**STATEMENT TO THE
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
OF THE UNITED STATES HOUSE OF REPRESENTATIVES**

**Hearing on
Using Technology to Address Climate Change**

16 May 2018

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Major points:

- There are multiple causes of climate variability and change, and climate is just one element of the complex causes of vulnerability of human and natural systems.
- In adapting to climate variability and change, we need to acknowledge that we cannot know exactly how the climate will evolve in the 21st century, we are certain to be surprised and that we will make mistakes along the way.
- Possible scenarios of incremental worsening of weather and climate extremes don't change the fundamental storyline that the U.S. is highly vulnerable to current extreme weather and climate events and has an adaptation deficit relative to the current climate state and historical extreme events.
- Rather than 'bouncing back' from extreme weather and climate events, we can 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices.
- A focus on local policies that support resilience and anti-fragility avoids the hubris of thinking we can predict the future climate.
- Rather than negotiating an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent.
- Climate models are not the only, or best, way to generate future scenarios of regional climate change. Current climate model predictions neglect important aspects of natural variability.
- All scientifically plausible scenarios of future climate change need to be on the table to inform adaptation, not just those selected by a particular heuristic, e.g. emissions scenarios.
- On regional and decadal time scales, the greatest vulnerability to climate change is not associated with the smooth long-term trend but rather with rapid shifts in frequencies and intensities of extreme weather and climate events that are driven by natural internal climate variability.
- Sea level rise is an issue for which anticipatory adaptation is justified by our scientific understanding of the direction (if not the magnitude) of future sea level change.
- Large-scale ocean circulations can cause regional sea level rise to exceed global mean sea level rise by an order of magnitude.
- In many of the locations that are most vulnerable to sea level rise, natural oceanic and geologic processes plus land use practices are the dominant causes of current local sea level rise problems.
- The focus of climate science on mitigation-relevant science (e.g. attribution, sensitivity) has diverted resources away from regional climate dynamics and prediction of extreme events on weekly to seasonal time scales that would support tactical and strategic adaptation decisions.

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I thank the Chairman and the Committee for the opportunity to offer testimony today on 'Using Technology to Address Climate Change.' I am Professor Emeritus of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. I have devoted four decades to conducting research on a variety of topics related to weather and climate. In recent years my focus has been on uncertainty and the interface between climate science and policy. As President of Climate Forecast Applications Network LLC, I have been working with decision makers to use weather and climate information to reduce vulnerability to extreme weather and climate events.

In 2014, I was privileged to host to host the *UK-US Workshop on Climate Science Needed to Support Robust Adaptation Decisions*.[1] The Workshop participants included some of the world's leading thinkers and practitioners on climate adaptation. The Workshop was motivated by the recognized gap between what science is currently providing in terms of information about climate variability and change, versus the information desired by decision to make robust development and adaptation plans for managing climate-related risks and responding to opportunities. The focus was on timescales out to 2050 and regional scales. The Workshop addressed perspectives from the public and private sectors[2] on climate adaptation, strategies for robust decision making,[3] limits of climate models,[4] and broadening the portfolio of climate information.[5] The insights from this Workshop provide the framing for my testimony.

Adapting to climate change

In context of the debate on climate change, two overarching policy response options have been articulated:

1. Mitigation of climate change through reduction of greenhouse gas emissions
2. Pre-emptive adaptation to climate change through improved infrastructure, land use practices and management of resources.

[1] https://judithcurry.com/2014/02/10/uk-us-workshop-on-climate-science-needed-to-support-robust-adaptation-decisions/
[2] https://judithcurry.com/2014/02/12/uk-us-workshop-part-ii-perspectives-from-the-private-sector-on-climate-adaptation/
[3] https://judithcurry.com/2014/02/14/uk-us-workshop-part-iii-strategies-for-robust-decision-making-for-climate-adaptation/
[4] https://judithcurry.com/2014/02/18/uk-us-workshop-part-iv-limits-of-climate-models-for-adaptation-decision-making/
[5] https://judithcurry.com/2014/03/19/uk-us-workshop-part-v-broadening-the-portfolio-of-climate-information/

In strategizing about both mitigation and adaptation to climate change, it is important to recognize that both policy options exist in context of a broad and complex policy environment:

1. Mitigation impacts global, national and regional policies on energy, transportation, agriculture and environmental quality, with concomitant issues related to economics and security
2. Adaptation is in response to both human caused and natural climate variability and weather extremes, and is driven by local vulnerabilities, economic capacity, cultural values and governance. The impacts of weather and climate extremes are exacerbated by growing populations and the associated resource requirements, plus increasing development on low-lying coastal regions, floodplains and hill slopes that are well known to be vulnerable to storms.

Nearly all human societies and activities are sensitive to weather and climate. People have always adapted to weather extremes and climate variability, and many community coping strategies already exist. The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Extreme Events*[6] acknowledges that there is not yet evidence of changes in the global frequency or intensity of hurricanes, droughts, floods or wildfires. The existence of a signature of human-caused global warming on sea level rise acceleration is still being debated. Nevertheless, the focus of analyses of adaptation to human caused climate change has been on anticipatory adaptation to new conditions that are outside of the range of those previously experienced, that are predicted in response to human-caused warming based on climate model simulations.

The extreme damages from recent hurricanes such as Katrina, Sandy and Harvey plus the recent billion dollar disasters from floods, droughts and wildfires, emphasize that the U.S. is highly vulnerable to current weather and climate disasters, not to mention the more extreme disasters that were encountered in the U.S. during the 1930's and 1950's. Possible scenarios of incremental worsening of weather and climate extremes over the course of the 21st century doesn't change the fundamental storyline that the U.S. is not well adapted to the current weather and climate variability, let alone the range that has been experienced over the past several centuries.

As a practical matter, adaptation has been driven by local crises associated with extreme weather and climate events, emphasizing the role of 'surprises' in shaping responses. Advocates of adaptation to climate change are not arguing for simply responding to events and changes after they occur; they are arguing for anticipatory adaptation. But arguments for preparing for the consequences of global warming rest on an implicit assumption that we can reliably anticipate the changes to which we will be adapting and therefore that we can sensibly plan for those changes. Unfortunately, climate models do not provide us with the information needed to anticipate the local consequences of climate variability and change.

The challenge for climate change adaptation is to work with a broad range of information about regional vulnerabilities and climate variability in the context of a decision-analytic framework that acknowledges deep uncertainty.

Resilience, anti-fragility and thrivability

In adapting to climate change, we need to acknowledge that we cannot know how the climate will evolve in the 21st century, we are certain to be surprised and we will make mistakes along the way. There is much to be learned from the extraordinary adaptations of species and ecosystems in the natural world.

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[6] http://www.ipcc.ch/report/srex/

'Resilience' is the ability to 'bounce back' in the face of unexpected events. Resilience carries a connotation of returning to the original state as quickly as possible. Vulnerabilities to extreme events typically reveal a gap between the present situation and what is needed to reduce future vulnerability. Hence, we need to 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices.

The concept of 'thrivability' has been articulated by Jean Russell:[7]

> *"It isn't enough to repair the damage our progress has brought. It is also not enough to manage our risks and be more shock-resistant. Now is not only the time to course correct and be more resilient. It is a time to imagine what we can generate for the world. Not only can we work to minimize our footprint but we can also create positive handprints. It is time to strive for a world that thrives."*

A related concept is Nicholas Taleb's 'anti-fragility'[8] that focuses on approaches that enable us to thrive from high levels of volatility, particularly those unexpected extreme events. Taleb argues that the most profound and important of these unexpected events are by their very nature unpredictable. Taleb regards the real opportunity to be learning and growth from volatility and unexpected events – not to return to where you were, but to become even better as a result of encountering and overcoming challenges. Anti-fragile systems are dynamic rather than static, thriving and growing in new directions rather than simply maintaining the *status quo*. Anti-fragile systems require random events to strengthen and grow, and so avoid becoming brittle and fragile.

Strategies to increase anti-fragility include economic development, reducing the downside from volatility, developing a range of options, tinkering with small experiments, and developing and testing transformative ideas. Anti-fragility is consistent with decentralized models of policy innovation, that create flexibility and redundance in the face of volatility. This 'innovation dividend' is analogous to biodiversity in the natural world, enhancing resilience in the face of future shocks.[9]

A focus on policies that support resilience and anti-fragility avoids the uncertainties of attributing climate change to humans versus nature and avoids the hubris of thinking we can predict the future climate. The questions then become:

- How can we best promote the development of transformative ideas and technologies?
- How much resilience can we afford?

Decision – analytic approaches

Traditional approaches to risk management work well when the future is changing slowly, is predictable and doesn't generate much disagreement. Predict-then-act methods can backfire when uncertainties are underestimated, competing analyses engender disagreement and decision makers are blinded to surprises. Acting on forecasts of the unpredictable can contribute to bad decisions.

Climate-related decisions involve incomplete information from a fast-moving and irreducibly uncertain science. There are many different interests and values in play, the relevant time scales are

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[7] https://www.amazon.com/Thrivability-Breaking-through-World-Works/dp/1909470287
[8] Taleb, N 2012 *Antifragile: Things That Gain From Disorder*. Random House.
[9] Amanda Lynch, Climate Change Adaptation Policy Innovation: Subsidiarity, Diversity ad Redundancy. https://judithcurry.com/2014/02/14/uk-us-workshop-part-iii-strategies-for-robust-decision-making-for-climate-adaptation/

long and there is near certainty of surprise. Current policies often neglect known unknowns – leading to overconfidence and poor decisions.

The bottom-up resource-based vulnerability perspective[10] determines the major threats to local and regional water, food, energy, human health, and ecosystem function resources from extreme events including those from climate but also from other social and environmental issues. Relative risks can be compared with other risks in order to adopt optimal preferred mitigation/adaptation strategies. This is a more inclusive approach for policy makers to deal with the complexity of the spectrum of social and environmental extreme events that may occur, beyond just the focus on greenhouse gases as emphasized in the IPCC assessments.

Rather than seeking an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent. Flexible strategies can be quickly adjusted to advancing scientific insights and new conditions that arise. Robust decision making strategies[11] manage deep uncertainty by running the analysis backwards: start with a proposed strategy, identify future scenarios where strategy does and does not meet its goals, and identify steps that can be taken so strategy may succeed over a wider range of future scenarios. Stakeholders can then debate about how much robustness they can afford – which is more useful than debating what the future will be.

Climate Informed Decision Analysis (CIDA)[12] is an approach that identifies which scenarios of climate change would affect the project and then determines the likelihood of those scenarios. As a process committed to acceptance of deep uncertainties, CIDA does not attempt to reduce uncertainties or make predictions, but rather focuses on determining which decision options are robust to a range of plausible futures.

Adaptive governance[13] focuses on decentralized decision-making structures in the face of the complexity and uncertainty associated with rapid environmental change. This allows large, complex problem like global climate change to be factored into many smaller, more tractable problems. In an integral sense, addressing these smaller problems corresponds to adaptation to profound uncertainties that are inherent in complex systems that limit predictability. Planning to meet projected targets and timetables is secondary to continuing appraisal of incremental steps toward long-term goals. Each step in such trial-and-error processes depends on politics to balance and integrate the interests of multiple participants to advance their common interest.

The climate knowledge gap

The focus of the UN Framework Convention on Climate Change[14] on mitigation policies has arguably led the adaptation problem and its solutions in a direction that relies on mitigation-relevant science (i.e. attribution of global climate change and sensitivity to CO_2), rather than on understanding natural climate variability and regional risks in the context of vulnerability.

Climate models consistently indicate that the mean global temperature of the planet will rise with increasing CO_2 emissions. However, models show systematic errors in the simulated global mean temperature that is similar in magnitude to the size of the historical change we are seeking to

[10] https://pielkeclimatesci.files.wordpress.com/2012/10/r-3651.pdf
[11] https://www.rand.org/pubs/research_briefs/RB9701.html
[12] http://elibrary.worldbank.org/content/workingpaper/10.1596/1813-9450-6193
[13] http://press.uchicago.edu/ucp/books/book/distributed/A/bo8917780.html
[14] https://unfccc.int

understand.[15] Further, it is important to recognize that mean global climate is not what any one locale or nation will be adapting to.

There is a gap between the scale on which models produce consistent information and the scale that is relevant for human adaptation to climate change.[16] Attempts to 'downscale' the output of climate models are still in the early stages of development. Dynamical downscaling uses a higher-resolution regional model that is forced at the boundaries by outputs from the global climate models. The obvious problem with dynamical downscaling is that if the boundary conditions derived from the global climate model are in error, then these errors will propagate into the regional model.

Finally, existing climate models are unable to simulate realistically extreme outcomes such as a rapid disintegration of the West Antarctic Ice Sheet. Hence global climate models provide little relevant information regarding unlikely but potentially catastrophic impacts.

It is not at all obvious we will ever be able to model climate on scales that are quantitatively informative to adaptation decisions. Failure to appropriately communicate this 'weakest link' has been a critical failure of science-based policy-making.

Scenarios of 21st century climate variations and change

Adaptation strategies require information about future climate change, from both natural and human causes. Given the deep uncertainties surrounding regional climate change, a range of scenarios are needed in the context of robust decision making strategies.

The primary narrative for communicating climate change to decision makers has been as a gradual and predictable process, driven by emissions scenarios. This allegedly predictable signal is distinct from the unpredictable natural climate variability. Hence decision makers have focused on the apparently predictable trend associated with increasing emissions. However, to support decision making needs, all scientifically plausible scenarios need to be on the table, not just those selected by a particular heuristic, e.g. emissions scenarios.[17]

Natural climate variability refers to forcing from the sun, volcanic eruptions and natural internal variability associated with chaotic interactions between the atmosphere and ocean. The most familiar mode of natural internal variability is El Nino/La Nina. On longer multi-decadal time scales, there is a network of atmospheric and oceanic circulation regimes, including the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation. It is these circulation regimes that dominate climate variability and extreme events on regional and decadal time scales.

20th century climate change is most often explained in terms of external forcing, with natural internal variability providing high frequency 'noise.' However, the role of large-scale multi-decadal ocean oscillations is increasingly understood to play a more fundamental role,[18] whereby the external forcing projects onto the modes of natural internal variability, producing 'shifts' in the climate system.[19] These circulation patterns act as a buffer on the climate system to small perturbations, but

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[15] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012MS000154
[16] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/2010/80-AdaptationtoGlobalWarming-2010.pdf
[17] https://www.researchgate.net/publication/305723870_Reconciling_anthropogenic_climate_change_and_variability_on_decadal_timescales
[18] https://www.nature.com/articles/19745
[19] Tsonis, A et al. 2007: A new dynamical mechanism for major climate shifts. *Geophys. Res. Lett.,* 34, L13705. https://pantherfile.uwm.edu/aatsonis/www/2007GL030288.pdf

over time can lead to an abrupt shift to a new state. These interactions on timescales from decades to centuries produce step changes in warming that integrate into a long-term complex trend. These complex interactions are a major determinant of changing climate risk, particularly with regards to extreme weather events and 'hot spots' of sea level rise.

Significant climate shifts in the past 50 years include:

- 1976/1977 Great Pacific Climate Shift: major shifts in atmospheric circulation patterns and extreme weather events, changes in the biota of the Pacific Ocean, greater frequency of El Nino events.[20]
- 1995 shift of the Atlantic Multidecadal Oscillation to the warm phase: shift to the active phase of Atlantic hurricanes, with a substantial increase in the number U.S. landfalls[21]
- 2001 synchronization of multiple climate modes: early 21st century 'hiatus' in warming[22]

The characterization of climate risk on regional and decadal time scales changes substantially if climate change is characterized as being gradual versus subject to shifts. Prediction of trends over decadal time scales may not be useful if the climate does not behave in a trend-like fashion. Of greater relevance for decision making is understanding the statistics of extreme events and potential future shifts in the climate.

For climate shifts, the main approach is no longer predicted trends based on global climate models, but rather a diagnostic approach based on the climate dynamics of the large-scale ocean circulation regimes. Step changes in climate can lead to significant changes in the frequency and magnitude of extremes and periodic shifts in means can be anticipated. A better understanding of how climate shifts, system complexity and systemic response may affect decision making should be a priority for developing scenarios of regional climate change.

Scenarios of global climate change

The scenarios of future global climate change provided by the IPCC AR5 are incomplete, focusing only on emissions scenarios and ignoring natural climate variations:

- *"With regard to solar forcing, the 1985–2005 solar cycle is repeated. Neither projections of future deviations from this solar cycle, nor future volcanic radiative forcing and their uncertainties are considered."* [IPCC AR5 WGI Section 12.2.3]
- *"Any climate projection is subject to sampling uncertainties that arise because of internal variability. [P]rediction of the amplitude or phase of some mode of variability that may be important on long time scales is not addressed."* [IPCC AR5 WGI Section 12.2.3]

Additional scenarios that should be considered for the trend of 21st century global climate change (individually or in combination):

- Scenario of volcanic activity matching the 19th century eruptions
- Grand solar minimum in the mid 21st century
- Shift to the cold phase of the Atlantic Multidecadal Oscillation (AMO)
- Lower values of climate sensitivity to carbon dioxide that are consistent with observationally-based energy budget analyses[23]

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[20] http://horizon.ucsd.edu/miller/download/climateshift/climate_shift.pdf
[21] https://www.researchgate.net/publication/235243382_The_Recent_Increase_in_Atlantic_Hurricane_Activity_Causes_and_Implication
[22] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008GL037022
[23] Nicholas Lewis and Judith Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, [https://doi.org/10.1175/JCLI-D-17-0667.1]

There are known structural inadequacies in global climate models (e.g. inadequate treatments of solar indirect effects, vertical ocean heat transfer and processes related to clouds). Hence in addition to sensitivity studies using climate models, semi-empirical methods should also be used in developing these additional scenarios.

Scenarios of regional climate change

Climate models are not the only, or best, way to generate future scenarios of regional climate change. Climate Informed Decision Analysis (CIDA) uses a broader range of climate scenarios[4]:

> *"Climate scenarios can be generated parametrically or stochastically to explore uncertainty in climate variables that affect the system of interest. This allows sampling changes in climate that include but are not constrained by the range of climate model projections. Scenarios can be developed as part of a stakeholder-driven, negotiated process, and climate projections can be used in this process. For scenarios in which the climate consequences exceed coping thresholds, it is then fruitful to evaluate the plausibility of the scenarios. Climate projections, paleoclimate reconstructions, and subjective climate knowledge could all inform such discussions."*

Several empirical strategies have been developed for providing scenarios of regional climate change:

- Pattern scaling: the main assumption is that the spatial pattern of change is assumed to remain constant at any time horizon or forcing scenario[24]
- Projections based on regional estimates of Transient Climate Sensitivity[25]
- Ensemble random analog prediction[26].

On decadal time scales, the greatest vulnerability is to extreme weather events such as floods, droughts, heat waves, heavy snowfalls and tropical cyclones. The future time series is of less relevance than decadal frequencies of extreme events (including clusters) and worst-case scenarios over the target time interval. Coarse-resolution global climate models do a poor job of simulating extreme weather events. A novel strategy has been proposed whereby high-resolution numerical weather prediction models are used in a hypothetical climate setting to provide tailored narratives for high-resolution simulations of high-impact weather in a future climate. [27]

My company Climate Forecast Applications Network (CFAN) has been developing a network-based dynamic climatology framework for developing regional decadal scenarios of future climate, focused on the decadal statistics of extreme weather events.[28] Central to this framework is the multi-decadal ocean oscillations, notably the Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO). These oscillations have a substantial impact on the frequency and intensity of tropical cyclones and on patterns of droughts and floods. The methodology for scenario generation includes generation of a synthetic climatology of the extreme events for each of the climate regimes as defined by the phase of ocean oscillations.

The greatest vulnerability is not to the smooth long-term changes but rather to the prospect by relatively rapid shifts in the climate or a clustering of extreme weather events in a particular location. The network-based scenario generation framework is ideally suited to incorporating projections of

[24] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/2014/Robustness-of-pattern-scaled-climate-change-scenarios-for-adaptation-decision-support.pdf

[25] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL076649

[26] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/1999-and-before/28-RandomAnalogueNonLinProcesses-1997-Paparella-etal.pdf

[27] https://www.nature.com/articles/nclimate2450

[28] https://docs.wixstatic.com/ugd/867d28_838be4ad291c4922857a0987685d635f.pdf

future climate shifts. Several recent efforts have focused on predicting the next shift in ocean circulation regimes, but this remains at the forefront of climate dynamics research.

Worst-case scenario

The worst-case scenario plays an important role in clarifying the upper bound of possible scenarios that would be genuinely catastrophic. The worst-case scenario is judged to be the most extreme scenario that cannot be falsified as impossible based upon our background knowledge.

It is estimated that fully melting Antarctica would contribute over 60 meters of sea level rise, and Greenland would contribute more than 7 meters, with an additional 1.5 meters of sea level rise from glaciers. How much of this is potentially realizable in the 21st century?

The IPCC AR5 predicted a likely range of sea level rise for the 21st century between 0.26 and 0.85 m (10 to 33 inches), depending on the emission scenario [Summary for Policy Makers]. This is compared to an observed sea level rise of 8 inches over the 20th century. Additional sea level rise of 1 or 2 feet over a century can be a relatively minor problem if it is managed appropriately. The primary concern over future sea level rise is related to the potential collapse of the West Antarctic Ice Sheet, which could cause global mean sea level to rise substantially above the IPCC's 'likely' range in the 21st century. The IPCC AR5 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 [AR5 WG1 Chapter 13].

Subsequent to the 2013 IPCC AR5, there has been considerable focus on the worst-case scenario for global sea level rise. Strategies for generating the worst-case scenarios include process modeling that employs the worst-case estimate for each component, estimates from the deglaciation of the last ice age and the previous interglacial, and expert judgment.

Recent estimates of the worst-case scenario for global sea level rise in the 21st century range from 1.6 to 2.9 m (5 – 9.5 feet), with the recent NOAA Report[29] using a value of 2.5 m (8 feet). These values of sea level rise imply rates of sea level rise as high as 50 mm/yr by the end of the 21st century. For reference, the current global rate of sea level rise is about 3 mm/yr. Are these scenarios of sea level rise by 2100 plausible? Or even possible?

From the IPCC AR5:

> "*These high rates are sustainable only when the Earth is emerging from periods of extreme glaciation. During the transition of the last glacial maximum about 21,000 years ago to the present interglacial . . . coral reef deposits indicate that global sea level rose abruptly by 14 to 18 m in less than 500 years, in which the rate of sea level rise reached more than 40 mm/yr.*" [AR5 WG1 FAQ 5.2]

Rohling et al. (2013)[30] provide a geologic/paleoclimatic perspective on the worst-case scenario for 21st century sea level rise. These high projected rates of sea level rise are larger than the rates at the onset of the last deglaciation, even though today's global ice volume is only about a third of that at the onset of the last deglaciation. Starting from present-day conditions, such high rates of sea level rise would require unprecedented ice-loss mechanisms, such as collapse the West Antarctic Ice Sheet or activation of major East Antarctic Ice Sheet retreat.

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[29] https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf
[30] https://www.nature.com/articles/srep03461

Can human caused global warming trigger such an extreme scenario on the time scale of the 21st century? While on the subject of worst-case scenarios of sea level rise, we should not ignore potential geologic 'wild cards'. In the more likely category of geologic impacts on the time scale of the 21st century is geothermal heat flux in the vicinity of the Greenland and Antarctic ice sheets.[31] The worst-case scenario of a collapse of the West Antarctic Ice Sheet seems more likely to be caused by a geological event than by greenhouse gas emissions. However, it is impossible to assign probabilities to such unprecedented wild card events, and they are regarded as extremely unlikely.

Sea level rise

Global mean sea level has increased by about 8-9 inches since 1880, with about 3 inches occurring since 1993. There is no question that local sea levels are increasing in some coastal regions at rates that are causing damage. However attributing sea level rise to human-caused global warming is very challenging. This is because there are much larger impacts on local sea level rise from regional ocean circulations, local geological processes, land use practices and coastal engineering. This challenge was recognized in the IPCC AR5 WGII Report:

- *[L]ocal sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification. As a consequence, the detection of the impact of climate change in observed changes in regional sea level remains challenging.* [AR5 WG II Section18.3.3]

- *Anthropogenic causes of regional sea level rise include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal. Regional sea level rise can exceed global mean sea level rise by an order of magnitude reaching more than 10 cm/yr.* [AR5 WG II Section5.3.2.2]

Sea level rise is one impact area where anticipatory adaptation strategies make sense; while there are substantial uncertainties about its magnitude, the sign of future sea level change is clearly positive.

Causes of regional sea level change

Sea levels have not been rising uniformly across the globe. One reason for the regional variations is dynamic redistribution of ocean mass via ocean circulations. Figure 1 shows that the Pacific Decadal Oscillation has resulted in recent sea level trends ranging from >10 mm/yr in the western Pacific to less than 1 mm/yr at several regions on the U.S. west coast [for reference, the global average value is ~ 3 mm/yr].

Short-term accelerations in sea level rise along the U.S. Atlantic coast have repeatedly occurred over the last century. These 'hot spots' can exceed rates of 4 inches in five years, and can occur anywhere along the U.S. Atlantic coast. A recent paper[32] argues that the North Atlantic Oscillation (NAO), a seesaw pattern in air pressure over different regions of the North Atlantic Ocean, could explain the shift in the position of short-term variations in sea level rise. Shifts in the NAO alter the position of

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[31] A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. Van Wyk, de Vries, Maximillian et al. Geological Society, London, Special Publications (2018)

[32] https://www.nature.com/articles/nature14491

the jet stream, wind patterns and storm tracks, all of which affect the distribution of water in the North Atlantic basin. The cumulative effects of NAO determine whether water will pile up to the north or south of Cape Hatteras. Thus, water piled up preferentially to the north of Cape Hatteras in the period 2009-2010, and to the south from 2011 to 2015.

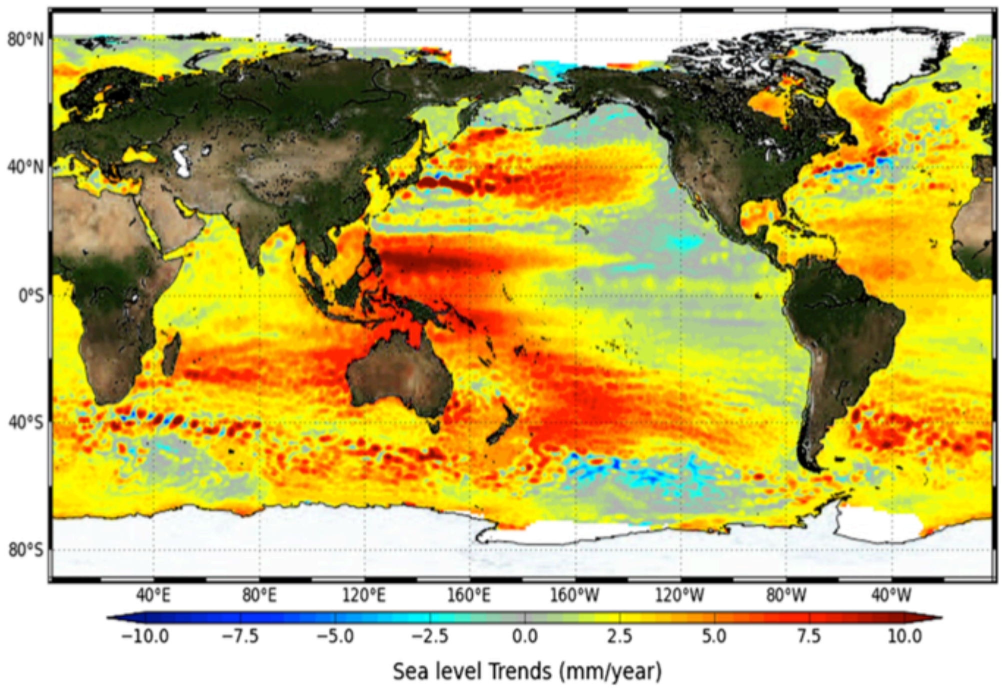

Figure 1. Satellite-derived rates of sea level rise over the period 1993-2015. Ablain et al. (2016) [33]

Glacial Isostatic Adjustment is the ongoing response of the solid Earth to land-ice shrinkage since the end of the last ice age. Melting glaciers and ice sheets and changes in land-water storage not only change ocean mass and thus global mean sea level, but also produce regionally distinct signatures from changes in the Earth's gravitational field and rotation, and lead to regional vertical land motion.

Vertical Land Motion can be a significant factor in the overall rate of local sea level rise. The highest rates of vertical land motion are found in regions of Louisiana (8–10 mm/year), Texas (4–7 mm/year) and along the Northeast Atlantic from Virginia to New Jersey (3–5 mm/year) (NOAA). In these regions, glacial isostatic adjustment and sediment compaction add about 0.5–2 mm/year to sea level change, and groundwater and oil/gas extraction processes further enhance local sea level rise. Land subsidence rates of 2–5 mm/year or more are not uncommon for the Northeast Atlantic and Gulf Coasts. For reference, global mean sea level rise is currently 3 mm/yr.

Local vulnerabilities and confounding factors

Observed and predicted rates of mean global sea level rise have little relevance for specific locations. There are numerous regional and local confounding factors that dominate local sea level rise, relative to the mean global rate. Examples are provided from some of the most vulnerable regions in the U.S.

[33] https://link.springer.com/article/10.1007/s10712-016-9389-8

Barrier islands are a type of dune system that forms by wave and tidal action parallel to the mainland coast. Barrier islands are prominent on the U.S. East Coast and Gulf Coast. The morphology of barrier islands is very dynamic. Storms and engineering practices that influence the natural flow of sediment have a substantial influence on this morphology, independent of sea level rise. Particularly for the barrier islands that have wealthy communities, aggressive engineering strategies are being developed. These most vulnerable islands are becoming laboratories for coastal sea level rise adaptation strategies. But it is futile to expect these changeable islands to remain as geologically stable entities for a very long times.

Isle de Jean Charles. Much ado has been made about the 'climate refugees' from Isle de Jean Charles off the coast of Louisiana, which is disappearing – in 1955, there were 22,000 acres while there are 320 acres today[34]. The principal problem traces back to the Great Mississippi Flood of 1927 when the U.S. Army Corps of Engineers responded by building giant levees to constrain the river, which stopped the flow of sediment into its delta. These refugees are more accurately referred to as 'Mississippi flood mitigation refugees.'

New Orleans. The issues of sea level rise and land loss in the Mississippi delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers[35]. Since the 1950s, the suspended sediment load of the Mississippi River has decreased by ~50% due primarily to the construction of dams in the Mississippi basin. A new subsidence map of coastal Louisiana[36] finds the coastal region to be sinking at about one third of an inch per year (or 9 mm/yr) [for reference, the average rate of global mean sea level rise of 3 mm/yr]. For a city whose elevation averages one to two feet below sea level, sea level rise from human caused warming is not the dominant driver for the problems that New Orleans is facing. The Louisiana Coastal Protection and Restoration Authority, using funds from the British Petroleum oil spill settlement, is moving forward with two large sediment diversions. These diversions will start channeling huge volumes of river water in new directions, in a bid to protect areas around New Orleans in particular.[37]

Miami. Miami has a population of more than 5.5 million living at an elevation of 6 feet above sea level. Around 2011, the slow upward creep of the accelerated: from 2011 to 2015, the rate of sea level rise across the southeastern U.S. increased by a factor of six, from 3 mm/year to 20 mm/year, which was caused by a change in the NAO ocean circulation pattern. In South Florida, the main problem is drainage.[38] The systems here were designed to let storm water drain into the ocean when it rains. With sea levels now often higher than the exits to the run-off pipes, saltwater is instead running up through the system and into the streets. There is a growing recognition that at some point, certain areas in South Florida will no longer be viable places to live. The challenge is to ensure that the economy as a whole, including tourism, continues to thrive.

New York City. In New York City, sea level has risen 11 inches over the past century,[39] which is a greater rate than mean global sea level rise. It has been estimated[40] that land subsidence [sinking] in the New York City area has been roughly 3-4 inches per century. New York City is particularly

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[34] https://www.independent.co.uk/news/world/americas/time-almost-up-island-louisiana-sinking-into-the-sea-american-indians-coastal-erosion-isle-de-jean-a8280401.html
[35] https://www.sciencedirect.com/science/article/pii/S0025322716303553#bb0365
[36] https://phys.org/news/2017-06-highlights-louisiana-coast.html
[37] https://www.washingtonpost.com/news/energy-environment/wp/2018/04/11/seas-are-rising-too-fast-to-save-much-of-the-mississippi-delta-scientists-say/?utm_term=.dfa274d9c508
[38] http://www.bbc.com/future/story/20170403-miamis-fight-against-sea-level-rise
[39] https://tidesandcurrents.noaa.gov/sltrends/
[40] https://www.climate.gov/news-features/features/superstorm-sandy-and-sea-level-rise

vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. The City's waterfront is among its greatest assets. There is also substantial infrastructure and municipal facilities along the coast that are at risk from sea level rise, including roads, bridges, parks, waste transfer stations and wastewater treatment plants. Following Hurricane Sandy, a comprehensive plan has been developed: *City of New York: Building a Stronger, More Resilient New York*.[41] New York has developed a broad range of coastal protection measures that match the risks facing a given area: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

San Francisco Bay area. Sea level has been measured in the San Francisco Bay area since the 19th century. Over the past the past 100 years, sea level has risen by 7.7 inches,[42] which is slightly lower than the global average rate. Landfill zones are sinking due to soil compaction, at a rate as much as one-half inch per year, threatening coastal infrastructure including the San Francisco International Airport. Another major contributor to sinking is groundwater pumping. Communities in the San Francisco Bay area have developed comprehensive plans to adapt to sea level rise.[43] Nevertheless, the San Francisco Bay Bridge ramp was recently built without any consideration of sea level rise. Less than two years after its completion, a report by the Metropolitan Transportation Commission finds that sea level rise is expected to permanently inundate several areas of the new span of the Bay Bridge and recommends a series of construction projects to protect the Bay Bridge, costing taxpayers an additional $17 million.[44]

At the 2017 *Conference on Regional Sea-level Changes and Coastal Impacts*, Kathleen White of the U.S. Army Corps of Engineers made the following statement:

> "*If we only look at the problem starting with just the climate signal, then it leads down a different path than if we look at components of sea level rise that are important to decision-makers.*"[45]

Conclusions

Climate-related decisions involve incomplete information from fast-moving and irreducibly uncertain science. In responding to climate change, we need to acknowledge that we cannot know exactly how the climate will evolve in the 21st century, we are certain to be surprised and that we will make mistakes along the way.

Acting on forecasts of the unpredictable can contribute to bad decisions. Current policy making practices often neglect known unknowns – leading to overconfidence. Rather than negotiating an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent. Flexible strategies can be quickly adjusted to advancing scientific insights and new conditions that arise.

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41 http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf
42 https://tidesandcurrents.noaa.gov/sltrends/
43 http://sf-planning.org/sea-level-rise-action-plan
44 https://blog.ucsusa.org/juliet-christian-smith/a-bridge-over-troubled-waters-how-the-bay-bridge-was-rebuilt-without-considering-climate-change?
45 http://sciencedocbox.com/Geology/74213642-Conference-report-regional-sea-level-changes-and-coastal-impacts-july-2017-new-york-usa.html

On regional and decadal time scales, the greatest vulnerability to climate change is not associated with the smooth long-term warming trend but rather with rapid shifts in frequencies and intensities of extreme weather and climate events that are associated with natural internal climate variability. The challenge for climate change adaptation is to work with a broad range of information about regional climate variability and vulnerabilities in the context of a decision-analytic framework that acknowledges deep uncertainty and that we are almost certain to be surprised about future regional climate conditions and extreme weather events.

Rather than 'bouncing back' from extreme weather and climate events, we can 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices. A focus on policies that support resilience and anti-fragility avoids the hubris of thinking we can predict the future climate.

A regional focus on adapting to the risks of climate change allows for a range of bottom-up strategies to be integrated with other societal challenges, including growing population, environmental degradation, poorly planned land-use and over-exploitation of natural resources. Even if the threat from global warming turns out to be small, near-term benefits to the region can be realized in terms of reduced vulnerability to a broad range of threats, improved resource management, and improved environmental quality.

The focus on mitigation policies has led climate science in the direction that is targeted at attribution of global climate change and determining the sensitivity of climate to CO_2. There has been little focus on understanding natural internal climate variability and regional climate dynamics that is needed to inform adaptation to climate variability and change. A new emphasis of climate science on understanding natural climate variability and its regional impacts is needed to better understand our vulnerabilities to climate change in the 21st century.