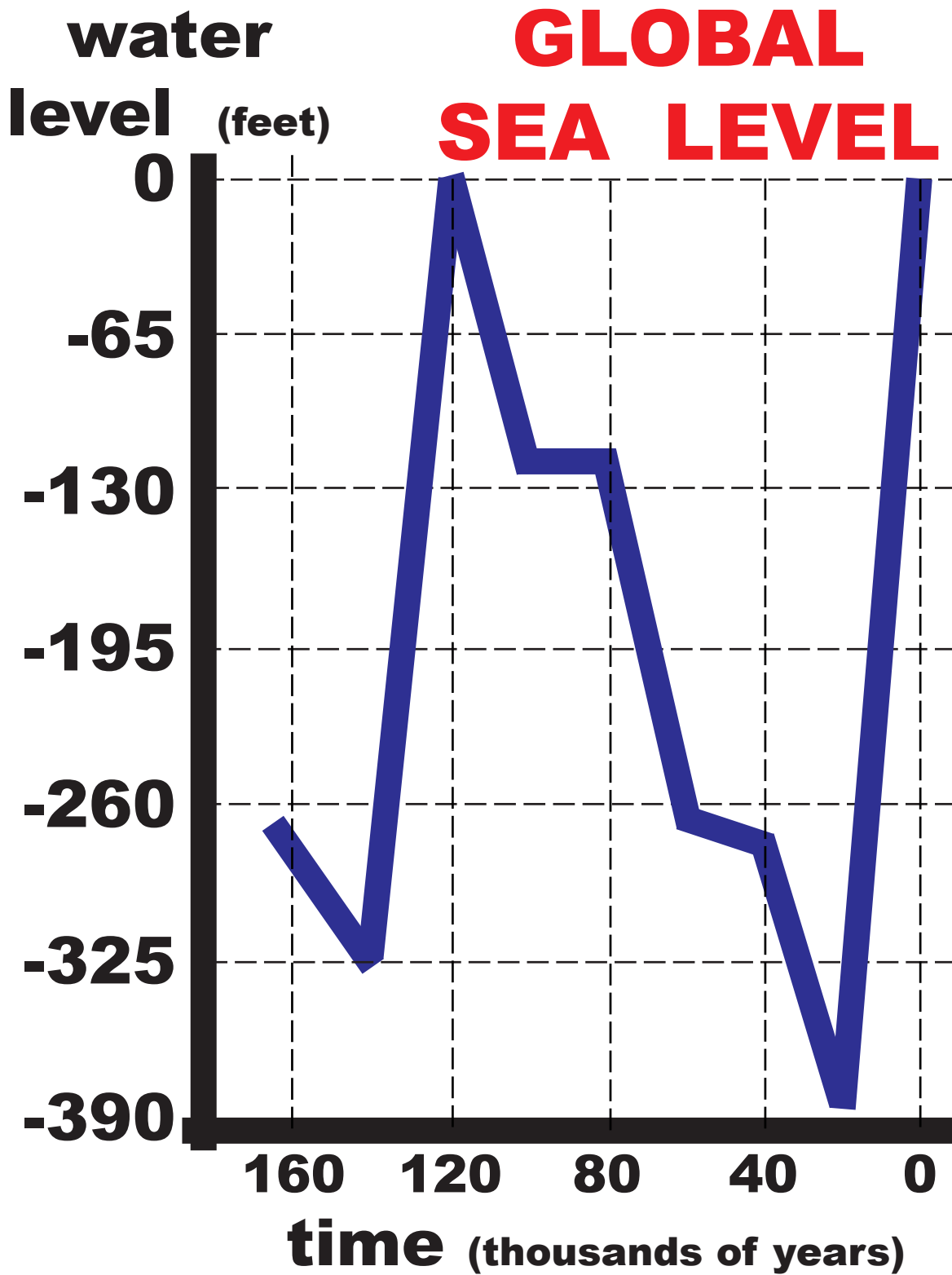


Figure 7: Sea level changes in feet estimated over last 160,000 years. (after Hine et.al. 2016)

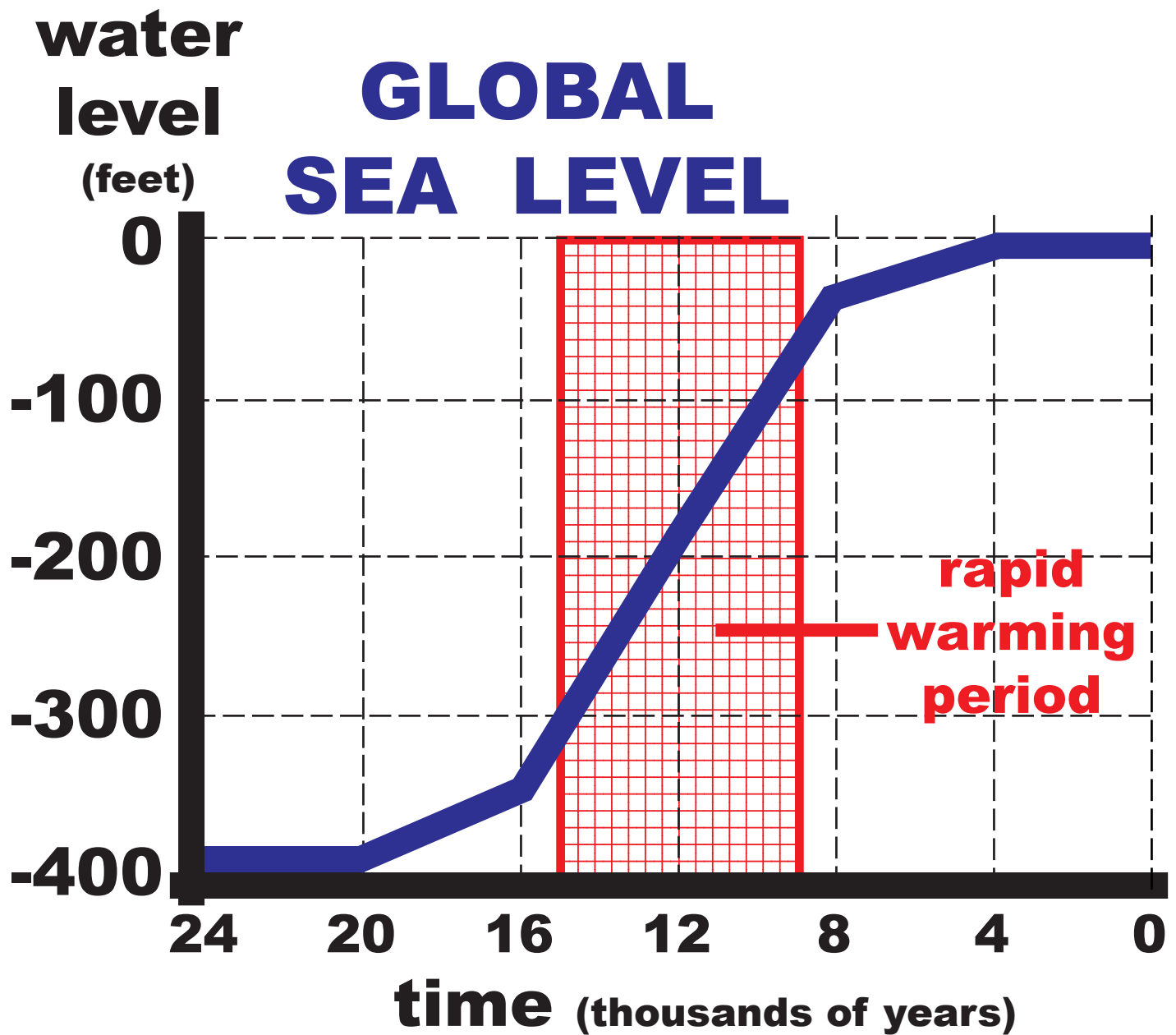


Figure 8: Sea level rise in feet since last glacial maximum.
(after Englander 2014)

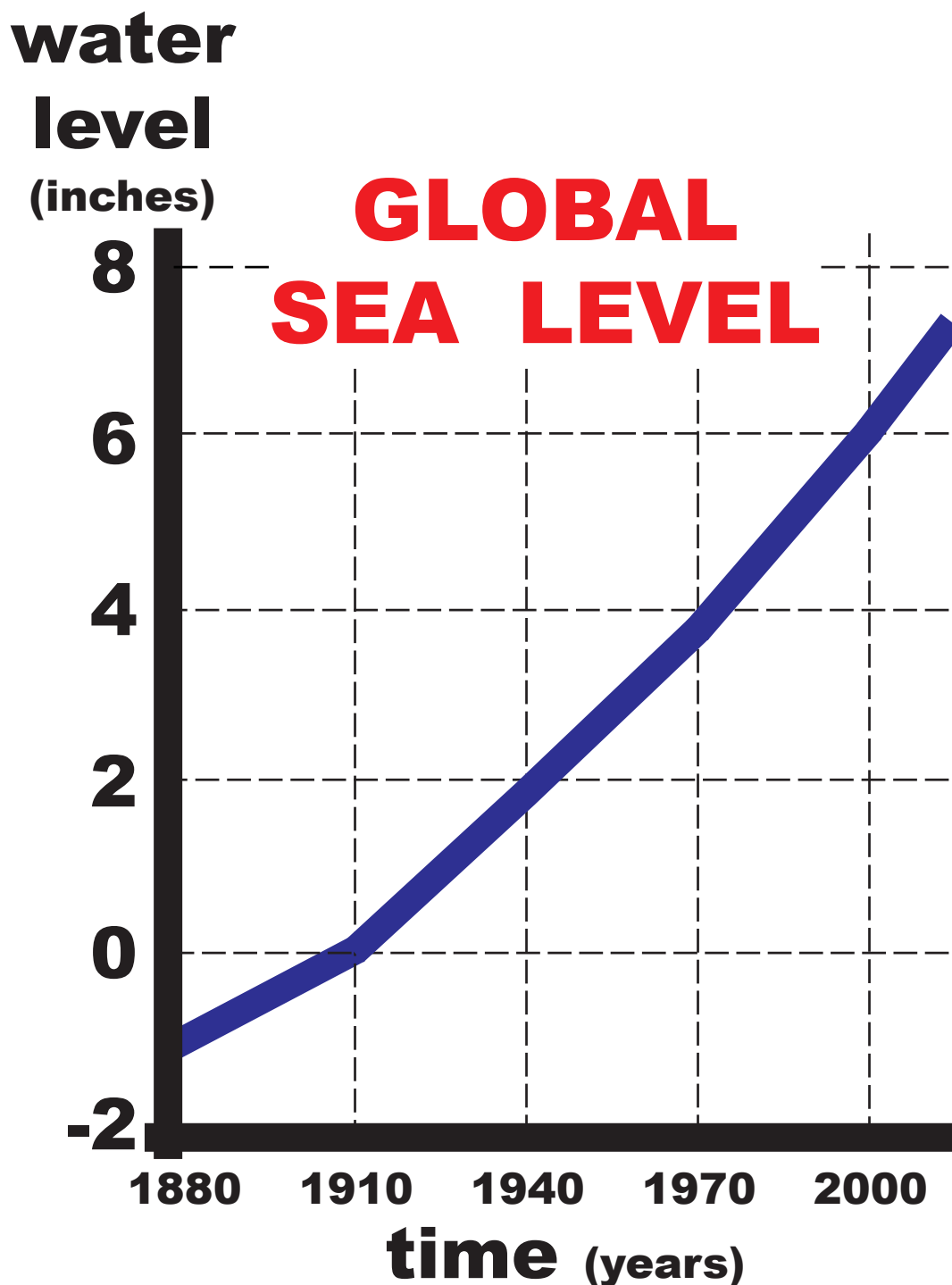


Figure 9: Average annual sea level change in inches over last 130 years. (after Hine et.al. 2016)

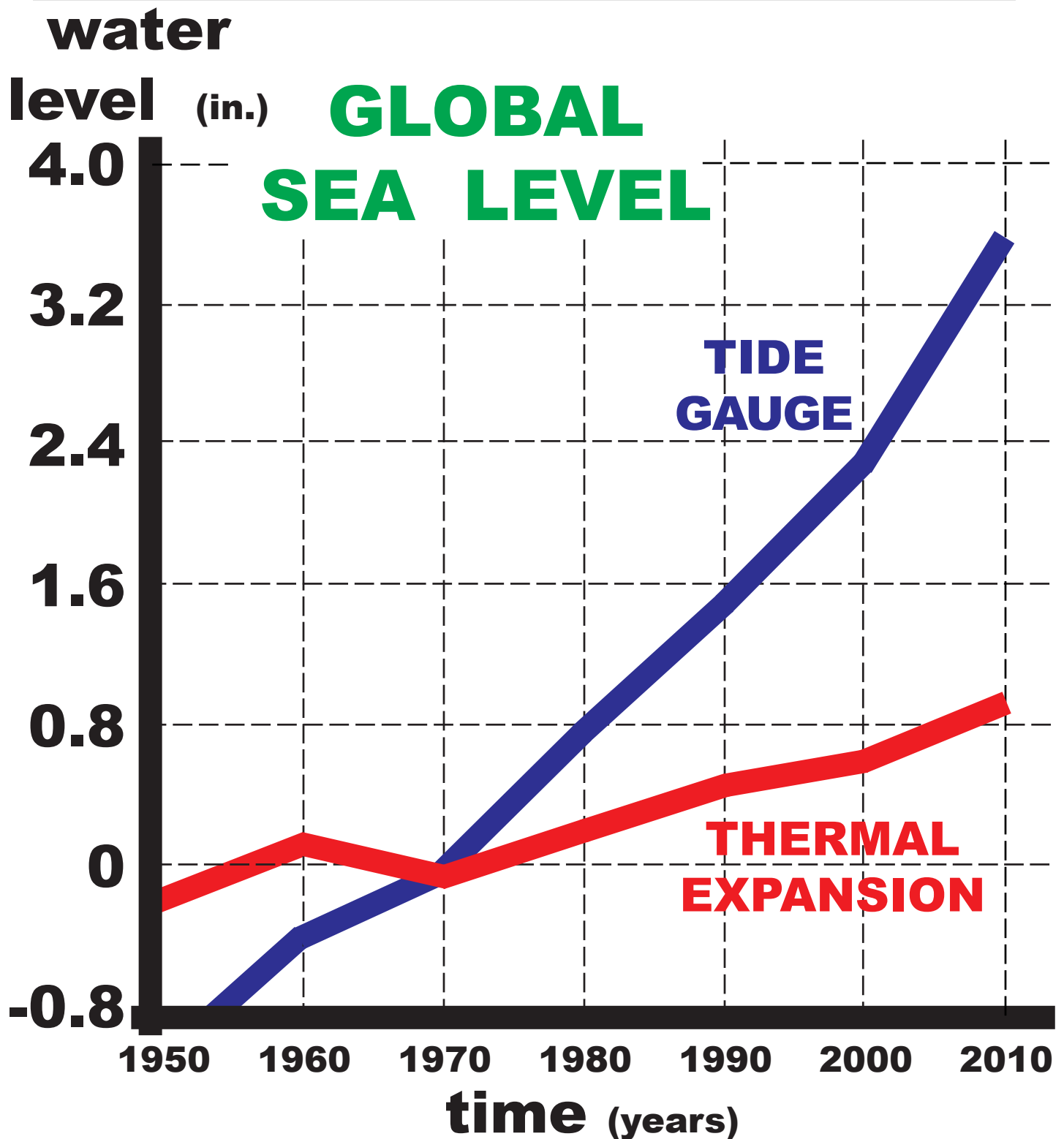


Figure 10: Average annual sea level change in inches over last 60 years from tide gauges and thermal expansion in the top 2,300 feet of ocean. (after Hine et.al. 2016)

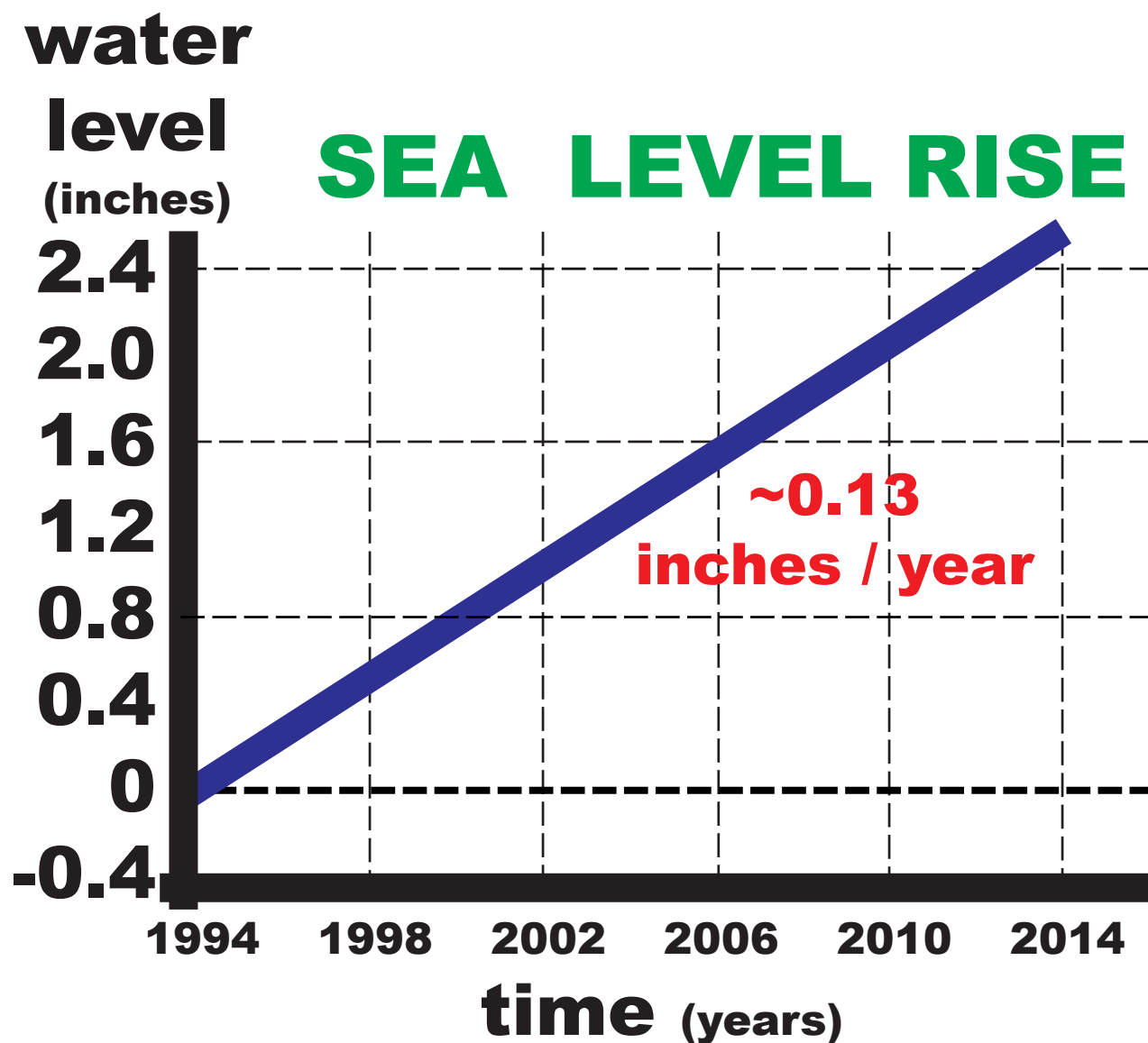


Figure 11: Average annual sea level rise in inches since 1993. (after Englander 2014)

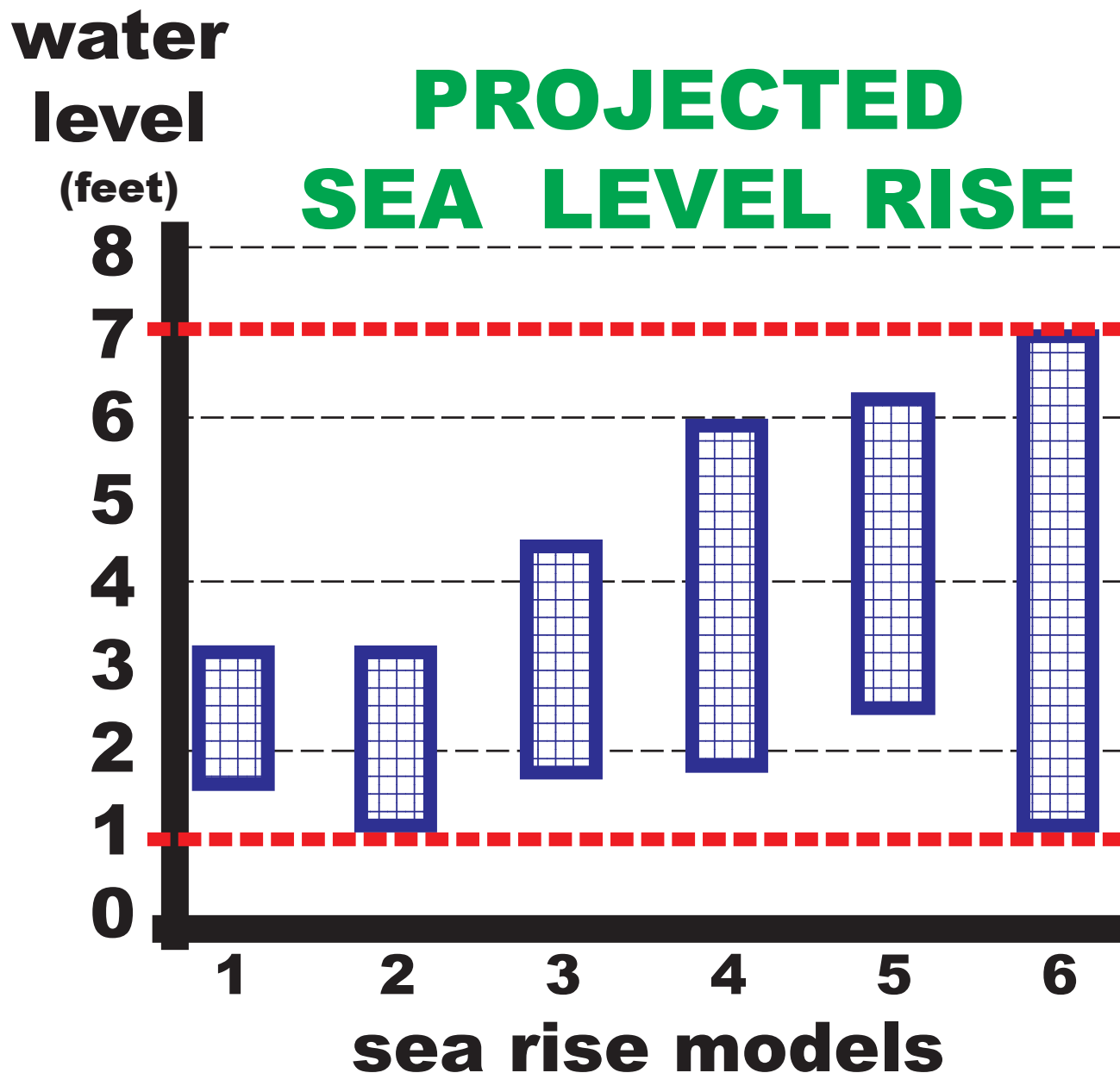
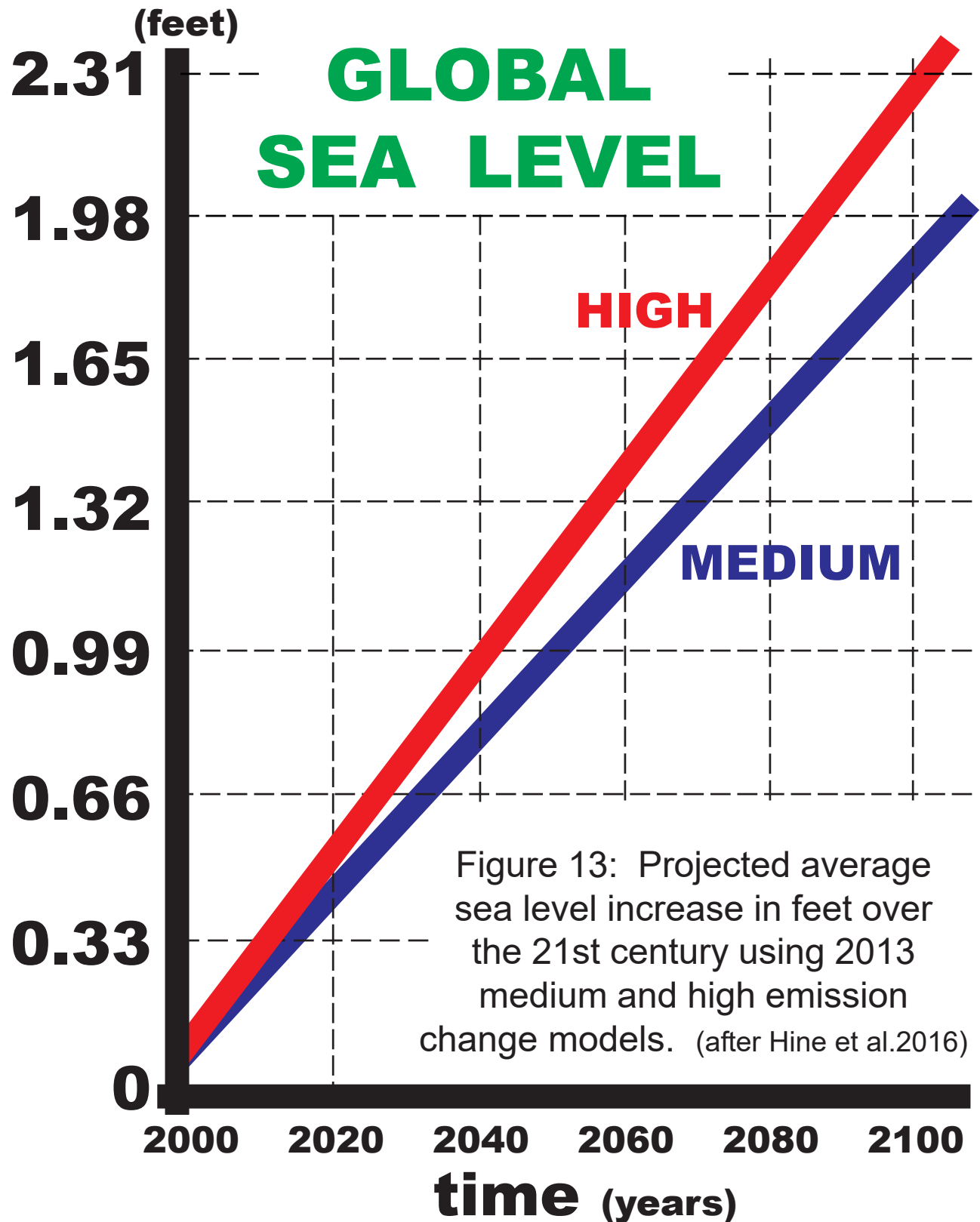


Figure 12: Projected sea level rise in feet by year 2100 based upon six different models. (after Englander 2014)

water level



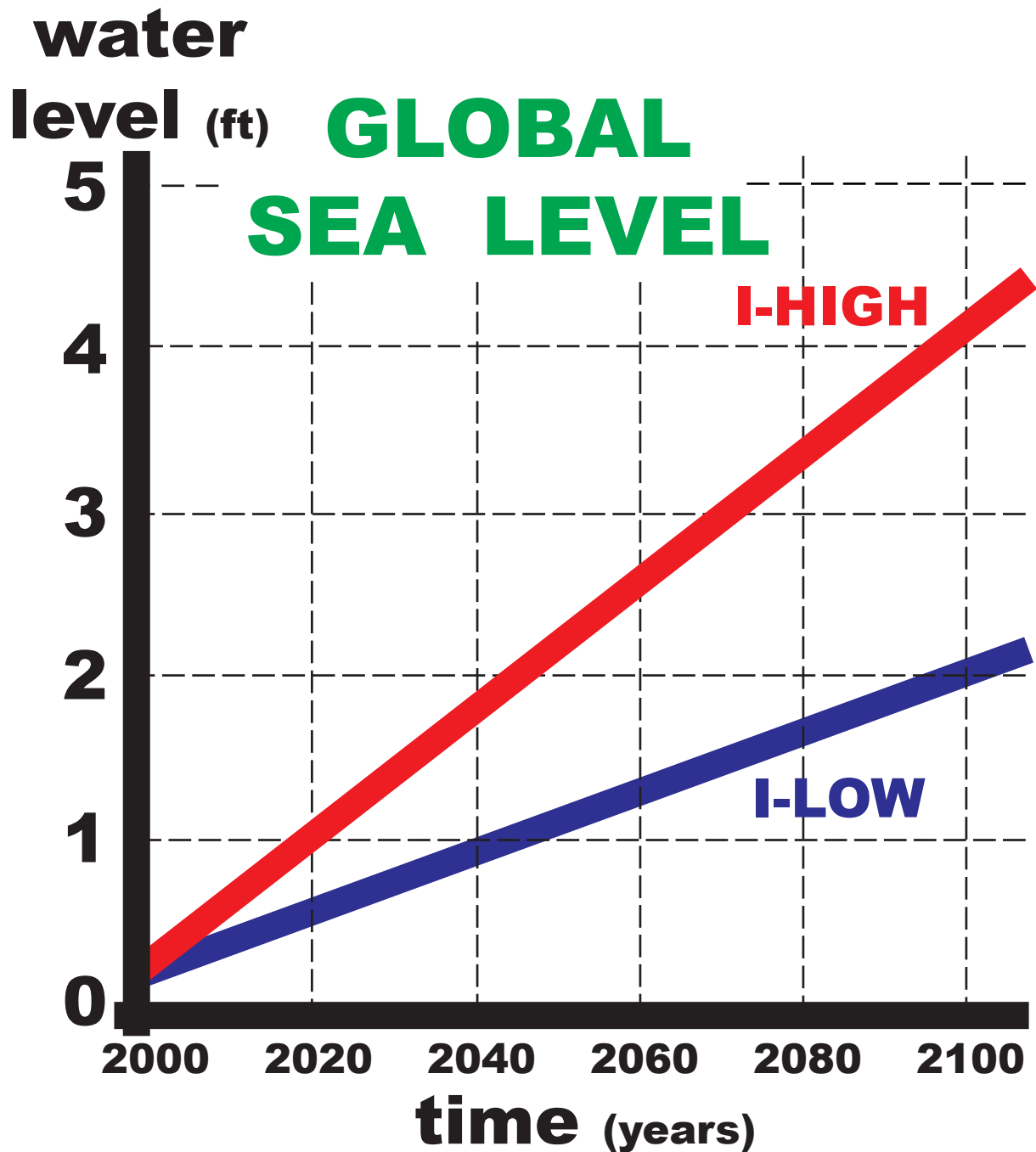


Figure 14: NOAA projected sea level increase in feet over the 21st century developed for regional planning purposes using an intermediate high and an intermediate greenhouse gases emission scenarios.

(after Hine et.al. 2016)

SEAWATER / FRESHWATER INTERFACE

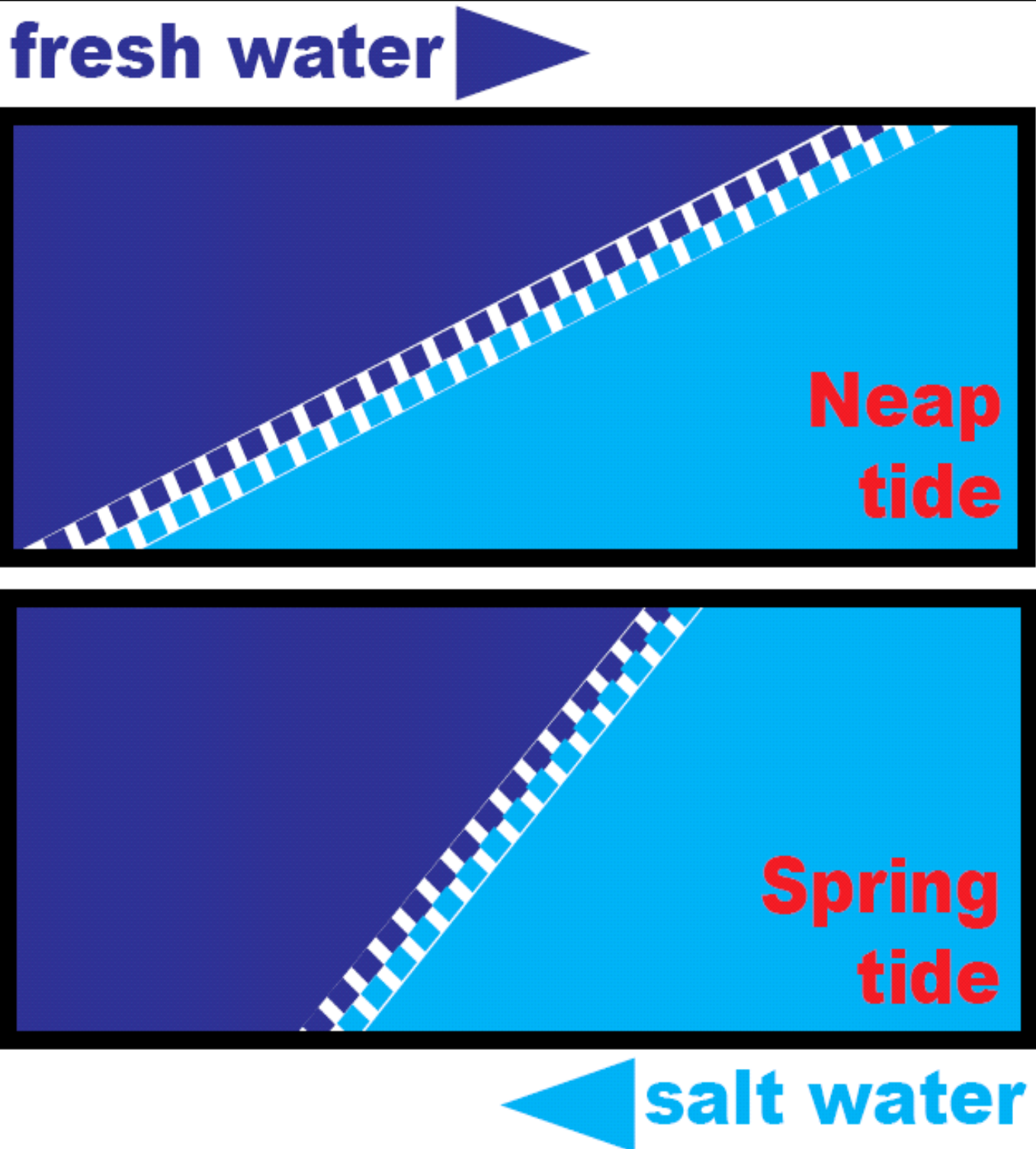


Figure 15: Movement of seawater / freshwater interface in coastal rivers with either more freshwater flow and smaller tide (top), or less freshwater flow and higher tide (bottom). (Conrads et.al. 2013)

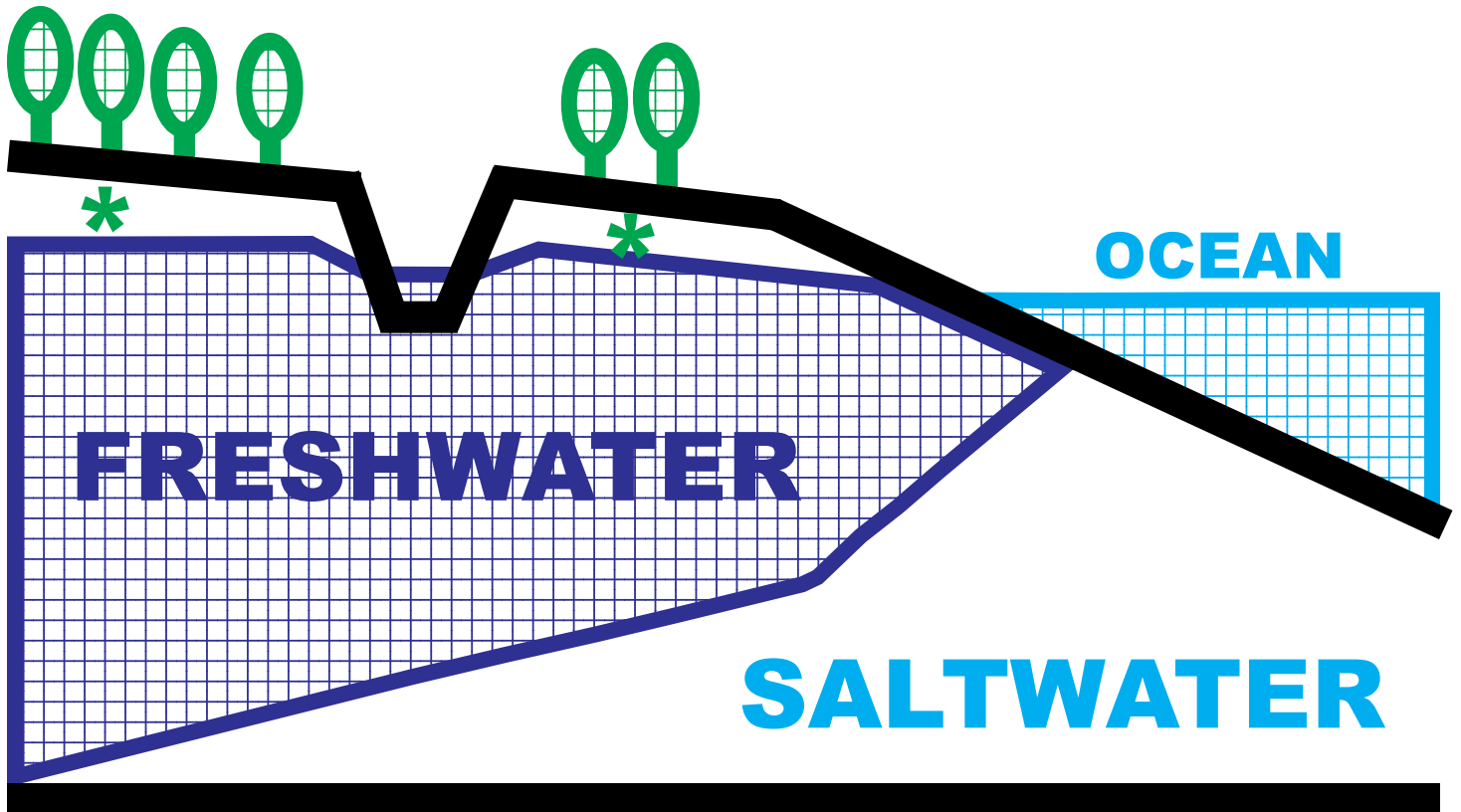


Figure 16: Salt- and freshwater interface.
(after Hine et.al. 2016)

- 1. ocean level rises**
- 2. freshwater table rises**
- 3. interface moves inland & up**
- 4. waterway flow increases**
- 5. ecological viable space declines**

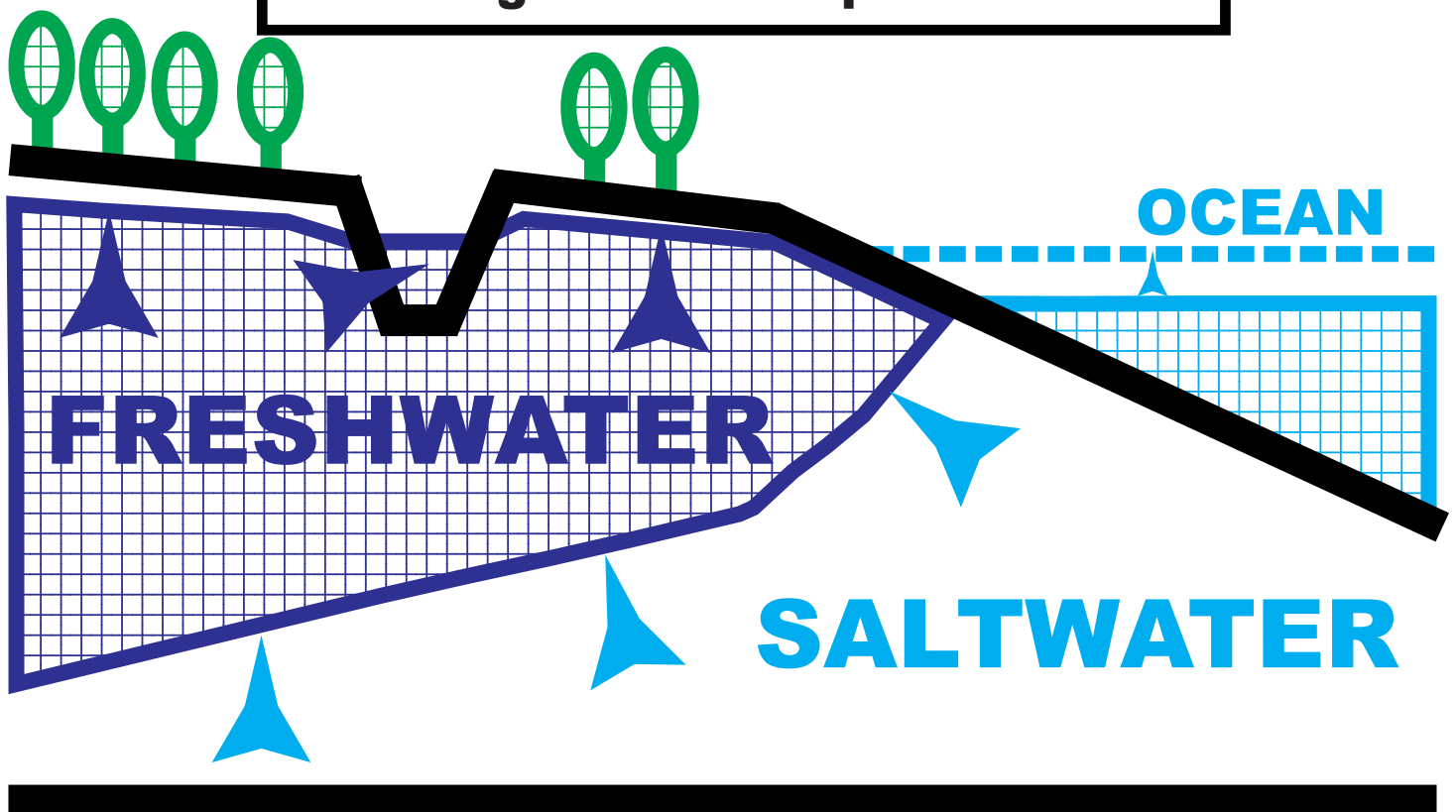


Figure 17: Salt- and freshwater interface changes with increased sea level. (after Hine et.al. 2016)

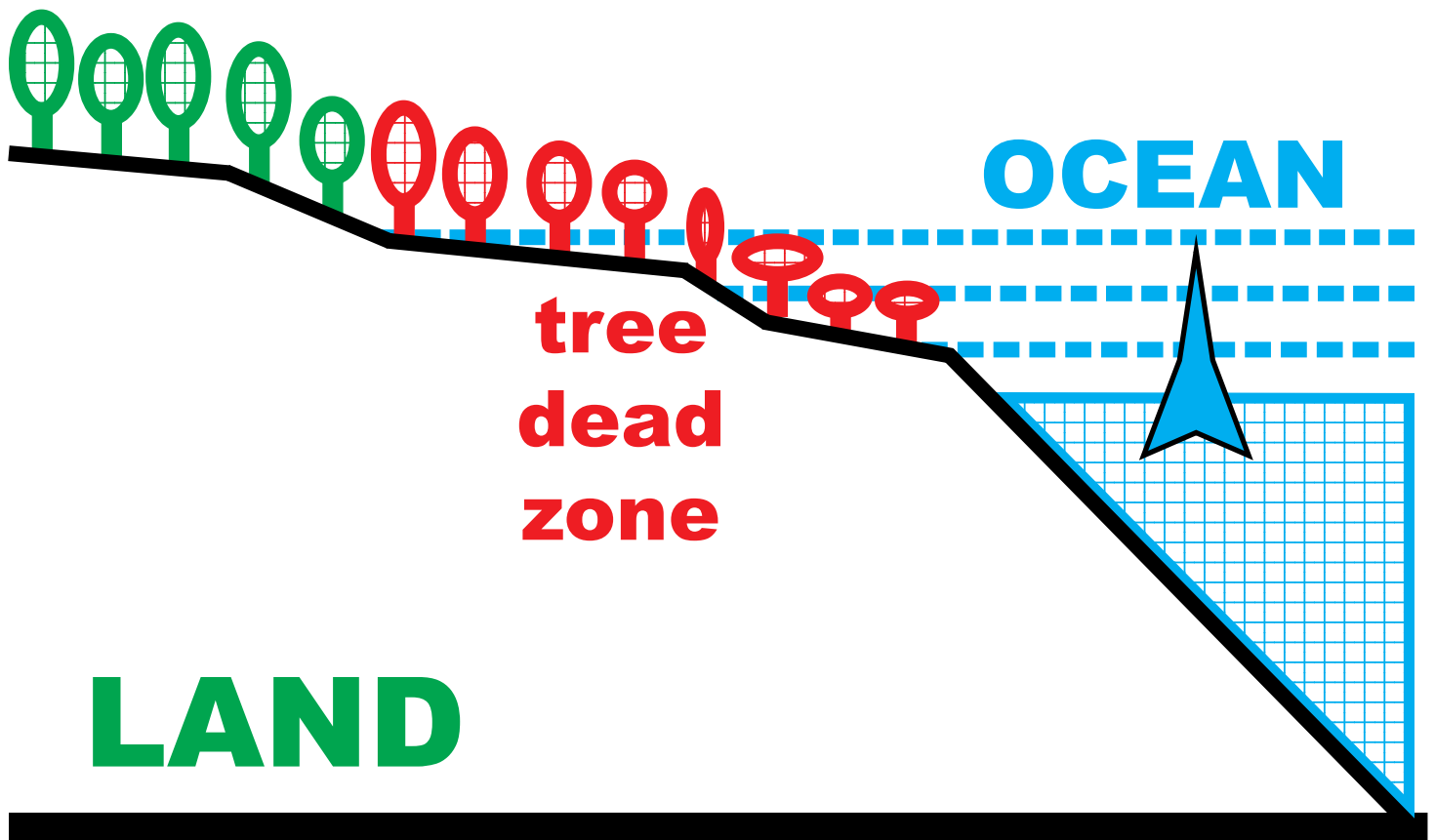


Figure 18: Rising ocean levels impacting maritime forest.
(after Hine et.al. 2016)

BARRIER ISLAND FLOATING FRESHWATER LENS

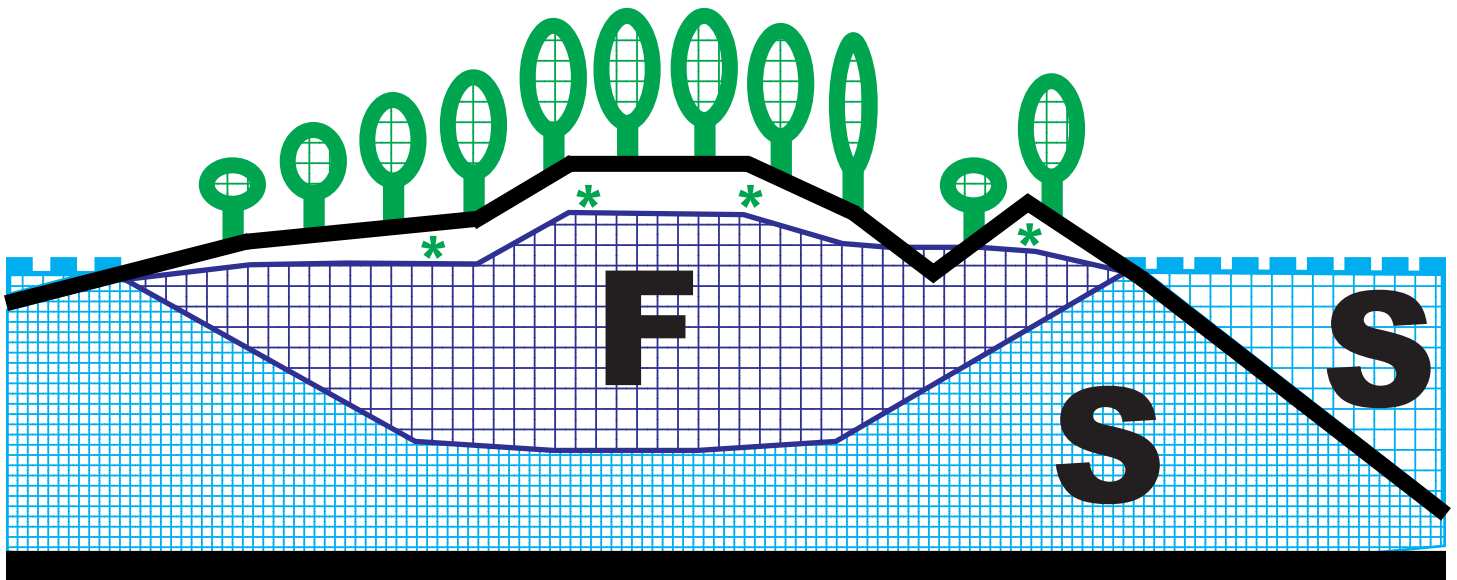


Figure 19: Barrier island freshwater lens and
ecologically viable volume for trees.
(after Hine et.al. 2016)

BARRIER ISLAND FLOATING FRESHWATER LENS

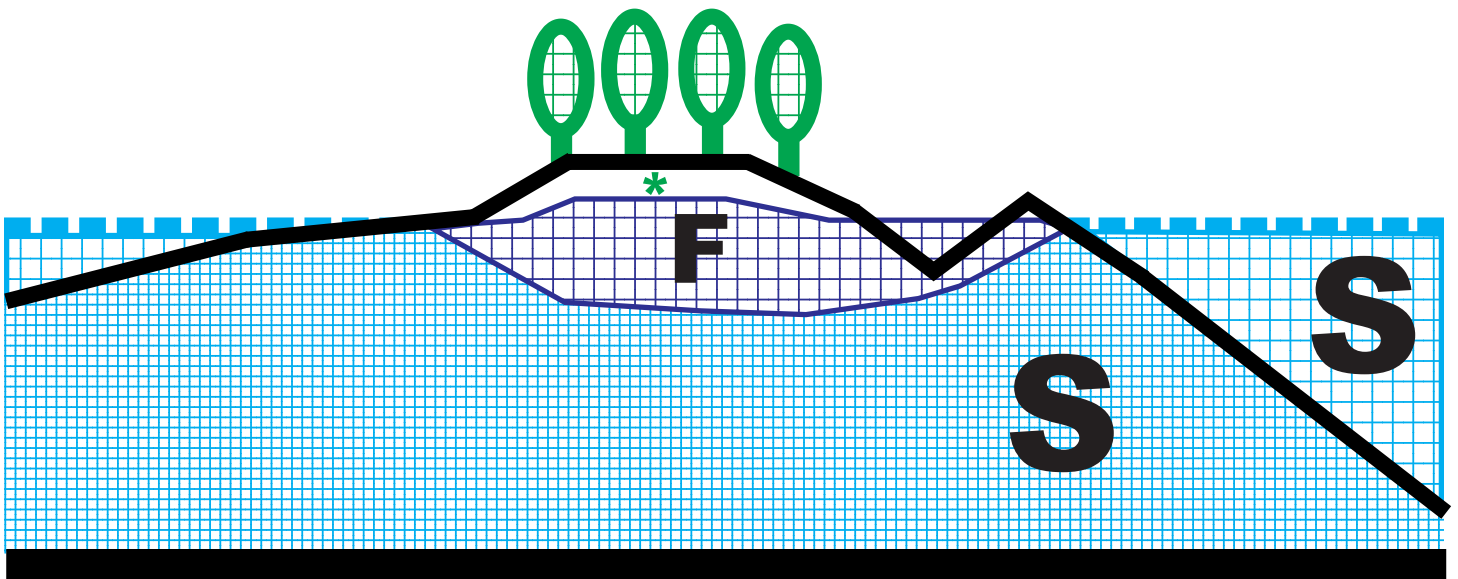


Figure 20: Rising ocean levels impacting barrier island freshwater lens, aerated / drained tree soils, and ecologically viable volume for trees.

(after Hine et.al. 2016)

SEA LEVEL RISE **IMPACTS ON TREES**

- 1. beach & bluff retreat**
- 2. shoreline recession**
- 3. island thinning**
- 4. island washover**
- 5. wetland conversion**
- 6. marshland expansion inland**
- 7. maritime forest die-off**

Figure 21: Rising ocean levels impact on maritime forests.
(after Hine et.al. 2016)

TREE SITE & LANDSCAPE DRAINAGE

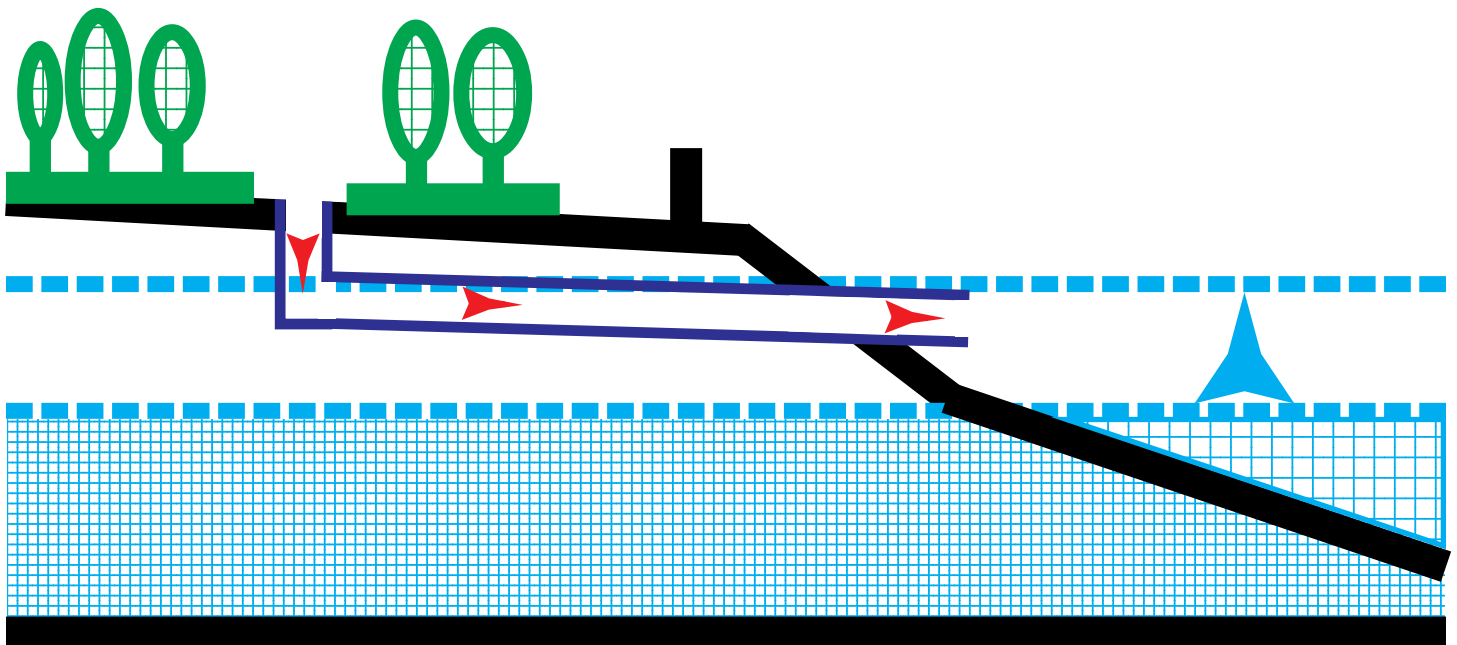


Figure 22: Rising ocean levels impact on tree sites and landscape drainage capacity (reduced flow & reverse flow).
(after Hine et.al. 2016)

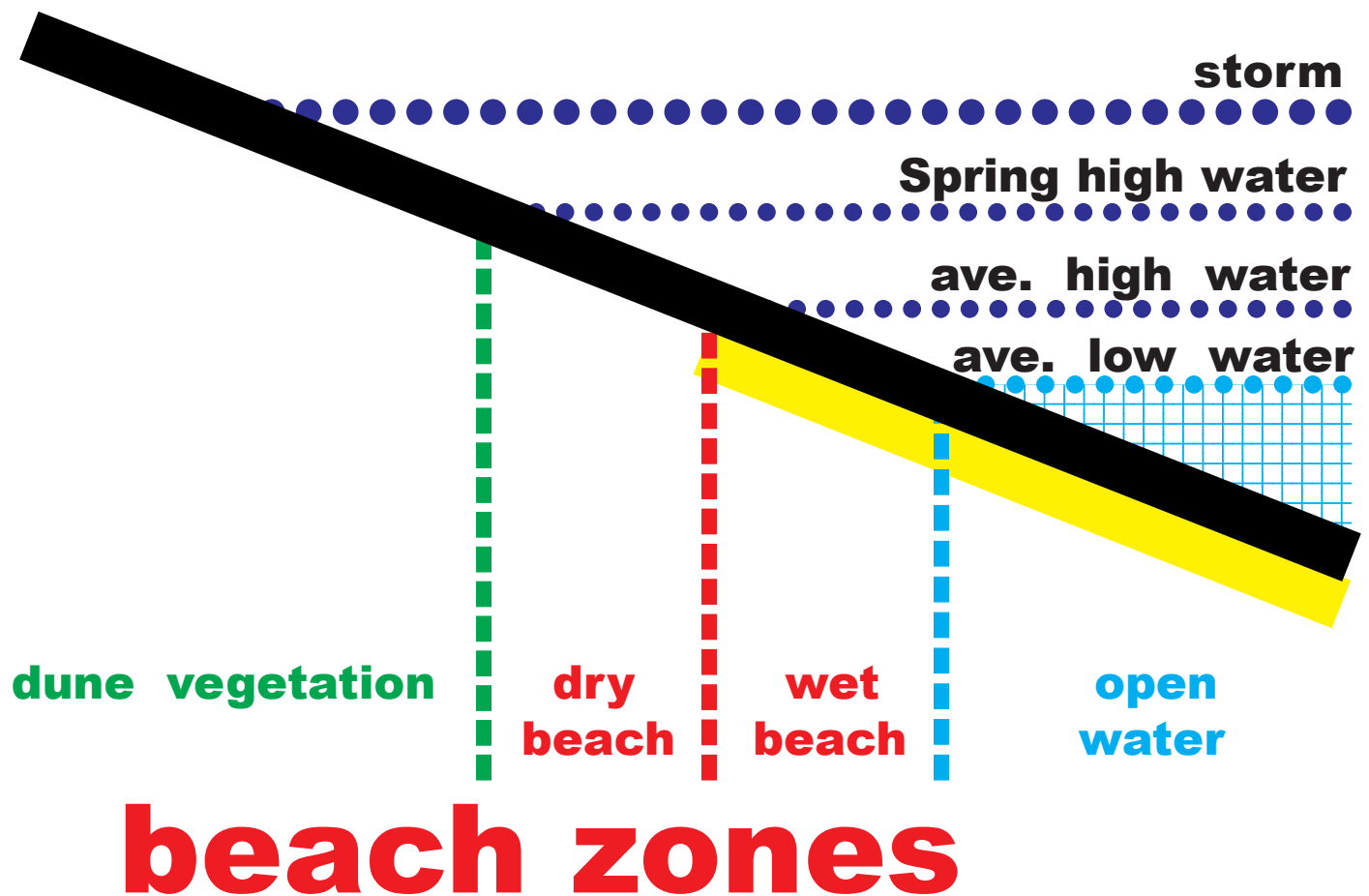


Figure 23: Ocean beach zones associated with sea level, and the usual location of public ownership (yellow line). (Titus, 2009)

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