Written testimony of

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Thank you, Chairman Neal and Ranking Member Brady, for the opportunity to be here. I am a climate scientist, and my research uses computer models, satellite observations, and reconstructions of past climate to study the past, present, and future of climate change. While I work for Columbia University and with the NASA Goddard Institute for Space Studies, I am testifying here as a private citizen.

Imagine every square foot of Earth illuminated by a sixty-watt light bulb during the daytime- that's about how much energy we get from our Sun. About thirty percent of this is immediately reflected back to space by clouds or the surface of the Earth.[1] But the rest is absorbed and re-radiated to space as thermal energy: light in colors we cannot see. The energy coming from the planet is infrared light with a longer wavelength and lower energy than the visible light from the sun. **Anything that alters the delicate balance between energy in and energy out can change the temperature of the planet.** Human activities are changing it right now.

One carbon and two oxygen atoms make three: a molecule called carbon dioxide. These atoms can vibrate when hit by particular kinds of light. They turn the energy carried by the light into vibration, re-emitting energy into their surroundings when the vibration stops. But not all light has the right energy to make the molecules vibrate. Visible light from the sun streams right through carbon dioxide. But the thermal energy- infrared light- that our planet radiates back to space *does* cause the molecules to vibrate. They absorb this energy and, once the vibration stops, release it back into the atmosphere in all directions. Some of this energy is released toward space, but some of it is directed back down toward the ground. This excess energy, trapped by the gases, heats the planet. We call molecules that behave in this way *greenhouse gases*. **This is well-established science: the heat-trapping properties of greenhouse gases were first understood in the 1820s** and discovered experimentally in the 1860s[2]. The first scientific paper to suggest a connection between increasing carbon dioxide and warming temperatures was written in 1896.[3]

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[1] https://earthobservatory.nasa.gov/features/EnergyBalance

[2] See On the Temperatures of the Terrestrial Sphere and Interplanetary Space (*Jean-Baptiste Joseph Fourier*(1824)) and On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction (*John Tyndall* (1861)), both collected in Archer, David, and Ray Pierrehumbert, eds. *The warming papers*. John Wiley & Sons, 2011.

[3] https://www.rsc.org/images/Arrhenius1896_tcm18-173546.pdf

Naturally occurring greenhouse gases make up a tiny fraction of our planet's atmosphere- about one tenth of one percent. The vast majority of the atmosphere consists of nitrogen and oxygen, molecules that are not greenhouse gases[4]. **But even though greenhouse gases are scarce, they are powerful.** If our atmosphere contained no greenhouse gases whatsoever, the average temperature of our planet would be well below freezing (around 0 degrees Fahrenheit), and none of us could exist. *With* them, the average temperature is around 59 degrees Fahrenheit[5].

Human activities are increasing the atmospheric composition of these powerful heat-trapping gases. Carbon dioxide is the byproduct of combustion, the chemical reaction that converts fossil fuels into energy. So the more fossil fuels we burn, the more CO2 is released into the atmosphere. Humans have increased atmospheric carbon dioxide levels by about 45% since the beginning of the industrial revolution[6]. And the planet has warmed up in response. **Global temperatures have warmed by 1.9 degrees F since 1880[7].**

Scientists know that climate change can be influenced by natural factors like variations in the Sun's energy, changes in the Earth's orbit, and volcanic eruptions[8]. But these are not responsible for the recent long-term climate changes we have observed[9]. We have very good measurements of the Sun and our orbit around it, and these simply cannot explain the warming trend we have seen. In fact, over the past 30 years, solar output has not increased, but Earth has continued to warm[10]. Major volcanic eruptions like Mt. Pinatubo in 1991 can spew gas and dust into the atmosphere, which, because they block sunlight, have a substantial cooling effect[11]

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[4] Wallace, John M., and Peter V. Hobbs. *Atmospheric science: an introductory survey*. Vol. 92. Elsevier, 2006.

[5] https://www.giss.nasa.gov/research/briefs/ma_01/

[6] https://climate.nasa.gov/vital-signs/carbon-dioxide

[7] https://climate.nasa.gov/vital-signs/global-temperature

[8] For a clear visualization, see Bloomberg News, *What's Really Warming The World?* https://www.bloomberg.com/graphics/2015-whats-warming-the-world/

[9] Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang, 2013: Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[10] Matthes, Katja, et al. "Solar forcing for CMIP6 (v3. 2)." *Geoscientific Model Development* 10.6 (2017): 2247-2302.

[11] Hansen, James, et al. "Potential climate impact of Mount Pinatubo eruption." *Geophysical Research Letters* 19.2 (1992): 215-218.

. But volcanic eruptions can't explain the long-term warming. We also know that climate change occurs against a backdrop of natural climate variability: the seasonal cycle, day-to-day weather, and natural cycles like El Niño[12]. But we know of no natural cycle that could result in such a long term sustained warming. **If one believes that the warming is natural, one must also explain why the physics of greenhouse gases, something well-understood for over a century, would not apply here.**

I have sometimes heard people say that the climate has changed before, as if that were evidence that humans could not be causing present-day climate change. This is like telling a detective hunting for a serial killer that people die of natural causes. In fact, **understanding how the climate has changed in the past is crucial to understanding present day human-caused warming.** Earth has left behind clues for us about past climate changes[13], in the chemistry of ancient shells buried within the ocean floor, the width of tree rings, and bubbles trapped in ice cores[14]. The last time carbon dioxide levels were this high was three million years ago during the Pliocene epoch, when the planet was two or three degrees C (3.6-5.4 F) warmer and sea levels were up to seventy-five feet higher[15]. The planet's past provides powerful evidence that carbon dioxide and climate are connected, and that sweeping climate changes can result in mass extinctions[16]. But these natural processes occurred over thousands or millions of years. Because of human activities, CO2 is now entering the atmosphere 100 times faster than previous natural increases like those that occurred at the end of the last ice age [17].

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[12] https://www.climate.gov/enso

[13] Many datasets compiled from proxy measurements of past climates can be freely downloaded at https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets

[14] Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao and A. Timmermann, 2013: Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[15] Dutton, A., et al. "Sea-level rise due to polar ice-sheet mass loss during past warm periods." *Science* 349.6244 (2015): aaa4019.

[16] For a readable and accessible introduction, see Brannen, Peter. *The Ends of the World: Volcanic Apocalypses, Lethal Oceans, and Our Quest to Understand Earth's Past Mass Extinctions.* Harper Collins (2017).

[17] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

So how much of global warming are humans causing? **All of it.** The recent US National Climate Assessment[18] found that between 93% and 123% of the observed temperature increase between 1951 and 2010 was due to human activities.

Climate change is not a problem for future generations- it's already here. Scientists have observed shifting rainfall patterns[19], changes in cloud cover[20], increased humidity[21], and rising sea levels[22]. We have seen the lower atmosphere- the troposphere- warm, while the stratosphere cools, a pattern characteristic of carbon dioxide but impossible to achieve with increased solar activity[23]. We have directly observed carbon dioxide increasing the greenhouse effect at the Earth's surface[24]. These changes are incompatible with our best understanding of natural climate variability, and they are not explicable by the sun, changes in Earth's orbit, or volcanoes. Observations of the atmosphere[25] and ocean[26], from the tropics to the poles, taken

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[18] https://nca2018.globalchange.gov

[19] Marvel, Kate, and Céline Bonfils. "Identifying external influences on global precipitation." *Proceedings of the National Academy of Sciences* 110.48 (2013): 19301-19306.

[20] Norris, Joel R., et al. "Evidence for climate change in the satellite cloud record." *Nature* 536.7614 (2016): 72.

[21] Santer, Benjamin D., et al. "Identification of human-induced changes in atmospheric moisture content." *Proceedings of the National Academy of Sciences* 104.39 (2007): 15248-15253.

[22] Kopp, R. E., A. C. Kemp, K. Bittermann, B. P. Horton, J. P. Donnelly, W. R. Gehrels, C. C. Hay, J. X. Mitrovica, E. D. Morrow, and S. Rahmstorf, 2016:Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences of the United States of America* 113 (11), E1434–E1441 doi:10.1073/pnas.1517056113.

[23] Santer, Benjamin D., et al. "A search for human influences on the thermal structure of the atmosphere." *Nature* 382.6586 (1996): 39.

[24] Feldman, Daniel R., et al. "Observational determination of surface radiative forcing by CO2 from 2000 to 2010." *Nature,* 519.7543 (2015): 339.

[25] Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[26] Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, 2013: Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

from space and from ground-based measurements, and compiled by different research groups and countries all add up to a coherent picture of change.

Climate change has implications for society beyond rising temperatures alone. **Sea levels are rising at an increasing rate.** About 90 percent of the excess heat caused by our carbon dioxide emissions is absorbed by the ocean[27]. Warmer water expands, and this is one reason sea levels are rising. Another contributing factor is the melting of glaciers and land-based ice sheets. As a result, global average sea level is nearly seven inches higher than it was a hundred years ago. Coastal communities have already seen large increases in nuisance flooding, and as sea levels rise destructive storm surges can push farther inland. And it will get worse: global sea levels are projected to rise between 1 and 4 feet by the end of this century[28].

We are already experiencing extreme events that can be linked to climate change. It is true that climate is almost never the only factor contributing to weather-based disasters. Other human actions like land management, population changes, and policy can certainly exacerbate or mitigate extreme weather events like heat waves, hurricanes or wildfires. **But it would be a mistake to assume that if climate change isn't the *only* factor, it isn't an important factor.** Warmer air temperatures make heat waves more frequent and more severe[29]. Warmer ocean temperatures provide the energy to feed stronger hurricanes. Warmer temperatures and drier conditions increase the risk of wildfires[30].

We know that as the temperature rises, extreme events like floods and droughts can become more frequent or more severe. One of the most well-understood consequences of warming is an increase in atmospheric water vapor- about four percent per degree Fahrenheit of warming[31]. And this means that there is more water that can fall as rain, leading to more

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[27] https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

[28] Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[29] Heat waves are one of the most well-understood consequences of climate change. The European heat wave of 2003 was one of the first extreme events for which a human contribution was demonstrated (Stott, Peter A., Dáithí A. Stone, and Myles R. Allen. "Human contribution to the European heatwave of 2003." *Nature,* 432.7017 (2004): 610.).

[30] Abatzoglou, John T., and A. Park Williams. "Impact of anthropogenic climate change on wildfire across western US forests." *Proceedings of the National Academy of Sciences,* 113.42 (2016): 11770-11775.

[31] This is a direct consequence of the Clausius-Clapeyron equation relating saturation vapor pressure to temperature. Basic physics dictates that the the saturation vapor pressure increases 7% per°C of warming.

intense downpours. Hurricane Harvey poured rain on Houston that would not have been so heavy without climate change[32]. Scientists are confident that such downpours will become more frequent and intense in the future. But at the same time, warmer air evaporates more water from the surface of the planet, and evidence shows that climate change is likely contributing to droughts. We believe that drought risk in the Central and Great Plains - America's breadbasket - will reach levels more severe than any time in the last millennium[33].

What does the future hold? There is much scientists still have to learn about how our planet responds to rapid change. **But the greatest uncertainty in climate science is what *we* will do**. If human-caused emissions of greenhouse gases continue to increase, we can expect warming of 2.5 to 10 degrees Fahrenheit by the end of the century. Even at the low end of this range, we are headed for potentially irrevocable damage to vulnerable peoples and systems. We will see more droughts, floods, and heat waves, hurricanes will become more intense, and sea levels will rise. Climate change will produce increasing adversity and destabilize societies, potentially resulting in mass migration, food and water insecurity, and biodiversity loss. The US military views climate change as a "threat multiplier" that poses a threat to US interests and security[34].

The science is clear: there is no status quo. Change is inevitable. But the fact that we understand what's causing climate change gives us power. **It means we can choose the change we experience.** We can choose to continue on our current path, which the science indicates will lead to disruptive climate changes and extreme events worse even than the ones we are now experiencing. These will be at best economically devastating for many, and at worst catastrophic for all. Or we can choose to take charge, which means taking urgent action to rapidly reduce emissions. As a scientist, I can only tell you what the climate consequences of those choices might be. As a human being and a citizen, I hope that we will seize the opportunity to create the future we want.

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[32] Every year, the Bulletin of the American Meteorological Society publishes a special issue on "Explaining Extreme Events from a Climate Perspective". The most recent issue is at https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/.

[33] For an visualization of the science presented in Cook, Benjamin I., Toby R. Ault, and Jason E. Smerdon. "Unprecedented 21st century drought risk in the American Southwest and Central Plains." *Science Advances* 1.1 (2015): e1400082., see https://svs.gsfc.nasa.gov/11753.

[34] https://www.acq.osd.mil/eie/downloads/CCARprint_wForward_e.pdf