Assessment of projected sea level rise scenarios for the New Jersey Coast

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SUMMARY

This report (hereafter, the 'CFAN Review') evaluates the projections of sea level rise for the New Jersey coast provided in the 2019 Report entitled "New Jersey's Rising Seas and Changing Coastal Storms," led by a team of scientists from Rutgers University (hereafter referred to as the 'Rutgers Report').

Projections of sea level rise in the Rutgers Report are evaluated relative to projections provided by the Intergovernmental Panel on Climate Change (IPCC). The Rutgers projections are substantially higher than the IPCC projections (including those provided in a 2019 IPCC report), owing to their method of incorporating extreme scenarios of instability in the West Antarctic Ice Sheet.

The Rutgers Report did not present any scenarios for future sea level rise beyond those driven by global warming from emissions. New Jersey sea level rise out to 2050 is expected to be modulated by natural variations in ocean circulation patterns. These same ocean circulation patterns also dominate the activity of Atlantic hurricanes and expected landfall locations.

Making good decisions under conditions of deep uncertainty is far more complex than merely selecting the 'best' scenario for a specific application, which is the recommendation provided in the Rutgers Report. The CFAN Review describes best practices for adaptation to sea level rise and coastal storms, suitable for the different categories of events that could occur.

The summary conclusions of the CFAN Review are:

- The sea level projections provided by the Rutgers Report are substantially higher than those provided by the IPCC, which is generally regarded as the authoritative source for policy making. The sea level rise projections provided in the Rutgers Report, if taken at face value, could lead to premature decisions related to coastal adaptation that are unnecessarily expensive and disruptive.
- Scenarios out to 2050 for sea level rise and hurricane activity should account for scenarios of variability in multi-decadal ocean circulation patterns.
- Best practices in adapting to sea level rise use a framework suitable for decision making under deep uncertainty. The general approach of Dynamic Adaptive Policy Pathways is recommended for sea level rise adaptation on the New Jersey coast.

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1. Introduction

This report (the CFAN Review) evaluates the projections of sea level rise for the New Jersey coast provided by the 2019 Report entitled "New Jersey's Rising Seas and Changing Coastal Storms," led by a team of scientists from Rutgers University (hereafter referred to as the Rutgers Report). The materials used in evaluating the Rutgers Report are reports from the Intergovernmental Panel on Climate Change (IPCC), recent national assessment reports, and recent publications in the scientific literature.

The analysis presented here draws on the extensive experience of Climate Forecast Applications Network (CFAN; see Appendix A) in supporting climate risk assessment and management for corporations and governments. CFAN's climate services are distinguished by: historical analysis and projections that include natural climate variability as well as manmade global warming; comprehensive evaluations of uncertainties in projections; assessment of the plausibility of 'worst case' scenarios; and development of scenarios that support frameworks for decision making under deep uncertainty. CFAN has recently produced two major assessment reports that are directly relevant to this report:

- Hurricanes and Climate Change (CFAN, 2019)
- Sea Level and Climate Change (CFAN, 2018)

The CFAN review addresses the different types and levels of uncertainty associated with projections of sea level rise and coastal storms impacting the New Jersey coast, in the context of adaptation decision making:

- *likely* range [17-83%] of sea level rise associated with global warming from moderate emissions
- a deeply uncertain 'Dragon King' scenario associated with rapid destabilization of the West Antarctic Sheet and extreme sea level rise
- the possibility of a major hurricane landfall

The CFAN review includes the following topics:

Section 2 summarizes recent projections of global sea level rise, evaluating the projections used in the Rutgers Report relative to projections from the IPCC.

Section 3 describes the sources and levels of uncertainties in the global sea level rise projections, including the contingent assumptions and limitations. This includes worst case scenarios associated with instabilities of the West Antarctic Ice Sheet, which features prominently in the predictions in the Rutgers Report.

Section 4 addresses local sea level rise in New Jersey. An analysis is provided of the dominant modes of variability of the historical record of sea level, including the current 'hot spot' in sea level rise. Data on vertical land motion in the New Jersey coastal region is provided. Recommendations are made for projections of sea level rise for New Jersey.

Section 5 addresses the variability of coastal storms impacting New Jersey, including the roles of natural variability as well as global warming in Atlantic hurricanes and mid-Atlantic landfalls.

Section 6 presents an overview of adaptation strategies under conditions of deep uncertainty, including Dynamic Adaptive Policy Pathways. Examples of local/regional best practices in adapting to sea level rise are provided.

Section 7 provides conclusions and recommendations.

2. Global sea level rise projections

Global sea level rise projections provide a basis for projecting local sea level rise, such as for the New Jersey coast. The analysis in this section places the projections provided by the Rutgers Report in context of other assessment reports. The analysis provided below demonstrates that the Rutgers projections of sea level rise are substantially higher than those provided by other recent assessment reports, including those from the Intergovernmental Panel on Climate Change (IPCC) and recent U.S. national assessments for which Kopp and Sweet (lead authors on the Rutgers Report) were also lead authors.

Global sea level rise projections are tied to projections of global mean surface temperature, which are typically based upon simulations from global climate models. However, projections of sea level rise are only partially based on the global climate model simulations. Here are the component processes that contribute to global sea level change, and the extent to which they are determined based on outputs from global climate model simulations [IPCC AR5 WG I, Section 13.5.1]:

- Thermal expansion associated with warming of the ocean is derived directly from the global climate model simulations.
- Changes in glacier and ice sheet surface mass balance are calculated from regional models or empirical relationship between increased precipitation and climate model simulations of increased surface temperature.
- Contributions from ice sheet dynamics are assessed from either ice sheet models and/or statistical projections.
- Projections of changes in land-water storage due to human intervention is assessed from the published literature and is treated as independent of the rate of warming.

2.1 IPCC's 21st century sea level rise projections

Projections of global warming and sea level rise made by the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports are generally regarded as the most authoritative projections for policy purposes. The IPCC provides Assessment Reports every 5 or 6 years, and also Special Reports. The IPCC Reports considered here include:

- IPCC 5th Assessment Report (AR5, 2013), based on the CMIP5 suite of simulations by global climate models.
- IPCC Special Report on Oceans and Cryosphere in a Changing Climate (SROCC, 2019), based on the CMIP5 suite of simulations by global climate models.
- IPCC 6th Assessment Report (AR6; 2021 forthcoming), based on the CMIP6 suite of simulations by global climate models.

The CMIP simulations are based on more than 30 different global climate models from international climate modeling groups. The climate models simulate changes based on a set of scenarios of manmade forcings from changing atmospheric composition (notably carbon dioxide, CO_2) driven primarily by fossil fuel emissions.

The temperature and sea level rise projections from the IPCC AR5 (2013) are shown below in Table 2.1, for different emissions scenarios – low (RCP2.6); moderate (RCP4.5, RCP6.0) and high (RCP8.5). The AR5 values for the highest emissions/concentration scenario, associated with a temperature increase of 3.7°C (6.7°F), produces a *likely* range of sea level rise of 0.45 to 0.82 meters (17.7 to 32.3 inches).

Table 2.1: IPCC AR5 emission scenario-based projected change in global mean surface air temperature and global mean sea level rise for the mid- and late 21st century, relative to the reference period of 1986–2005. (*Table SPM.2 | {12.4; Table 12.2, Table 13.5} formatting preserved.*)

		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range[c]	Mean	*Likely* range[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
	Scenario	Mean	*Likely* range[d]	Mean	*Likely* range[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

In 2019, the IPCC published a "Special Report on Oceans, Cryosphere and Climate Change" (SROCC), which included updated sea level rise projections (Table 2.2) based on the same CMIP5 climate model simulations that were used in the IPCC AR5. It is instructive to compare the sea level rise projections in the second-order draft of the SROCC versus the values in the final report. The SROCC values for RCP2.6 and RCP4.5 are comparable to the AR5 values shown above. However, the SROCC sea level rise projections for RCP8.5 (high emissions scenario) are significantly higher than the AR5 values. It is notable that the RCP8.5 values in the final SROCC report are substantially *lower* than in the second order draft. The volatility of the sea level rise projections for RCP8.5 (high emissions scenario) reflects deep uncertainties in understanding of the dynamics and potential instability of the West Antarctic ice sheet and its influence on future sea level rise.

Table 2.2: Projections of global mean sea level rise for 2100 from the IPCC SROCC (baseline period 1986-2005).

Emission Scenario	2nd Order Draft	Final Report
RCP2.6	0.42 m (0.28 - 0.57 m)	0.43 m (0.29 - 0.59 m)
RCP4.5	0.55 m (0.39 - 0.71 m)	0.55 m (0.39 - 0.72 m)
RCP8.5	0.97 m (0.55 - 1.40 m)	0.84 m (0.61 - 1.10 m)

The sea level rise scenarios from the forthcoming IPCC AR6 are not yet available. However, a publicly available letter (King et al. 2020) cited the following values from the 2nd order draft of the AR6: projections for 2100 range from 0.82 - 0.98 meters (32.3 - 38.6 inches), for a surface temperature increase of 4.3 - 4.8°C (7.8 – 8.6 °F). While the AR6 temperature projections are higher than the AR5, the CMIP6 sea level rise projections for the emissions/concentration scenario equivalent to RCP8.5 are *lower* than the values in the SROCC. It remains to be seen whether the sea level rise projections will change in the AR6 final report.

While there is general convergence in the IPCC reports on the projected *likely* range for sea level rise for the low and intermediate emissions/concentration scenarios (RCP2.6, RCP4.5), there is substantial uncertainty and disagreement regarding sea level rise for the high emissions scenario (RCP8.5). This uncertainty is associated with the impact of potential instabilities in the West Antarctic Ice Sheet, which could be triggered by large values of warming.

2.2 NOAA 21st century sea level scenarios

In 2017, the U.S. National Oceanic and Atmospheric Administration (NOAA) published a Technical Report entitled "Global and Regional Sea Level Rise Scenarios for the United States" (NOAA, 2017). Sweet and Kopp (lead authors of the Rutgers Report) were also lead authors for the NOAA Report.

Rather than focus on a *likely* range such as the IPCC, the NOAA Report used a different approach. They sought to bound the plausible global mean sea level scenarios for the year 2100. Relative to a previous NOAA Report (2012), the 2017 Report raised the lower bound from 0.2 meters (7.9 inches) to 0.3 m (11.8 inches) and raised the upper bound from 2.0 meters (6.6 feet) to 2.5 meters (8.2 feet).

The NOAA scenarios are anchored in year 2000 (i.e., a 1991–2009 epoch). They formulated six sea level rise scenarios for 2100:

- Low: 0.3 meters (11.8 inches)
- Intermediate-low: 0.5 meters (19.7 inches)
- Intermediate: 1.0 meters (3.3 feet)
- Intermdiate-High: 1.5 meters (4.9 feet)
- High: 2.0 meters (6.6 feet)
- Extreme: 2.5 meters (8.2 feet)

For reference, the lower bound of the *likely* range for RCP2.6 from the SROCC is 0.26 meters (0.85 feet) which is below the lower plausible bound from the NOAA Report, and the SROCC upper bound of the *likely* range for RCP8.5 is 1.1 meters (3.6 feet). The primary rationale for the Extreme scenario of 2.5 meters was a paper by DeConto and Pollard (2016) that indicated increased likelihood of extreme outcomes from Antarctic ice sheet instability. The rationale for increasing the lower bound is based on tide gauge and satellite-based estimates of the rates of global mean sea level change over the past quarter-century and of recent modeling of future low-end projections.

Table 2.3 provides probabilities of the global mean sea level exceeding each sea level rise scenario for each of three emissions scenarios (RCPs). The three highest sea level rise scenarios have probabilities of exceedance of ≤ 1.3% for all emissions scenarios.

Table 2.3: Probability of exceeding global mean sea level (median value) scenarios in 2100. (*Table 4 | NOAA 2017 formatting preserved*.)

GMSL rise Scenario	RCP2.6	RCP4.5	RCP8.5
Low (0.3 m)	94%	98%	100%
Intermediate-Low (0.5 m)	49%	73%	96%
Intermediate (1.0 m)	2%	3%	17%
Intermediate-High (1.5 m)	0.4%	0.5%	1.3%
High (2.0 m)	0.1%	0.1%	0.3%
Extreme (2.5 m)	0.05%	0.05%	0.1%

The NOAA (2017) Report translated the projections of global mean sea level rise into local values by accounting for local vertical land motion. The NOAA analysis of local sea level rise along regions of the Northeast Atlantic (Virginia coast and northward) found that the projected values are greater than the global average.

Projections for four U.S. cities are shown in Figure 2.1 from the NOAA Report, including New York City (The Battery). For each of these cities, the observations for the period 2000-2015 are tracking at or below the lowest two scenarios. It is seen that the range of year-to-year variability since 2000 is comparable to the magnitude of the trend.

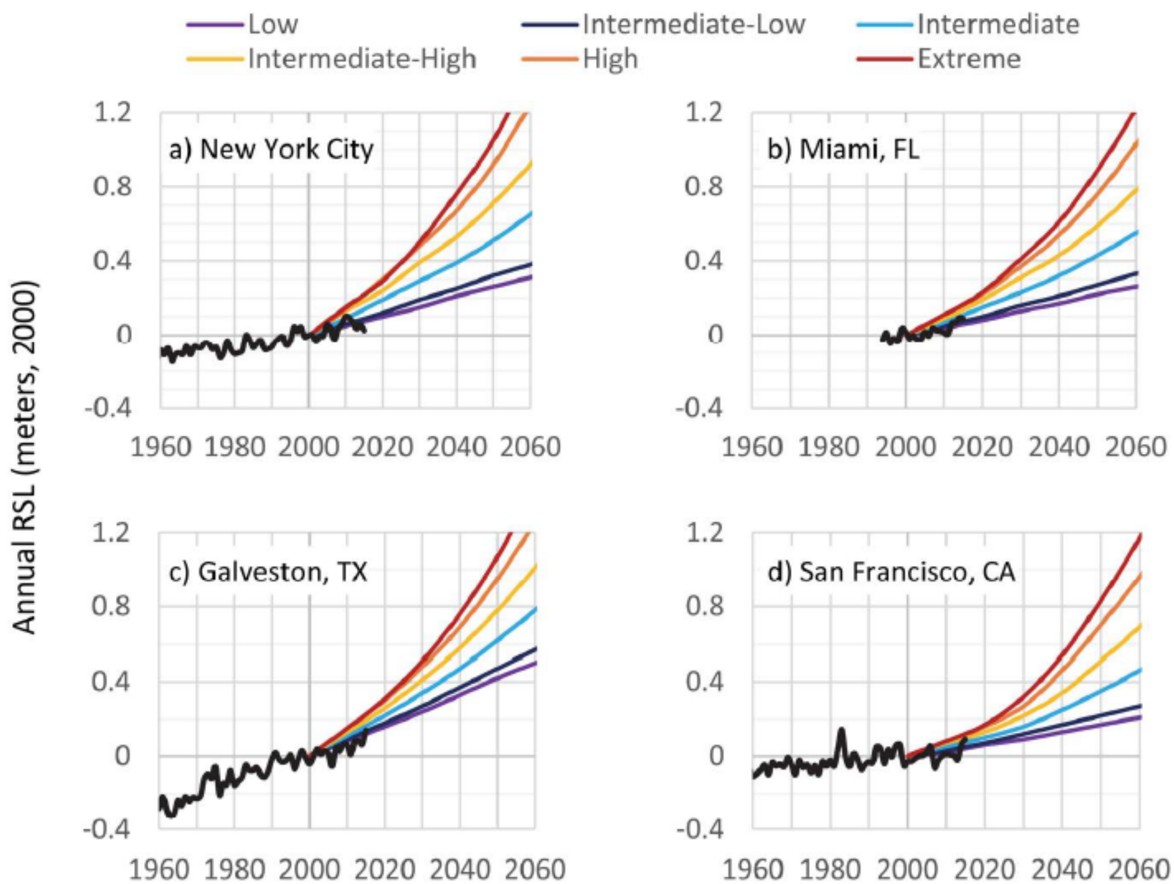

Figure 2.1: Sea level rise projection annual averages for four large US cities based on different climate model projections. (Figure *14 | NOAA 2017*)

In 2017, the 4th U.S. National Climate Assessment (NCA4) was published. Chapter 12 of the NCA4 on Sea Level included as authors Sweet and Kopp (lead authors of the Rutgers Report). The NCA4 formulated the sea level rise projections in terms of a *very likely* range (10% chance of the outcome lying outside of the bounds) that incorporates the low, medium and high emissions scenarios together:

> "Relative to the year 2000, global mean sea level is *very likely* to rise by 0.3–0.6 feet (0.09–0.18 m) by 2030, 0.5–1.2 feet (0.15–0.38 m) by 2050, and 1.0–4.3 feet (0.30–1.30 m) by 2100"

2.3. Global sea level rise projections used in the Rutgers Report

The emissions scenarios used in the Rutgers Report do not directly relate to the emissions scenarios used in the IPCC AR5 and SROCC (e.g. RCP2.6, RCP4.5, RCP8.5). Rather, the Rutgers Report selects two scenarios based on the amount of warming since early industrial (1850-1900): 2^{o}C (low emissions) and 5^{o}C (high emissions). The Rutgers high emissions scenario is close to RCP8.5 through 2100. However, the Rutgers low emissions scenario reflects more warming than RCP2.6. They then averaged the sea level rise projections for their high and low emissions scenario to create a moderate emissions scenario, nominally associated with a temperature increase of 3.5^{o}C.

The rationale for using these new definitions of high and low emissions scenarios is to accommodate the Bamber et al. (2019) expert elicitation on sea level rise associated with potential instability in the West Antarctic ice sheet, which used the 2^{o}C and 5^{o}C scenarios. It is somewhat surprising that the Rutgers Report elected to structure their scenarios following Bamber et al., since the Report states that "SEJ [structured expert judgment], however, is not fully accepted by the ice-sheet modeling community, as it relies on the calibrated mental models of the participating experts rather than explicit physical models."

Since the Rutgers Report didn't use the same emissions scenarios as the IPCC, it is not straightforward to compare them. Global sea level rise projections that are cited in the Rutgers Report as providing the basis for their local sea level rise projections are: Kopp et al. (2014), Kopp et al. (2017), Rasmussen et al. (2018) and Bamber et al. (2019). Kopp et al. (2014) yields projections of *likely* global mean sea level changes that are broadly consistent with IPCC SROCC. Kopp et al. (2017) replaced the original Antarctic ice-sheet mass loss projections of Kopp et al. (2014) with those from the Antarctic ice-sheet modeling study of DeConto and Pollard (2016). Bamber et al. (2019) replaced the Greenland and Antarctic ice-sheet projections of Kopp et al. (2014) with projections based on an expert elicitation of ice-sheet changes associated with climate scenarios leading to 2°C and 5°C of warming by 2100.

Table 2.4 compares the *likely* range predicted by Kopp (2014) and Kopp (2017) with the IPCC projections. While the Kopp (2014) projections are fairly close to the SROCC, the Kopp (2017) projections are almost twice as high as the IPCC projections for RCP4.5 and RCP8.5. While not directly comparable to the other projections, the Bamber et al. (2019) values are even higher.

Table 2.4: Comparative projections of global mean sea level rise (meters) for 2100 based on different emission scenarios.

	RCP2.6	**RCP4.5**	**RCP8.5**
IPCC AR5 (2013)	0.28 – 0.61	0.36 – 0.71	0.52 – 0.98
SROCC (2019)	0.29 - 0.59	0.39 - 0.72	0.61 - 1.10
Kopp (2014)	0.37 – 0.65	0.45 – 0.77	0.62 – 1.00
Kopp (2017)	0.37 – 0.78	0.66 – 1.25	1.09 – 2.09

To accommodate the Bamber et al. sea level rise projections, which do not include a moderate emissions scenario analogous to RCP4.5, the Rutgers Report created a moderate scenario by averaging the percentiles of their low and high scenarios. Moderate sea level rise projections thus created are shown in Table 2.5, for the same group of projections shown in Table 2.4. Creation of the 'moderate' SLR scenario by averaging the 'high' and 'low' scenarios effectively gives too much weight to the 'high' scenario (based on the RCP8.5 emissions scenario). This bias arises since some of the processes are nonlinear with temperature, with the resulting sea level rise being not very 'moderate' in terms of being consistent with the targeted emissions scenario (RCP4.5). For RCP8.5 projections having an upper bound that exceeds 1.0 m, the derived Moderate (AVG) scenario is 10-25% higher than the corresponding RCP4.5 values.

Table 2.5: Comparative projections of global mean sea level rise for 2100 based on different emission scenarios with the addition of linear based “Moderate” scenario.

	RCP2.6	**RCP4.5**	**Moderate (AVG)**	**RCP8.5**
IPCC AR5 (2013)	0.28 – 0.61	0.36 – 0.71	0.40 – 0.80	0.52 – 0.98
SROCC (2019)	0.29 – 0.59	**0.39 – 0.72**	0.45 – 0.85	0.61 - 1.10
Kopp (2014)	0.37 – 0.65	0.45 – 0.77	0.50 – 0.83	0.62 – 1.00
Kopp (2017)	0.37 – 0.78	0.66 – 1.25	**0.73 – 1.44**	1.09 – 2.09

For evaluative purposes that are most relevant to decision making, it is useful to compare the Moderate(AVG) scenario from Kopp et al. (2017) with RCP4.5 from the SROCC (indicated by the **bold** values). It is seen that the Kopp et al. (2017) Moderate(AVG) projections are twice as high as the SCROCC RCP4.5 projections. The majority of this differential is associated with the fundamentally higher projections in Kopp et al. (2017). However, about 20% of this discrepancy is associated with averaging the high and low scenarios to create a moderate scenario.

The Rutgers scenarios of future climate change are formulated in a fundamentally different way than the IPCC. The IPCC provides a range of temperature and sea level rise projections for a discrete number of emissions scenarios. This results in a continuum of temperature and sea level rise projections whose *likely* range overlaps among the different emissions scenarios. By contrast, the Rutgers Report provides distributions of sea level rise for two temperature scenarios: 2^{o}C and 5^{o}C. A third, intermediate scenario is provided by simply averaging the temperature and the sea level rise percentile. The Rutgers approach does not discriminate in a meaningful way the range of temperature scenarios (including the lower bound) for which the potential instability of the West Antarctic ice sheet might contribute substantially to sea level rise in the 21st century – the relevant processes are nonlinear with temperature and cannot be interpolated based on temperature in a meaningful way.

2.4 Summary

The IPCC has a well-established formalism for providing a range of outcomes (e.g. temperatures, sea level rise) based on forcing from different emissions scenarios. The Rutgers Report breaks with this formalism by providing sea level rise projections for two temperature change scenarios: 2^{o}C and 5^{o}C. The apparent rationale for this is to accommodate the expert elicitation of Bamber et al. (2019) on outcomes related to instability in the Antarctic ice sheet, which were elicited for these two temperature changes.

While it is not straightforward to compare the Rutgers projections for the New Jersey coast with the IPCC projections of global sea level rise, the global sea level rise projections underlying the Rutgers projections are substantially higher than those provided by the IPCC – by more than a factor of two.

The reason for these excessively high projections is the method whereby the Rutgers team incorporated extreme scenarios of Antarctic Ice Sheet instability, motivated primarily by DeConto and Pollard (2016). The year 2017 (when the NOAA Report was published) arguably marked the peak influence of expectation for such an extreme scenario during the 21st century; subsequent analyses have backed off from this extreme scenario (see Section 3.5 of the CFAN Review). Most significantly, subsequent IPCC assessments are not producing such exceptionally high projections of sea level rise, even for the RCP8.5 (high emissions) scenario. Further, the manner in which the Rutgers Team incorporates this extreme scenario into their projection probabilities contaminates even the low and moderate emissions scenarios (as evidenced by Kopp et al. 2017 in Table 2.5). This apparently results from assumptions made in creating their probability distribution functions, effectively manufacturing a large tail influence of this extreme scenario even for small amounts of warming under the low emissions scenario (RCP2.6)

The Rutgers Report characterizes their projections as "Consensus Science to Support Planning for Sea Level Rise in New Jersey." While their projections may reflect a 'consensus' among the authors of the Rutgers Report, they do not reflect a consensus of international experts on climate change and global sea level rise. The consensus on climate change and sea level rise is better represented by the IPCC assessment reports.

3. Sources and levels of uncertainty

For policy and decision making purposes, a clear understanding is needed of the contingent assumptions, limitations and uncertainties associated with projections of future climate change and sea level rise.

It is important to understand that the temperature and sea level rise projections provided by the IPCC and NOAA are *not* predictions of actual outcomes. Rather, these projections should be regarded as sensitivity analyses relative to increasing emissions. These projections neglect any changes in natural climate variability that would influence actual sea level rise outcomes in the 21st century. Chapters 11 and 12 of the IPCC AR5 (2013) describe uncertainties and limitations of the climate model projections:

> "Projections of future states of the global climate are subject to several sources of uncertainty. The first source of uncertainty arises from natural internal variability, which is intrinsic to the climate system, and includes phenomena such as variability in the mid-latitude storm tracks and the ENSO. The existence of internal variability places fundamental limits on the precision with which future climate variables can be projected. The second is uncertainty concerning the future forcing of the climate system by natural and anthropogenic forcing agents such as greenhouse gases, aerosols, solar forcing and land use change. The third is uncertainty related to the response of the climate system to the specified forcing agents, which is referred to as the 'climate sensitivity." [AR5 WG I Section 11.3.1.1]

> "Simplifications and the interactions between parameterized and resolved processes induce 'errors' in models, which can have a leading-order impact on projections. Also, current models may exclude some processes that could turn out to be important for projections) or produce a common error in the representation of a particular process." [AR5 WG I Section 12.2.3]

A key issue is the extent to which these uncertainties and model errors produce erroneous decision-relevant model outcomes. This section evaluates the uncertainties and limitations in emissions scenarios, sensitivity of warming to increasing CO_2 and uncertainties in stability of the West Antarctic ice sheet.

3.1 Emissions scenarios

There is growing evidence that the RCP8.5 emissions scenario (equivalent to the 'high emission' scenario used in the Rutgers Report) is implausibly high. RCP8.5 pathways are driven by: very high population growth, very high energy intensity of the economy, low technology development, and a high level of coal in the energy mix. Wang et al. (2016) and Ritchie and Dowlatabadi (2018) challenge the bullish expectations for coal in the RCP8.5 scenarios, which is counter to recent global energy outlooks and exceeds today's known conventional reserves. Burgess et al. (2020) further highlight the implausibility of the RCP8.5 scenario owing to contradictions in the assumptions used in building the scenario. Pielke and Ritchie (2020) concluded that RCP8.5 is systematically misused for policy making purposes. While RCP8.5 remains widely used in scientific research papers, Ritchie and Dowlatabadi (2018) recommend that RCP8.5 should not be used as a benchmark for policy studies.

The 2019 World Energy Outlook Report from the International Energy Agency (IEA, 2019) challenges the near-term RCP emissions scenario projections through 2040. The IEA examined three scenarios: a current policy scenario where no new climate or energy policies are enacted by countries, a stated policies scenario where Paris Agreement commitments are met, and a sustainable development scenario where rapid mitigation limits late 21st century warming to well below 2°C. The IEA projections through 2040 are close to the RCP4.5 scenario.

The significance of rejecting the RCP8.5 in scenarios of 21st century sea level rise is this. The greatest uncertainties in 21st century sea level rise projections are associated with possible large instabilities in the West Antarctic Ice Sheet arising from the highest temperature projections. By eliminating RCP8.5, the highest sea level rise projections are eliminated. In context of the Rutgers Report, this would eliminate their high emissions scenario and compromise their moderate emissions scenario (which was obtained simply by averaging the outcomes of the high emissions scenario with the low emissions scenario.)

3.2 Are climate models trending too 'hot'?

Climate model projections of future warming can be evaluated by comparing the projections with recent observations of global mean surface temperature. Figure 11.25 from the IPCC AR5 (2013) compared the near-term climate model temperature projections (CMIP5) with recent observations. The observed temperatures between 2000-2012 were at the bottom of the envelope of climate model simulations (see Figure 3.1). As a result of this comparison, the IPCC "reduced the warming projections by 10% to take into account the evidence that some models may be too sensitive to anthropogenic forcing." [IPCC AR5 WG1 Section 11.3.6.3].

The author of Figure 11.25 in the IPCC AR5 – Professor Ed Hawkins of Reading University – provides an annual update of the figure. Figure 3.1 includes the global surface temperature data through 2020. The red hatching in Fig. 11.25 reflects the judgment cited above by the AR5 authors that lowers the projected warming out to 2035 relative to the climate model simulations.

The large El Niño of 2016 returned the observed temperature curve to near the middle of the envelope of climate model simulations; however the previous large El Niño of 1998 was at the top of the envelope of climate model simulations. The recent observations continue to indicate that the sensitivity of at least some of the climate models to carbon dioxide emissions is too high, producing too much warming.

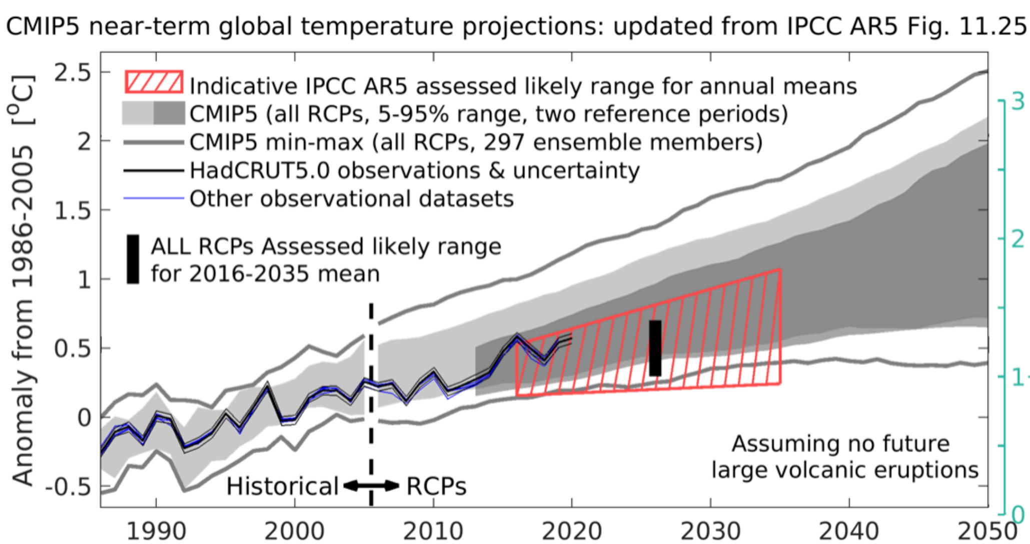

Figure 3.1: Synthesis of near-term projections of global mean surface air temperature (GMST). Simulations and projections of annual mean GMST 1986–2050 (anomalies relative to 1986–2005). The maximum and minimum values from climate models using all ensemble members and the 1986–2005 reference period are shown by the grey lines. Black lines show annual mean observational estimates. [following IPCC AR5 WG I Figure 11.25]

A key issue in projecting future climate change is sensitivity of climate model-predicted warming to increasing amounts of atmospheric carbon dioxide. It is the range of sensitivity to increasing CO_2 across the different climate models produces the range of *likely* values of sea level rise projections (shown in Tables 2.1-2.4) for a given emissions/concentration scenario. The equilibrium climate sensitivity (ECS) is a measure of the global mean surface temperature change in response to a doubling of atmospheric CO_2. For the past 30+ years, climate scientists have presented a *likely* range for ECS that has hardly changed: the ECS range of 1.5−4.5^{o}C in 1979 (Charney et al. 1979) is unchanged in the *likely* range of the 2013 IPCC AR5. The climate model values of ECS cited by the AR5 range between 2.1 and 4.7^{o}C, which does not sample the bottom 20% (between 1.5 and 2.1^{o}C) of the IPCC's *likely* range.

Reasons for thinking that climate models are predicting too much warming include:

- The RCP8.5 emissions scenario is implausible.
- Observed warming for the past two decades is less than the average rate of warming predicted by climate models.
- The ensemble of climate model simulations does not sample the full range of *likely* values of equilibrium climate sensitivity, neglecting the lowest 20% of the *likely* range from the IPCC AR5.
- Climate models do not include solar variability and volcanic eruptions, with plausible scenarios for a cooling effect in the 21st century. Ignoring volcanic eruptions ignores their cooling effects (Bethge et al, 2017. Most projections of solar variability for the 21st century expect cooling relative to the 20th century (Matthes et al. 2017).

Specifically with regards to the Rutgers Report, their scenario of a 5^{o}C temperature increase (4^{o}C over the 21st century) increasingly looks implausible.

3.3 Levels of incertitude

The different dimensions of incertitude in context of decision making are characterized as (for an overview, see Curry, 2018):

- *Complete certainty* – implies deterministic knowledge, with no uncertainty.
- *Risk (statistical uncertainty)* – possible outcomes and their likelihoods can be reliably estimated; we know the odds. Precise, decision-relevant probability statements can be provided for each potential outcome.
- *Scenario uncertainty* – a range of plausible outcomes (scenarios) are enumerated, but with a weak basis for ranking them in terms of likelihood; we don't know the odds.
- *Deep uncertainty (recognized ignorance)* – fundamental uncertainty in the mechanisms being studied and a weak scientific basis for developing scenarios; future outcomes may lie outside of the realm of regular or quantifiable expectations; no agreement on how to define the possible outcomes.
- *Total Ignorance* – little basis for developing possible outcomes; we don't know what we don't know

In context of these classifications, the 21st century climate change projections are evaluated to be associated with the following levels of incertitude (Curry, 2018):

- Climate sensitivity: *scenario uncertainty* – values of climate sensitivity are credibly bounded (weakly bounded on the high end), but we have a weak basis for preferring low or high levels. This relates directly to the *likely* range of outcomes for a specific emissions/concentration scenario, where there is little basis for preferring low or high levels.

- Sea level rise in response to moderate temperature increase: *scenario uncertainty.*
- Sea level rise in response to large amounts of warming or 'Dragon King' events such as major instability of the West Antarctic ice sheet: *deep uncertainty*.

Kopp et al. (2017) state:

> "The breadth of published projections, as well as of remaining structural uncertainties, highlight the fact that future sea-level rise remains an arena of *deep uncertainty*."

Characterizing the level of incertitude is relevant for assessing the confidence to place in 'best' estimates, *likely* ranges, extreme outcomes and probabilities of future outcomes. The IPCC's specification of a *likely* range is consistent with the scenario uncertainty associated with sea level rise. By contrast, the NOAA report provides precise probabilities for each sea level rise scenario. Subsequently, the Rutgers Report provided a range of probabilities for each sea level rise scenario.

Portrayal of probabilities of outcome scenarios, particularly under conditions of deep uncertainty, can mislead decision makers who use such information in a risk-based decision framework such as cost-benefit analysis. A further problem with generating probability distributions under conditions of deep uncertainty is that the statistical manufacture of tail probabilities can produce implausible outcomes on the high end of the distribution, while contaminating the lower end of the distribution with processes that influence only the higher end of the distribution.

There are several alternative approaches for characterizing scenarios of future outcomes and their likelihood under conditions of deep uncertainty. One alternative method is to regard each of the outcomes as a possibility, and then characterize the level of justification for each scenario. This alternative avoids the misleading precision of probabilities and eliminating from consideration plausible scenarios outside of the *likely* range. Another alternative is to divide the outcome scenarios into two groups: the first group reflecting the sea level rise outcomes (e.g. *likely*, *very likely* ranges for the IPCC scenarios) that do not include the processes that contribute to deep uncertainty (e.g. ice sheet instability); and the second group reflecting outcomes that are considered for the plausible worst case and cannot be associated in a meaningful way with outcome probabilities or a *likely* range.

3.4 Worst case scenarios, Dragon Kings and gray swans

The plausible worst case such as the Extreme scenario presented in the NOAA Report can play an important role in certain decision making frameworks. However, considerable care is needed in formulating the plausible worst-case outcome so as to be relevant and useful for decision makers. All three of NOAA's highest scenarios (ranging from 1.5 to 2.5 meters) are within the published range of worst-case sea level rise scenarios, and this is how these three scenarios should be regarded. However, the probabilities assigned to these scenarios in the NOAA Report are fairly meaningless, since they are associated with deep uncertainty and a high level of recognized ignorance.

Outcomes of future climate change are associated with deep uncertainty, and plausible outcomes (especially on the high end) are weakly constrained. Experts inevitably disagree on what constitutes a plausible worst-case scenario when the knowledge base is uncertain (Bamber et al. 2019 is a case in point). Curry (2019) has developed a classification of worst-case scenarios based on the extent to which borderline implausible parameters or inputs are employed in developing the scenario via physical or mental models. This classification is inspired by the Queen in "Alice in Wonderland:" "Why, sometimes I've believed as many as six impossible things before breakfast." This classification articulates three categories of worst-case scenarios:

- ***Conceivable worst case***: formulated by incorporating all worst-case parameters/inputs into a model; the outcome does not survive refutation efforts.
- ***Possible worst case (borderline impossible)***: Includes multiple worst-case parameters/inputs in model-derived scenarios; the outcome survives refutation efforts (at least temporarily).
- ***Plausible worst case***: Includes at most one borderline implausible assumption in model-derived scenarios.

The plausible worst-case scenario is most relevant for decision making. Candidates for the plausible worst-case scenario can be evaluated by assessing the input assumptions and parameters that are used in developing the scenario. Inevitably, there will be disagreement as to what constitutes an implausible input, and hence there is a range of candidate worst-case scenarios to consider.

A 'black swan event' (Taleb, 2007) is a metaphor that describes an event that comes as a surprise, has a major effect, and is often inappropriately rationalized after the fact with the benefit of hindsight. In assessing the climate change impacts on sea level rise and coastal storms, attempts are made to foresee worst-case scenarios. There are two different types of plausible worst-case scenarios of relevance to the assessment of coastal threats from climate change:

- Gray swan: a high-impact event that may be foreseeable using historical data combined with physical knowledge. Gray swan scenarios are of relevance for worst-case impacts from a single landfalling hurricane (Lin and Emanuel, 2015)
- Dragon King: an event that is extremely large in size or impact, occurring in nonlinear and complex systems that is generated from positive feedbacks, tipping points, bifurcations, regime shifts. By understanding the underlying dynamics, there may be some potential predictability. Major instabilities in West Antarctic ice sheet fall into the Dragon King category (Sornette, 2009).

Gray swans are somewhat different from Dragon Kings in that our understanding is sufficient to formulate plausible gray swan scenarios of individual extreme events, whereas Dragon Kings imply a large-scale event arising from instability or a regime shift.

A number of different scenarios should be formulated for plausible gray swan and Dragon King events. Probability distributions can be formulated for gray swan and Dragon King events, based on a distribution of inputs. However, it is important to keep in mind that such probability distributions do not relate directly to outcomes, but rather to the plausibility of the individual scenarios as the worst case. For Dragon Kings, any estimated probabilities will evolve with increasing knowledge. When there is sufficient reason to believe that a Dragon King event could occur, it is best for decision making purposes if the distribution for the Dragon King regime are presented separately from the probabilities for the range of outcomes that are better understood (Ranger et al 2013).

While speculative scenarios can be useful in support of the decision making process, formulation of the plausible worst case scenario(s) for decision making applications requires justification for the assumptions that went into the model (physical or mental), including the plausibility of the assumptions. A major concern about the Bamber et al. (2019) expert elicitation that was used in the Rutgers Report is that the individual respondents were not required to provide justification for their predicted outcomes.

Due to ignorance, misaligned incentives, and cognitive biases, there is often a failure to adequately anticipate Dragon King and gray swan events. However, when explicit efforts are undertaken to anticipate such events, their importance and likelihood can be over-emphasized and there is a great deal of uncertainty and speculation that needs to be acknowledged.

3.5 Plausibility of major instability in the West Antarctic ice sheet

The primary concern over future sea level rise in the 21st century is related to potential dynamical instabilities in the West Antarctic Ice Sheet. The West Antarctic Ice Sheet rests on bedrock below sea level, making the ice sheet vulnerable to melting from the ocean. If these marine ice shelves – the floating extensions of glacial ice flowing into the ocean – lose mass, their buttressing capacity is reduced, accelerating seaward ice flow. This self-sustaining process is known as Marine Ice Sheet Instability (MISI).

The IPCC AR5 (2013) has medium confidence that this additional contribution from the West Antarctic ice sheet would not exceed several tenths of a meter of sea level rise during the 21st century [IPCC AR5 WG1 Chapter 13]. Subsequent to the IPCC AR5, there has been considerable focus on the worst-case scenario for global sea level rise, and our 'background knowledge' is rapidly changing. DeConto and Pollard (2016) articulated a mechanism whereby disappearance of ice shelves allows formation of ice cliffs, which may be inherently unstable if they are tall enough to generate stresses that exceed the strength of the ice. This ice cliff failure can lead to ice sheet retreat via a process called marine ice cliff instability (MICI), that is hypothesized to cause partial collapse of the West Antarctic Ice Sheet with increased warming.

The IPCC SROCC (2019) provides an updated summary on the potential contribution of dynamical instabilities in the West Antarctic Ice Sheet to global sea level rise. The IPCC SROCC assessed the amount of sea level rise increase from dynamical instability of the West Antarctic ice sheet to be 16 centimeters (range: 2–37 cm). The SROCC notes that the expert elicitation approach (Bamber et al., 2019; used in the Rutgers Report) suggests considerably higher values for sea level rise from the West Antarctic ice sheet than provided in Table 4.3 of the IPCC SROCC.

If RCP8.5 is assumed to be implausible and the focus is on the moderate emissions scenarios (RCP4.5), what constitutes the plausible worst-case scenario for sea level rise? Specifically with regards to the DeConto and Pollard (2016) mechanism, the SROCC makes the following statement:

> "The results by DeConto and Pollard (2016) indicate significantly higher mass loss even for RCP4.5, potentially related to their high surface melt rates on the ice shelves as contested by Trusel et al. (2015). This early onset of high surface melt rates in DeConto and Pollard (2016) leads to extensive hydrofracturing of ice shelves before the end of the 21st century and therefore to rapid ice mass loss. For this reason, their results and probabilistic (e.g., **Kopp et al., 2017**; Le Bars et al., 2017) and statistical emulation estimates that build on them (Edwards et al., 2019), are **not used** in SROCC sea level projections."

A recent publication by Donat-Magnin et al. (2021) uses improved estimates of surface melt rates, and finds that for RCP4.5 only the Abbot glacier in the Amundsen sector is expected to become unstable to hydrofracturing (the DeConto-Pollard mechanism) during the 21st century. Edwards et al. (2019) further supports at most a small contribution in the 21st century from RCP4.5 for the DeConto-Pollard mechanism.

Specifically with regards to the Marine Ice Cliff Instability (MICI) of DeConto and Pollard (2016), the IPCC SROCC makes the following statement:

> "Overall, there is *low agreement* on the exact MICI mechanism and *limited evidence* of its occurrence in the present or the past. Thus the potential of MICI to impact the future sea level remains very uncertain" [Cross-Chapter Box 8]

At this point, there isn't an obviously plausible Dragon King scenario for sea level rise in the 21st century under RCP4.5.

3.6 Summary

Projections of temperature and sea level rise projections that are cited by the IPCC, NOAA and the Rutgers Report are *not* predictions of actual outcomes. These projections are contingent upon a number of assumptions that are not mentioned in the Rutgers Report.

Given the implausibility of the RCP8.5 emissions scenario, use of RCP4.5 (moderate emissions) is justified by the IEA Report, at least out 2050. Specifically considering the amount of warming associated with the RCP4.5 scenario, my assessment is that temperature change is *very unlikely* to exceed the upper bound of the IPCC AR5 *likely* range. Unfortunately, the moderate emissions scenario outcomes in the Rutgers Report does not relate to RCP4.5 and produces values that are substantially higher than the IPCC's RCP4.5 sea level rise outcomes.

The Rutgers Report relies on expert elicitation for assessing worst-case sea level rise outcomes (Bamber et al, 2019). To credibly include the results of such elicitations in sea level rise scenarios for decision making, justification for each candidate worst case outcome should be provided and assessed, in context of the plausibility of the assumptions and inputs relative to our background knowledge. Incorporation of possible extreme outcomes associated with deep uncertainty into probability distributions of outcomes can produce statistical projections that are misleading and biased towards the extreme outcome.

A key assumption from the Rutgers Report is that the ice sheet instability process described by DeConto and Pollard (2016) is expected to have a substantial impact on sea level rise in the 21st century. This assumption in the Rutgers Report is not supported by the latest assessment provided by the IPCC SROCC (2019).

4. New Jersey sea level change

Local sea level changes can differ global sea level change owing to factors that are important at regional/local scales: 1) shifts in ocean circulation patterns; 2) changes in the Earth's gravitational field and rotation, and the flexure of the crust and upper mantle due to melting of land-based ice; and 3) vertical land movement due to glacial isostatic adjustment, sediment compaction, groundwater and fossil fuel withdrawals, and other non-climatic factors.

4.1 Historical variability and change

There are three fairly long-term tide-gauge records along the New Jersey coast - Atlantic City, Cape May and Sandy Hook; also relevant is the tide gauge record from The Battery in New York. These tide gauge records (as plotted by NOAA) are shown below.

The observed values of sea level rise along the New Jersey coast are substantially higher than rates of global sea level rise. As summarized by Karegar et al. (2016), many places in the Eastern U.S. have been sinking for thousands of years and will continue to sink for thousands more, in response to adjustments from the retreat of glacier ice following the last Ice Age. Even though the glacier ice retreated long ago, the U.S. East Coast and Great Lakes regions are still slowly sinking.

Ground water withdrawal and sediment compaction are additional factors influencing the local rate of sinking. Locations that sit atop a coastal plain, such as the Jersey Shore, are seeing the fastest rates of subsidence, since the geology of the coastal plain features more settling of the land from groundwater depletion and long-term sediment compaction. By contrast, Mid-Atlantic coastal locations that are built on top of bedrock, such as New York City, have relatively low sinking rates.

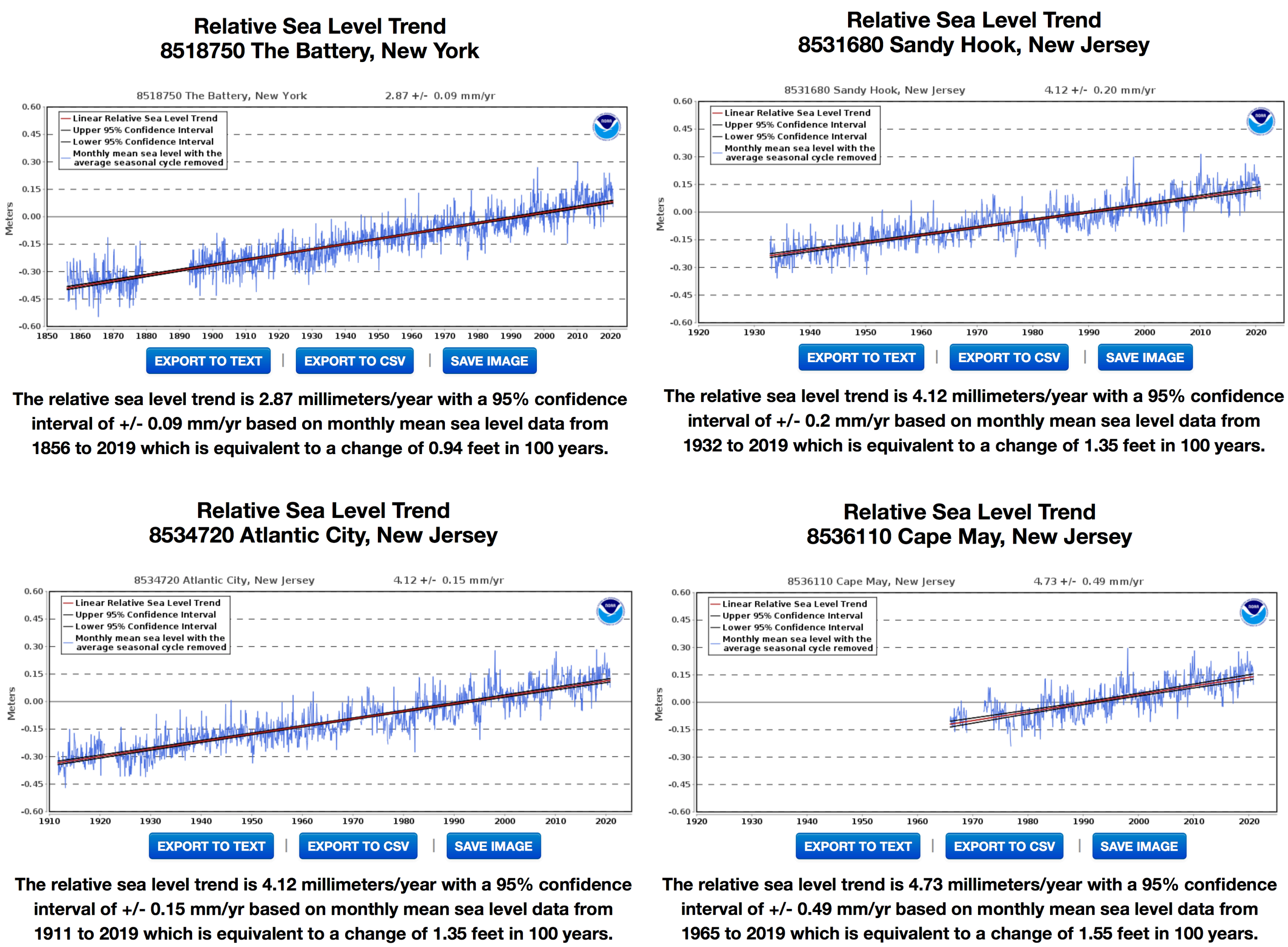

Figure 4.1: Historic monthly relative sea level values and trends for NJ locations of Sandy Hook (upper right), Atlantic City (lower left) and Cape May (lower right) as well as The Battery in New York (upper left). All plots can be reproduced at https://tidesandcurrents.noaa.gov/map/index.html?region=New%20Jersey

There are numerous estimates of vertical land motion for tide gauges along the Jersey coast and The Battery. The most consistent and reliable estimates are for The Battery, with local GPS measured vertical land motion of -1.32 mm/yr. Estimates for locations along the Jersey shore are based on regional GPS measurements (ranging from -1.25 to -1.53 mm/yr; Karegar et al, 2016) and by comparison of tide gauge records with observations of global sea level rise (-2.10 to -2.27 mm/yr; NOAA, 2013). For reference, 1.5 millimeters is equivalent to the thickness of a penny.

4.2 Causes of sea level variability

There is substantial year-to-year and decadal variability in rates of sea level rise (Figure 4.1). In addition to the underlying trend of increasing sea levels, large-scale atmospheric and oceanic circulation patterns influence sea level variability on time scales of months to decades. Even abrupt events such as major volcanic eruptions can have lasting cooling impacts on a global scale.

Overviews of the processes that contribute to year-to-year and decadal-scale variability in mid-Atlantic coastal sea level rise are provided by Little et al. (2019) and Piecuch (2020). U.S. East Coast sea level variability on decadal time scales has been related to changes in various components of the North Atlantic Ocean circulation, such as the Florida Current, Gulf Stream, and Atlantic Meridional Overturning Circulation. In addition, there is the year-to-year 'noise' of local wind forcing near the coast. Anomalous onshore or alongshore winds can raise local sea level. Such locally forced coastal ocean processes account for a large portion of the variability in tide-gauge sea level records along the U.S. east coast north of Cape Hatteras on interannual and decadal periods.

The U.S. Atlantic coast north of Cape Hatteras has been identified as a 'hotspot' of late 20th century sea level rise that has been detected since the 1970's (e.g. Sallenger et al. 2012). Gehrels et al. (2020) examined salt-marsh-sediment-based sea level reconstructions, and found that there was a period of rapid multi-decadal sea level acceleration on the U.S. northeast coast in the 1700s (a 'hotspot'), which was almost as rapid as accelerations observed during the twentieth century. Gehrels et al. associate the hot spots with centennial changes in the North Atlantic Oscillation, whereas Kenigson and Han (2016) find a signal from the ~60 year Atlantic Multidecadal Oscillation. The mechanisms for producing the hot spot may relate to ocean circulation patterns and also associated variations with northern hemisphere changes in glaciers and the mass balance of Greenland (e.g. Ruan et al. 2020).

In recent decades, the Gulf of Maine has warmed much faster than the global average, marine heat waves have grown longer and more frequent, and the Gulf Stream has grown increasingly unstable (notably the Gulf Stream North Wall). Long tide gauge records along the U.S. East Coast also show changes in tidal range, from more minor gradual oscillations to major abrupt changes (see recent reviews by Talke and Jay 2020; Haigh et al. 2020).

These various influences can work collectively in either a dampening or amplifying manner with regards to hotspots of sea level rise in this region. The hot spot indicates that natural variations in ocean circulation and tidal patterns can have significant impacts on decadal variability of local sea level rise, which is of direct relevance for projections out to 2030 and 2050.

4.3 Evaluation of predictions from the Rutgers Report: 2000-2020

The projections provided in the Rutgers report use as a baseline the period 1991-2009 (nominally the year 2000). Hence, the observed tide gauge data through 2020 can be evaluated against the sea level rise projections in the Rutgers Report (Table 4.1). With regards to the 2030 projections, we are already more than 2/3 through this period. When based on the trends since 1980 there is only 3.02 inches (0.25 feet) increase at The Battery, 3.66 inches (0.31 feet) at Sandy Hook, 3.51 inches (0.29 feet) at Atlantic City and 3.9 inches (0.33 feet) for Cape May. Reaching 9.6 inches (0.8 feet) by 2030 (the Rutgers scenario with 50% chance) would require a very substantial acceleration for the remainder of the 2020's.

Figure 4.2 overlays the observed time series since 1980 of sea level on top of the Rutgers sea level rise projections for Atlantic City. The projections for 2030 and 2050 are independent of emissions scenario. The solid blue line is the Rutgers ~50%; the dash line reflects the *likely* bounds (17-83%) and the dotted line reflects the *very likely* bounds (5-95%).

The short-term trend in the observed sea level record is dominated by large year-to-year variability. The observed sea level record between the period 2000 and 2020 appears to be tracking between bottom of the *likely* and *very likely* ranges of the Rutgers forecast.

Table 4.1: Sea level rise projections for different 'chance' categories at different future dates. (*Table 3 | Rutgers Report 2019 formatting preserved*.)

Table 3. New Jersey Sea-Level Rise above the year 2000 (1991-2009 average) baseline (ft)*

		2030	2050	2070			2100			2150		
				Emissions								
	Chance SLR Exceeds			Low	Mod.	High	Low	Mod.	High	Low	Mod.	High
Low End	> 95% chance	0.3	0.7	0.9	1	1.1	1.0	1.3	1.5	1.3	2.1	2.9
Likely Range	> 83% chance	0.5	0.9	1.3	1.4	1.5	1.7	2.0	2.3	2.4	3.1	3.8
	~50 % chance	0.8	1.4	1.9	2.2	2.4	2.8	3.3	3.9	4.2	5.2	6.2
	<17% chance	1.1	2.1	2.7	3.1	3.5	3.9	5.1	6.3	6.3	8.3	10.3
High End	< 5% chance	1.3	2.6	3.2	3.8	4.4	5.0	6.9	8.8	8.0	13.8	19.6

**2010 (2001-2019 average) Observed = 0.2 ft*

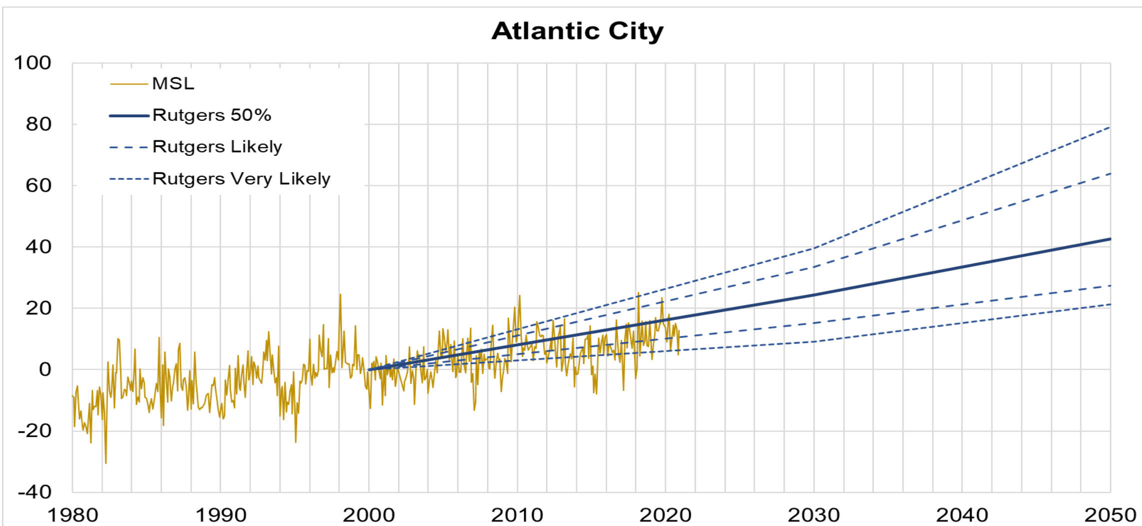

Figure 4.2: Historic and projected relative sea level in centimeters (y axis) over time (x axis) for the period 1980 to 2050 in Atlantic City. Historic data is based on data utilized in figure 4.1 from NOAA tidal records. Future data is based on values found in the Rutgers Report Table 6.

4.4 Recommended scenarios of sea level rise for New Jersey

Based upon the recent historical record since 2000, there seems little justification for a 2030 prediction that exceeds the bottom of the *likely* range (>83% chance exceedance).

For the period to 2050, consideration is needed of the natural modes of ocean circulation patterns, especially given the current period with the Northeast U.S. coastal 'hot spot.' A further issue of relevance is the influence of these same ocean circulation patterns in the North Atlantic on the mass balance of Greenland. The bottom of the *likely* range in the Rutgers Report also seem like a good bet out to 2050.

For projections to 2100, emissions scenario RCP4.5 seems the most appropriate to use. However as described in Section 2.3, the projections of sea level rise in the Rutgers Report for the moderate emissions scenarios do not relate to RCP4.5. The IPCC's projections for RCP4.5 are more consistent with the

Rutgers low emissions scenario. Table 2.5 is reproduced below, which compares the IPCC SROCC RCP4.5 *likely* range with the Kopp et al. (2017) low emissions *likely* range (**bold**).

Table 2.5: Comparative projections of global mean sea level rise for 2100 based on different emission scenarios with the addition of linear based "Moderate" scenario.

	RCP2.6	RCP4.5	Moderate (AVG)	RCP8.5
IPCC AR5 (2013)	0.28 – 0.61	0.36 – 0.71	0.40 – 0.80	0.52 – 0.98
SROCC (2019)	0.29 – 0.59	**0.39 – 0.72**	0.45 – 0.85	0.61 - 1.10
Kopp (2014)	0.37 – 0.65	0.45 – 0.77	0.50 – 0.83	0.62 – 1.00
Kopp (2017)	0.37 – 0.78	0.66 – 1.25	**0.73 – 1.44**	1.09 – 2.09

The wild card (potential Dragon King) and largest uncertainty is associated with a potential large contribution from instability in the West Antarctic ice sheet. The IPCC SROCC (Chapter 4) assessed this contribution to be considerably lower than that provided by the expert elicitation of Bamber et al. (2019), which is used in the Rutgers Report. The forthcoming IPCC AR6 will review more recent studies as well.

For decision making and policy purposes, the most important outstanding issue is continued investigation and assessment of the contribution of West Antarctic ice sheet instability under moderate temperature increases associated with emissions scenario RCP4.5. They key issue is assess whether or not there is a plausible Dragon King scenario that should be considered for the moderate emissions scenario.

Near term predictions of future sea level rise (out to 2050) should include scenarios of variations in rates of natural sea level change.

5. Coastal storms

This section addresses the potential impacts of climate variability and change on storm surge from extra-tropical cyclones and also hurricanes.

Storm surge and storm tide are two separate metrics that describe the storm-induced rise in water levels. Storm *surge* is the anomalous rise in water level above the predicted astronomical tide (excluding the impacts of waves), and storm *tide* is the total rise in water level due to the combination of storm surge and astronomical tides. For example, Hurricane Sandy's peak hourly averaged water levels occurred at high tide at the Battery with a storm tide of 13.6 feet above 2012 MSL and a storm surge of 12.4 feet. The return time for a storm tide of this magnitude at The Battery has been estimated to range from a 1-in-900 year event (Sweet et al. 2013) to a 1-in-1600 year event (Lin et al., 2012).

With regards to storm surge and flooding from coastal storms along the mid-Atlantic coast, Orton et al. (2019) states that 15 of the top 22 top historical storm surge events impacting New York City have been caused by extratropical cyclones (mid-latitude weather systems), which impact the region far more often than hurricanes. However, the maximum wind speeds for extratropical cyclones are much lower than those for hurricanes or hybrids. In storm tide data going back to 1844 and news reports back to the 1700s, no extratropical cyclone-driven storm tide has exceeded 7.2 feet.

The Rutgers Report concluded that there is no definitive consensus at this time regarding changes to the frequency and characteristics of coastal storms impacting the New Jersey coast. However, the Report emphasized that sea level rise will exacerbate future coastal storm impacts for the state of New Jersey, even if there is little or no systematic change in storm characteristics. Apart from the underlying issue of sea level rise, the Rutgers Report states that there is no clear basis for planning guidance for New Jersey to deviate from the most recent examinations of storm tide issues by the New York City Panel on Climate Change (Orton et al., 2019).

Table 5.1 from Orton et al. (2019) provides a summary of the different evaluations of return periods for storm tides at The Battery. There are substantial differences among these estimates of return periods, arising from the use of historical storm tide data versus model-based data and the probabilistic frameworks that were used. Following Hurricane Sandy, FEMA (2013) increased the values by about 30%, with estimates of 100- and 500-year floods of 11.3 feet and 14.8 feet, respectively.

Table 5.1: Storm tide return periods for The Battery based on different studies since Hurricane Sandy (*Table 4.1 | Orton 2019 formatting preserved*).

		Return period			
		1	10	100	500
Study	Study type				
FEMA (2007)	Model		6.4	8.6	10.8
Lin *et al.* (2012)[b]	Model			6.7	10.2
FEMA (2013)	Model		7.0	11.3	14.8
Lopeman *et al.* (2015)	Historical Monte Carlo		6.5	11.1	
Nadal-Caraballo *et al.* (2016)	Historical Monte Carlo		6.1	8.0	
Cialone *et al.* (2015)	Model	4.7	7.5	11.2	14.9
Buchanan *et al.* (2016)	Historical	4.7	6.1	8.4	10.7
Orton *et al.* (2016b)	Model		6.4	8.9	12.8
NOAA (2017)	Historical	4.0	6.1	8.0	
Range over studies		4.0–4.7	6.1–7.5	6.7–11.3	10.2–14.9

[a]Values are given in feet above any given year's mean sea level (MSL).
[b]Lin *et al.* (2012) analyzed only tropical cyclones based on the period 1980–2000, and is included for comparison to the longer 100- and 500-year return period storm tides.

Brandon et al. (2014) argue that tide gauge data alone is generally too short to either obtain accurate extreme value statistics or to evaluate the skill of extreme flood probabilities derived from model simulations. Historical documentation of storm activity (i.e. newspapers, nautical logs, etc.) can extend storm records back to the mid-1600s for the U.S. East Coast. While these records provide valuable information on the occurrence of storms, detailed quantitative information on specific storm characteristics prior to 1844 is limited, particularly with respect to flood magnitudes (Talke et al. 2014).

Further, the assumptions underlying the estimates of return time (Table 5.1) are that the climate is stationary, which is a poor assumption. Apart from the issue of global warming, climate varies naturally on multi-decadal to millennial time scales. Hence, estimation of a 1-in-100 or 1-in-500 year event can be misleading. This non-stationarity is described by Scileppi and Donnelly (2006), who used sedimentary deposits to assess hurricane activity near New York City prior to the historical record. While identifying the major historical landfalls since the late 17th century, they found little evidence of intense hurricane landfalls in the region for several hundred years prior to the late 17th century. However before this quiet period, the sedimentary record indicated frequent, intense hurricane landfalls in the region during the period between 900 and 2200 years ago.

This section addresses scenarios of Atlantic hurricane activity to 2050 and 2100, including 'gray swan' events that could plausibly impact the New Jersey coast with catastrophic impacts.

5.1 Historical mid-Atlantic hurricanes

An alternative to the return period approach (e.g. Table 5.1) is to identify the characteristics of the strongest storms in the record for as far back as the historical record will allow and use paleoclimate analyses where possible. Since 1851, 27 hurricanes have struck the mid-Atlantic coast (from Virginia to New York). Three of these hurricanes have been Category 3 at landfall (wind speed > 110 mph).

Tide gauge records at the Battery identify five floods with storm tides greater than 2 meters (6.6 feet) since 1900: 1950, 1953, 1960, 1992 and 2012. Hurricane Sandy (2012) reflects the highest storm tide in the historical tide gauge record. Historical records (Ludlum, 1963) show four documented strong hurricanes (Category 2 or higher) making landfall near New York City prior to 1900: 1893, 1821, 1788 and 1693, with high storm surges (exceeding 9 feet). Donelley et al. (2001) examined sediments at Whale Beach, NJ and identified three intense storms prior to the historic record: 1821, 1438 and 1278 A.D.

While Hurricane Sandy was record breaking in context of published tide gauge records, earlier historical accounts suggest that the Cape May Hurricane in 1821 may have had a similar storm tide and a substantially larger storm surge. The 1821 hurricane struck New York City at low tide with roughly 4.0 to 4.1 m of storm surge, compared to Sandy's 2.8 m of storm surge. Sedimentary analysis (Brandon et al., 2014) reveals that while the Hurricane Sandy deposit was much thicker than the 1821 deposit, it had a smaller maximum grain size. This is consistent with historic accounts and simulation results that suggest that the 1821 hurricane was a smaller but significantly more intense storm compared to Hurricane Sandy. Sea-level rise and peak surge occurring at high tide combined to give Sandy record-breaking water levels, but the 1821 hurricane probably had a significantly larger overall storm surge.

The factors that influence the magnitude of a storm surge include the following characteristics of the storm: intensity (maximum winds), horizontal size (radius of maximum winds), forward speed of motion, and storm trajectory direction relative to the coast. Larger and slower storms like Hurricane Sandy have significantly longer flood durations than for the smaller and faster moving 1821 event.

In assessing the likelihood of another storm surge impacting New Jersey during the remainder of the 21st century that exceeds 9 feet, it is useful to consider other major hurricanes that have impacted the mid-Atlantic states, with regards to storm surge and documented coastal damage.

Hurricane of October, 1749 was perhaps one of the strongest storm ever in the Mid-Atlantic. It has been estimated that this was Category 4 hurricane at landfall, near Norfolk, VA.

Great September Gale of 1815 was a major hurricane that struck Long Island and brought an 11 foot storm surge to Providence, RI. On the south shore of Long Island, it broke through the barrier beach and created the inlet that still isolates Long Beach, which had previously been an eastward extension of The Rockaways.

Midnight Storm 1893 was Category 1 or 2 hurricane that made landfall on the swamp that is now JFK airport. The storm tide was reported to be as high as 30 feet, even though it struck at low tide. Hog Island, a resort island off the Rockaways, largely disappeared as a result of this storm. A forensic analysis of the storm by Coch (2019) inferred that the large storm surge was associated with a large horizontal extent (but nowhere near as large as Sandy), and an angle of attack that amplified the funneling effect in the New York Bight.

Long Island Express 1938 made landfall over Long Island and Connecticut as a Category 3 hurricane. The storm surge was 8.5 feet at The Battery and the tide surge was 16.8 feet at Willets Point.

The Great Atlantic Hurricane 1944 was of Category 3 intensity at landfall on Long Island. The hurricane hit the coast from a direction that produced a relatively low storm surge.

Hurricane Carol 1954 made landfall as a Category 3 hurricane over Long Island, New York and Connecticut, with a tide surge of 14.4 feet measured at Providence, RI.

5.2 Variability of Atlantic hurricanes

There is credible data on frequency and intensity of Atlantic hurricanes since 1850, with the intensity data being most reliable since 1944, when aircraft reconnaissance flights began. Prior to the onset of satellite coverage in 1966 when hurricanes were undercounted, NOAA has adjusted total basin-wide counts upward based on historical records of ship track density (Knutson et al. 2010).

Figure 5.1 shows the yearly values for the adjusted time series since 1850, for total North Atlantic hurricane counts and major hurricane counts (Category 3 and higher). While the number of major hurricanes prior to 1944 is probably undercounted, it is noteworthy that the number of major hurricanes during the 1950's and 1960's was at least as large as the last two decades.

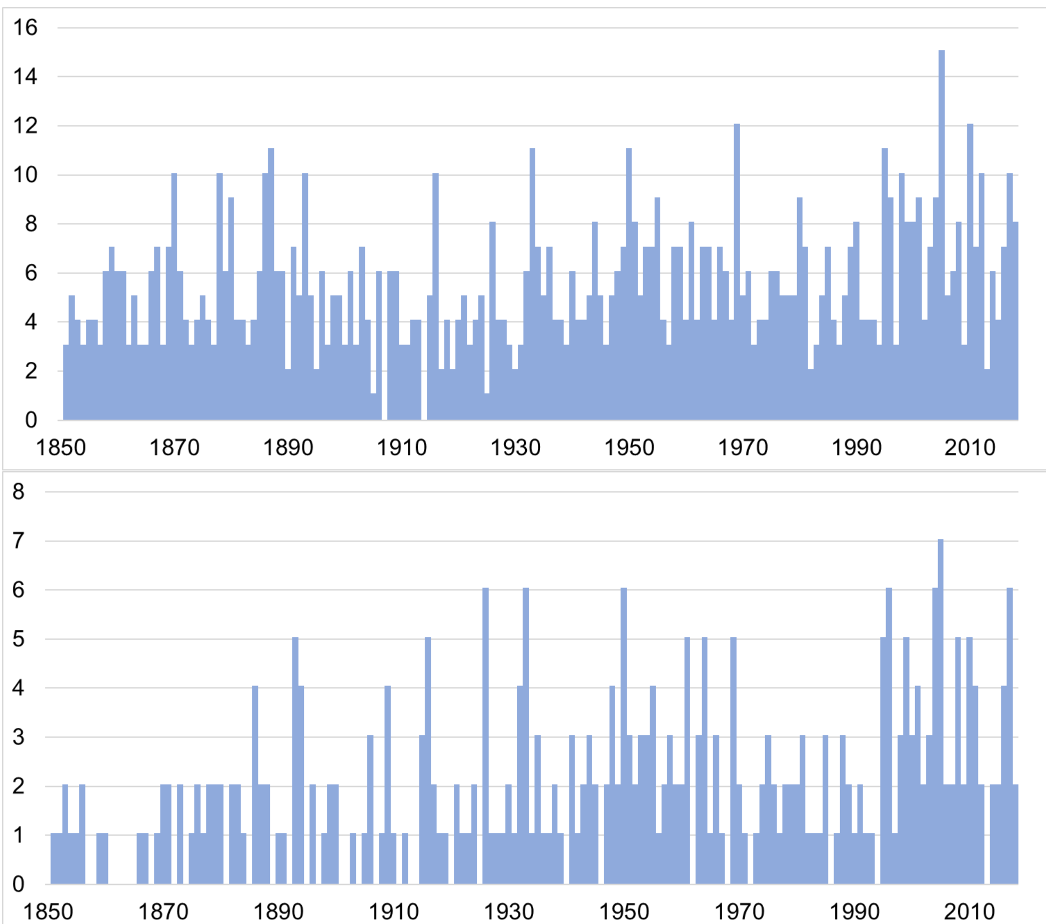

Figure 5.1: Adjusted numbers of total (x axis) Atlantic hurricanes (top) and major hurricanes (bottom). Source: http://www.aoml.noaa.gov/hrd/hurdat/comparison_table.html

Atlantic hurricane processes are influenced substantially by the natural modes of ocean circulation variability in the Atlantic, notably the Atlantic Multidecadal Oscillation (AMO) (Goldenberg et al. 2001). The main hurricane-relevant variables that change with the regimes of the AMO are spatial patterns of sea surface temperature and wind patterns. Hurricane genesis (formation) locations, tracks and intensification are temporally and spatially modulated by these large–scale circulation changes. The number of major hurricanes in the Atlantic is particularly influenced by the AMO. All measures of Atlantic hurricane activity show a significant increase since 1970. However, high values of hurricane activity (comparable to the past two decades) were also observed during the 1950's and 1960's, and by some measures also in the late 1920's and 1930's.

5.3 Hurricanes and global warming

There is little evidence from the observational record of changes in global or Atlantic hurricanes that exceeds the bounds of natural variability. Inferences and conclusions about changes in hurricane activity as a result of global warming are based primarily on theoretical considerations and the results of climate model simulations, as synthesized by expert judgment.

With regards to 21st century projections of hurricane activity, the World Meteorological Organization (WMO) Expert Committee on Tropical Cyclones (Knutson et al. 2019) concluded that 2^{o}C (3.6^{o}F) of warming is projected to impact hurricane activity as follows:

i) The most confident hurricane-related projection is that sea level rise accompanying the warming will lead to higher storm inundation levels, assuming all other factors are unchanged.

ii) For hurricane precipitation rates, there is at least medium-to-high confidence in an increase globally, with a median projected increase of 14%.

iii) For hurricane intensity (maximum wind speed), there is medium-to-high confidence that the global average will increase. The median projected increase in lifetime maximum surface wind speeds is about 5% (range 1–10%).

iv) For the global proportion of hurricanes that reach Category 4–5 levels, there is at least medium-to-high confidence in an increase, with a median projected change of +13%.

Author opinion from the WMO Committee was more mixed and confidence levels lower for the following projections:

vi) A decrease of global hurricane frequency, as projected in most studies

vii) An increase in global very intense hurricane frequency (Category 4–5),

viii) A slowdown in hurricane translation speed.

Specifically with regards to projections for the North Atlantic, NOAA GFDL (2019) provides the following:

> "The GFDL hurricane model supports the notion of a substantial *decrease* (~25%) in the overall number of Atlantic hurricanes and tropical storms with projected 21st century climate warming. However, the hurricane model also projects that the lifetime maximum intensity of Atlantic hurricanes will increase by about 5% during the 21st century. At present we have only **low confidence for an increase in category 4 and 5 storms in the Atlantic**; confidence in an increase in category 4 and 5 storms is higher at the global scale."

The tradeoff between a 25% decrease in the overall number of hurricanes versus a 5% increase in intensity (maximum wind speed) depends on the specific nature of coastal vulnerability under consideration. To put a 5% increase in intensity into perspective, a 5% increase is smaller than the 10%

uncertainty in landfall intensity commonly cited by the National Hurricane Center. However, a 5% intensity increase is meaningful in context of storm surge since the magnitude of the storm surge scales with the square of the intensity (maximum wind speed).

There are two topics of relevance to New Jersey that were not addressed in these assessment reports. The first is hurricane size, which directly relates to the magnitude of storm surge and was a particular factor for Superstorm Sandy. Using the NOAA GFDL hurricane modeling system, Knutson et al. (2015) found that projected median hurricane size is expected to remain nearly constant globally, but with an increase in the North Atlantic.

Another topic is the issue of hurricanes undergoing extratropical transition (such as Superstorm Sandy), which is summarized by Catto et al. (2019). The annual frequency of hurricanes undergoing extratropical transition does not show any statistically significant trend in the present climate. For warmer climate scenarios, some studies show that the number of hurricanes undergoing extratropical transition will increase over the North Atlantic partly due to spatial shifts in the formation locations for hurricanes.

And finally, even if there is confidence in future projections of overall activity of Atlantic hurricanes, it is not at all straightforward to relate any change in overall activity to U.S. hurricane landfalls, or landfalls in a particular region.

5.4 Scenarios out to 2050, 2100

Even if there is no change in hurricane activity in the coming decades, the high water line from storm surges will increase owing to sea level rise (e.g. Lin et al. 2016).

The Rutgers Report (and the references therein) do not provide any scenarios for future hurricane activity impacting the New Jersey coast, beyond citing estimates of the 100-yr and 500-yr storm surge (Orton et al. 2019). However, our understanding of plausible scenarios for future hurricane activity is much better bounded than the extreme scenarios for sea level rise presented in the Rutgers Report. Considering a broader range of outcomes for 21st century Atlantic hurricane activity impacting the New Jersey coast can provide important input for developing coastal adaptation strategies.

The drivers for coastal impacts from hurricanes (and hybrid storms such as Hurricane Sandy) relate to the frequency, intensity and size of the storms that make landfall in the region or otherwise influence the region from storm surge or heavy rainfall. Some locales may be susceptible only to the strongest storms, whereas other locales may be more susceptible to frequency of the events. Damage from mid-Atlantic coastal storms has occurred primarily from storm surge and heavy rainfall.

A rationale is described here for developing 21st century scenarios of mid-Atlantic landfalling hurricanes:

- frequencies and intensities to 2050, assuming a shift to the cold phase of the Atlantic Multidecadal Oscillation (AMO)
- development of gray swan scenarios of plausible storms that could exceed the storm surge associated with Superstorm Sandy

5.4.1 Scenarios to 2050

Since 1995, Atlantic hurricane activity has been elevated relative to the previous two decades (1970-1994). Atlantic hurricane activity in the current active period is comparable to the previous active period (1930's to 1960's); see Figure 5.2. The relatively active and quiet periods for North Atlantic hurricane activity have been linked to the warm and cool phases of the Atlantic Multidecadal Oscillation (AMO).

Given the dominant influence on Atlantic hurricanes of the Atlantic Multidecadal Oscillation (AMO), arguably the single most important factor for the next 30 years is a likely shift to the cool phase of the AMO. The timing of a shift to the AMO cool phase is not predictable; it depends to some extent on unpredictable weather variability. However, analysis of historical and paleoclimatic records suggest that a transition to the next cold phase is expected prior to 2050. Enfield and Cid-Serrano (2006) used paleoclimate reconstructions of the AMO to develop a probabilistic projection of the next AMO shift. Their analysis indicates that a shift to the cool phase should occur within the next 15 years, with a 50% probability of the shift occurring in the next 6 years.

The average number of U.S. landfalling hurricanes in cool phase of the AMO (1970-1994) is 1.24 per year, compared with 1.7 per year during the current warm phase (1995-2019). The preferred location of the U.S. landfalls is also influenced by the phase of the AMO, with Florida and North Carolina showing markedly fewer hurricane landfalls during the cool phase of the AMO, and the Mid Atlantic region (north of NC) showing slightly more landfalls during the cool phase.

5.4.2 Grey swan scenarios

Superstorm Sandy and the 1893 hurricane are reminders that a storm nominally having Category 1 force winds can produce a greater storm surge and overall more damage than a more intense Category 3 hurricane. The strong surge from Sandy was associated with extratropical transition and its subsequent very large horizontal extent, a westward track that directly struck the coast, and landfall at high tide.

Sandy was not a worst-case scenario for New Jersey; a substantially higher storm surge (estimated at 13 feet) occurred for the 1821 Cape May hurricane. If the 1821 hurricane had occurred at high tide, slower forward motion and with a larger horizontal extent, the storm tide would have been substantially higher.

Lin and Emanuel (2015) define 'gray swan' hurricanes as high-impact storms that would not be predicted based on history but may be foreseeable using physical knowledge together with historical data.

There are several strategies for generating scenarios of gray swan hurricanes that should be considered in assessing risks impacting the New Jersey coast:

- Consider the occurrences of previous storms in the historical, archaeological and geologic records that impacted the mid-Atlantic states. If it has happened before, it can happen again.
- Synthetic scenarios can be created by combining plausible worst-case storm elements into individual scenarios.
- The intensity (maximum wind speed) can be increased by 5% and 10% to account for possible global warming impacts on hurricane intensity.

In developing grey swan scenarios of relevance to storm surge in a particular location, the following storm parameters can be varied within a physically plausible range:

- Intensity (maximum winds): up to Category 4 (a category 5 landfall as far north as New Jersey is judged to implausible).
- Horizontal size: up to the size of Hurricane Sandy, although such a large horizontal size is inconsistent with the strongest hurricane intensities.
- Speed of forward motion of the storm: slower forward motionproduces the largest surge.
- Angle of approach to the coastline: the straight east-west track is the worst case for NJ.
- Time of landfall relative to the astronomical tide: high tide is worst case.

6. Decision making under deep uncertainty

Making good decisions under conditions of deep uncertainty is far more complex than merely selecting the 'best' scenario for a specific application, which is the recommendation provided in the Rutgers Report. This recommendation in the Rutgers Report is outdated, particularly in context of the Kopp et al. (2019) publication entitled "Sea-level science on the frontier of usability." CFAN's analysis provided below is more consistent with Kopp et al. (2019) than with the Rutgers Report.

Because of the clear expectation for continued sea-level rise, proactive coastal management approaches can be developed and deployed. A range of adaptation measures can be used, depending on the local vulnerabilities, land use and nature of the assets at risk: protection, accommodation, reclamation, retreat.

However, the large range of potential future sea levels poses the question: "When and how much to adapt?" Deep uncertainties in the rate and magnitude of sea level rise, particularly in the second half of the century, complicate decision making on coastal adaptation.

The deep uncertainty associated with future sea level rise poses substantial challenges for long-lived decisions with high stakes and high sunk (irreversible) costs, such as major infrastructure, building developments and land use planning. If long-term sea level change is not accounted for appropriately, it could mean greater risks, locking into greater costs, or wasted investments.

Uncertainty in climate projections and potential instability in the West Antarctic ice sheet is not expected to narrow in the near term. The challenge facing policy makers is how to make good decisions in the near term, while ensuring that long-term options for addressing uncertain future conditions are not pre-empted or made unnecessarily costly by earlier decisions.

Deep uncertainty due to climate change requires moving away from the 'predict and act' paradigm to one of 'robust decision making' characterized by continuous learning and dynamic adaptation.

The 'dynamic robustness' approach incorporates flexibility into adaptation plans that can be changed over time as more is learnt or as conditions change. The 'Adaptation Pathways' approach (Ranger et al. 2013) identifies the timing and sequencing of possible ‘pathways’ of adaptation measures over time under different scenarios. These concepts have been integrated into an overall 'Dynamic Adaptation Policy Pathways' (DAPP) approach (Haasnoot et al. 2013). DAPP is a framework for identifying present and future uncertainties, evaluating vulnerabilities and alternative solutions, taking necessary actions in the short term, and monitoring changes and gathering insights that might indicate that new decisions or reassessments are required. Flexibility and iterative planning are core elements of the approach.

In the DAPP approach, a plan includes an initial action, emphasis on monitoring data, and a series of actions over time (pathways) depending on future scenarios that may emerge. DAPP is predicated on a strong understanding of the decision problem itself, rather than focusing on climate projections. The decision-centered approach of DAPP focuses on understanding the characteristics of the decision problem (the objectives and values of stakeholders, trade-offs, constraints and decision criteria), the vulnerability of the system and the adaptation options themselves.

Prominent applications of an adaptive approach to uncertain sea level rise include:

- The Thames Estuary study to protect the city of London (Ranger et al. 2013)
- New Zealand with a national guidance to coastal adaptation (Bell et al. 2018)
- In the Netherlands an adaptive approach has been put into practice for adaptation to SLR within the Delta Program (Van Alphen, 2016)

An example of the DAPP approach applied locally in the U.S. is provided by Obeysekera et al. (2020), for adaptation to sea level rise in the Little River Basin, Miami, Florida.

An important conclusion from these studies is that the DAPP approach implies different needs from climate science:

- a shift in emphasis away from probabilistic modeling;
- greater investment in observations and monitoring;
- improved understanding of historical climate variability; and
- improved understanding of relevant processes and their representation in models to enhance 'best guess' models and to better bound future projections using narrative scenarios.

This section addresses several topics in the context DAPP that are perceived to be of relevance to adaptation for the New Jersey coast:

- scenarios and their use in DAPP
- time line challenges for major infrastructure investments
- managed retreat.

6.1 Scenarios and Dynamic Adaptive Policy Pathways

In the decision-centered DAPP approach, scenarios of climate change are not the main driver for the process. Nevertheless, scenarios of future change play an obvious and important role in the decision making process.

The Rutgers Report provides a full probability distribution of future sea-level change that incorporates both the *likely* range and worst-case scenarios, conditional upon an emissions scenario. A problem with this approach is that the probability density functions (PDFs) are highly conditional on the methods that produced them and provide only a limited sampling of the uncertainties. Kopp et al. (2019) recognizes this by stating: "For processes subject to deep uncertainty, alternative justifiable approaches to constructing a probability distribution can yield quite divergent answers."

While the motivation for probabilistic approaches driven by climate model simulations is to support decision making in the context of cost-benefit analysis, this approach can be counter productive for DAPP (apart from the issue of non-uniqueness of the probability distribution). Climate models are at best partial scenario-generators (see section 2), which is at odds with the requirement of robust decision making to map the range of plausible outcomes. Further, DAPP approaches are scenario neutral, in that decisions do not require information about the probability or likelihood of different future scenarios.

Smith and Stern (2011) argue that there is value in scientific speculation on policy-relevant aspects of plausible, high-impact scenarios, even though we can neither model them realistically nor provide a precise estimate of their probability. A set of narrative scenarios can be formulated that use empirical models and expert judgment to complement outputs from climate models. This approach produces a much wider range of scenarios than would be generated by climate models. The potential problem of generating a plethora of potentially useless future scenarios is avoided if they are focused on scenarios that are expected to be significant in a specific decision making context.

The objective of DAPP is to develop an iterative, learning decision process that cost-effectively reduces risk today while avoiding foreclosing future options. Considering the full range of plausible scenarios, the DAPP approach provides clear information on the effectiveness and timing of options, enabling analysts to assess under what conditions and on what timescale a plan could fail. The approach explicitly recognizes that adaptation over time will be determined not only by what can be anticipated today, but also what is observed and learned in the future. The approach ensures that the short- to medium-term plan is set in a framework that will not be maladaptive if climate change progresses at a rate that is different from current expectations.

DAPP is designed to perform adequately under a wide range of possible future states. 'Low-regret' measures are implemented in the near-term. Low-regret measures are those that reduce risk immediately and cost-efficiently under a wide range of climate/sea level rise scenarios. Low-regret measures can buy time to monitor and learn before making a major investment. DAPP plans are designed to be adjusted over time as more is learnt about the future. In this way, flexibility is built into the long-term strategy—the timing of new interventions and the interventions themselves can be changed over time.

DAPP planning provides a framework for incorporating engineering in flexibility, so that infrastructure can be adjusted or enhanced in the future at minimal additional cost. This includes include safety margins, where infrastructure is over-engineered to cope with greater than expected change; this approach is effective where the marginal cost is low.

A route-map lays out the options and provides information on when and how decisions should be made. The route-map is used to identify a set of a decision points, triggering specific options or pathways, conditional on observations of sea level rise and other indicators.

The DAPP approach is robust not only to climate change, but also to all other sources of risk and uncertainty, including socioeconomic uncertainties and uncertainties resulting from a lack of data. As long as the pathways account for such potential surprises and learning, allowances for adjustment can be incorporated into the plan.

6.2 Timescales of adaptation

DAPP frameworks have mostly been applied to more gradual shifts of climate change, rather than extreme and abrupt changes. Hasnoot et al. (2020) addresses the concern of adaptation for extreme scenarios of sea level change from instability of the West Antarctic ice sheet (a Dragon King scenario) that could involve rapid onset and high rates of change. Such an event would be associated with a very short time to adapt, which can have large consequences for decision making.

Hasnoot et al. (2020) identify the decision making challenges arising from potentially accelerated sea level rise. Decisions may need to be taken when there is still large uncertainty about the sea level rise at the end of the envisioned lifetime and the lead time of follow-up interventions. The time required for planning and implementation can be decades for large coastal defense projects and other major infrastructure (e.g. bridges), which are designed for a lifetime exceeding a century. Most coastal defense and major infrastructure decisions have a long lifetime and cannot easily be solved with incremental or flexible measures, and these decisions will thus have to account for high amounts of sea level rise at once.

Worst-case sea level rise scenarios can be used to assess under what conditions alternative adaptation pathways are needed, which can help to prepare and enable timely adaptation. Consideration of the worst case scenario reinforces the notion that an adaptive approach should be incorporated both in the plan itself. This can be accomplished through flexible measures and preparatory actions to keep options open (e.g. spatial reservations for future options), and in the design of structures to enable long-term adaptation (e.g. a large foundation of a structure to build higher later).

The time horizon of a pathways study should be chosen by considering the envisioned functional lifetime. For decisions with a long lifetime (>100 years), the focus should not be on projections of sea level rise for a specific time horizon. When looking at longer time horizons, it is more useful to consider the perspective that for some decisions it is not a matter of *whether* SLR will rise to certain levels, but *when* this will occur. This perspective may help to overcome decision paralysis due to uncertainty.

6.3 Managed retreat

'Managed retreat' essentially means shifting development inland from the coast either by the physical movement of structures or changing the restrictions and management of coastal areas. Abandonment and movement of people away from the coast by attrition constitutes 'unmanaged retreat.' Managed retreat is an adaptation option when accommodation and protection strategies are too expensive or otherwise infeasible.

U.S. flood management has historically focused on enabling people and infrastructure to remain in at-risk areas: resisting floods with walls and levees, adding sand to eroding beaches, or elevating homes to avoid rising tides. After a flood or other natural disaster, the typical response has been to simply restore what had been there. The following anecdote is cited by Carey (2020): a home in Mississippi worth only about $70,000 has been rebuilt or restored 34 times in 32 years, at a cost of $663,000 in federal tax dollars.

To date, managed retreat has generally been reactive, following major hazard events and their associated damage. As cited by Siders (2019), since 1989, FEMA has funded managed retreat in over 1,100 counties, acquiring more than 40,000 properties. Examples of managed retreat in the U.S. are:

- Staten Island: property buyout for three neighborhoods, following Hurricane Sandy.
- Pacifica State Beach Park, California: property buy-out, demolition of structures, wetlands restoration, beach nourishment, relocation of parking lot and bike path, dune vegetation planting.
- Isle de St. Charles, Louisiana: relocation of entire community.

Unmanaged retreat creates costs and missed opportunities. Homeowners or towns may leave if they are unable to afford rising insurance premiums, hardening, elevation, or repeated recoveries from disasters. A decade after Hurricane Katrina, New Orleans had tens of thousands of abandoned properties.

In dense urban areas on the coast, managed retreat is not typically a preferred option. However, in less developed areas, managed retreat has the potential for increasing shoreline access for recreation and coastal safety.

Community opposition to proposals for managed retreat is commonplace. Public tolerance of risk is typically higher before a natural disaster than afterwards. Many people have strong ties to their place of residence. Coastal settings are desirable places to live. Add to this, uncertainties over when to adapt, how to plan for changing risk and design funding frameworks exacerbates public opposition to proposals for managed retreat.

A managed retreat approach typically involves regulating the type of structure allowed near the shore to ensure that buildings are small enough and constructed in a way to facilitate relocation when needed. An additional approach is instituting relocation assistance and/or buy-back programs to help with relocation costs or compensate property owners when their property becomes unusable (Lawrence, 2020). However, there is no 'one-size-fits-all' approach to managed retreat and governments and residents will have to consider what acquisition, infrastructure, regulatory, and market-based tools, if any, can be adapted to meet state and local needs.

Policy issues that enable the effective implementation of managed retreat include governance, community engagement, regulation, institutional design and funding. Planning and preparing for implementation of a managed retreat strategy requires identification of options, selection of adaptation actions and identification of different pathways a retreat could take. This includes identifying thresholds, and trigger points for activating adaptation choices and the development of programs to monitor the predetermined signals and triggers to avoid intolerable adaptation thresholds defined by the community and responsible agencies.

Managed retreat can happen over a long time scale, in terms decades of shifting development along a coastline. Implementation actions that are phased over time allows governments to better formulate budgets and investments with the timelines associated with physical coastal impacts. Phasing actions can minimize the potential adverse consequences or costs of managed retreat by distributing those costs over extended time periods (Lawrence, 2020).

7. Conclusions and recommendations

The context for the Rutgers Report, and the adaptation challenges facing New Jersey, is a rapidly changing environment for our understanding of the risk from sea level rise, particularly with regards to possible extreme scenarios associated with instability of the West Antarctic ice sheet. Further, advanced in decision science and frameworks for dealing with deep uncertainty are increasingly being applied to sea level rise adaptation. These decision making frameworks are moving away from and 'predict then act' paradigms towards a decision-centered robust decision making paradigm that emphasizes flexibility, monitoring and revisiting/revising plans as conditions evolve.

Best practices in developing scenario outcomes for climate change adaptation start with the scenarios provided by the IPCC assessment reports. Experts or other practitioners generating scenariooutcomes for a specific application may choose to select specific IPCC scenarios or generate scenarios beyond what the IPCC provides, but these choices should be justified relative to what the IPCC has provided. While the IPCC scenarios can become outdated owing to the cycle of publication of their assessment reports, the IPCC has recently published the Special Report on Oceans and Cryosphere in a Changing Climate (SROCC, 2019), which relates directly to the topic of the Rutgers Report. Further, the IPCC AR6 is forthcoming in 2021 and R. Kopp is a lead author on Chapter 9 (which relates to sea level rise).

With this context, the Rutgers Report develops its own scenarios of sea level rise and does not reference the sea level rise scenarios of the IPCC AR5, SROCC or the AR6. Rather, they rely on five publications that include R. Kopp as lead author or co-author. However, the approach used in the Rutgers Report that relies heavily on publications by Kopp et al. (2017) and Bamber et al. (2019) does not pass muster in the IPCC SROCC (2019) Report in context of their choices for sea level rise projections:

> "For this reason, their results and probabilistic (e.g., **Kopp et al., 2017**; Le Bars et al., 2017) and statistical emulation estimates that build on them (Edwards et al., 2019), are **not used** in SROCC sea level projections."

> "The expert elicitation approach (**Bamber et al., 2019**), which applied elicitation to both ice sheets, suggests considerably higher values for total SLR for RCP2.6, RCP4.5 and RCP8.5 than provided in Table 4.3."

Experts inevitably disagree owing to inadequate data, insufficient understanding, different evaluations of the various classes of evidence, and different logical frameworks for linking the available evidence. 'Which experts' are included in a particular assessment report or expert elicitation makes a difference to the outcome conclusions. Therefore, it is important for a practitioner developing scenarios for policy applications to provide context from other assessments (particularly the IPCC) and other experts, as well as the temporal rate of change of expert opinion on the topic at hand. None of this context is provided in the Rutgers Report.

Individual experts can be out ahead of the IPCC assessments in developing better scenarios. However, the CFAN Review does not judge this to be the case with the Rutgers Report. While the Rutgers Report was published in November 2019, it appears that much of the Report was prepared in 2018. The near coincidental publication of the IPCC "Special Report on Oceans and Cryosphere in a Changing Climate" (SROCC) in November 2019 is only mentioned in the Rutgers Report in context of their conclusions regarding hurricanes and climate change and observed rates of sea level rise; there is no mention in the Report of the SROCC sea level rise scenarios for the 21st century. Further, Kopp, Sweet et al. authored an article entitled "Usable Science for Managing the Risks of Sea-Level Rise" that was submitted in May and published in *Earth's Future* in November, 2019. The Kopp et al. (2019) paper echoes a number of points raised in CFAN's Review, that are at odds with the strategy used in the Rutgers Report.

Specific concerns that are raised in CFAN's Review of the Rutgers Report:

- The Rutgers Report selects two scenarios of warming as the basis for developing projections of sea level rise. One of these scenarios (5^{o}C temperature increase) is arguably implausible. This selection of scenarios does not adequately cover the *likely* range of temperature outcomes that are drivers of sea level rise outcomes.
- The *likely* ranges of sea level rise projections from the Rutgers Report are about twice as high as reported by recent IPCC assessment reports (SROCC, 2019). For the period 2000-2020, the observed values of sea level rise in New Jersey track between the bottom bounds of the *likely* and *very likely* ranges of the Rutgers projections.
- The Rutgers Report manufactures a medium emissions scenario for sea level rise by averaging the percentiles from the high and low emissions scenario. This creates a misleading medium emissions scenario of sea level rise that is not related to the IPCC's RCP4.5 or RCP6.0 medium emissions scenarios, and does not account for nonlinearities of sea level rise with temperature.
- Their approach of producing projection probabilities for conditions of deep uncertainty is misleading and arguably not useful for decision-centered risk management approaches. The manner in which the Rutgers team incorporates extreme scenarios into their projection probabilities contaminates even the low emissions scenario.
- While the Rutgers Report expends substantial effort related to the worst-case scenario for sea level rise, it ignores the worst-case scenario for landfalling hurricanes.
- Scenarios out to 2050 for sea level rise and hurricanes are expected to be substantially modulated by multi-decadal natural modes of variability.
- The Rutgers Report is prepared in context of the 'predict then act' paradigm, providing a use example whereby decision makers choose a reference tide gauge, an emissions scenario, a time horizon and sea level rise estimates. This approach is not recommended in the current decision science literature for conditions of deep uncertainty.

The Rutgers team and their collaborators have appropriate scientific expertise for supporting the state of New Jersey in adaptation decision making related to sea level rise and coastal storms. However, reliance on an outlier perspective on sea level rise scenario outcomes from a single research group does not provide a sound basis for adaptation decision making. It is recommended that the Rutgers Report be revised to account for the new IPCC assessment reports (including the forthcoming AR6) and improvements in our understanding how to best manage adaptation to sea level rise under conditions of deep uncertainty. Specific recommendations include:

- Articulate a general framework for decision support that is consistent with the Dynamic Adaptation Policy Pathways (DAPP) approach, including specific thresholds of concern for decision making.
- Provide sea level rise projections that are consistent with the IPCC SROCC and AR6 *likely* ranges for 2050 and 2100, with a focus on RCP4.5.
- Provide a justified range of plausible worst-case sea level rise outcomes that are of relevance for 2100 and 2150, with a focus on RCP4.5.
- Formulate a range of scenarios out to 2050 associated with Atlantic circulation patterns of relevance to the 'hot spot' and other regional factors, that would influence local sea level rise on decadal scales.
- Formulate plausible worst-case scenarios of landfalling hurricanes along the New Jersey coast.

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Appendix A: CFAN Overview

Climate Forecast Applications Network (CFAN) is a weather and climate services company that develops innovative weather and climate forecast tools to support decision-oriented solutions for our clients in public and private sectors. CFAN was founded in 2006 by Judith Curry and Peter Webster and launched under Georgia Tech's Enterprise Innovation Institute VentureLab program.

CFAN's weather and climate forecast products provide daily, weekly, and seasonal probabilistic forecasts of extreme weather events. CFAN's climate services include:

- Climate scenarios and impact assessments
- Climate risk management strategies
- Expert reports and testimony
- Support for climate-related litigation

CFAN employs a staff of 12 individuals, including 7 scientists holding a Ph.D. in atmospheric sciences. Summary qualifications of CFAN's owners:

Judith Curry, PhD 1982 U. Chicago (Geophysical Sciences). Dr. Curry is President and majority owner of CFAN. Curry's research areas are climate dynamics, probabilistic prediction of extreme weather events, socioeconomic impacts of weather and climate variability and decision making under deep uncertainty. Curry is Professor Emerita and former Chair of the School of Earth and Atmospheric Sciences at Georgia Tech. She is coauthor of the books *Thermodynamics of Atmospheres and Oceans* and *Thermodynamics* and *Kinetics and Microphysics of Clouds.* She has published 190 refereed journal articles. Dr. Curry is Fellow of the American Association for the Advancement of Science, American Meteorological Society and American Geophysical Union.

Peter Webster, PhD 1972 MIT (Meteorology). Dr. Webster is co-owner and Chief Scientist of CFAN. Webster's area of research spans tropical atmospheric and ocean large-scale climate dynamics and the applications of these fields to prediction of rainfall, floods and droughts. Webster is Professor Emeritus in Earth and Atmospheric Sciences at Georgia Tech. He has published 170 refereed journal articles. He is author of the book *Tropical Meteorology and Climate*. Dr. Webster is Fellow of the American Geophysical Union, American Meteorological Society, and American Association for the Advancement of Science and an Honorary Fellow of the Royal Meteorological Society. Research Awards include the Charney Award and the Rossby Research Medal from the American Meteorological Society and the Adrian Gill Award and Mason Gold Medal from the Royal Meteorological Society.

Relevant Prior Research and Climate Change Assessment Projects

A. Small Business Innovation Research grants

CFAN has received three Small Business Innovation Research (SBIR) grants:

I. Department of Energy: **Application of Global Weather and Climate Model Output to the Design and Operation of Wind Energy Systems.** This project addressed the challenge of providing weather and climate information to support the operation, management and planning for wind-energy systems. CFAN developed a hybrid statistical/dynamical forecasting scheme for delivering probabilistic forecasts on time scales from one day to seven months. The project also provided a framework to assess future wind power through developing scenarios of interannual to decadal climate variability and change. https://www.sbir.gov/sbirsearch/detail/410156

II. National Oceanic and Atmospheric Administration: **Probabilistic subseasonal weather forecasts for the energy & agricultural sectors.** The focus of this project was on developing and implementing a strategy to provide improved subseasonal forecasts for the energy and agricultural sectors, including applications to renewable energy. A comprehensive assessment of predictability of relevant variables by region, initial and target month, and atmospheric flow regimes provided the basis for assessing the confidence of individual forecasts and for identifying forecast 'windows of opportunity.' Advanced ensemble interpretation techniques support scenario predictions of extreme events.
https://www.sbir.gov/sbirsearch/detail/1240933

III. Department of Defense: **Predicting Extreme Events Associated with Climate Variability/ Change Having Implications for Regional Stability in Asia**
https://www.sbir.gov/sbirsearch/detail/13021 Two reports are publicly available:

Impact of extreme weather/climate events on regional stability of Asia. The Office of the Secretary of Defense funded CFAN to assess natural disaster and climate change impact threats in South Asia - Pakistan, Afghanistan, Bangladesh and India. The objectives of project were to relate CFAN's regional weather and climate predictive capability to a comprehensive regional analysis of weather hazards and climate impacts as security threat accelerants, and to address how effective use of this predictive capability could proactively reduce the threat acceleration associated with these events. The report highlighted the interplay between security and uncertainty in a number of South Asian nations across areas that are highly susceptible to climate change impacts: food security, energy, and water resources. http://media.wix.com/ugd/867d28_089850cf3dff497c88182f07e814b923.pdf

Integrated Assessment of the 2010 Pakistan floods. CFAN prepared a comprehensive analysis for the U.S. Office of the Secretary of Defense of the flooding of the Indus River system in Pakistan during the summer and autumn of 2010. This event represented not only a humanitarian disaster on a cataclysmic scale, but also a significant threat to U.S. security interests. The destruction wrought by the 2010 floods weakened Pakistan's struggling civilian administration and add to the burdens on its' military, distracting from its efforts to keep the Pakistani Taliban in check. Our analysis examined the causes and impacts of the floods, including how the floods have acted as a threat accelerant to an already unstable nation. http://media.wix.com/ugd/867d28_c9d8e672555f4eeab0f4172e3dc18735.pdf

B. World Bank and USAID Projects (publicly available)

Projected Economic Impacts of Hurricanes in Latin America 2020-2025. As part of a World Bank project to assess the potential consequences of climate destabilization in Latin America (2009), CFAN conducted an assessment of the potential economic impacts of hurricanes during the period 2020-2025. CFAN developed scenarios for the statistics of landfalling tropical cyclones for different regions in Latin America for a five-year period ca. 2020–2025, accounting for the impacts of both natural variability and global warming on tropical cyclone frequency, intensity, and tracks. The hurricane projections were combined with projections of population and GNP and damage estimates from past hurricanes to estimate the future risk of hurricane damage in each of the regions. These estimates of future hurricane damage included exposure to hazard, the frequency or severity of the hazard, and the vulnerability of exposed elements. The projections of hurricane damage were interpreted in the context of country vulnerability indices. These projections were used to guide World Bank investments in specific countries that would have the greatest impact on reducing losses and increasing resilience.
http://siteresources.worldbank.org/INTLAC/Resources/Assessing_Potential_Consequences_CC_in_LAC_3.pdf

Climate Forecast Applications in Bangladesh (CFAB) Every few years, major floods engorge the Brahmaputra and Ganges Rivers for periods ranging from a few days to a month or more, often displacing tens of millions of people and devastating agricultural production. With funding from USAID and CARE, CFAN developed an extended-range probabilistic flood forecasting system for the Ganges and Brahmaputra (time scales from days to 6 months) to predict the probability that river water level heights will exceed critical levels. A new experimental dissemination program brought warnings directly via a cell phone network to more than 100,000 residents in five rural provinces in Bangladesh. On the basis of these forecasts, entire areas were evacuated ahead of the floods. Early harvesting of some crops occurred, and livestock and belongings were saved.
http://media.wix.com/ugd/867d28_f7f3852a70f04417b3909fcc0ee10b35.pdf

An extended-range water management and flood prediction system for the Indus River basin. Pakistan has the highest percent irrigation usage on the planet and is an integral component of the nation's agriculture. Flooding during the summer monsoon period is a constant threat and water managers have to contend with the delicate balance between withholding water for drought periods and leaving sufficient storage capacity to contain flood pulses while maintaining sufficient discharge for power generation. This report formulates a strategy for extended-range prediction of drought, floods and Indus River streamflow. A new coupled hydrological model was developed for the entire Indus River basin, including a new flood plain/inundation module. Specific recommendations were made about how extended streamflow forecasts could be developed for use in country-wide commerce, power and agriculture optimization and hazard mitigation.
http://webster.eas.gatech.edu/Papers/PAKISTAN_FLOOD_WB_RPT.pdf

Building resilience for sustainable development of the Sunderbans. The Sunderbans are a highly susceptible coastal region occupying the Indian and Bangladeshi coastlines at the head of the Bay of Bengal. The cost of environmental damage and health effects in this region is as high as 10% of Sunderban's gross domestic product each year, and many socioeconomic and biophysical tipping points have already been exceeded. Working with a team from the World Bank, CFAN participated in an assessment report to support socioeconomic development of the Sunderbans under future uncertain conditions related to storms and sea level rise. The report includes a menu of policy options to address the future uncertainties that would contribute to improving overall social and ecosystem resilience.
https://openknowledge.worldbank.org/bitstream/handle/10986/20116/880610REVISED00ns000Strategy0Report.pdf?sequence=1

Scenarios of Climate Variability for the Hindu-Kush-Himalaya (HKH) Region out to 2050. As part of a current (to be published in 2021) World Bank project on *Climate Impacts on the Himalayas: Aerosol-Precipitation Interaction Sensitivity Analysis,* CFAN developed scenarios of climate variability for the HKH region out to 2050 that account for both natural and human caused climate change. Variability of decision relevant variables (e.g. glacier mass balance, streamflow) was determined using statistical relationships developed from large-scale circulation indices and high-resolution reanalyses. The possibility of extreme drought/monsoon failure during the period is assessed. The underlying philosophy of the approach is full representation of the relevant uncertainties, so as to be able to realistically bound the possible outcomes.

C. Other client-funded assessment reports (publicly available)

- Climate Change: What's the Worst Case? https://judithcurry.com/2019/08/22/climate-change-whats-the-worst-case/
- Hurricanes and Climate Change https://docs.wixstatic.com/ugd/867d28_32f52bbef6d24cbfb018540b6b8d60bd.pdf

- Sea Level and Climate Change
  https://docs.wixstatic.com/ugd/867d28_b238a31cc22c4d398b4a6cec0159f78d.pdf
- Projections of future U.S. landfalling hurricanes
  https://docs.wixstatic.com/ugd/867d28_8dcbe3b4b5a045c4a78a87c2d1b98891.pdf

D. Selected recent Congressional Testimony (Judith Curry)

- House Committee on Oversight and Reform, “Contending with Natural Disasters in the Wake of Climate Change” 6/12/19 https://curryja.files.wordpress.com/2019/06/testimony-oversight-and-reform-2019-v2.pdf
- House Committee on Natural Resources, “Climate Change: Impacts and the Need to Act,” 2/6/19 https://curryja.files.wordpress.com/2019/02/curry-testimony-house-natural-resources.pdf
- House Committee on Science, Space and Technology, “Using Technology to Address Climate Change,” 5/16/18 https://curryja.files.wordpress.com/2018/05/curry-house-science-testimony.pdf
- House Committee on Science Space and Technology, “Climate Science: Assumptions, Policy Implications and the Scientific Method,” 3/29/17 https://curryja.files.wordpress.com/2017/03/curry-house-science-testimony-mar- 17.pdf