Statement of

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Thank you, Chairwoman Johnson, Ranking Member Lucas, and committee members for inviting me to speak today.

My name is Robert Kopp. I am the Director of the Rutgers Institute of Earth, Ocean, and Atmospheric Sciences[1] and a Professor in the Department of Earth and Planetary Sciences at Rutgers University–New Brunswick. I also serve as co-director of Rutgers' Coastal Climate Risk & Resilience (C2R2) initiative, which trains graduate students to work together across disciplines and with stakeholders to address coastal resilience challenges. I am also one of the directors of the Climate Impact Lab[2], a multi-institutional collaboration applying climate modeling and Big Data approaches to assess the economic risks of climate change. My research focuses on past and future sea-level change, on the interactions between physical climate change and the economy, and on the use of climate risk information in decision making.

I served as one of the twenty-nine lead authors of Volume 1 of the Fourth National Climate Assessment (NCA). I am also currently serving as a lead author of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, which is due out in 2021.

While the bulk of my testimony is focused on presenting the findings of the Fourth NCA, I am speaking on my own behalf. My testimony is not itself a product of the assessment process, nor does it necessarily represent the positions of the US Global Change Research Program or of Rutgers University. I also would like to note that I was not one of the three coordinating lead authors who oversaw Volume 1, nor was I an author of Volume 2. My comments on Volume 2 are based on my technical contributions and my reading of it as a climate scientist who is up to date with in much of the relevant literature.

The National Climate Assessment process

In 1990, President George H. W. Bush signed the Global Warming Response Act of 1990, which established the interagency U.S. Global Change Research Program (USGCRP) under the auspices of the National Science and Technology Council's Subcommittee on Global Change Research. One of the key tasks of the USGCRP was to undertake a quadrennial National Climate Assessment, which "1) integrates, evaluates, and interprets the findings of the Program . . .; 2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and 3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years."[3]

The first NCA was released by USGCRP in the year 2000; the second in 2009; and the third in 2014. The Fourth NCA was developed in two volumes: the first volume, published in 2017, focusing on the physical science, and the second volume, in 2018, on Impacts, Risks, and Adaptation. The report is data-driven and transparent, with nearly 2000 extensively referenced pages and key findings backed by detailed traceable accounts.

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[1] For more information: eoas.rutgers.edu

[2] For more information: impactlab.org

[3] *Global Change Research Act of 1990*. Pub. L. No. 101-606, 104 Stat. 3096-3104, November 16, 1990. https://go.usa.gov/xE5Js.

Both volumes underwent extensive review processes involving an open review by external experts and the general public, a thorough review by independent experts convened by the National Academies of Sciences, Engineering, and Medicine, and multiple rounds of interagency review. Report authors provided written responses to all the review comments, which are available online for the external and National Academies reviews.

Climate science is a massive enterprise; while at a global scale, the fundamentals are well established, and in many cases have been known for many decades, even over a century, the scientific understanding of the details is rapidly evolving.

As the periodic nature of the NCA reports reflects, the goal of the NCA process is to provide an up-to-date assessment of the scientific understanding of climate change, its current effects on the United States, and its potential future impacts across a broad range of emissions scenarios. It considers a broad range of possible futures, from one in which fossil fuel use and emissions continue to grow to one in which emissions are rapidly reduced and reach zero before the end of the century.

Key messages of the Fourth National Climate Assessment

The National Climate Assessment draws out key findings from the massive body of peer-reviewed science in order to support scientifically informed climate risk management by federal, state, local, and private-sector decision-making. In addition, by identifying key decision-relevant uncertainties, it can also help direct scientific inquiry toward decision-relevant ends.

The most fundamental messages of Volume 1 of the report are simple, and they are not novel:

1) Climate change is real, it is here now, and humans are responsible for it.

2) Every additional amount of greenhouse gas emitted makes climate change more severe.

3) The faster we reduce our emissions, the less severe the effects and the lower the risk of unwelcome surprises.

Volume 2 expands upon the human consequences of climate change and how the US is responding to them. It tells us that:

1) Climate change is not an issue for the distant future – it is already affecting Americans in every region of the country.

2) Climate change is not just an environmental challenge; it is an economic challenge, an infrastructure challenge, a public health challenge and a national security challenge.

3) Though the pace is not yet adequate to minimize climate risk, Americans are already starting to respond by reducing emissions and beginning to adapt to climate change impacts.

Let me expand upon these points.

Climate change is real, it is here now, and humans are responsible for it.

Our planet is running a fever.

To quote the NCA:

> Global climate is changing rapidly compared to the pace of natural variations in climate that have occurred throughout Earth's history. Global average temperature has increased by about 1.8°F from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause.[4]

Global average carbon dioxide concentration are now about 410 parts per million – nearly 50% higher than they were at the start of the Industrial Revolution, and a level not seen on this planet for at least about three million years. Carbon dioxide's role as a heat-trapping gas has been known since the discoveries of Eunice Foote and John Tyndall in the mid-19th century. Thus, a warming planet should be entirely expected.

In contrast, to quote the NCA,

> Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and there is no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate.[5]

It is *likely* – a term the NCA uses to mean a chance of at least two in three – that the human contribution to global warming over 1951–2010 is between 93 to 123 percent. (Values larger than 100 percent reflect that, in the absence of human emissions, the planet might actually have cooled over this time period.)

Further, "Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor."[6]

- "Heat waves have become more frequent in the United States since the 1960s, while extreme cold has become less frequent."[7]

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[4] K. Hayhoe et al., *Our Changing Climate*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 72–144, 73 (D. R. Reidmiller et al. eds., 2018), doi:10.7930/NCA4.2018.CH2.

[5] D. J. Wuebbles et al., *Executive summary*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 10–34, 14 (D. J. Wuebbles et al. eds., 2017), doi: 10.7930/J0DJ5CTG.

[6] *Id.* at 10.

[7] *Id.* at 11.

- “Heavy rainfall is increasing in intensity and frequency across the United States.”[8]
- Higher temperatures are making soil drier, contributing to the intensity of droughts.[9]
- Global average sea level has risen by about 8 inches since 1900,[10] and recent work published since Volume 1 of the NCA was completed shows that global average sea level is now rising at more than 1.5 inches per decade – close to three times the average rate over the last century.[11] This has led to an increase in the frequency of coastal flooding: frequencies that, in some cities, have increased by a factor of ten since the middle of the last century.[12]

Every additional amount of greenhouse gas emitted makes climate change more severe.

In the words of the NCA,

> The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally. Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less.[13]

To a first approximation, carbon dioxide warms the planet in proportion to the total amount emitted – every ton of CO_2 emitted increases the planet’s temperature a little, every trillion tons by about 0.4°–1.2°F (0.2–0.7°C).[14] As a reference, current global annual CO_2 emissions are about 42 billion tons,[15] so if CO_2 emissions were frozen at the current levels, we would expect global average temperature to increase by about 1°F every 25 years – in fact, somewhat faster due to the effects of greenhouse gases other than CO_2.

The CO_2 warming is extremely long-lived – most of it happens within a decade or two of emission, and most of it persists for well over a millennium.[16]

The consequence of these physical relationships is that, in order to stabilize global climate, human emissions of CO_2 must be balanced by human removal of CO_2 from the atmosphere,

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[8] *Id.* at 11.

[9] M. F. Wehner et al., *Droughts, Floods, and Wildfires*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 231–256 (D. J. Wuebbles et al. eds., 2017).

[10] William V. Sweet et al., *Sea level rise*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 333–363 (D. J. Wuebbles et al. eds., 2017).

[11] WCRP Global Sea Level Budget Group, *Global sea-level budget 1993–present*, 10 EARTH SYSTEM SCIENCE DATA 1551–1590 (2018).

[12] Sweet et al., *supra* note 10.

[13] Wuebbles et al., *supra* note 5 at 11.

[14] Matthew Collins, Reto Knutti & others, *Chapter 12: Long-term Climate Change: Projections, Commitments and Irreversibility*, *in* CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS , 12 (Thomas F. Stocker, Dahe Qin, & others eds., 2013), http://www.ipcc.ch/report/ar5/wg1/.

[15] Corinne Le Quéré et al., *Global Carbon Budget 2018*, 10 EARTH SYSTEM SCIENCE DATA 2141–2194 (2018).

[16] F. Joos et al., *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*, 13 ATMOSPHERIC CHEMISTRY AND PHYSICS 2793–2825 (2013).

whether by expanding forests or using new, little-tested technologies. In other words, to stabilize global climate, net global CO_2 emissions must be brought to zero.

The faster we reduce our emissions, the less severe the effects and the lower the risk of unwelcome surprises.

For example, rapid emission reductions could limit warming this century over the contiguous United States to about 1-5°F, whereas sustained emissions growth could lead to 6-12°F of warming – with extreme high temperatures rising even faster.[17] Similarly, global average sea level rise this century will very likely be less than 3 feet in a low-emissions future, whereas a high-emissions future raises the odds on extreme Antarctic instability, potentially leading to 6 feet or more of rise over the course of this century.[18]

And the less we push the Earth's climate from the historical conditions that gave birth to modern civilization, the lower the odds that it will surprise us in potentially dangerous ways.[19]

The first volume's final chapter, which I helped lead, offers a perspective on the way the climate system might surprise us, and comes to three key conclusions:

First, one way the climate system might surprise us is through the cumulative effects of multiple, or 'compound' extreme events – for example simultaneous heat and drought, wildfires associated with hot and dry conditions, flooding associated with high precipitation on top of snow or waterlogged ground, or – to take one recent and now sadly familiar example – multiple severe hurricanes in quick succession. The human impacts of these compound extremes can be larger than that of the individual extremes in isolation. This area is an emerging area of research that is just now starting to come into focus; thus the potential for surprises.

Second, both modeling and geological records of past climate changes demonstrate that self-reinforcing cycles "within the climate system have the potential to accelerate human-induced climate change and even shift the Earth's climate system, in part or in whole, into new states that are very different from those experienced in the recent past – for example, ones with greatly diminished ice sheets or different large-scale patterns of atmosphere or ocean circulation."[20] It is such feedbacks that undergird the potential for high-end sea-level rise mentioned earlier.

Third, comparison of the geological record and climate model simulations reveal another insight. Climate models often have difficulty reproducing past warm climates, which we can learn about from the geological record. In the words of the NCA, "The systematic tendency of climate models to underestimate temperature change during warm paleoclimates suggests that climate models are more likely to underestimate than to overestimate the amount of long-term future change."[21] For example, some of the reconstructions of past warm periods from the geological record may be explained if, above some threshold of CO_2 higher than the current level,

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[17] R. S. Vose et al., *Temperature changes in the United States*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 185–206 (D. J. Wuebbles et al. eds., 2017), doi: 10.7930/J0N29V45.

[18] Sweet et al., *supra* note 10; Robert E. Kopp et al., *Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections*, 5 EARTH'S FUTURE 1217–1233 (2017).

[19] Robert E. Kopp et al., *Potential surprises – compound extremes and tipping elements*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I 411–429 (D. J. Wuebbles et al. eds., 2017).

[20] *Id.* at 411.

[21] *Id.* at 411.

widespread reductions in cloud cover increases the sensitivity of the climate to greenhouse gases – a possibility pointed to by a few studies.[22]

These large scale, global effects are important, but nobody lives at the global or national average – everyone lives somewhere, and Volume 2 looks at the human effects of these changes.

Climate change is not an issue for the distant future – it is already affecting Americans in every region of the country.

To help with planning at a state and local level, the report details impacts and adaptation measures in ten regions covering the United States and its affiliated islands. For example, as Hurricanes Harvey and Irma reminded us,

> The Southeast's coastal plain and inland low-lying regions support a rapidly growing population, a tourism economy, critical industries, and important cultural resources that are highly vulnerable to climate change impacts. The combined effects of changing extreme rainfall events and sea level rise are already increasing flood frequencies, which impacts property values and infrastructure viability, particularly in coastal cities. Without significant adaptation measures, these regions are projected to experience daily high tide flooding by the end of the century.[23]

Scientists are increasingly able to evaluate the ways in which climate change is making weather more extreme. For example, studies show that climate change intensified the dry, hot summer of 2011 in Texas and Oklahoma and the 2012-2017 drought in California. A warm, moisture-laden atmosphere led to more intense rainfall during Hurricane Harvey in 2017 – as much as 38% more rain, one study estimated, over the entire duration of the storm.[24] And sea-level rise has made every severe coastal flood, including that of Hurricane Sandy in 2012, more intense and damaging.[25] Sensitive assets like roads, hospitals, power plants, and contamination sites are increasingly frequently threatened.[26]

Climate change is not just an environmental challenge; it is an economic challenge, an infrastructure challenge, a public health challenge and a national security challenge.

The National Climate Assessment notes, drawing in part on my work with my collaborators in the Climate Impact Lab, that "in the absence of more significant global mitigation efforts, climate change is projected to impose substantial damages on the U.S. economy, human health, and the environment. Under scenarios with high emissions and limited or no adaptation, annual

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[22] For example, Rodrigo Caballero & Matthew Huber, *State-dependent climate sensitivity in past warm climates and its implications for future climate projections*, 110 PNAS 14162–14167 (2013).

[23] L. Carter et al., *Southeast*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 743–808, 744 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH19.

[24] Wehner et al., *supra* note 9; Vose et al., *supra* note 17.

[25] Kenneth G. Miller et al., *A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast*, 1 EARTH'S FUTURE 3–18 (2013).

[26] K. Kloesel et al., *Southern Great Plains*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 987–1035 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH23.

losses in some sectors are estimated to grow to hundreds of billions of dollars by the end of the century."[27]

The report notes that "the health and well-being of Americans are already affected by climate change, with the adverse health consequences projected to worsen with additional climate change. Climate change affects human health by altering exposures to heat waves, floods, droughts, and other extreme events; vector-, food- and waterborne infectious diseases; changes in the quality and safety of air, food, and water; and stresses to mental health and well-being."[28]

And it notes that "Climate change, variability, and extreme events, in conjunction with other factors, can exacerbate conflict, which has implications for U.S. national security. Climate impacts already affect U.S. military infrastructure, and the U.S. military is incorporating climate risks in its planning." [29]

This finding about national security impacts is echoed by the US Intelligence Community's most recent Worldwide Threat Assessment, which notes that "Global environmental and ecological degradation, as well as climate change, are likely to fuel competition for resources, economic distress, and social discontent through 2019 and beyond."[30]

Though the pace is not yet adequate to minimize climate risk, Americans are already starting to respond by reducing emissions and beginning to adapt to climate change impacts.

In terms of mitigation, for example, the report notes that 110 cities have adopted emissions reduction targets; several states have mandatory or voluntary targets; and an increasing number of companies are implementing emissions reduction target and internal carbon prices as well.

In terms of adaptation, the report highlights a multitude of examples from around the country. For example, it notes municipal adaptation planning efforts for climate change and/or more frequent flooding in New York City, Boston, Atlanta, and Charleston.[31] Transport systems like the Port Authority of New York and New Jersey and the Metropolitan Atlantic Rapid Transit Authority are building climate resilience into their infrastructure plans.[32] In the Midwest, the report highlights the use of cover crops and water management systems to limit soil erosion in response to more intense rains, as well as the use of green infrastructure to handle stormwater in

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[27] J. Martinich et al., *Reducing Risks Through Emissions Mitigation*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1346–1386, 1347 (C. W. Avery et al. eds., 2018), doi: 10.7930/NCA4.2018.CH29.

[28] K. L. Ebi et al., *Human Health*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 572–603, 540 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH14.

[29] J. B. Smith et al., *Climate Effects on U.S. International Interests*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 604–637, 605 (C. W. Avery et al. eds., 2018), doi: 10.7930/NCA4.2018.CH16.

[30] DANIEL R. COATS, WORLDWIDE THREAT ASSESSMENT OF THE US INTELLIGENCE COMMUNITY 23 (2019), https://www.dni.gov/files/ODNI/documents/2019-ATA-SFR---SSCI.pdf.

[31] L. A. Dupigny-Giroux et al., *Northeast*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 669–742 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH18; Carter et al., *supra* note 23.

[32] Dupigny-Giroux et al., *supra* note 31; Carter et al., *supra* note 23.

cities like St. Louis and Minneapolis.[33] On the west coast, the report highlights the growing use of dry farming methods in places like Oregon's Willamette Valley, as well as the growing number of Native American nations that have begun to consider relocation as a last resort.[34] In the Southwest, it highlights the multistate, binational efforts to manage Colorado River waters.[35] In Texas, the Edwards Aquifer Recovery Implementation Program Habitat Conservation Program – addressing the aquifer that provides water to San Antonio, San Marcos, and Austin – incorporates advanced water conservation and market-based solutions for dealing with groundwater pumping during droughts. Forty-four public water supply desalination plants in Texas are helping increase water supply in times of drought.[36]

Scientific uncertainty and climate risk management

Uncertainty is integral to science, and one of the main drivers of scientific pursuits. There is a strong tendency among scientists to focus on what is new, tantalizing, and unknown, rather than what is old and well understood.

In the world of scientific assessments, a great deal of effort has gone into formalizing language for evaluating what is known and how well it is known. The National Climate Assessment, like the Intergovernmental Panel on Climate Change, uses a set of specific definitions for terms like '*likely*,' '*very likely*', and '*virtually certain*.' For example, '*likely'* means 'at least two chances in three,' '*very likely*' means 'at least nine chances in ten', and '*virtually certain*' means 'at least ninety-nine changes in one-hundred.' These judgements of likelihood are based upon an expert evaluation that looks across the available scientific literature.

Similarly, these assessments have defined a set of formal language to characterize the strength of the relevant evidence. For example, '*very high confidence*' conclusions have strong evidence, for example based on well-established theory, multiple sources with consistent results, and well accepted methods. '*Medium confidence*' conclusions have suggestive evidence (e.g., a few sources with limited consistency using emerging methods). '*Low confidence*' conclusions are used to highlight areas of inconclusive evidence, inconsistent findings, and limited agreement on methods and conceptual frameworks.

Here are some examples from the first volume of the Fourth NCA:

> Global annual average temperature (as calculated from instrumental records over both land and oceans) has increased by more than 1.2°F (0.65°C) for the period 1986–2016 relative to 1901–1960; the … change over the entire period from 1901–2016 is 1.8°F (1.0°C) (*very high confidence*[).][37]
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> Many lines of evidence demonstrate that it is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century. Over the

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[33] J. Angel et al., *Midwest*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 872–940 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH21.

[34] C. May et al., *Northwest*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1036–1100 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH24.

[35] P. Gonzalez et al., *Southwest*, *in* IMPACTS, RISKS, AND ADAPTATION IN THE UNITED STATES: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME II 1101–1184 (D. R. Reidmiller et al. eds., 2018), doi: 10.7930/NCA4.2018.CH25.

[36] Kloesel et al., *supra* note 26.

[37] Wuebbles et al., *supra* note 5 at 13.

> last century, there are no convincing alternative explanations supported by the extent of the observational evidence. Solar output changes and internal natural variability can only contribute marginally to the observed changes in climate over the last century, and there is no convincing evidence for natural cycles in the observational record that could explain the observed changes in climate. (*Very high confidence*)[38]
>
> The frequency and intensity of heavy precipitation events in the United States are projected to continue to increase over the 21st century (*high confidence*). There are, however, important regional and seasonal differences in projected changes in total precipitation: the northern United States, including Alaska, is projected to receive more precipitation in the winter and spring, and parts of the southwestern United States are projected to receive less precipitation in the winter and spring (*medium confidence*).[39]
>
> Relative to the year 2000, [global average sea level] is *very likely* to rise by 0.3–0.6 feet (9–18 cm) by 2030, 0.5–1.2 feet (15–38 cm) by 2050, and 1.0–4.3 feet (30–130 cm) by 2100 (*very high confidence in lower bounds; medium confidence in upper bounds for 2030 and 2050; low confidence in upper bounds for 2100*).[40]

For effective climate risk management, it's important to consider not only high-confidence conclusions, but also low-confidence ones. Low-confidence conclusions are often associated with areas subject to what is sometimes called 'deep uncertainty': areas where there is little agreement among experts about the relative importance of different processes or likely values of key variables.[41] In many cases, deep uncertainty is associated with what the report also calls 'potential surprises.'

An archetypal example of this, given the current scientific understanding, involves the behavior of the Antarctic ice sheet late in this century and beyond. As the report notes, "Emerging science regarding Antarctic ice sheet stability suggests that, for high emission scenarios, a [global average sea level] rise exceeding 8 feet (2.4 m) by 2100 is physically possible, although the probability of such an extreme outcome cannot currently be assessed."[42] This deep uncertainty arises in large part from expert disagreement about the importance of different processes that can give rise to self-reinforcing cycles leading to relatively rapid ice-sheet loss.

What does the presence of deep uncertainty mean for risk management?[43]

Consider two dice games, played against the house (in this case, Mother Nature). In both games, there is a large pot on the table, representing assets at risk, and you have no choice but to play the game.

In the first game, if you roll snake-eyes on a pair of dice, you lose the pot; otherwise you keep it. Thus, there is a well-defined, 1-in-36 chance of losing. A risk-neutral player should be willing to

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[38] *Id.* at 14.

[39] *Id.* at 21.

[40] Sweet et al., *supra* note 10 at 333.

[41] Robert J. Lempert, *A new decision sciences for complex systems*, 99 PNAS 7309–7313 (2002).

[42] Sweet et al., *supra* note 10 at 333.

[43] The remainder of this section of my written testimony is based on my own research and experience, not on the Fourth National Climate Assessment.

spend 1/36th of the pot to insure the rest. In the game, this expenditure might be a side bet; with respect to sea-level rise, it might represent investment in protective measures against global mean sea-level rise exceeding 1.2 feet by 2050.

In the second game, Mother Nature has written a number between 2 and 7 on a piece of a paper you cannot see. If you roll above this number, you get to keep the pot; if you do not, you lose it. This game exhibits deep uncertainty: different expert players might have different conceptual models underlying how this number was selected and may not agree on how likely different numbers are.

You definitely would not play this game the same way you would play the first game – deep uncertainty does not justify assuming the most optimistic possible state of the world. Unless you are extremely risk averse, you probably also would not play the game the same way you would if you knew for certain a seven was written down; if you did that, there is a fair chance you would lose a good deal, though not as much as if you were too optimistic.

This second game is roughly analogous to the current state of understanding of the prospect of global average sea-level rise between 4 and 8 feet over this century under a high-emissions future.

Fortunately, we are not playing a one-shot game. Sea-level rise takes place over time, and we will not get 8 feet of sea-level rise tomorrow. Scientific understanding is evolving, and it is quite possible that within thirty years research will reveal what number is written on that sheet of paper. It might also turn out within thirty years that we are on course for a low-emissions future, in which case the uncertainty will be less deep and more closely resemble that of the first game.

Many decisions have a timeframe within the next thirty years and are not affected by this deep uncertainty in sea-level rise. Other decisions may require action now for the long-term. For instance, the existing rail tunnels under the Hudson River are about a century old. In building a new tunnel – a process that is slow and yields a product that may well last for over a century – it may be more cost-effective to build now for high-end sea-level rise rather than trying to retrofit if it turns out in a couple decades that the world is on course for a high-end rise.

Still other decisions permit staged, adaptive management: take action for the next thirty years but know now what follow-on actions you will take depending on what number turns out to be written down. This last approach may be the best for jointly minimizing climate and investment risk when managing complex systems, such as the portfolio of actions required to protect coastal populations from sea-level rise.

This last approach of adaptive management is also known in the literature as a ‘flexible adaptation pathways’ approach. A key part of such approaches is the inclusion of research investments focused on narrowing key uncertainties as one part of a portfolio of risk management strategies. Another key part is drawing up contingency plans for different possible futures in advance and mapping out which future discoveries will trigger which actions. Managing climate risk in this way requires long-term, sustained investment in research that cuts across the disciplinary boundaries of climate science, social science, engineering, and decision science.

Advancing the climate science enterprise for climate risk management[44]

The recognition of the urgent need for scientific knowledge to inform action has led to the development of what is sometimes called 'transdisciplinary' science.[45] Transdisciplinary science brings researchers from different disciplines together with stakeholders to tackle a common real-world problem. Transdisciplinary science is not necessarily applied research, as it may aim not only to translate existing understanding into practice but also to address some of the fundamental scientific uncertainties relevant to effective risk management. The tie to real-world problems is, however, a core element.

Climate risk management calls out for such transdisciplinary research, as well as for educational initiatives preparing students to conduct such research. At Rutgers, we have a number of such efforts. For example, our Coastal Climate Risk and Resilience program[46] trains graduate students to work with natural scientists, social scientists, engineers, urban planners, and stakeholders to manage coastal risk. The New Jersey Climate Change Alliance[47] is a University-managed network of stakeholders that links scientific experts with local, state, and private decision-makers. And we are a partner in the Climate Impact Lab, which is bringing climate scientists, economists, and data scientists together with stakeholders in state governments and the private sector to better integrate economic assessments of climate risk into regulatory and investment decisions.

But true transdisciplinarity is hard – it requires a considerable investment on the part of researchers or their institutions in maintaining strong, working, trusting relationships with stakeholders. And building such relationships takes time – if it must be done from scratch, it does not fit well with the time pressures faced by pre-tenure faculty or graduate students.

Right now, in the climate risk area, most transdisciplinary collaborations are driven by strong personalities or short-term funding opportunities. But the climate risk problem is not going to go away. Society is not well served if the networks that sustain such collaborations have to be rebuilt when individuals leave an institution or funding temporarily dries up.

Fortunately, there is an example of academic institutions supporting transdisciplinary collaborations that has worked in the United States for over a century, long before the modern jargon of 'transdisciplinarity' was coined.

In 1862, amidst the bloodshed of the Civil War, Abraham Lincoln signed the Morrill Act, establishing the United States' land-grant college system. The Morrill Act and follow-on legislation transformed higher education in the United States. They established a network of universities devoted to training the next generation of farmers and engineers, conducting innovative and useful research to advance agriculture, and engaging with farmers to disseminate the fruits of this research. The Smith-Lever Act of 1914 established cooperative extension

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[44] This section of my written testimony is based on my own research and experience, not on the Fourth National Climate Assessment.

[45] Gertrude Hirsch Hadorn et al., *The Emergence of Transdisciplinarity as a Form of Research*, *in* HANDBOOK OF TRANSDISCIPLINARY RESEARCH 19–39 (Gertrude Hirsch Hadorn et al. eds., 2008), https://doi.org/10.1007/978-1-4020-6699-3_2 (last visited Feb 6, 2019).

[46] For more information: c2r2.rutgers.edu

[47] For more information: njadapt.rutgers.edu

services at land-grant institutions with the aim of bringing scientific knowledge about agriculture out of the universities and into the country. The cooperative extension services have placed agents in every US county and built networks of trust that link the land-grant institutions to the (primarily agricultural) community.

It is worth considering an investment analogous to that of cooperative extension in expanding the infrastructure for scientific climate risk management. The unique advantage of land-grant universities is the extension tradition, upon which can be built robust networks to sustain stakeholder engagement in climate risk research and education. This requires support to shift the maintenance of stakeholder networks away from individual investigators and grants and to the institution.

Building upon the extension strength also requires addressing countervailing incentives at the level of the individual scientist. Transdisciplinary research is inherently slower than more ivory-tower research, requiring that researchers invest time in stakeholder engagement. More flexible tenure evaluation processes that recognize the value of this engagement can help advance this mission, and this shift would be assisted by appropriate nudges from funding agencies.

In conclusion:

The National Climate Assessment provides an extensively reviewed evaluation of a vast body of scientific literature. It shows that:

Climate change is real, it is here, and we humans are responsible for it. To stabilize global climate, we need to bring net global greenhouse gas emissions to zero; the sooner we do this, the smaller the risks – to our economy, infrastructure, health, and national security – that we will have to manage. But even with strong emission reductions, there will still be major adaptation challenges ahead. It is therefore essential that climate change become a routine and integrated part of decision-making at all levels – public and private; federal, state, and local.

Thank you for holding this hearing today. It's my hope that, as the Science Committee, you will look closely at both how to advance the climate science enterprise in a manner that supports climate risk management and also at how to support climate risk management that is scientifically informed.