Spring 2020

ENGINEERING AND CLIMATE CHANGE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7,000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/Publications/Bridge.aspx.*

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The National Academies of
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The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

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President's Perspective

Climate Change – A Call to Arms for the NAE

John L. Anderson,
President, NAE

> "He that lives upon hope will die fasting."
> – Benjamin Franklin

As I visited different regions of the country to hold town hall meetings with NAE members over the past six months, I heard a recurring message: The NAE must be more involved and proactive in addressing the impact of the Earth's changing climate, which is occurring on a human rather than geologic time scale. Members argued that engineers should address both mitigation of and adaptation to the changing climate, and work with scientists who are focusing on causes and predictions.

The fact that the global climate is changing in response to human causes, especially emissions of greenhouse gases, is undeniable based on the scientific evidence (NAS 2014). The important questions are (1) What are the most promising technical routes to mitigation of the changes? and (2) How can society adapt to the results of climate change?

This issue of *The Bridge* presents timely articles relevant to these questions, and joins a series on related topics.[1] Moreover, the National Academies are actively working to advance understanding of climate science and its intersection with many areas of science, engineering, and medicine and providing guidance on options for limiting the magnitude of climate change and adapting to its impacts.[2] We are also enhancing accessibility to our extensive body of work, for use by decision makers and the public to inform their decisions.

Climate change is an example of unintended consequences of technology. Carbon-based fuels drove the Industrial Revolution, enabled food production to support global population growth, and in many ways improved health and quality of life. But the effect of greenhouse gases, primarily carbon dioxide and methane, on the atmosphere was not anticipated. This example should be emblazoned in our memory to ensure that we consider potential negative consequences of new technologies and how to avoid or minimize them.

The challenge of addressing climate change should involve not only global-scale efforts, such as geoengineering, but also local experiments. A beautiful example of the latter is the carbon-free farm described by Jay Schmuecker (2019). Its energy needs are met solely by solar energy, which drives electrolysis cells to produce hydrogen for fuel and chemical feedstock, and uses the Haber-Bosch process to produce ammonia from nitrogen and hydrogen for use as fertilizer and fuel. As the author admits, scale-up of the carbon-free farm is problematic, but at small scale it shows that a zero-carbon emission system is feasible. More such experiments are needed—for example, with renewable energy sources for electrical micro/nano grids (Shahidehpour et al. 2017; World Bank 2019).

The Benjamin Franklin quotation summarizes the situation: hoping for the best is not enough. Similarly, merely understanding the causes of climate change is not enough. Individuals, governments, industries, and universities must act. Effectively mitigating and adapting to climate change also requires attention to social and political dynamics.

The NAE is in a position to lead the way on technical strategies, and it is our duty to do so.

John

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[1] *Bridge* issues on engineering for disaster resilience (summer 2019), infrastructure upgrades (summer 2018), and energy and the environment (summer 2015)

[2] Climate at the National Academies, https://sites.nationalacademies.org/sites/climate/index.htm

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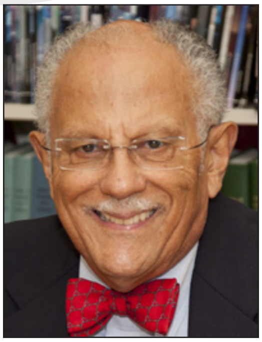
World Bank. 2019. Mini grids have potential to bring electricity to half a billion people, according to new World Bank study. Press release, Jun 25. Washington.

Follow-up on My Inaugural Column

I am very pleased by the number of responses to my column in the winter 2019 issue, in which I considered a concise definition of engineering. NAE members and other readers weighed in with thoughtful and in some cases novel ideas as well as competing arguments for specific words to be included (e.g., design, create, systems, processes,…). As I expected, the question defies an easy answer and will continue to generate exploration. No definition is uniquely correct, but developing one is a good process for our profession. The most important thing is for us to think about what engineering is in general terms so that we can readily offer a useful, accessible explanation in any situation.

Editors' Note

Engineering and Geoengineering Approaches to Climate Change


Warren M. Washington


Antonio J. Busalacchi


Cameron H. Fletcher

Warren Washington (NAE) retired as a senior scientist at the National Center for Atmospheric Research (NCAR). Antonio Busalacchi (NAE) is president of the University Corporation for Atmospheric Research (UCAR). Cameron Fletcher is managing editor of *The Bridge*.

Research on and responses to climate change involve observations, numerical prediction models, adaptation, and mitigation strategies. The field of engineering is involved in all of these endeavors.

Impacts to the Earth system caused by a warming planet—for example, changes to permafrost, local and global water cycles, and sea level rise—require careful monitoring as well as adaptation and mitigation solutions. These may not solve the climate change problem but can support efforts to cope with the changes and impacts, reduce fossil fuel energy usage, decrease or slow increases in greenhouse gas concentrations in the Earth's atmosphere, or even change the Earth's energy balance by introducing upper atmospheric aerosols that mimic the cooling effect of large volcanic eruptions. The latter is a type of geoengineering, a term that refers to deliberate large-scale intervention in the Earth's natural systems to mitigate climate change.

The position of the National Academies of Sciences, Engineering, and Medicine[1] based on their consensus reports is that:

> **Climate change is happening today.** Scientists have known for some time, from multiple lines of evidence, that humans are changing Earth's climate, primarily through greenhouse gas emissions.
>
> **The evidence is clear and compelling.** Earth's atmosphere and oceans are warming, the magnitude and frequency of extreme climate and weather events are increasing, and sea level is rising along our coasts.
>
> **Climate change is increasingly affecting people's lives.** It is having significant effects on infrastructure, agriculture, fisheries, public health, and the ecosystems that support society. It is also changing the environment in ways that affect the distribution, diversity, and long-term survival of species of plants, animals, and other forms of life on Earth.
>
> **Decision makers are taking climate into consideration in a variety of contexts**—such as federal energy policies and standards, state infrastructure investments, community adaptation plans, which crops to plant, public health strategies, approaches to ecosystem management, sustainable business practices and procedures, national security policy and infrastructure, and personal financial investments and education.

The seven articles in this issue cannot cover all engineering-related aspects of climate change, but they highlight several areas of concern.

In the first article, **Claire L. Parkinson** briefly reviews the Earth's climate history over the past 2 million years

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[1] Posted at the site for Climate at the National Academies, https://sites.nationalacademies.org/sites/climate/index.htm.

before sketching the evolution of climate change recognition and understanding since the 19th century. She then describes information sources such as ice cores, in situ and satellite measurements, and the critical role of engineering in monitoring and research on climate change.

Next, William E. Schnabel, Douglas J. Goering, and Aaron D. Dotson compellingly explain the challenges of infrastructure built at high latitudes on frozen ground. Arctic infrastructure built on permafrost is particularly vulnerable to a warming climate, and the authors consider engineering challenges and mitigation techniques for, among others, unheated structures and water and wastewater services.

Dennis P. Lettenmaier and **Jay R. Lund** explore the impacts of climate change on California's water resources. The state's water system was designed and evolved from the late 1800 to 1970s with an assumed stationary precipitation pattern, but climate change is introducing nonstationarity to rainfall patterns. The authors suggest a portfolio of management actions that take into account current and future climate effects to accommodate water users, system managers, and regulators.

Soroosh Sorooshian and his coauthors discuss the intersection of hydrology and population growth, especially expanding urban growth, and relate current and future flooding to hydrologic extremes. They are careful to elucidate the challenges and shortcomings of modeling, even when based on regional and global recorded observations of precipitation, to predict trends.

Jennifer Wilcox quotes from Shel Silverstein's poem "The Giving Tree" to draw apt comparisons with the "the giving Earth." Options for combating rising atmospheric CO_2 concentrations and their harmful effects may include negative emissions technologies, direct air capture, and carbon capture and storage. She also considers market and workforce implications.

Jochen Hinkel and Robert J. Nicholls address projected climate change effects on sea level rise and examine adaptation responses for different circumstances such as subsidence associated with development, coastal erosion, and degradation of ecosystems. Besides engineering needs, the choice of response should consider economic factors, stakeholder risk tolerance, and differences in impact for populated versus rural, wealthy versus poorer areas.

Alan Robock considers possible benefits and risks of stratospheric solar radiation management for climate intervention (often referred to as geoengineering). The author is careful not to recommend this method because of possible adverse side effects and its cost to implement. Many scientists and engineers call for significantly cutting back on the emissions of carbon compounds in the atmosphere.

In the issue's EES Perspective column, Elke Weber provides a sober reminder of the ethical issues related to climate change.

We regard climate change as one of society's major challenges. The articles in this issue illustrate a few of the ways that scientists and engineers are working on novel solutions to it.

Acknowledgments

We are grateful to the following readers who provided evaluative comments and constructive suggestions to help ensure the coverage, accuracy, and substantiation of the articles: Waleed Abdalati, Roger Aines, Mike Anderson, **Ana Barros**, Kevin Bjella, Steve Burges, Francis Chung, Miguel Esteban, Peter Gleick (NAS), Ben Kravitz, Colin McCormick, Simone Tilmes, Roderik van de Wal, and John Zarling.

Finely engineered instruments enable important advances in climate measurements and understanding.

Engineering in the Detection of Climate Change

Claire L. Parkinson

Claire Parkinson (NAE/NAS) is climate change senior scientist at NASA Goddard Space Flight Center.

Climate change has occurred throughout the estimated 4.5 billion years of Earth's existence and has been an important factor in the evolution of life on this planet, from its beginning to the extinction of species all along the path of the evolutionary time line. It has affected human societies in major ways, with substantial evidence that it may even have been a major factor in the downfall of entire civilizations (e.g., Diamond 2005; Linden 2006; Mayewski and White 2002). Individuals have probably noticed climate changes since early in human history and responded accordingly, for instance by moving inland as sea level rises. This article presents a small sampling of what has been learned in the past few decades about climate change and the importance of engineering to these advances.

Progression of Climate Change Recognition Methods Since the 19th Century

Knowledge of substantial climate changes over time took a major step forward in the 19th century when Louis Agassiz and others accumulated evidence that large areas of northern Eurasia and North America had at times been overlain by massive ice sheets, during what are now referred to as the Ice Ages (e.g., Agassiz 1837, 1840; Imbrie and Imbrie 1979). This knowledge was obtained largely by observant individuals wandering the landscape, noticing unusual or out-of-place features, recognizing their similarities with visible changes in the regions of then-current glaciers, and putting together coherent narratives of past climate changes. Little or no engineering was involved.

What a difference exists between the lack of engineering used in the initial recognition of past ice ages and the immense amount of engineering required for much of the wealth of climate change information determined since the 19th century! Certainly some important in situ observations can still be made without engineering, such as the number of weeks a year ice occurs on individual lakes, or the dates of first occurrence of springtime blooming of specific flowers in specific locations, or the advance and retreat of mountain glaciers and ice caps. However, these are now the exceptions when considering the quantified information about climate change obtained in the past several decades, a vast amount of which would not have been possible without significant engineering efforts.

It is only relatively recently that the tools have been available to quantify changes in many key climate variables.

It is only relatively recently that the tools have been available to quantify changes in many key climate variables. From the now ubiquitous thermometer, easily held in a hand, to massive drilling equipment for obtaining deep sea cores, all of the tools that have allowed quantification of climate changes beyond those that are simple counts have required engineering.

Assessing Climate over the Past 2 Million Years

The understanding of past climate changes has come quite a ways since the surprising and initially controversial 19th century revelation that northern Europe at some point in the past was covered by ice. It is now recognized that over the past 2 million years the Earth experienced a sequence of ice ages, with ice covering the northern regions of Europe, Asia, and North America, and with corresponding changes in precipitation patterns and vegetation in low, middle, and high latitudes. Earlier still, there were extended periods with far more ice than during the last 2 million years and also extended periods with far less ice than exists today. The further back in time one considers, the greater the uncertainties become, but a coherent picture, approximate as it may be, has emerged of what climate and other changes have occurred through the estimated 4.5 billion years of Earth's existence (e.g., Hazen 2012; Parkinson 2010).

Information about the past has come through many sources, including deep sea cores, ice cores, tree rings, corals, stalagmites, and lake sediments (along with a substantial amount of theory and speculation). Irrespective of the source, engineering has typically played a crucial role, as illustrated here with information obtained from ice cores.

Information from Ice Cores

Deep ice cores drilled vertically through the Antarctic and Greenland ice sheets provide a record of conditions going back tens of thousands to hundreds of thousands of years, in some cases covering the last eight glacial-interglacial cycles. These cores have revealed details of past climate changes such as the following: Southern Hemisphere atmospheric circulation was likely significantly different during the last interglacial, about 130,000 years ago, than today, based on the composition of dust particles in an Antarctic ice core (Aarons et al. 2019); interannual to decadal climate variability in the Antarctic region at the time of the last glacial maximum was almost double the variability in the past 11,700 years (Jones et al. 2018); average global ocean temperature increased about 2.57°C in the first 10,000 years after the peak of the last ice age about 20,000 years ago (Bereiter et al. 2018).

Of relevance to current concerns about increasing greenhouse gases in today's atmosphere, deep ice core records have revealed that (i) changes in the greenhouse gas carbon dioxide (CO_2) have been highly correlated with temperature changes over the past 800,000 years, as atmospheric CO_2 and temperature rose and fell together through several ice age/interglacial cycles (Luthi et al. 2008; Petit et al. 1999; Siegenthaler et al. 2005); and (ii) the greenhouse gases methane and nitrous oxide are similarly strongly correlated with temperature (e.g., Schilt et al. 2010; Spahni et al. 2005). Furthermore, they have revealed that climate can change overwhelmingly faster than had been imagined prior to the collection of ice core records (e.g., Mayewski and White 2002). In the words of Penn State geoscientist Richard Alley (2000, p. 111), regarding a major climate change in Greenland near the end of the Younger Dryas cold period about 11,500 years ago: “I cannot insist that the climate changed in one year, but it certainly looks that way.”

Shallower ice cores from around the world have also revealed considerable climate change information. For examples: Analyses of an ice core from the Siberian Altai Mountains reveal that the modern Altai glaciers were formed during the Younger Dryas and provide a record of air temperature fluctuations in the Altai region since then (Aizen et al. 2016); ice cores from the Peruvian Andes include evidence of the Younger Dryas in the tropics and warming of perhaps 8–12°C since the last glacial stage (Thompson et al. 1995); an ice core from the Swiss-Italian Alps provides a record of mineral dust that suggests which periods in the past 800 years likely had drier winters in North Africa and increased spring/summer precipitation in west-central Europe (Thevenon et al. 2009); and ice cores from the Tibetan Plateau have revealed that this plateau has become warmer and wetter since the mid-19th century (Thompson et al. 2018).

Arriving at climate change conclusions from ice core records requires significant interpretation and analysis by scientists. This includes establishing a correct timeline through the depth of the core and making appropriate conversions from the information directly calculated from the ice, such as the ratio of oxygen isotopes, to the information desired, such as past temperatures. The latter conversions are neither trivial nor uniform across all sites, requiring considerable scientific insight and expertise (e.g., Jouzel 2013; Thompson et al. 2000).

The Role of Engineering

In addition to the considerable science involved in determining past climate conditions, there is a need for considerable engineering. None of the information revealed about past climates through ice cores comes without engineering, as engineering is essential for constructing the drill itself.

A basic ice core drill consists of a metal pipe with teeth cut into the end that leads into the ice. The pipe is spun and forced downward. For deep ice cores, the core must be brought up in numerous sections, necessitating a means of preventing the ice surrounding the hole from filling the hole before the full core has been collected. Other complications include how to handle the ice chips that form as the drilling proceeds. Solutions vary, but the case of the ice core from the Greenland Ice Sheet Project 2 (GISP2) provides an informative example (figure 1).

The GISP2 ice core was drilled to bedrock in central Greenland, obtaining a core of 3.05 kilometers (1.90 miles), brought up sequentially in sections up to 5.5 meters in length using a drill approximately 18 meters long, raised and lowered on a 3.7 km Kevlar cable (Mayewski and White 2002). Coring began in 1989 and finished in mid-1993. To prevent the ice from filling the hole during this extended period of drilling, the hole was filled with liquid butyl acetate, chosen for its environmental friendliness, nontoxic nature, and sufficiently low viscosity for the drill to drop rapidly through it; the ice chips were pumped up along the outside of the drill barrel to a holding chamber (Alley 2000).

> *Climate can change overwhelmingly faster than had been imagined prior to the collection of ice core records.*

Engineering needs continue far beyond the collection of the ice core:

- Fine-tuned engineering is needed to cut the ice into slices for analysis and to release the ancient air trapped in bubbles in the ice without contaminating it with modern air.
- Electrodes are used to measure electric conductivity and obtain both a measure of the acidity of the ice and a record of volcanic eruptions (Alley 2000).
- Accelerator mass spectrometers are used to determine carbon isotope ratios and in turn to help date the ice cores (Jenk et al. 2007).
- Mass spectrometers are also used to determine isotope ratios used in the estimation of past temperature changes (Aizen et al. 2016; Sigl et al. 2009), and inductively coupled mass spectrometry is used for trace element analysis (Beaudon et al. 2017).
- Scanning electron microscopes, transmission electron microscopes, and energy-dispersive X-ray

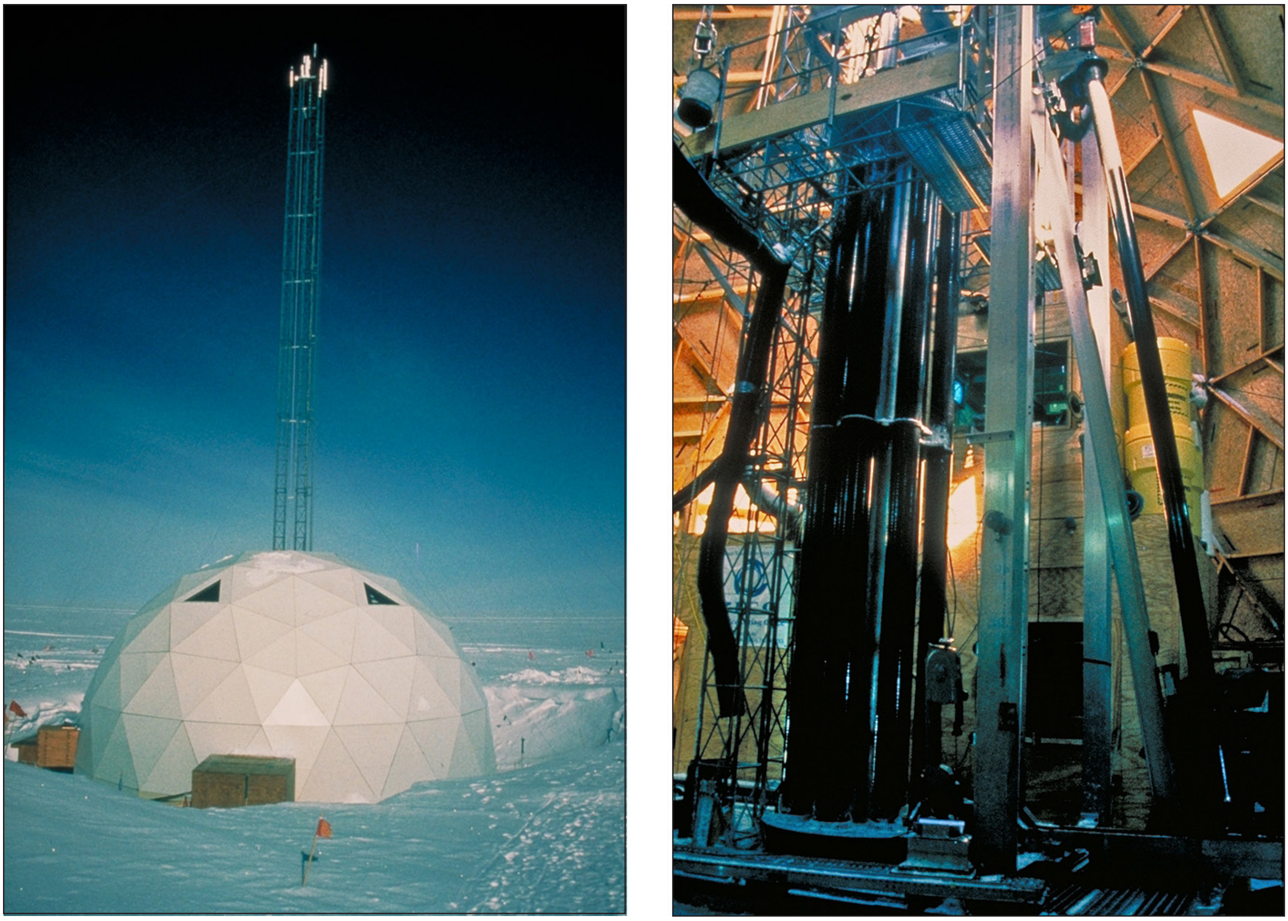

FIGURE 1 The Greenland Ice Sheet Project 2 (GISP2) 32.5 m–diameter drill dome and 37 m tower (*left*), and a view of the GISP2 drill from inside the drill dome (*right*). The dome is connected to the ice core processing facilities via trenches and shafts, and a 3.7 km Kevlar cable is used to lower the drill into the borehole. The two photographs give a sense of the scale of the engineering effort needed for deep ice core drilling. Photos by Mark Twickler/University of New Hampshire.

spectrometers are all used in analysis of the ice core particulate matter (Ellis et al. 2015).

These highlight just a few of the many carefully engineered instruments used in the analysis of ice core records (e.g., Thevenon et al. 2009).

Monitoring Recent Climate

Once the measurement tools—all engineered in one way or another—are available, changes in climate variables can be monitored as they happen. Among the variables most important for climate change that are now being monitored at individual locations on a routine basis are atmospheric temperature and atmospheric CO_2. Some atmospheric temperature measurements exist for the 18th century, but attempts at global temperature records from in situ measurements rarely start earlier than the second half of the 19th century. These records reveal an uneven but also unmistakable warming since that time (Hansen et al. 2010; Jones et al. 1999; Lenssen et al. 2019).

In Situ Measurements

The most famous CO_2 record is the multidecadal Mauna Loa record initiated by Charles David Keeling in 1958, when he began CO_2 measurements at a new US Weather Bureau meteorological observatory on the mountain of Mauna Loa in Hawaii. This record shows a prominent annual cycle, but also a consistent increase in CO_2 year after year, in marked contrast to the uneven temperature record (Keeling 1998, 2008). The CO_2 increase is largely attributed to human activities, particularly combustion of fossil fuels, production of cement, and deforestation.

Keeling's initial Mauna Loa measurements were made with a commercially available continuous infrared gas analyzer composed of a thermostated cell, an optical system, and an electronic amplifier. The analyzer was augmented by a gas handling system, calibrated reference gases, and an electric power supply; further engineered improvements came later (Keeling 1998).

In situ CO_2 measurements are now made at numerous locations, and in situ temperature measurements are made at vastly more locations, with buoys and automated measuring devices significantly improving the spatial coverage over what it had been prior to the second half of the 20th century, before which measurement sites were predominantly in populated land areas. Still, the spatial coverage of in situ measurements remains very incomplete and uneven.

Satellite Measurements

The relative newness of the technology tremendously limits the length of satellite records, but satellites allow data collection for the entire Earth surface and for the full depth of the atmosphere, and they make measurements as easily for remote locations as for populous ones. In the case of CO_2 measurements, they show the two major features of the Mauna Loa record—the annual cycle and the rise in CO_2 over time—on a near-global basis rather than just at selected locations (see animation at https://svs.gsfc.nasa.gov/4533).

Some satellite records are now long enough to indicate important information about climate change. For instance, they show cooling in the stratosphere (in the upper atmosphere), with prominent warm peaks following the eruptions of El Chichon in 1982 and Mount Pinatubo in 1991 (figure 2a; also, Maycock et al. 2018), and warming in the troposphere (the lower atmosphere), with prominent peaks highlighting the strong El Niños in 1998 and 2016 (figure 2b; also, Mears and Wentz 2017). They show increases in annual snowmelt duration in high northern latitudes (Kim et al. 2015), decreases in the masses of both the Greenland ice sheet (figure 2c; also, Bevis et al. 2019) and Antarctic ice sheet (figure 2d; also, Shepherd et al. 2018; Velicogna et al. 2014), and a rise in sea level (figure 2e; also, Nerem et al. 2018) due to both the input of water into the oceans through the reduction of land-based ice and thermal expansion of the warming waters. Each of these particular changes, qualitatively, is in line with expectations based on increases in greenhouse gases.

Satellites also provide a decades-long record (since the 1970s) of both Arctic sea ice, showing a prominent downward trend overriding considerable interannual

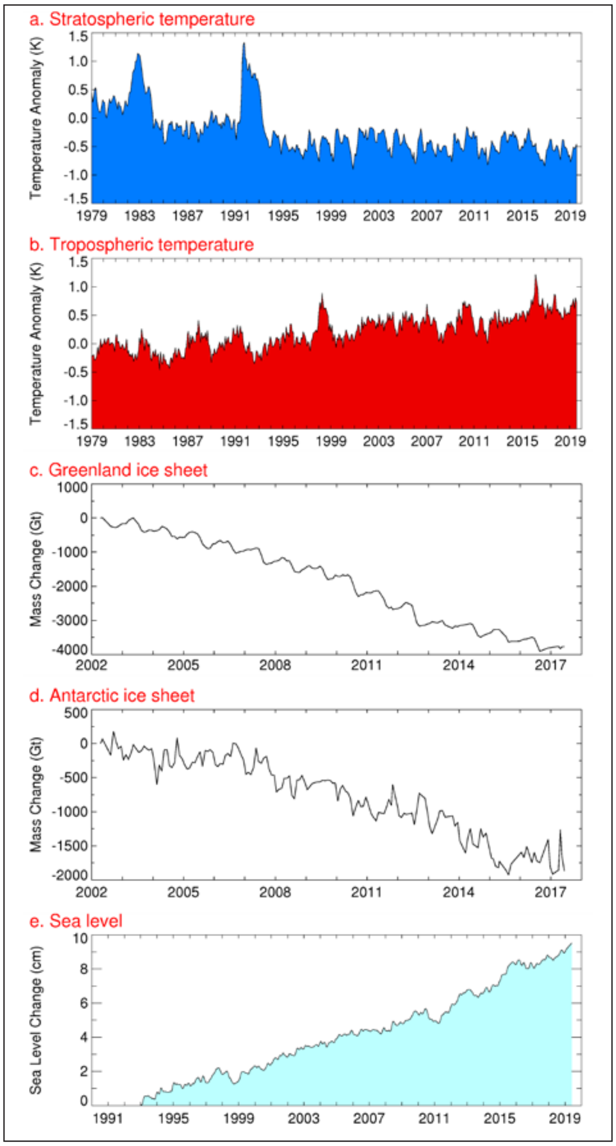

FIGURE 2 Satellite-derived time series of a sampling of key climate variables: (**a**) Near-global (82.5°S–82.5°N) monthly temperature anomalies in the lower stratosphere, Jan 1979–Jul 2019, from satellite microwave sounders (data obtained from www.remss.com; see Mears and Wentz 2009); (**b**) Near-global (70.0°S–82.5°N) monthly temperature anomalies in the lower troposphere, Jan 1979–Jul 2019, from satellite microwave sounders (data obtained from www.remss.com; see Mears and Wentz 2017); (**c**) Greenland ice sheet mass changes, Apr 2002–Jun 2017, from satellite-based gravity measurements (data obtained from https://climate.nasa.gov; see Wiese et al. 2016); (**d**) Antarctic ice sheet mass changes, Apr 2002–Jun 2017, from satellite-based gravity measurements (data obtained from https://climate.nasa.gov; see Wiese et al. 2016); (**e**) Global sea level change, Jan 1993–May 2019, from satellite radar altimetry (data obtained from https://climate.nasa.gov/vital-signs/sea-level; see GSFC 2017). Year labels on the x-axis are centered on the tick marks at the start of the year. Figure generated by Nick DiGirolamo/SSAI in collaboration with the author.

FIGURE 3 Launch of NASA's Aqua satellite, May 4, 2002, carrying six Earth-observing instruments from the United States, Japan, and Brazil. Satellite-based instruments must be engineered not only to make the desired measurements but also to withstand the vibration, noise, heat, and acceleration of a satellite launch. Photo by Bill Ingalls/NASA.

variability (e.g., Meier et al. 2014; Parkinson and DiGirolamo 2016), and Antarctic sea ice, showing an overall upward trend through 2014 followed by a rapid decrease (Parkinson 2019). The decreasing Arctic sea ice coverage was expected, in light of Arctic warming, and fits well in a coherent pattern of changes in the Arctic, many also recorded in satellite observations (e.g., Boisvert and Stroeve 2015; Jeffries et al. 2013; Walsh 2013). The sea ice changes in the Antarctic are more puzzling, and scientists have sought explanations both for the sea ice expansion from the late 1970s through 2014 (e.g., Meehl et al. 2016; Stammerjohn et al. 2008; Turner et al. 2009) and for the rapidity of the sea ice retreat since then (e.g., Meehl et al. 2019; Schlosser et al. 2018; Stuecker et al. 2017), with neither so far having a consensus explanation.

The Role of Engineering in Satellite Measurements

Engineering is required to build the satellites and the Earth-observing instruments, to launch the satellites into space, to maneuver the satellites into and retain them in their desired orbits, to transmit the data from the satellites to the users, and to analyze the data with the help of computers. The Earth-observing instruments need to be finely tuned to make the measurements and to continue making them for years, with limited possibility for repairs or upgrades, and constructed to withstand the considerable rigors of a launch (figure 3) and the harsh environment of outer space, thermal and otherwise (e.g., Hengeveld et al. 2010; Wise 1986).

By now, a large variety of satellite instruments have been engineered to obtain data about the Earth's climate, including passive instruments measuring radiation from each of the wavelength regions of the electromagnetic spectrum most important for Earth observations—ultraviolet, visible, infrared, and microwave—and active instruments sending radar and laser beams downward and measuring the timing and strength of the returned signal. Passive instruments that measure visible radiation produce images showing the Earth and its features as they might be seen from above with human eyes, while instruments that measure ultraviolet, infrared, and microwave data make it possible to monitor and quantify changes in variables that cannot be seen directly with the human eye (as well as those that can), among them gaseous constituents of the atmosphere (each of which presents its own unique radiative signature) and temperatures of land, ocean, and ice surfaces. A particular strength of active instruments is the information they provide on surface topography, relevant, for instance, to the thinning and thickening of ice sheets.

Among the major climate measurements enabled by finely engineered Earth-observing satellite instruments are

- atmospheric temperatures from infrared (e.g., Tian et al. 2019) and microwave (e.g., Maycock et al. 2018; Mears and Wentz 2017) data,

- sea surface temperatures from infrared data and microwave data (e.g., Minnett et al. 2019),
- surface temperatures from infrared data (e.g., Susskind et al. 2019),
- ozone from ultraviolet and visible data (e.g., Levelt et al. 2018),
- atmospheric carbon dioxide and methane from infrared data (e.g., Chahine et al. 2008 for CO_2; Zou et al. 2019 for methane),
- sea ice coverage from microwave data (e.g., Parkinson 2019),
- snow cover from visible data (e.g., Kunkel et al. 2016),
- sea level from radar altimeters (e.g., Nerem et al. 2018),
- ice sheet topography from laser and radar altimeters (e.g., Zwally et al. 2011), and
- ice sheet mass changes and drought from gravity measurements (e.g., Bevis et al. 2019; Velicogna et al. 2014) and altimetry (e.g., Zwally et al. 2011).

Conclusions

In recent decades, major advances in the recognition and understanding of climate change are due in no small part to the engineering that is vital to the collection and analysis of climate data records. This article focuses largely on ice cores and satellites, although other comparably strong examples could have been highlighted, such as deep-sea coring.

Ice core records yield climate information for specific locations going back many thousands of years, to times when the Earth's climate was quite different from today's, and satellite records provide information about recent changes in numerous climate variables, from all latitudes and longitudes. Both types of records provide a tremendous wealth of information about climate change, based on a combination of engineering to construct the instrumentation and science to analyze and interpret the collected data.

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The pursuit of technological advances should continue as engineers seek to design stable infrastructure on an increasingly unstable landscape.

Permafrost Engineering on Impermanent Frost

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The Arctic is often considered ground zero for climate change because arctic air temperatures are rising at approximately twice the rate compared to the rest of the globe (Meredith et al. 2019). However, the diverse facets of arctic climate change (e.g., sea ice loss, hydrologic changes, permafrost thaw) affect the built environment to a greater extent than one might assume based on warming air temperatures alone. Impacts include erosion of arctic shorelines (Jones et al. 2018), altered river dynamics (Toniolo et al. 2017; Zheng et al. 2019), increased wildfire risk (Hu et al. 2015), and decreased foundational integrity of terrestrial infrastructure (Nelson et al. 2001; Raynolds et al. 2014).

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Climate change in Alaska's Arctic promises many of the same outcomes as it does worldwide, such as community displacement (Marino 2012; Rawlings 2015), ecological disturbances (Tape et al. 2018; Wolken et al. 2011), and profound economic disruption (Melvin et al. 2016). But a key element unique to cold regions is the impact of a warming climate on permafrost.

Arctic Infrastructure and Permafrost

Infrastructure is constructed with permafrost as a bearing base in much of the Arctic, and thawing of those soils can diminish their bearing capacity. Thus, one distinguishing outcome of arctic climate change is that engineers must give more consideration to protecting permafrost beneath built structures. Indeed, the Intergovernmental Panel on Climate Change (IPCC) recently estimated that by 2050, 70 percent of arctic infrastructure will be located in areas considered to be at risk from permafrost thaw and potential ground subsidence (Meredith et al. 2019). This increased risk will likely be felt in Alaska, where much of the infrastructure is located in permafrost areas (figure 1).

Effective design, construction, and maintenance of arctic infrastructure often require protection of permafrost from thawing and erosion. Arctic engineers have learned that lesson the hard way. During construction of the World War II–era Alaska Highway, for instance, engineers were not well prepared for challenges created by ice-rich permafrost, and soon noted that the ostensibly solid structural roadbed provided by permafrost soils can rapidly transform into mire in response to construction-related surface disturbances (figure 2).

Ice-rich permafrost is common to Alaska. On some portions of the Arctic Coastal Plain—the main area of oil production—the upper sections of permafrost can contain up to 90 percent ice by volume (Kanevskiy et al. 2013). Structures in these areas can survive only if the underlying permafrost is protected from thawing. Permafrost temperature also plays an important role in infrastructure stability because the bearing capacity of frozen soil is greatly decreased as permafrost temperatures rise toward the melting point.

Thus, arctic engineering has evolved into a field driven largely by both the desire to protect soil in its frozen state and the need to predict the effects of localized thaw and find engineering solutions for maintaining foundation stability. In a warming Arctic, these objectives are challenged by interrelated processes that inch foundational soils ever closer to a state of thaw.

Conversations regarding permafrost thaw often focus on global or regional processes, but it is the permafrost directly beneath or proximal to the infrastructure footprint that is most relevant to designers. While the permafrost may well thaw completely throughout some regions over the coming decades, it may persist in colder regions, with thaw limited primarily to soils near the ground surface. In either case, regional or localized thaw beneath built infrastructure can pose significant risk to structural integrity.

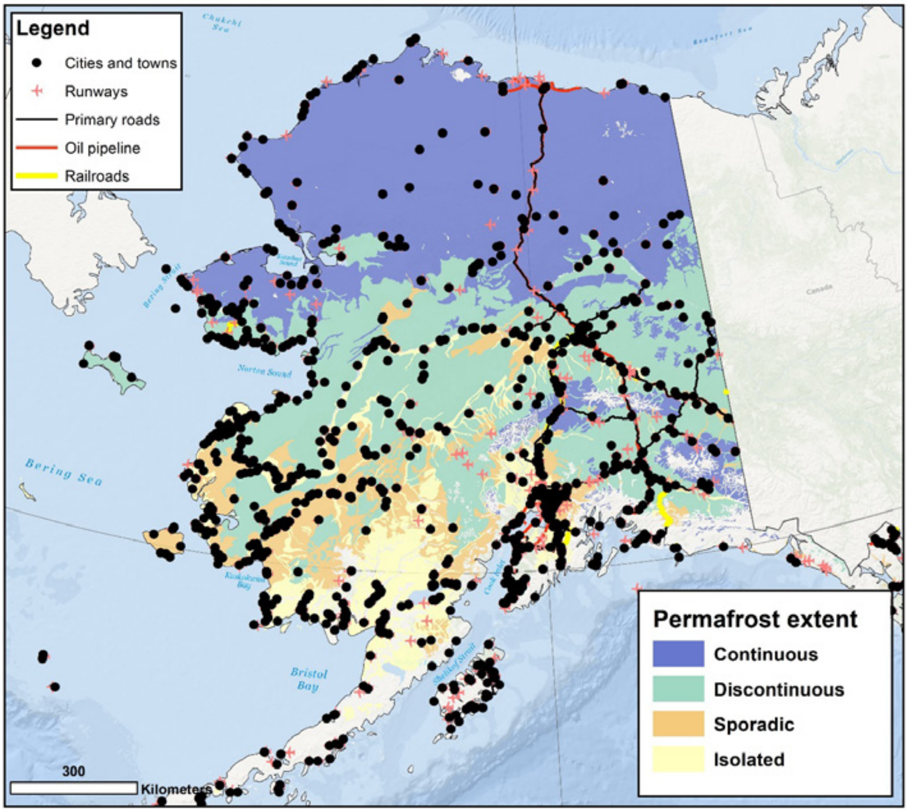

FIGURE 1 Distribution of permafrost and infrastructure in Alaska. Modified from Jorgenson et al. (2008); image modification credit: Ben Jones.

FIGURE 2 Permafrost-related challenges experienced during construction of the Alaska Highway, circa 1942. Surficial disturbances such as removal of overlying vegetation can cause rapid near-surface permafrost thaw, resulting in decreased bearing capacity of the soils. While the mired bulldozer shown here likely represented a mere inconvenience to the construction crew, permafrost thaw under permanent structures such as roads, pipelines, and buildings can cause major structural damage. Photo credit: Alaska State Library, Alaska Highway Construction Photograph Collection, ASL-P193-023.

Permafrost Characteristics

Permafrost (perennially frozen ground) underlies about 25 percent of the Earth's terrestrial surface in the Northern Hemisphere. It is defined as ground (soil or rock with or without ice present) that remains below 0°C for at least 2 consecutive years. As a result of the changing climate, permafrost around the globe is getting warmer; a recent study reported that global average permafrost temperature increased by 0.29±0.12°C between 2007 and 2016 (Biskaborn et al. 2019).

Permafrost regions are characterized in zones according to the extent of permafrost: continuous (frozen soils underlying 90–100 percent of the surface), discontinuous (50–90 percent), sporadic (10–50 percent), and isolated (<10 percent). As illustrated in figure 1, Alaska's permafrost is distributed across all four zones.

Permafrost is insulated from the atmosphere by vegetation and an active surface layer of soil that thaws annually in the summer and refreezes in the winter. In a continuous permafrost zone, the active layer may be as thin as 30–50 cm, whereas in the warmer zones the active layer may be several meters thick. Large ice accumulations do not build up in the active layer, but the upper layers of the permafrost immediately beneath the active layer often contain large amounts of ground ice.

In some cases only relatively thin ice lenses are finely distributed throughout the soil structure; in others large coherent massive-ice bodies of meters or more (such as ice wedges) may occur.[1] Thawing of massive-ice bodies is a particularly acute hazard for structures, as it can create voids in the subsurface leading to subsidence of the surface features (thermokarst). In recent decades, widespread thawing of ice wedges has been observed in many regions across the Arctic, including northern Alaska (Jorgenson et al. 2006; Liljedahl et al. 2016).

As a general rule, permafrost with high ice content is considered thaw-unstable because of its loss of strength upon thaw. It is this loss of soil structural integrity that leads to physical instability of the ground surface and the potential failure of surface infrastructure.

Engineering Challenges and Mitigation Techniques

A significant engineering challenge associated with infrastructure in permafrost areas is that of providing a solid, enduring foundation for structures. Even ice-rich permafrost can provide an adequate foundation for most infrastructure if thawing can be avoided.

Heated Structures

Warm structures such as heated buildings or warm pipelines must be separated from ice-rich permafrost so that their heat does not induce thawing. Often these types of structures are separated from the ground surface by ventilated space and situated on a foundation with pilings that are frozen into the permafrost (figure 3). In the warmer discontinuous permafrost zone, thermal piles are often used (figure 4A). They contain a thermosiphon (gravity-assisted heat pipe) cooling system that enhances winter-time cooling of the piling and surrounding permafrost, helping to ensure that the permafrost remains frozen and enhancing the frozen soil-piling surface (adfreeze) bond strength that provides vertical support for the piling and its load.

An alternative to a pile-supported building is to construct the building on-grade with insulation and a cooling system installed below the building footprint to

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[1] Massive ice refers to large masses of ground ice, including ice wedges, buried ice, and large ice lenses. An ice wedge is a vertical triangular ice mass (pointing down, flat surface on top) formed as a result of the thermal cracking of the ground and often having dimensions of several meters or more; an ice lens is a horizontal ice formation that can heave overlying rock or soil upward.

avoid permafrost thaw (figures 4B,C). In these cases, cooling can be provided by mechanical refrigeration, ventilation ducts, or thermosiphon cooling systems designed to use low winter air temperatures to intercept and dissipate heat leaving the base of the building.

Unheated Structures

Linear structures such as roads, airports, railways, or other unheated structures can sometimes be located in permafrost areas with only minimal consideration of protection of the permafrost from thaw. This is particularly true in the continuous permafrost zone, where unheated structures are less likely to cause enough warming to induce thawing. In these areas it is possible to design linear structures with an embankment height that ensures that the annual summer thaw will not penetrate the permafrost.

In the discontinuous permafrost zone, conditions are generally warmer and more advanced mitigation techniques may be required (figure 4D). The mere placement of roads or rail embankments can cause permafrost thaw simply through surface disturbances that remove native vegetation and warmer surface temperatures, especially in the case of black asphalt roadways.

Snow accumulation along embankments also leads to significant increases in ground temperatures due to the insulating properties of the snow itself. As a result, road maintenance costs are generally higher in warmer areas with discontinu-

FIGURE 3 The Trans Alaska Pipeline System is elevated above the ground surface over approximately half its length to minimize degradation of underlying permafrost. Thermosiphons are incorporated in the pilings to dissipate ground heat. Photo credit: Doug Goering.

FIGURE 4 Mitigation measures for construction on permafrost at various sites in Alaska. **A**: Thermopiles supporting raised construction in Bethel. **B**: Vertical thermosiphons promote passive heat transfer in Kaktovik. **C**: A gravel pad insulates underlying permafrost from fuel tanks in Kaktovik. **D**: Horizontal thermosiphons installed in a road embankment in Fairbanks. Photo credits: A, D: Doug Goering; B, C: Yuri Shur.

ous permafrost compared to the costs in colder continuous permafrost areas.

Water and Wastewater Services

The provision of piped community water and wastewater services has historically been a challenge in permafrost-prone regions, and that challenge is exacerbated in a warming Arctic.

In communities with buried pipes, the surrounding permafrost must be thermally protected from the warm flowing liquid by insulation of the pipes. This challenge can be mitigated by using insulated arctic pipe or heavily insulated utilidors above the ground surface.

> *The challenge of providing piped community water and wastewater services is exacerbated in a warming Arctic.*

Given permafrost-related design considerations and the relatively low number of residences in many arctic communities, buried and/or aboveground piped systems often entail capital costs that make such systems unattainable (USARC 2015). Approximately 20 percent of homes in rural Alaska lack piped water and wastewater services (Thomas et al. 2016), and for communities that do have piped systems, climate change tends to intensify the challenge of maintaining permafrost stability beneath utilities. Arctic communities impacted by permafrost thaw may experience a greater rate of negative health outcomes due to lack of sufficiently available in-home water (Thomas et al. 2016).

Warm Permafrost

Regardless of infrastructure type, the thermal balance between permafrost foundation soils and overlying infrastructure is frequently a delicate one. In the discontinuous permafrost zone, permafrost temperatures are often within 1°C of the ice melting point. Surface disturbances due to construction activities tend to swing that balance toward permafrost thaw. In recent years, that situation has been exacerbated by warmer atmospheric air temperatures, which result in a deepening active layer and thawing of the upper (often ice-rich) layer of permafrost, causing ground surface instability and thermokarsting.

Warmer temperatures also render cooling systems (thermal piles, thermosiphons, or air ducts) less effective by reducing the air freezing index available to chill the permafrost, and they reduce the ability of a given embankment to contain the annual thaw and protect underlying permafrost. For pile foundations, warmer permafrost can be detrimental because of the sensitive adfreeze bond strength, which decreases rapidly as the soil-foundation interface warms.

While some amount of climate warming can be accommodated via more conservative designs, in some cases it may be difficult or impossible to adjust to a wholesale permafrost regime shift (e.g., widespread thaw).

Beneficial Technologies

Engineers have been designing infrastructure in permafrost regions for over 100 years. Successful designs predict and avoid localized permafrost thaw resulting from the construction process, and mitigate thermal imbalances produced by the built infrastructure itself. In a warming Arctic, additional predictive and observational capabilities are required to accommodate the shifting nature of the ambient conditions. Such technologies will be useful for addressing the following questions:

- What landscape-scale changes are anticipated in the vicinity of and over the design life of the infrastructure component?
- What are the permafrost characteristics and thaw stability of the soils across the entire infrastructure footprint?
- What are the fine-scale thermal processes that will likely impact structural stability?

Fortunately, advances in cyberinfrastructure, high-performance computing, and observational and predictive technologies have enhanced engineers' ability to assess the characteristics of land proximal to planned arctic infrastructure. For example, a National Science Foundation–sponsored effort, the Permafrost Discovery Gateway (https://permafrost.arcticdata.io), will provide a widely available browser-based platform for visualizing and exploring big data with a focus on satellite images of arctic regions. The gateway will allow users to interact with historical or predicted geospatial time series to identify changes down to the submeter scale. Such changes include ice wedge degradation, surface water coverage, thaw slumps, and erosion of ocean, river, and lake shorelines.

The Arctic Environmental and Engineering Data and Design Support System (Arctic-EDS; under development) is intended to inform engineering design in arctic regions. Funded by the US Department of Defense Environmental Security Technology Certification Program, Arctic-EDS will develop and deploy online technologies presenting design-relevant environmental data for use in web-based maps, modules, and notebooks. Up-to-date georeferenced data collated by state and federal agencies will be curated for arctic infrastructure design use and combined in a single online hub. Beta tests of Arctic-EDS are expected to commence in summer 2021, and final product release is expected in early 2023.

Recent advances in geophysical techniques have made it possible to more fully characterize soils beneath the footprint of planned infrastructure. While traditional techniques such as drilling will likely remain a key component of geotechnical investigations, geophysical and remote sensing methods can allow engineers to better understand subsurface conditions between the boreholes. For example, electrical resistivity has proven effective for identifying massive subsurface ice bodies as well as characterizing the physical state of interstitial water (Mollaret et al. 2019; Trochim et al. 2016). By employing a geophysical survey over the entire footprint at the outset of a geotechnical investigation, designers can identify optimal locations for the placement of boreholes and make more informed inferences about the characteristics of soils not physically sampled.

Advances in computational capabilities and modeling techniques will allow engineers to better predict thermal processes and the resulting structural impacts associated with new infrastructure built on permafrost soils in a warming climate. Commercial thermal modeling software can be used to help understand the details of heat transfer in arctic soils beneath planned infrastructure. The models generally include specific routines for simulating the complexities of the ground surface energy balance, have phase change routines that are customized for the soil types often found in permafrost regions, and can incorporate cooling systems such as thermosiphons or air ducts in the analysis. They are capable of simulating the progression of permafrost thaw that may occur as a response to either climate change or the placement of warm infrastructure. As such, they provide tools that are becoming a critical component of the design process for infrastructure in a warming arctic.

Conclusion

Engineers managing the effects of climate change in the Arctic face many of the same challenges as engineers worldwide, including challenges associated with rising sea level, erosion, flooding, wildfire, and social displacement. However, the increased risk of structural damages related to warming permafrost is unique to the Arctic and similar cold regions.

Because permafrost thaw can result from a host of disturbances (e.g., construction activities, infrastructure-related thermal inputs, hydrologic changes, wildfires, or increased ambient temperatures), it is often difficult to discern the specific cause of the thaw. What is certain is that ambient permafrost temperatures are rising (Biskaborn et al. 2019), thus increasing permafrost's susceptibility to thaw resulting from any type of disturbance.

> *The increased risk of structural damages related to warming permafrost is unique to the Arctic and similar cold regions.*

Arctic engineers have developed numerous techniques to prevent or mitigate infrastructure damage related to permafrost thaw, most often involving efforts to keep the soils frozen. Passive techniques generally employ mechanisms to restrict heat flux from the infrastructure to the underlying ground; in some cases active measures are employed to facilitate cooling. In all instances, warmer ambient temperatures impose additional challenges to maintain soils in a frozen state.

Infrastructure design in a warming Arctic can be enhanced through improvements in the ability to observe and predict regional and local changes in permafrost properties. Advances in remote sensing, modelling, design support systems, and imaging techniques, and continued development thereof, can aid engineers now and in the future.

In addition to its negative impacts, climate change is promoting accessibility and generating renewed interest in arctic development. Going forward, arctic engineers can expect to not only manage existing infrastructure but also design and maintain new infrastructure associated with anticipated development. The pursuit of technological advances should therefore continue, as engineers seek to design stable infrastructure on an increasingly unstable landscape.

Acknowledgments

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A portfolio approach is essential to California's response to climate change. There is no silver bullet.

How Will Climate Change Affect California's Water Resources?


Dennis P. Lettenmaier


Jay R. Lund

Dennis P. Lettenmaier and Jay R. Lund

Water is the lifeblood of civilization. From the earliest times, civilizations managed water extremes—too much (flooding) or too little (drought). More economically advanced civilizations developed infrastructure and institutions to manage these extremes.

Background

Anglo settlement of North America began in regions with relatively reliable natural water supplies that required modest engineering. Westward migrants in the 1800s encountered more variable climates (particularly precipitation and runoff) than in the eastern part of the country. Recognition of the challenges in "reclaiming" (providing water to) western lands resulted in formation of the US Geological Survey (USGS) in 1879, and a decade later construction of the first modern stream gauge (on the Rio Grande River at Embudo, NM), followed 13 years later by formation of the US Bureau of Reclamation, which was charged with "making the desert bloom."

Figure 1 shows the much greater variability of annual precipitation and, to a lesser extent, annual streamflow in the Western states than in the East.

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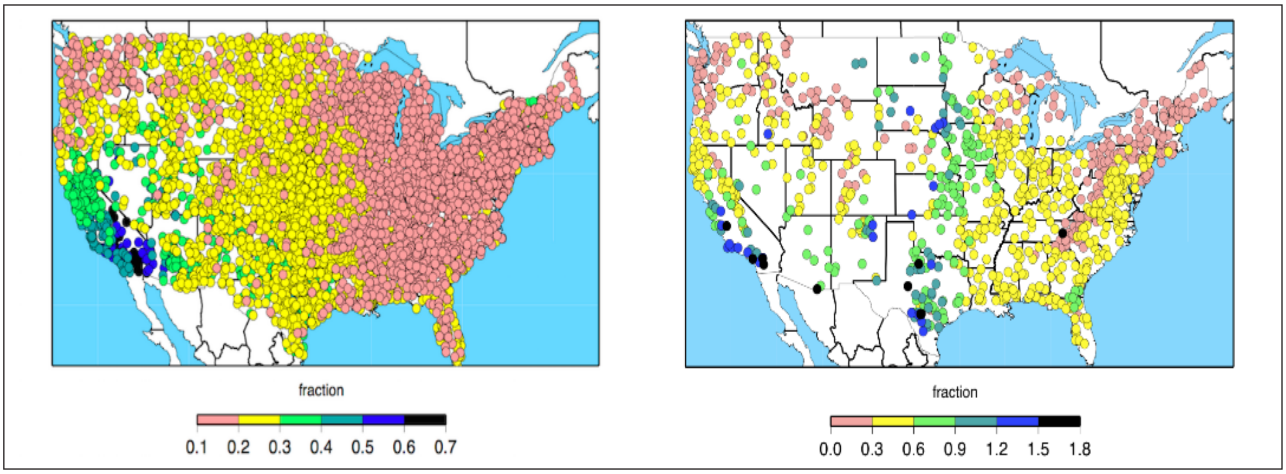

FIGURE 1 Interannual variability (as coefficient of variation) of annual precipitation (*left*) and annual streamflow (*right*) across the conterminous United States, water years (Oct–Sep) 1951–2008. Note maximum in Southern California. Reprinted from Dettinger et al. (2011), Creative Commons CC BY-NC-SA 3.0.

Generally, high streamflow variability follows high precipitation variability, and both increase from east to west. Coefficients of variation (standard deviation divided by the mean) are typically greater for streamflow than for precipitation.

Although managing the variability of water resources, particularly in the Western states, is challenging, water infrastructure has helped support reliable water supplies. Usually, reservoirs and use of groundwater help store water from wetter periods for use in drier periods.

Reservoir planning methods date at least to the work of Rippl (1883), Hazen (1914), and Sudler (1927) and typically use observations (usually of streamflow, for reservoir design) to represent the natural variability that reservoirs and aquifers dampen to provide a reliable supply. Early hydrologists recognized that a historical record (time series) is but one realization of many outcomes that could occur in a future planning period.

When the computer age arrived, hydrologists developed approaches termed *synthetic hydrology* or *streamflow synthesis* to incorporate uncertainties in hydrologic design. These methods are essentially variants of ensemble prediction now widely used in weather forecasting. Variations of these approaches are embedded in the design and operation of reservoir systems to provide reliable water supplies given interseasonal and interannual streamflow variability. Reservoir systems also serve other purposes, including flood protection, hydropower generation, and recreation.

The Changing Climate of the American West

Although the particulars of design and planning methods vary and their sophistication has evolved, essentially all assume statistical stationarity. Stationarity holds that the probability distribution (of, for instance, streamflow) is unchanging in time (both at the margin, say as pertains to streamflows in any given year, and jointly, as pertains to, e.g., covariances of streamflows among years). That assumption does not hold if the probability distributions change over time in ways more complex than, for instance, recurring seasonal variations.

This foundational assumption of stationarity has been challenged as climate change increasingly affects hydrologic processes (Milly et al. 2008). Climate nonstationarity poses new challenges for managing water, especially in the West. When large water works were being planned in the Western states (from the late 1800s to about 1970), a key limitation was short record lengths—few historic climate or hydrologic records exceeded about 30 years.

Now, a half-century past the era of large water infrastructure construction in the United States, much longer records are available, but how best to use them isn't obvious because of nonstationarity. Nor, for that matter, is the question of how best to incorporate nonstationarity in water planning resolved. Most studies of the sensitivity of water resources to climate change have employed scenario analysis (e.g., Wang et al. 2018), which is useful for examining possibilities but less so for prescribing management responses.

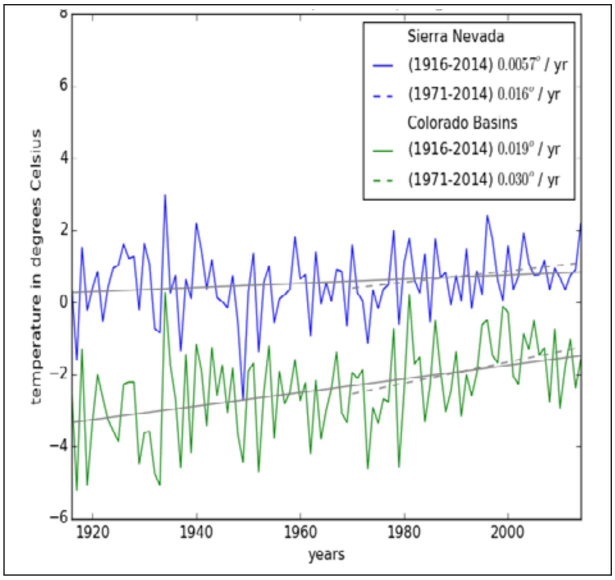

FIGURE 2 1916–2014 trends in winter (Nov–Mar) average temperature over (*top*) the Sierra Nevada (blue lines), defined by average Apr 1 snow water equivalent (SWE) > 50 mm, and (*bottom*) the five-headwater Colorado River basins (green lines) that contribute most of the Colorado's flow at Lees Ferry, per Xiao et al. (2018). Data extended from Hamlet and Lettenmaier (2005) through 2014.

The problem of nonstationary climate for water management is especially prevalent in California, which has a large water infrastructure, mostly designed and constructed decades ago. Well over half of the state's population (and millions of acres of irrigated agricultural lands) depends on a system of dams and aqueducts that moves water long distances. Most notably, water is transported from Northern California and the Colorado River basin for agricultural use in the Central and Imperial Valleys and coastal cities, notwithstanding trends toward increased conservation and greater use of local water supplies.

While figure 1 indicates the high natural variability that water systems in California are intended to manage, the elephant in the room is nonstationarity in the hydrologic system due mostly to warming temperatures. Figure 2 shows winter temperatures in the Sierra Nevada (headwaters for most of California's water supply) and in the most hydrologically productive subbasins of the upper Colorado River basin (over 20 percent of the flow of the Colorado is diverted to California via the All-American Canal near Yuma, AZ). Both river basins have clear warming trends, somewhat higher in the Colorado basins than in the Sierra Nevada. Also, both headwater areas have higher trends (on an annual basis) since about 1970 than over the entire ~100-year period (this partly reflects the relative warmth early in the period, which includes the Dust Bowl years of the 1930s). The larger post-1970 trends (prevalent across the Western states) also may reflect more rapid growth in global greenhouse gas emissions since about the 1970s. In any event, the warming in both headwater regions exceeds that for the United States as a whole, consistent with many studies that show greater warming in the West (and generally less in the Southeast) (Vose et al. 2017).

Less Snow, Earlier Runoff

A major consequence of generally warmer winters in the West has been reductions in snowpack (typically measured by snow water equivalent, SWE, the depth of a snow core multiplied by its density). Figure 3a shows, for about 50 snow courses over the Sierra Nevada where long-term observations have been collected since 1950, trends in April 1 SWE binned by the average December–February temperature. As expected with a warming climate, the largest trends are at the warmest sites (generally lower elevations), with smaller trends at colder, higher elevations.

An interesting aspect of the results for 1950–97 (an anomaly in Mote et al. 2005, from which the data were taken) is positive trends at the highest elevations, where increased precipitation more than compensated for warming. In the longer 1950–2019 dataset, the positive trends no longer appear, which arguably is due to the addition of 22 years of record (1998–2019), a period that has been quite warm (especially the 2007–09 and 2012–16 droughts).

An important hydrologic consequence of warming is less snow (seen in downward trends in figure 3a), which shifts seasonal peak runoff (from snowmelt) to earlier in the year, increasing winter flows and reducing summer flows. Stewart and colleagues (2005) showed such trends across the Western states.

Figure 3b shows trends in spring pulse onset (essentially the beginning of the snowmelt period, as defined by Stewart et al. 2005) for a set of USGS stream gauges in the Sierra Nevada with long records, and minimum upstream effects of dams and diversions. Most sites show spring pulse onset advancing over the last ~60 years by amounts ranging from a few days to 3–4 weeks. This change in streamflow timing effectively reflects a loss of natural seasonal storage, which augments manmade reservoir storage. We discuss below implications of this loss of natural storage for California water management.

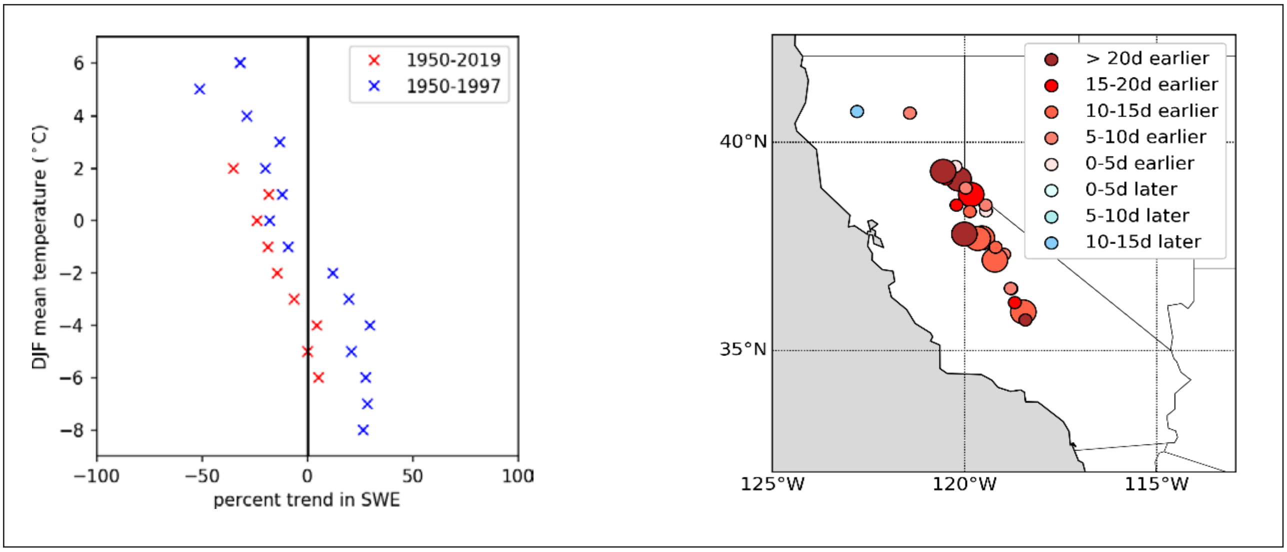

FIGURE 3 *Left:* Trends in Apr 1 snow water equivalent (SWE) for Sierra Nevada stations vs. mean Dec–Feb (DJF) temperature for 1950–97 (replotted from Mote et al. 2005) and the same stations for 1950–2019. *Right:* Trends in spring pulse onset for unregulated streams draining the Sierra Nevada for the period 1948–2019, calculated as described in Stewart et al. (2005); data courtesy of Iris Stewart, Santa Clara University.

Streamflow Sensitivity to Precipitation and Temperature Changes

Although the spring pulse onset in the Colorado basin has advanced similar to Sierra Nevada–heading streams (Stewart et al. 2005), the consequences are small for reservoir system operation (particularly the two immense reservoirs, Lakes Powell and Mead, which are the source of water transfers to California). This is because the combined usable storage in Lakes Powell and Mead is about four times their natural average annual inflow, so the reservoirs greatly reduce the effects of interseason and interannual streamflow variability on water deliveries. Therefore, the Colorado River system is much more sensitive to changes in annual inflow volumes than to their seasonal timing. Annual inflow volumes are sensitive to precipitation and to factors that influence basin evapotranspiration (often linked to temperature, notwithstanding arguments that temperature sensitivities can be somewhat misleading; see, e.g., Milly and Dunne 2011).

Sensitivity of river discharge to precipitation can be quantified by the elasticity of (average annual) streamflow to (average annual) precipitation (where elasticity is defined as in economics: the fractional change in streamflow divided by the fractional change in precipitation). For the Upper Colorado, various elasticity estimates (see Vano et al. 2014) center around about 2.0, implying that a 5 percent reduction (increase) in annual precipitation reduces (increases) annual streamflow by about 10 percent.

In contrast to precipitation elasticities, which are relatively easily estimated from observations (e.g., Sankarasubramanian et al. 2001), direct estimation of temperature sensitivities (which are more convenient than elasticities; e.g., the change in annual average streamflow per degree change in average annual temperature) is more challenging. This is because effects of temperature variations tend to be obscured by larger effects (on streamflow) of interannual precipitation variability.

Seasonal effects also can be important, with substantial differences in the sensitivity of annual streamflows to winter versus summer warming (Das et al. 2011). Nonetheless, overall most recent work suggests temperature sensitivities of Colorado River annual streamflow to warming in the range of 5–10 percent per degree Celsius—notwithstanding that recent coupled model results (Hoerling et al. 2019) suggest somewhat smaller values.

An important point in interpreting likely future changes is that essentially all climate models predict continued warming across the West (particularly in the Colorado River basin), consistent with observed warming over the last century shown in figure 2. Climate models also tend to show drying over the Colorado River basin (Milly et al. 2005), although more recent results

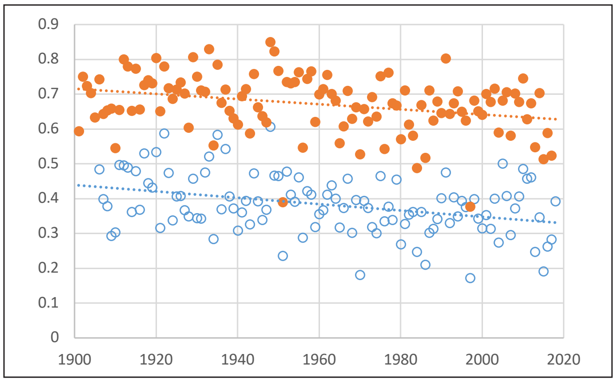

FIGURE 4 Trends in spring (Apr–Jul) proportion of annual runoff for California's Sacramento (open blue circles) and San Joaquin (solid orange circles) Rivers, 1900–2020. Data from California Department of Water Resources.

(e.g., Brekke et al. 2014) are less conclusive and tend to show, for both the Colorado Basin and California, small (albeit slightly negative) changes in precipitation. This suggests that the temperature signal may be the most important driver of future change.

For discussion, a conservative temperature increase estimate of about 2°C (by, say, the end of the century) and precipitation change from zero to a 5 percent decrease implies reduction of the mean annual flow of the Upper Colorado of 10–20 percent—the midpoint of which (15 percent) is comparable to the observed change in Colorado River runoff over the last century (Hoerling et al. 2019; Xiao et al. 2018). The possibility that changes of this magnitude could continue in the Colorado River basin and California (where water infrastructure is challenged by changes in both annual volumes and spring runoff timing) has given rise to considerations of how to strengthen existing water systems. We discuss below some possible adaptive responses.

Water Management Challenges

Changes in climate will bring operational challenges for water management in California. First, rising sea levels (Hinkel and Nicholls 2020) will reduce some coastal aquifer yields (due to sea water intrusion) and threaten the stability of lowlands and salinity control in the Sacramento–San Joaquin Delta. This delta is the major hub for California's interregional water conveyance, and delta-related issues impact the management of flows from contributing river basins.

Second, seasonal shifts in runoff from spring to winter from the loss of snowpack with warmer temperatures (figure 4) will disrupt reservoir operations based on historical reservoir inflow patterns, specifically refilling reservoirs with spring snowmelt after the winter flood season. Changes in both reservoir inflow timing and reservoir operations will challenge both water supply and flood management. Although runoff is shifting from spring to winter (figure 3b; Stewart et al. 2005), the implications of climate warming for flooding are less well understood (Wasko et al. 2019; Willis et al. 2011).

Third, higher temperatures may increase agricultural water demands, although the jury is still out on this effect (the effects of increased plant water use in a warmer climate, shorter growing season, and CO_2 fertilization effects are not completely understood and in any event likely are crop- and site-specific; Cai et al. 2015). A shift toward increased crop water use would challenge reservoir operation (given that roughly 80 percent of California's human water use is agricultural), which would be complicated by other challenges for maintaining cold water and flows for native fishes and other species.

Furthermore, higher temperatures could, without substantial precipitation increases, decrease California's access to Colorado River water, which today supplies about 10 percent of California's water use. Colorado River "surplus" diversions to California effectively ended in the last decade as the Upper Colorado River basin states take more of their allocations under the 1922 Colorado River Compact, even as total river flow has failed to reach total Compact allocation amounts (which were based on anomalously high pre-1922 flows). California historically took more than its Compact allocation when the Upper Basin states took less, which is no longer the case.

Finally, greater interannual variability in precipitation (predicted by many climate models) may increase the severity of droughts, especially when accompanied by warmer temperatures that accelerate spring and summer soil moisture depletions. All these effects will bring new operating challenges and needs for water policy changes.

California's water infrastructure (constructed mostly in the second half of the last century) is massive. However, total reservoir storage capacity (about 50 km^3) is small compared with average annual inflows of about 90 km^3 (the ratio of storage to mean inflow of about 0.44 compares with around 4.0 for the massive Colorado storage system). An additional 20–25 km^3 of water (on average) is stored seasonally as snowpack

(Mao et al. 2015). This means that most reservoir storage is seasonal (intended to move inflows from the high-runoff spring–early summer to the higher-demand, lower-runoff summer). Nonetheless, the largest reservoirs usually have storage capacity sufficient to supply water for one or two years of drought—but not longer droughts like the most recent (2012–16), which was mitigated mostly by groundwater pumping (and some water use reductions in agriculture and cities) (Lund et al. 2018).

Adaptive Responses

Two obvious responses to the additional stress on water operations from a changing climate are demand management and supply management (partly through increases in reservoir storage).

In recent decades, total US withdrawals of water (and likely consumptive use) have declined, with especially large declines in the most recent period for which data are available (2010–15; Dieter et al. 2018). In California declines in surface water withdrawals, especially for municipal use, were amplified by drought in 2012–16.

Additional reservoir storage would be useful in some cases but can only provide modest overall improvements in water reliability (partly because the most economical reservoir sites are already developed). California anticipates spending $2.7 billion to partially fund additional surface and groundwater storage capacity. However, even if all funded reservoirs were built, they would increase surface water storage capacity by only about 10 percent, with a smaller (percentage) effect on the ability of increased storage to provide reliable water deliveries.

Moving drought water storage from larger existing onstream reservoirs to aquifers or offstream reservoirs, combined with increases in some downstream flood flows and wetland capacities for groundwater recharge, along with better use of hydrologic forecasts, are options that can more flexibly, rapidly, and less expensively increase overall system abilities to manage floods and droughts. However, these options are limited by a combination of legal constraints (e.g., who "owns" flood flows directed to groundwater recharge) and (for flood flows) the limited volume of water available for groundwater recharge (Alam et al. 2020). Furthermore, such changes bring costs, impacts to summer reservoir recreation and hydropower, and higher water supply pumping and energy costs—although failure to act will likely have costs as well.

Groundwater as a Supplemental Water Supply

Recent droughts have highlighted the importance of groundwater as a supplemental water supply. The importance of such supplies, especially for agriculture during long droughts, has grown as California's agriculture has shifted to more profitable permanent crops that cannot easily be fallowed in dry years. However, greater reliance on groundwater has increased depletions of aquifers—by some estimates, over 55 km^3 in the recent 2007–09 and 2012–16 droughts alone (Lund et al. 2018; Xiao et al. 2017). (Some estimates show interdrought recovery, others do not; Xiao et al. 2017.)

> *Greater reliance on groundwater, especially for agriculture during long droughts, has increased depletions of aquifers.*

Recent California groundwater legislation (the Sustainable Groundwater Management Act) is intended to stabilize groundwater levels by ending overdraft, which should better accommodate growing seasonal and interannual variability in water availability. This also will require reducing overall irrigated area substantially, with economic harm especially in the southernmost part of the Central Valley. In any event, the often decades-long drawdown-refill periods expected for California's large aquifers and long droughts bring policy and operational challenges for local groundwater management and statewide groundwater regulations—challenges likely to increase as the climate continues to warm (Alam et al. 2019; Dogan et al. 2019).

New Technologies

New technologies may help California's water system adapt to climate change. In addition to increased aquifer recharge and capture of some seasonal floods, options include wastewater treatment and artificial recharge (already used by the Orange County Water District), advanced hydrologic flood forecasting for reservoir operation, and modeling to coordinate operation of multiple reservoirs.

Agronomic changes in crops and use of high-tech irrigation methods—both on the ground (e.g., drip irrigation) and through remote sensing (e.g., to better determine crop water use in real time)—also could help. However, improved crop irrigation efficiency often "saves" little water as it usually reduces aquifer recharge or return flows to streams—water already committed for droughts and instream or other uses.

Management of Ecosystems

One especially challenging area will be mitigation of water-related environmental and ecosystem management effects of climate change. Natural ecosystems are adapted to long historical hydroclimatic regimes, not the comparatively recent changes due to global (and local) human activities.

> *Natural ecosystems are adapted to long historical hydroclimatic regimes, not the comparatively recent changes due to human activities.*

Sustaining ecosystem functions will require defining ecosystem objectives achievable under uncertainty and may lead to expensive actions with many challenges, given the extensive impacts of human activities on virtually all California's ecosystems (Herman et al. 2018). One example is the mandate, under the Endangered Species Act, to restore native salmonid populations in the Sacramento and San Joaquin River systems. Environmental and ecosystem management is likely to be where climate change brings the greatest and most difficult impacts and challenges.

Balancing Management Actions with Climate Effects

California already deals with exceptional hydroclimatic variability (see figure 1). Responses to the challenges of operating the massive water infrastructure have included, among other actions, water conservation and water trading. Climate-related challenges will force changes in the state's water management, many of which are desirable even without climate change (Connell-Buck et al. 2011).

Importance of a Portfolio Approach

In part because of climate-related and other stresses, water management in California is increasingly portfolio-based, an approach that balances the use and operation of a variety of water sources with management options and activities intended to better align the behaviors of water users, system managers, and regulators. Expansion of the portfolio approach must be central in California's response to climate change; there is no silver bullet.

Arguably, the extreme variability of California's historical climate might make the state better prepared for still greater variability as the climate continues to warm, as contrasted with other regions with less variable climates (Madani 2019; Pinter et al. 2019). California water management has changed significantly in the past as it has dealt with nonstationary demands, technologies, and legal issues. Now water managers face nonstationary supplies as well.

Adaptation Strategies

Climate change gives California more incentive to accelerate and hone adaptation strategies, which will likely include the following:

- major changes to reservoir and aquifer operations, to respond to seasonal streamflow shifts, greater interannual variability, and higher water temperatures (Connell-Buck et al. 2011; Dogan et al. 2019);
- additional wastewater reuse and targeted desalination (e.g., of brackish waters) to help some urban areas, as well as continued urban water conservation efforts and more effective use of groundwater supplies by coastal cities;
- reductions in irrigated areas in the Central Valley to meet state requirements to end groundwater overdraft—it is estimated, for example, that, to the roughly 3 km^3/yr Central Valley groundwater overdraft of the recent past, climate change could add about 2 km^3/yr by the year 2100 (Alam et al. 2019);
- water markets to greatly reduce the costs of these transitions; and
- more effective and flexible regulations and environmental management.

Conclusion

If well managed, climate change effects to California's water management systems will not be catastrophic statewide for humans, but they may be catastrophic for many ecosystems and for people in some local areas (e.g., where currently irrigated land is retired). The associated changes and need for adaptation will also bring sizable statewide costs.

The greatest impacts of climate change on water uses in California are likely to be environmental and ecosystem losses, exacerbation of already large agricultural losses to end groundwater overdraft in the southern Central Valley, and an increase in overall costs of water. If state and local water managers adopt effective measures, the state economy seems likely to suffer more from other climate change effects. And the costs of not adapting to change may be much greater.

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Improved models for precipitation projections are needed to support water resource management and protection against floods and droughts.

Predictability of Hydrometeorological Extremes and Climate Impacts on Water Resources in Semiarid Zones: Expectations and Reality

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The following two questions are often asked by practicing professionals and the public:

1. How will climate change affect water availability and precipitation variability and change at regional scales?
2. Can changes in precipitation trends and variability be predicted?

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In this article we consider these questions in the context of observations and modeling to predict water availability and precipitation variability.

Globally, the amount of fresh water on average remains constant, but variability and changing trends at the continental, regional, and local scales are critical factors for planning and management.

Water is needed for domestic consumption, agriculture, industry, and ecosystem services, and as the world's population increases, so does the demand for freshwater supplies. Global population more than doubled from 3.7 billion in 1970 to over 7.5 billion today and it is projected to reach 10 billion by 2050.[1] In the Western United States, which is largely semiarid to arid, the population during 1970–2018 more than doubled, from nearly 34 million to 76 million.[2] And more densely populated and expanding urban developments spreading to flood plains and areas near inland waters such as lakes and rivers increase vulnerability to flooding associated with hydrologic extremes.

> *More densely populated and expanding development in flood plains and near rivers increases vulnerability to flooding associated with hydrologic extremes.*

Focusing on the precipitation component of the hydrologic cycle, we organize the rest of this article along two lines: First, what do historical recorded observations of precipitation reveal? Second, what do predictive models indicate about future trends and patterns of precipitation?

What Do Historical Precipitation Observations Reveal?

Historical observations can be categorized as instrumental observations or proxy and reconstruction records.

Instrumental Observations: Gauges, Radars, and Satellites

Instrumental observations come from three sources: rain gauges, radars, and, more recently, satellites.

Rain gauges are the source of the longest precipitation records—dating back to the late 1800s—and have served as the backbone for most of the information needs of operational and water resource engineering communities as well as hydrologic services around the world. The Global Precipitation Climatology Centre in Germany (operated by the country's national meteorological service, Deutscher Wetterdienst, under the auspices of the World Meteorological Organization), collects and archives rain gauge information provided by member nations, reported as monthly aggregates from some 6,000 gauges.[3] Its collection of global rainfall information started in 1891.[4]

US meteorological observations using rain gauges date from the 1880s. Cleveland Abbe (1888) described the standards for weather (rain) gauges to be used by the US Army Signal Corps, and the 8″ diameter gauge is still in use by many offices of the National Weather Service (NWS) and cooperative weather observers both nationally and internationally.[5] For the United States, an excellent source of information about extreme rainfall events and statistical precipitation frequency for any location/region of the country is the online Hydrometeorological Design Studies Center (HDSC) of the National Oceanic and Atmospheric Administration (NOAA).[6]

Weather radars are an important source of information about precipitation measurement, but they have limitations in mountainous and remote regions. Remotely sensed precipitation will likely become the dominant source of information in the future, although the value of ground-based rainfall measurements from gauges will never diminish.

We focus here on precipitation estimated from satellite observations that yield near-global estimates for continents and oceans, followed by specific illustrations of extreme precipitation and flooding.

Remotely Sensed Precipitation Observations

Although shorter in length than gauge observations, satellite data make it possible to observe and analyze pre-

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[1] World Population Perspective, United Nations Department of Economics and Social Affairs population division (https://population.un.org/wpp)

[2] United States Census Bureau (https://www.census.gov)

[3] The number of rain gauges changes depending on funding, political environment, and other factors.

[4] https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html

[5] https://www.weather.gov/iwx/coop_8inch

[6] https://www.nws.noaa.gov/oh/hdsc/index.html

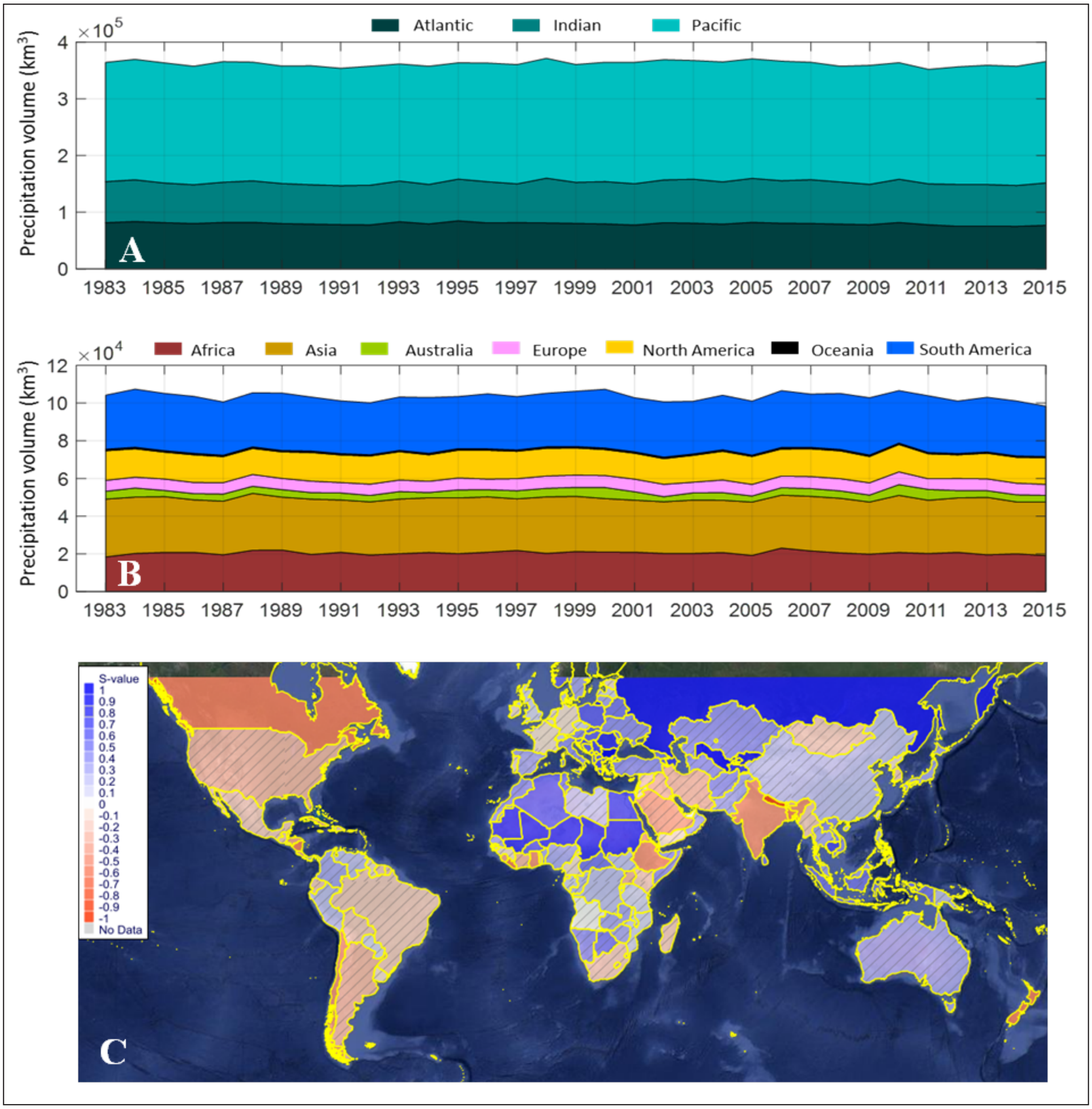

FIGURE 1 Precipitation volumes over (A) oceans and (B) continents, and (C) precipitation volume trends by country, 1983–2015. Based on data from the PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks)–Climate Data Record (CDR dataset (60°N–60°S). © American Meteorological Society. Reprinted with permission from Nguyen et al. (2018).

cipitation patterns at high resolution over oceans and continents down to country and regional scales. NOAA's Climate Data Record (CDR) program has released a relatively high resolution (daily, 0.25°) precipitation database, PERSIANN (Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks)–CDR, covering 60°N–60°S from 1983 to almost the present (the data are updated quarterly).[7] The data make it possible to examine historical patterns and trends at the watershed scale. The same data are also provided through a CHRS website (the algorithm and methods used to produce the data are described in Ashouri et al. 2015).[8]

A recent examination of global precipitation volume and variability over the oceans and continents for a 33-year period (1983–2015; figure 1A-B) shows no

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[7] https://www.ncdc.noaa.gov/cdr/atmospheric/precipitation-persiann-cdr

[8] http://rainsphere.eng.uci.edu/

statistically significant trends (according to the Mann-Kendall test; Nguyen et al. 2018). But the analyses show a different picture when the data are examined at the country level: The warmer colors (reds) in figure 1C indicate a downward trend in precipitation while the cooler colors (blues) indicate an upward trend (solid colors indicate significant changes; changes in hashed, lighter-colored areas are not statistically significant).

In addition to NOAA's CDR program, the Global Precipitation Measurement (GPM) mission is an international satellite program providing observations of rain and snow worldwide every 3 hours. A joint mission of NASA and the Japan Aerospace Exploration Agency (JAXA), the GPM Core Observatory satellite[9] was launched in February 2014. The Geostationary Operational Environmental Satellite Program (GOES),[10] a joint effort of NASA and NOAA, provides critical high resolution (in both time and space) data for precipitation estimation.

Numerous recent record-breaking events highlight the need for strategies to mitigate and adapt to precipitation extremes.

Other countries have similar meteorological satellite programs and international collaborations that make it possible to map meteorological events and estimate precipitation at the global scale.

In all of these efforts, advances in machine learning are playing a crucial role in processing vast amounts of satellite data to improve the capability of artificial intelligence algorithms for precipitation retrieval.

Evidence of Extreme Precipitation and Floods

NOAA's National Centers for Environmental Information (NCEI; formerly the National Climatic Data Center) are the steward and archive center for most precipitation and other meteorological records. Analysis of US rain gauge information over the 1901–2015 period reported in the fourth National Climate Assessment (NCA4) report (Easterling et al. 2017) pinpoints two key findings:

- Annual US precipitation averaged across the country has increased approximately 4 percent, albeit with regional and seasonal variations.
- The intensity of extreme precipitation as indicated by several metrics (e.g., 5-year maximum daily precipitation, 99th percentile daily precipitation) has increased.

The second finding appears to support conclusions about global warming and is illustrated by the following examples of extreme precipitation events across the globe:

- Typhoon Hagibis in October 2019 resulted in a record-breaking amount of rainfall over Japan—more than 3.3 feet in 24 hours. The storm's severe impacts on infrastructure and houses led to the evacuation of 8 million people and about $10 billion in insured losses (Freedman 2019).
- Cyclones Idai and Kenneth in March–April 2019 brought unprecedented rainfall and flooding in Mozambique, Zimbabwe, and Malawi, killing hundreds of people.[11]
- Also in March–April 2019, extreme precipitation in Eastern Iran after a multiyear drought caused extensive loss of life and property (Asanjan et al. 2019).
- In 2014 the United Kingdom experienced its wettest winter in 250 years (Vaughan 2014).
- In the Eastern United States and Atlantic coastal region, Hurricanes Florence and Michael in September and October 2018 resulted in rainfall of 20 to 30 inches, which produced catastrophic flooding (NCEI).
- Hurricane Harvey in 2017 was another record-breaking event, in both peak intensity and geographical extent its maximum precipitation exceeded 60 inches in 24 hours near Houston.[12]
- In January–February 2017, heavy precipitation delivered by a number of back-to-back atmospheric

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[9] www.nasa.gov/mission_pages/GPM/spacecraft/index.html

[10] https://www.nasa.gov/content/goes-overview/index.html

[11] "Mozambique flooding 'worse than thought': UN agency," BBC News, Apr 28, 2019 (https://www.bbc.com/news/world-africa-48087906)

[12] Precipitation Frequency Data Server, HDSC, NOAA (https://hdsc.nws.noaa.gov/hdsc/pfds)

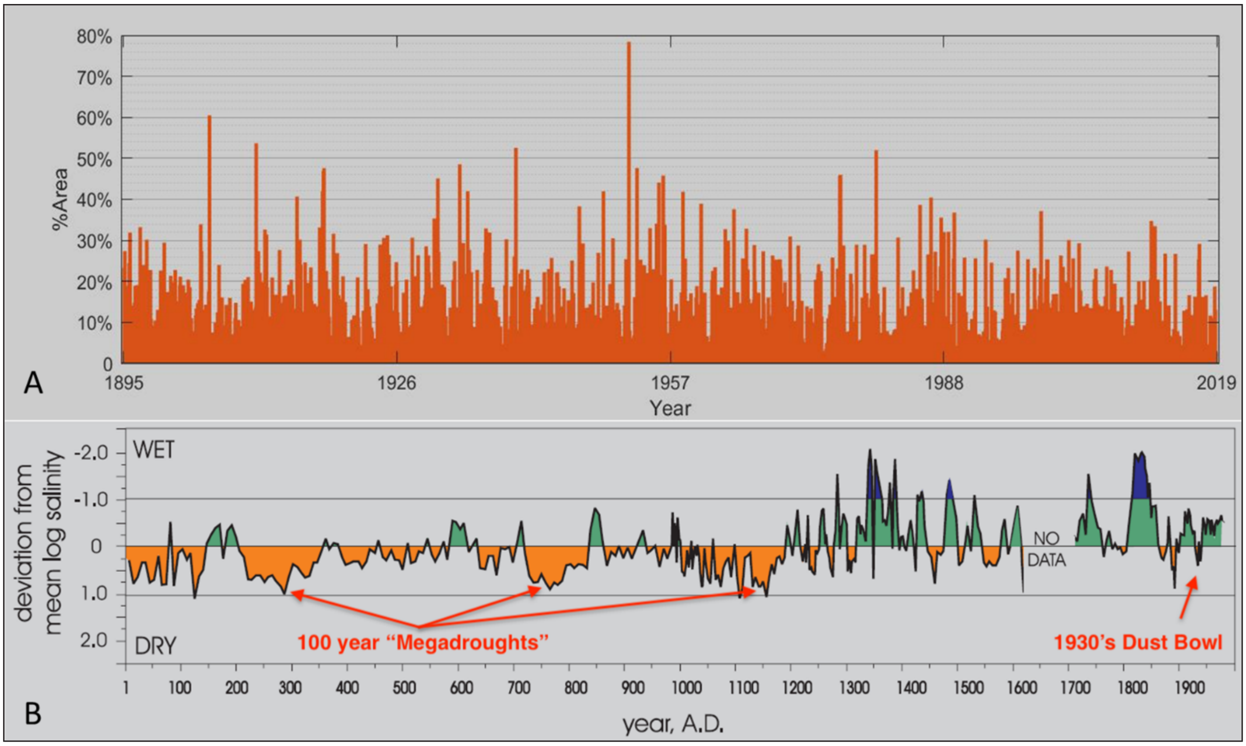

FIGURE 2 (A) US drought observations as a percentage of area, 1895–2019. Source: NCEI, Nov 2019. (B) 2,000-year North Dakota Moon Lake salinity record. © American Meteorological Society. Reprinted with permission from Woodhouse and Overpeck (1998).

rivers (narrow corridors of concentrated moisture in the atmosphere) caused major flooding in Northern California, which experienced its wettest winter in almost a century (NCEI).[13]

- In May 2015 Texas and Oklahoma experienced unprecedented amounts of rainfall that resulted in major flooding (NCEI).

These record-breaking events highlight the need for strategies to mitigate and adapt to such extremes.[14]

Proxy and Reconstruction Records for Droughts

At the other extreme, droughts have brought devastation and hardship to many regions of the world. While drought prediction remains a challenge, historical observations provide insight into their frequency and persistence. With respect to the United States, observations since 1895 have shown pronounced multiyear to multidecadal variability, but no evidence of long-term trends toward more or fewer droughts (figure 2A).[15]

What about drought evidence over much longer historical periods (i.e., thousands of years)? One way to address this question is to use reconstruction time series data from either isotopic studies of dried lake deposits or tree ring proxies of precipitation or river flow.

Figure 2B illustrates nearly 2,000 years (1–1980 AD) of hydroclimate history (Laird et al. 1996; Woodhouse and Overpeck 1998) over the US Great Plains based on analysis of North Dakota's Moon Lake salinity record. The figure shows deviations from mean log salinity values; negative values indicate low salinity and therefore wet conditions, positive values indicate high salinity and dry conditions. This reconstructed proxy history shows a number of megadroughts—lasting 100 years or more—before 1200 AD, and a shift since then to relatively wetter conditions. The Dust Bowl of the mid-1930s pales in comparison to the earlier periods.

Analysis of reconstructed tree ring time series in the Western United States shows similar multidecadal pat-

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[13] https://www.ncei.noaa.gov

[14] Two articles in the summer 2019 issue of *The Bridge* address the importance of climate-resilient infrastructures capable of withstanding floods and hurricanes (Ayyub and Hill 2019; Baecher et al. 2019).

[15] US Drought Monitor (https://droughtmonitor.unl.edu)

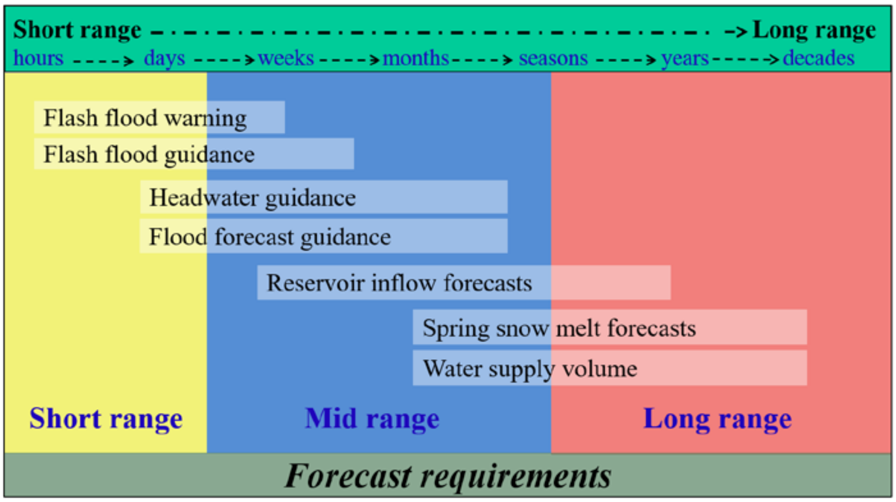

FIGURE 3 Necessary hydrometeorologic predictions.

terns of drought in the same time frame (Cook et al. 2004).

What Do Predictive Models Reveal about Future Trends and Patterns of Precipitation?

We now provide an overview of modeling used for generating forecasts and projections of precipitation, to support prudent water resource planning and decision making. Predictions are categorized as short, medium, and long range (figure 3).

Short-Range Forecasts

These are intended for flashflood and general flood forecasting and require models and observations within hours or days. They depend on close cooperation between the hydrologic modeling and weather forecast communities.

Advanced modeling and geographic information system tools allow for the development of models at very fine resolution (meters). However, for short-range forecasts they face important challenges in meeting parameterization and calibration requirements, and, more importantly, limited availability of high-resolution quantitative precipitation estimates from in situ observations and quantitative precipitation forecasts from numerical weather prediction models (current research and development efforts may improve the reliability of the latter). Such inputs are needed for the National Water Model, a hydrologic modeling framework under development that involves multiple governmental agencies and academic researchers and is intended to "provide high-resolution forecasts of soil moisture, surface runoff, snow water equivalent, and other parameters."[16]

Mid-Range Forecasts

Also known as seasonal forecasts, these cover periods from weeks to 3 months. A number of climate modeling and numerical weather prediction centers globally provide seasonal forecasts for operational purposes such as reservoir management. Official US seasonal forecasts are provided by NOAA's NWS Climate Prediction Center.[17]

Other centers, such as the International Research Institute for Climate and Society (IRI), provide probabilistic seasonal precipitation forecasts based on NOAA's North American Multi-Model Ensemble project. Figure 4 illustrates an example of the IRI's probabilistic seasonal forecast generated in December 2018 for January–March 2019. It shows two areas (circled in red) that experienced extreme precipitation not forecasted by the probabilistic multimodel system. This points to some limitations of the models and should provide an appreciation for the probabilistic nature of these predictions.

Seasonal forecast products are under continuous development and their consideration for any application and decision making should be approached with caution and appreciation of their probabilistic nature.

Long-Range Forecasts

The third category of required hydrometeorological predictions covers periods from years to decades. Such information is critical for many applications, especially water resource system planning, infrastructure design, and operations.

Over the past two decades much emphasis in the literature has been on results from the application of state-of-the-art climate models to examine future spatial and temporal precipitation patterns and trends and to evaluate potential climate change impacts on water resources in various regions of the world. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment

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[16] NOAA Office of Water Prediction, https://water.noaa.gov/about/nwm

[17] https://www.cpc.ncep.noaa.gov

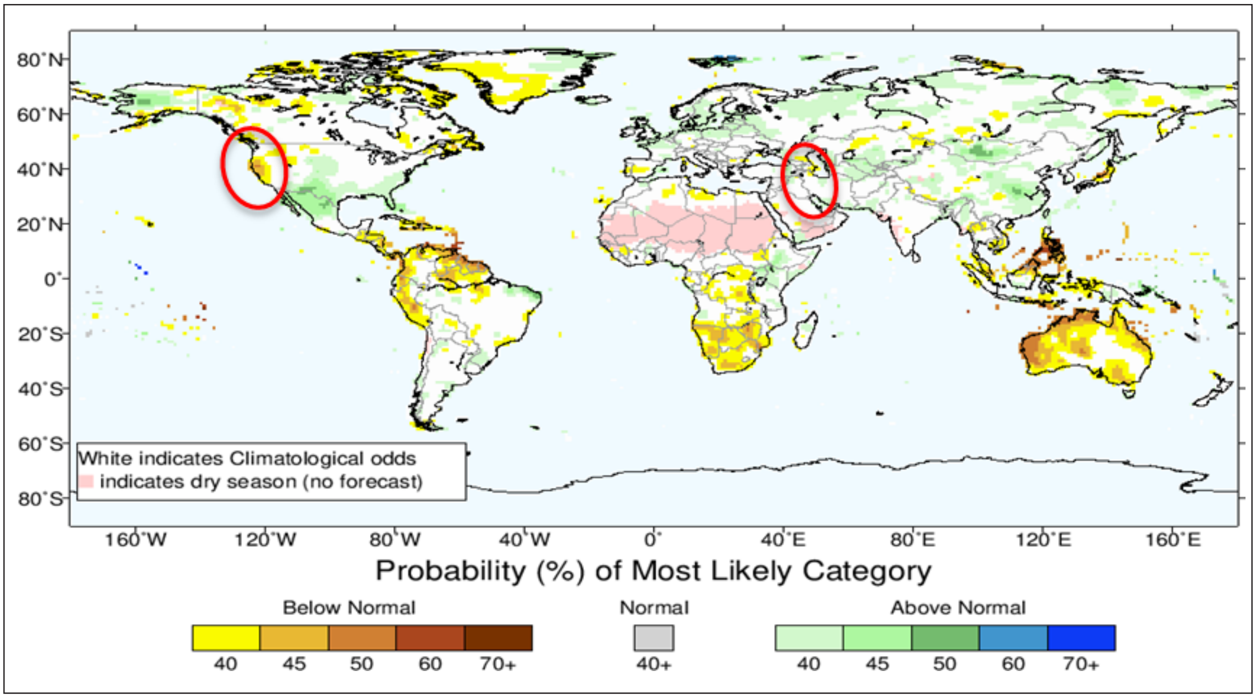

FIGURE 4 International Research Institute for Climate and Society (IRI) multimodel probability forecast for precipitation, January–March 2019, issued December 2018. Two areas (circled in red) experienced extreme precipitation not forecasted by the models. Source: IRI (https://iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts).

Report (AR4; Easterling et al. 2017) indicates trends of decreasing precipitation across most of the subtropics and increasing precipitation in tropical regions.

Examination of changes in precipitation trends in the Southwestern United States has resulted in numerous publications generally agreeing with the IPCC findings, expecting a drier region in this century and raising concerns about the future of southwestern water supplies (e.g., Cayan et al. 2010; Seager et al. 2007). The article by Seager and colleagues (2007) captured much attention although the authors acknowledged (in their abstract) "if these models are correct…," recognizing the limitations of the models' abilities and accuracy. The studies were all based on low-spatial-resolution general circulation model simulations, which do not capture the topography's influence on precipitation in the mountainous regions of the western states.

To investigate further the level of accuracy of the climate model projections, we examined outputs from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2012), an international effort to produce simulations for (i) investigating uncertainties in regional-scale projections (for 2040–70) of climate and (ii) generating future climate scenarios for use in impact research.

NARCCAP ran regional climate models (RCMs) at a spatial resolution of 50 km, driven by atmosphere-ocean general circulation models (AOGCMs) covering the contiguous United States and most of Canada. The AOGCMs were forced with the IPCC Special Report on Emissions Scenarios (SRES) A2, describing a very heterogeneous world for the 21st century (Nakicenovic et al. 2000). Simulations with these models were produced for the period 1971–2000. It is important to note that climate model projections do not attempt to predict the timing of meteorological events such as storms and droughts.

The results show substantial differences in the six pairs of RCM/AOGCM regional climate projections over the Western United States (figure 5). Half of the simulations indicate that precipitation will increase in the 2041–70 period compared with 1971–2000 under the SRES A2 emissions scenario, whereas the other half indicate that precipitation will decrease. This result demonstrates the inability of the models to agree on precipitation trends in the water-scarce western states and underscores the need for improvement of climate models.

We conclude that even state-of-the-art climate models hardly provide useful information about poten-

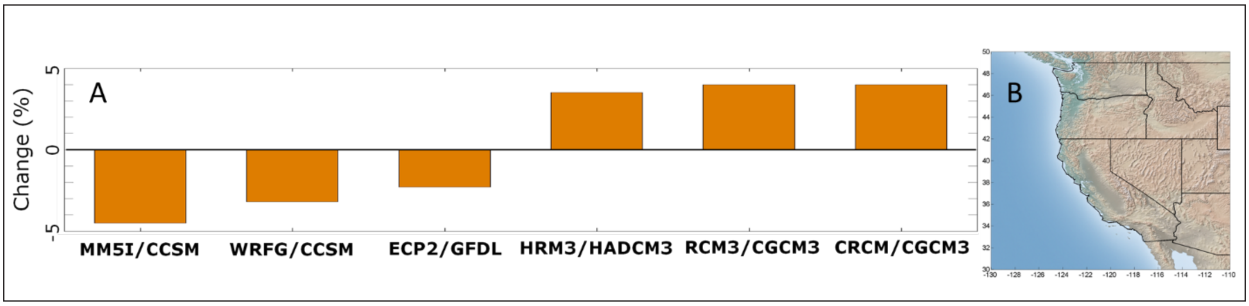

FIGURE 5 (**A**) Changes in mean precipitation over the Western United States indicated by six North American Regional Climate Change Assessment Program (NARCCAP) simulations, defined as [(Future − Current)/Current] × 100%. (**B**) NARCCAP simulation study region of the Western United States. CCSM = Community Climate System Model; CGCM3 = Third Generation Coupled Global Climate Model; CRCM = Canadian Regional Climate Model; ECP2 = Experimental Climate Prediction Center; GFDL = Geophysical Fluid Dynamics Laboratory; HADCM3 = Hadley Center Coupled Model, v. 3; HRM3 = Hadley Regional Model 3; MM5I = Fifth-Generation Penn State/National Center for Atmospheric Research Mesoscale Model run by Iowa State University; RCM3 = Regional Climate Model 3; WRFG = Weather Research and Forecasting Grell.

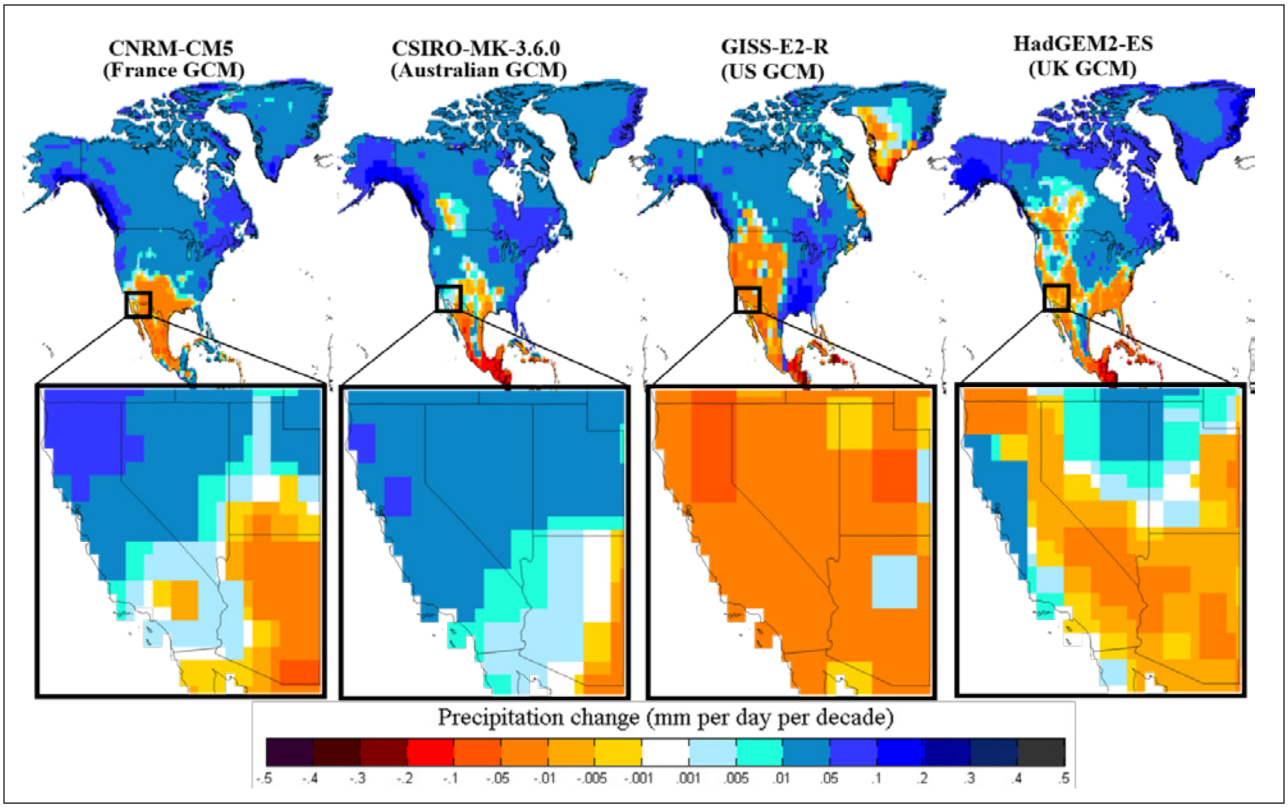

FIGURE 6 Precipitation changes from four climate model simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) over the Western United States for the "high" Representative Concentration Pathway (RCP) emission scenario: 8.5 W/m^2, equivalent CO$_2$ concentration of 936 ppm by 2100. Based on IPCC AR5 scenarios, 2006–09. CNRM-CM5 = National Centre for Meteorological Research–Climate Model 5; CSIRO = Commonwealth Scientific and Industrial Research Organisation; GCM = general circulation model; GISS-E2-R = Goddard Institute for Space Studies–Model E–Russell; HadGEM2-ES = Hadley Global Environment Model 2–Earth System. Data source: IPCC.

tial changes in precipitation trends in the future. Therefore, the best practice for water planning in this region should be to design resilient water systems that can cope with a wide range of scenarios of precipitation variability.

The NARCCAP study was reported in 2012, and in 2013 the IPCC Fifth Assessment Report (AR5; IPCC 2014) was released along with climate model simulations known as CMIP5 (Coupled Model Intercomparison Project Phase 5).[18] The CMIP5 outputs were produced for over 20 models from 20 modeling groups around the world. Four of the CMIP5 models were randomly selected and their projections of precipitation over the Western United States through the end of 21st century were compared. As shown in figure 6, the models differ substantially in their projections: some show increasing trends and others decreasing trends over the same areas.

Since the NARCCAP study and release of the CMIP5 model runs, research by modeling centers and the scientific community has yielded advances in both AOGCM and RCM, with better resolutions. When the CMIP6 climate model simulations for the Sixth IPCC Assessment Report are made available in 2021, it will be possible to assess (i) the models' performance with respect to their ability to capture both precipitation patterns and trends in retrospective studies against available observations and (ii) agreement between models and their projections.

Conclusions

We offer four key observations about models of future hydrologic extremes and the needs of the water resources community:

- Despite advances, prediction of hydroclimate variables such as precipitation remains a major challenge. The accuracy of hydroclimate models falls short of meeting requirements for water resources planning and decision making.
- Nature is complex, and efforts to observe and model its nonlinear behavior are imperfect. Therefore, one should exercise caution and a willingness to question the reliability and credibility of information generated by models.
- Long-term and sustained observation programs are critical for model development and testing. Without model testing against extensive observations, the full potential of models in operational settings will not be achieved.
- As called for in ASCE (2018), building resiliency into water resource system design and operation is the best approach to meet water demand and cope with and adapt to the hazards of extreme floods and droughts.

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[18] https://pcmdi.llnl.gov/mips/cmip5

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We must ensure that there never comes a day when the Earth has nothing left to give.

The Giving Earth

Jennifer Wilcox

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People all over the world must take action to wean from an addiction to fossil fuels. Otherwise, it would seem that Earth is simply here for humans to consume.

In *The Giving Tree* by poet Shel Silverstein (1964), the tree tells the once playful boy now grown into old age, “I wish that I could give you something … but I have nothing left. I am just an old stump. I am sorry. … well, an old stump is good for sitting and resting. Come, Boy, sit down. Sit down and rest.” The story teaches the importance of giving and being selfless; the tree is an example of perfect altruism, while the boy who took everything from her is an example of perfect selfishness.

Modern society’s relationship with Earth reflects the one between the boy and the tree: People have taken what is beneficial to them but have not continued to care for the planet.

What if methods could be engineered to render fossil energy “green” by replacing the pore space in rocks depleted of oil and gas with sequestered CO_2? This is possible,[1] but it does not seem a fair trade to Earth.

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[1] Recent studies show that the use of CO_2 from air for enhanced oil recovery (e.g., from a partially depleted oil reservoir) may result in the equivalent or even more CO_2 stored in the Earth than created from production, transport, refining, and oxidation of the fuel (Núñez-López et al. 2019).

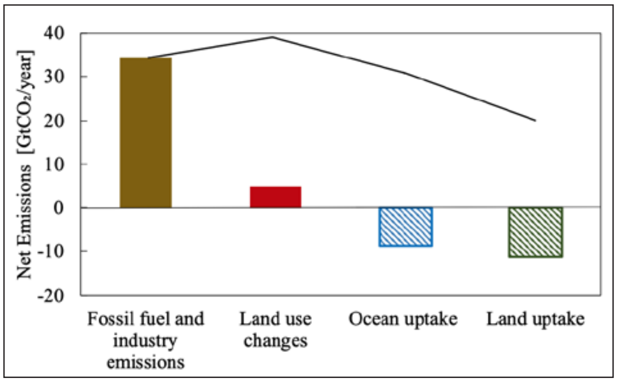

FIGURE 1 Visualization of net CO_2 emissions.

Introduction

Earth has sufficient fossil fuel to sustain the world's appetite for thousands of years to come.[2] But continuing down the path of Boy in the story and using up all this fuel would result in cumulative emissions of 50,000 billion tonnes of CO_2 ($GtCO_2$) (Wilcox et al. 2017). Since the Industrial Revolution roughly 1,800 $GtCO_2$ have been emitted into the atmosphere (Allen et al. 2009). The burning of fossil fuels for energy production and resulting accumulation of CO_2 in the atmosphere have created a world that is warming faster than at any other time in human history (Mann et al. 1999).

Alternatives based on the sun, water, and wind could meet global energy demands while preventing the reckless use of Earth's fossil resources. But, realistically, their widespread implementation will require a mediated transition based on collective work toward a common goal. The transition may include similar jobs that exist today in addition to new jobs and will involve the reverse flow of carbon back into Earth where it originated. It will require removing emissions that have been accumulating since the Industrial Revolution while simultaneously advancing deep decarbonization efforts, with renewables being a critical component of the transition.

Nature removes roughly half of global emissions each year through terrestrial and ocean uptake. But this takes a toll on natural systems; ocean acidification is the most prominent side effect. In 2018 alone, after land and ocean uptake and the release of CO_2 through land-use change (e.g., deforestation, forest fires), roughly 17 $GtCO_2$ were added to the atmosphere (Le Quéré et al. 2018).

The Need for Negative Emissions Technologies (NETs)

Recent studies (IPCC 2018; NASEM 2019) indicate that negative emissions technologies (NETs) will be required in addition to unprecedented reductions in anthropogenic emissions. However, atmospheric CO_2 concentrations will not be reduced until the combined uptake by natural carbon sinks and NETs outweigh anthropogenic emissions.

To illustrate, in 2018 fossil fuel and industrial emissions were 34.3 ± 2.0 $GtCO_2$/yr and land-use change accounted for 4.9 ± 3.0 $GtCO_2$/yr. But ocean uptake of CO_2 was 8.7 ± 2.0 $GtCO_2$/yr and land uptake was 11.2 ± 3.0 $GtCO_2$/yr. In this example, NETs would have to remove more than 20 $GtCO_2$ in just one year to reduce the accumulated atmospheric CO_2 (figure 1; NASEM 2019). This underscores the importance of a portfolio approach, and that NETs should not be viewed as a substitute for reducing CO_2 emissions in the first place.

Negative emissions technologies include planting biomass that may be harvested for energy production with emissions scrubbed of CO_2, storing carbon in soils, increasing CO_2 uptake from air through afforestation and reforestation, and reaction of CO_2 with alkaline-containing minerals in the earth to form carbonates (NASEM 2019).

Direct Air Capture as Part of a Broader Portfolio

A method called direct air capture (DAC) uses a chemical approach to capture CO_2 from air, not too different from how a forest does. The chemical approaches involved in DAC have a significantly greater efficiency and, unlike a forest, do not compete with food production for arable land. For example, a deciduous forest with an average tree density of 200 trees per acre requires roughly 390 km^2 for the net uptake of 1 $MtCO_2$. In contrast, a DAC facility that captures 1 $MtCO_2$ per year may require up to 7 km^2, or just short of 2 percent of the amount of land required by deciduous trees to meet the same target (NASEM 2019).

In a DAC plant, CO_2-selective chemicals are housed in large contactors with fans that push air through them to capture CO_2. As the air passes through the contactor, the CO_2 in it collides and reacts with the chemicals

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[2] This assumes combined reserves and resources for oil, natural gas (not including clathrates), and coal of 6.8 trillion barrels, 194,000 trillion ft^3, and 15,570 billion tonnes, respectively (Rogner et al. 2012).

while the primary components of air (nitrogen and oxygen) continue to move through. The contactors contain structured materials that moderate the air flow. If the air moves too fast, there may not be adequate time for reaction to take place, while air moving too slowly unnecessarily extends the time needed for the process. The captured CO_2 is recovered in pure form from the chemicals using heat, condensing it for transportation in a truck or pipeline (e.g., for storage).

The concentration of CO_2 in the atmosphere is roughly 300 times more concentrated than the CO_2 in the exhaust of more concentrated sources such as power plants. So why would one even consider capturing CO_2 from air at just 410 ppm? Why not first focus on natural gas- and coal-fired power plants, which produce roughly 100 to 300 times more CO_2 in their emissions streams? After all, natural gas and coal still represent 23 percent and 27 percent of the global energy resource mix, respectively (EIA 2019a). The minimum amount of thermodynamic energy required to capture CO_2 from air is 3 times greater than that required to remove it from the exhaust of a coal-fired power plant. The greater dilution of CO_2 in air translates to DAC requiring 300 times more contact area than coal-fired power plants to capture the equivalent CO_2 (Wilcox 2012). These differences translate directly to larger energy and capital costs for DAC compared to more concentrated sources.

Unfortunately, even aggressive efforts to limit emissions show that amounts of CO_2 will still be too high in the atmosphere, and for many greenhouse gas sources there simply is no method available to eliminate them. Earlier efforts might have supported the option of just mitigating emissions; now it is essential to both mitigate and remove emissions.

There is no silver bullet that will solve the climate crisis. The solution is difficult, and this difficulty is likely one of the reasons for general stalling on actions to avoid emissions on a significant scale. Efforts to achieve climate goals must include every tool available, including DAC.

Comparison of Commercial-Scale DAC Technologies

Leading DAC methods include two gas separation technologies: solid sorbents and liquid solvents. In both cases, air moves through a contactor to interact with chemicals that remove CO_2.

Solid Sorbents

With solid sorbents, the chemicals are bound to micro- and mesoporous materials embedded in the structured material that contains larger air transport channels (on the order of millimeters) so that the air can move through easily without requiring significant fan power.

The micro- and mesoporous materials have very high surface areas to maximize the number of chemicals on the surface for chemically binding CO_2. As an example, a microporous activated carbon may have a surface area up to 2,200 m^2/g, while in a single gram of material a metal organic framework sorbent may have a surface area up to 6,000 m^2/g—just over the size of a football field (Wilcox 2012).

> *Earlier efforts might have supported the option of just mitigating emissions; now it is essential to both mitigate and remove emissions.*

The solid sorbents are embedded in a honeycomb-like framework, not too unlike the catalytic converter in an automobile; just as exhaust from automobiles moves through the catalytic converter, the air moves through the channels in these materials.

Liquid Solvents

Instead of being bound on porous solid materials, CO_2-reacting chemicals may be dissolved in a liquid to form a solvent that is pumped over a structure with a high surface area so that the air interacts with the solvent quickly. This structure is called "packing material." First-generation packing materials for absorption processes were invented in the 1940s. The packing material allows the solvent to uniformly and thinly distribute to maximize the surface area between the gas containing CO_2 and the chemical in the solvent, similar to the solid sorbent method. An advantage of the solvent approach is that the solvent is inexpensive and easy to make in large quantities.

Comparison

The technologies differ in their cost breakdowns. The capital costs of the solvent-based systems are dominated by large chemical process equipment (NASEM 2019), which is also a benefit since it leads to economies of scale (i.e., cost-effective, large-scale deployment projects). One such project involves a partnership with a commissioning date of 2023, to be located in Texas (Carbon Engineering 2019). This first major DAC project is designed to capture 1 $MtCO_2$/yr.

Solid sorbent capital costs are dominated by the costs of manufacturing the necessary micro- and mesoporous materials (NASEM 2019), which do not benefit from economies of scale. Efforts are underway to reduce costs and increase the rate of materials production.

Power for DAC Plants

The energy required to carry out DAC on a scale of millions of tonnes of removal per year should not be underestimated. Depending on the energy resource, capturing 1 $MtCO_2$ per year requires 300–500 MW of power. Therefore, the design of a DAC plant must also include the design of a power plant coupled to it, to maximize the net removal[3] of CO_2 from air.

> *If the deployment of DAC can increase to millions of tonnes per year over the next decade or two, lower costs may be realized.*

For instance, with conventional natural gas power as the energy resource, for every 2 tonnes of CO_2 removed roughly 1 tonne would be emitted back into the atmosphere. Care should be taken to ensure that CO_2 is not emitted by the power source, which means that either renewable power or natural gas power with full capture should be used. Either option would be a significant component of the cost of the DAC plant.

Thus, to maximize the potential of DAC requires coupling the capture plants with carbon-free power, but one must be cautious that these valuable resources are not first more suitable for decarbonizing fossil-based sectors.

Costs of DAC and Anticipated Reductions

What is the true cost of DAC deployment today? Estimates in the literature range broadly and most are based on lab or demonstration-scale investigations. Only one company, Climeworks, has demonstrated through multiple deployments that the current cost of DAC is \$600/tCO_2 (Evans 2017; Gertner 2019). Since the power source coupled to the DAC plants operated by Climeworks is very low- to zero-carbon, the cost of removal roughly equates to the net removed cost. The company has publicly stated that it has plans to decrease these costs to \$200–300/tCO_2 within the next 5 years (Gertner 2019).

A number of studies estimate n^{th}-of-a-kind plants on the order of \$100/tCO_2 (e.g., Keith et al. 2018; NASEM 2019) that separate CO_2 from air to high purity (i.e., >98 percent) suitable for transportation and storage. If the deployment of DAC can increase from the current thousands of tonnes per year ($ktCO_2$/yr) removal, as demonstrated by Climeworks, to millions of tonnes per year over the next decade or two, as anticipated, the lower costs may be realized.

Other technologies that are still in development—such as electrochemical approaches (Bandi et al. 1995; Eisaman et al. 2009; Voskian and Hatton 2019) and the use of concentrated solar power for aqueous-phase absorption and crystalline-phase release (Brethome et al. 2018)—may be demonstrated as R&D in this field accelerates.

Paying for Large-Scale CO_2 Removal: The Role of Policy

In the United States, DAC qualifies for two policy incentives. The federal 45Q tax credit provides up to \$35/tCO_2 for utilization and up to \$50/tCO_2 for geologic storage (Christensen 2019). In addition, California has a low-carbon fuel standard (LCFS) that places a cap on the maximum carbon intensity (CI) of transportation fuels sold in California and grants credits for fuels below the CI requirement (CARB 2018). The credit is currently traded at \$150–\$200/tCO_2.

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[3] Depending on the carbon intensity of the energy and material input, and the CO_2 transportation to sink, there may be emissions into the atmosphere, which will reduce the plant's net removal of CO_2 from air. Emissions embodied in the materials or energy required to operate the DAC plant lead to an increase in the cost of CO_2 capture from air on a net removed basis.

An entity that operates DAC coupled to geologic storage anywhere in the world may qualify for LCFS. At current costs of DAC, these incentives are still unable to close the economic gap without reliance on today's small CO_2 market, such as enhanced oil recovery (EOR) (roughly 85 percent) and the food and beverage industries (roughly 10 percent).

It is important to recognize that the demonstrated costs of DAC are not a limiting factor for its deployment. Rather, the lack of policy that puts a price on the permanent removal of CO_2 is limiting progress in both conventional carbon capture and storage (CCS)[4] and DAC. The storage of gigatonnes of CO_2 per year in the Earth's subsurface will be essential to meet climate goals. Permanent storage of CO_2 will be required for capturing CO_2 at point sources such as power plants[5] in addition to CO_2 removal strategies from air, such as bioenergy with CCS and DAC. Without permanent storage, neither bioenergy nor DAC result in negative emissions.

Emerging CO_2 Markets and the Transition Away from Fossil Fuels

Utilization and geologic storage of CO_2 should not be viewed as an either-or option but rather as a continuum toward achieving climate goals. Beyond the current small CO_2 market, there are emerging markets for use of CO_2 as a feedstock, for example in synthetic aggregates[6] for construction and road building and in synthetic fuels.[7] These markets have the potential to use CO_2 as a feedstock on the scale of gigatonnes globally, with the first leading to permanent storage in the form of carbonate. With synthetic fuels, the approach is at best carbon neutral, assuming that the liquid fuel will be used for the transportation sector and reemitted into the air in a distributed fashion. With synthetic fuels using CO_2 and H_2 as reactants, both the source of H_2 and the DAC power must have minimal or zero associated carbon emissions to have the greatest CO_2 removal impact.

Today CO_2-EOR is the largest CO_2 market in the United States.[8] Although most CO_2 for EOR is sourced naturally, it is anticipated that with regulations such as California's LCFS and the federal 45Q tax credit, there will be greater incentive to use anthropogenic CO_2 and even CO_2 from air.

> *To meet climate goals, the geologic storage of CO_2 must increase at least a hundredfold by midcentury.*

Ultimately, CO_2 should be overused in the EOR process such that more CO_2 stays underground than the produced oil would create. This would require coupling projects suitable for both dedicated storage and EOR since the density of the carbon atoms in compressed CO_2 at the temperature and pressure conditions of the earth would never be greater than the density of carbon atoms in the oil to begin with. Projects that couple EOR with dedicated storage would be appropriate through a transition phase toward completely weaning away from the need to recover any oil. Perhaps policies would shift from subsidizing both EOR and storage projects to subsidizing only storage projects, allowing operators to gain experience in CO_2 storage while transitioning their business away from EOR.

Globally, roughly 30 $MtCO_2$/yr is stored through CO_2-EOR, with an additional 10 $MtCO_2$/yr stored through dedicated sequestration projects (Global CCS Institute 2019). To meet climate goals, the geologic storage of CO_2 must increase at least a hundredfold by midcentury.

Who Will Build and Operate the Facilities for Gigatonne Recovery? Workforce Impacts

The oil and gas industries support roughly 164,000 US jobs, just under 2 percent of total US employment

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[4] Conventional CCS is the capture of CO_2 from a point source, followed by compression for trucking or pipeline conditions, for transport to a geologic site where it can be injected and permanently stored in the Earth's subsurface.

[5] The electric power sector represented 33 percent of US energy-related CO_2 emissions in 2018 (EIA 2019a).

[6] Projections from 2014 estimated aggregate demand of 53.2 Gt/yr, composed of crushed stone, sand, and gravel (Grand View Research 2019).

[7] The global liquid fuel market today is 11 M barrels/day. Assuming that $CO_2 + H_2$ are a feedstock to synthetic fuel (density of 900 kg/m^3) equates to a CO_2 demand of roughly 5 $MtCO_2$/day (EIA 2019b).

[8] International CO_2-EOR opportunities also exist, with potential on the Gt-scale in Saudi Arabia, Russia, China, India, and Oman (Ward et al. 2018).

(BLS 2019b).[9] A recent article reveals that 20 fossil fuel companies have contributed to 35 percent of all energy-related CO_2 and methane emissions globally, totaling 480 $GtCO_{2eq}$[10] since 1965 (Taylor and Watts 2019). This group might naturally be expected to take significant steps toward the solution.

A short list of the positions that will be needed to transition away from being a global society addicted to fossil fuels includes key job categories in the oil and gas industries: geologists, geophysicists, geochemists, drilling engineers, mining engineers, petroleum engineers, chemical engineers, and surveyors. There will also be new jobs created at DAC facilities, perhaps jobs similar to those at utilities such as power plants.

To increase from $MtCO_2$/yr capture and storage to $GtCO_2$/yr will largely require talent that is already in the workforce. Drilling wells, understanding fluid transport in subsurface porous media, and advancing catalysis for fuel synthesis are areas of expertise that overlap between current oil and gas (fossil) energy and a fossil-free energy future.

Conclusion

Humans must recognize the toll of our selfishness on the giving Earth. We must minimize our carbon emissions, create infrastructure for geological storage, facilitate a transition to renewable energy, and develop negative emissions technologies to combat rising atmospheric CO_2 concentrations and their detrimental effects. Most of all, we must ensure that there never comes a day when the Earth has nothing left to give.

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[9] By comparison, the coal industry was responsible for employing 52,700 people in 2019 and 51,700 in 2018 (BLS 2019a).

[10] Because of possible methane leakage from natural gas processing and its transportation, $GtCO_{2eq}$ includes both CO_2 and methane emissions associated with the oil and gas industry.

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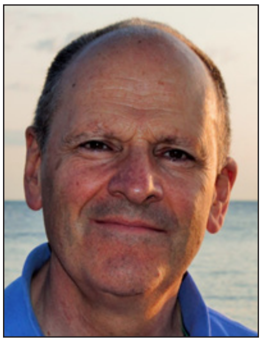
Even with stringent mitigation, sea levels will continue to rise for centuries to come. Coastal adaptation is therefore essential in any future.

Responding to Sea Level Rise

Jochen Hinkel and
Robert J. Nicholls


Jochen Hinkel


Robert Nicholls

Global mean sea levels are rising because of human-induced global warming (Oppenheimer et al. 2019). The recent *Special Report on the Ocean and Cryosphere in a Changing Climate* of the Intergovernmental Panel on Climate Change (IPCC) projects that if greenhouse gas emissions continue to rise unabated (i.e., RCP8.5[1]) there is a 66 percent chance that global mean sea level will rise 0.6–1.1 meters by 2100 and 2.3–5.4 m by 2300 (Oppenheimer et al. 2019) (figure 1).

Stringent reduction of greenhouse gas emissions may substantially reduce global sea level rise (SLR). The IPCC *Special Report* finds that if emissions are reduced to meet the Paris Agreement goal of limiting global warming "well below 2°C" (i.e., RCP2.6), there is a 66 percent chance that global mean sea level will rise 0.3–0.6 m by 2100 and 0.6–1.1 m by 2300. These ranges, like most in the SLR literature, are probabilistic, which means that sea levels may turn out to be above (or below) these ranges. Current sci-

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[1] The IPCC (2014) defines four Representative Concentration Pathways (RCPs) to characterize greenhouse gas concentration trajectories, from a low of 2.6 to a high of 8.5.

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entific understanding does not enable projection of an upper bound for SLR (Hinkel et al. 2019; Stammer et al. 2019).

Potential Impacts of Sea Level Rise

Sea level rise threatens the world's coasts through a range of impacts (Oppenheimer et al. 2019):

- permanent submergence of land by mean sea levels or mean high tides;
- more frequent or intense coastal flooding;
- enhanced coastal erosion;
- loss, degradation, and change of coastal ecosystems;
- salinization of soils and of ground and surface water; and
- impeded drainage.

These biophysical impacts will in turn have socioeconomic impacts on coastal residents and their livelihoods, such as significant flood damage to buildings, disruption of economic activities, and degraded coastal agriculture.

Three points about SLR impacts that are often obscured in the SLR literature are important to note upfront. First, SLR impacts are due to local relative sea level change, which differs from the global mean because of both climatic and nonclimatic factors, and this must be considered when evaluating future impacts and adaptation needs. One key nonclimatic factor is land subsidence; in densely populated sedimentary coastal plains human-induced land subsidence due to groundwater withdrawal and related processes can produce large relative rises in local sea levels (Kaneko and Toyota 2011).

Second, most of the impacts of SLR will be felt not through the gradual increase of mean sea level but rather through increases in extreme sea level (ESL) events such as combinations of tides, surges, and waves that rise with mean sea levels (Wahl et al. 2017). The notion that sea levels gradually submerge large coastal areas, as often depicted in the SLR literature and media coverage (e.g., Lu and Flavelle 2019), is misleading.

Third, in most cases potential SLR impacts are countered or strongly reduced by adaptation, especially where coastal zones are densely populated. Many coastal societies have a long history of adapting to local SLR and this is almost certain to continue. For example, a number of coastal megacities have experienced and adapted to relative SLR of several meters caused by human-induced land subsidence during the 20th century (Kaneko and Toyota 2011).

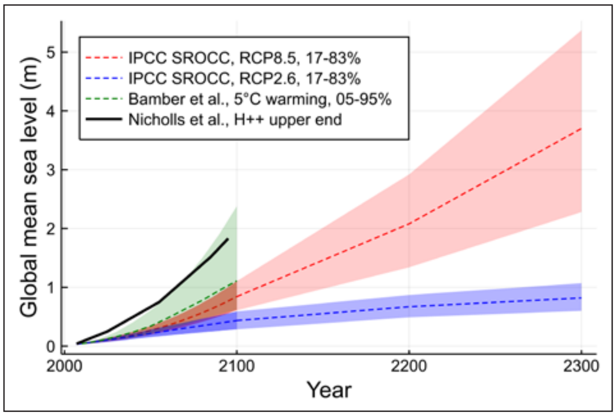


FIGURE 1 Global mean sea level (GMSL) rise. The red and the purple areas show GMSL rise ranges that have a 17% chance of being exceeded (i.e., 17th to 83rd percentiles of the GMSL distribution) for unabated (i.e., RCP8.5) and stringently reduced greenhouse gas emissions (i.e., RCP2.6) according to the latest report of the Intergovernmental Panel on Climate Change (IPCC; Oppenheimer et al. 2019). These ranges have been derived through the application of expert confidence judgments on the outputs of physical models for all contributions to GMSL rise. The IPCC authors don't report on GMSL above these ranges because confidence in higher percentiles is lower. The green area shows a GMSL range that has only a 5% chance of being exceeded (i.e., the 5th to 95th percentiles of the GMSL distribution) under a 5°C global warming scenario comparable to RCP8.5. This range has been derived by combining physical model output with expert judgment on contributions to GMSL from the melting of Greenland and Antarctica (Bamber et al. 2019), because these processes are not fully captured in existing physical models. The black line shows the upper end of the H++ scenario range derived by combining physical model output with other lines of evidence such as paleo records (Nicholls et al. 2014). This upper end is independent of emission scenarios and not associated with a probability. Dashed lines show the median values of the ranges. SROCC = *Special Report on the Ocean and Cryosphere in a Changing Climate*.

A realistic picture of SLR risk and impacts requires consideration of adaptation responses, which are the focus of this article.

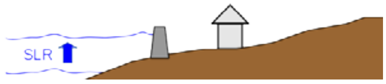
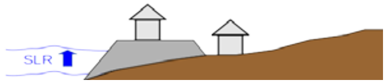
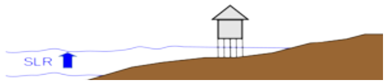
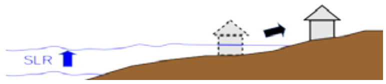
Adaptation Responses

Options

Adapting to SLR can be done in fundamentally different ways (table 1).

- *Protection* reduces the likelihood of coastal impacts and includes (i) hard engineered structures such as dikes, seawalls, breakwaters, and surge barriers,

TABLE 1 Adaptation options to sea level rise (SLR), their potential effectiveness in reducing SLR risks, and caveats. Adapted from IPCC (2019) and Oppenheimer et al. (2019).

Type of response option	Illustration	Potential effectiveness in reducing SLR risks	Caveats
Hard protection		Up to several meters of SLR	Cost efficient for cities, not affordable for rural and poorer areas
Advance			
Ecosystem-based adaptation (EbA)		***Coral reefs***: Effective up to 5 mm/yr SLR ***Marshes, mangroves***: Effective up to 5–10 mm/yr SLR	***Coral reefs***: Lost at 2°C in many places due to ocean warming and acidification ***Marshes, mangroves***: Decreased at 2°C, limited through pollution, infrastructure
Accommodation		Very effective for small amounts of SLR	Moral hazard (in the case of flood insurance)
Planned retreat		Effective if alternative safe locations are available	Socially and politically very challenging

and (ii) sediment-based measures such as beach and shore nourishment and dunes (also referred to as soft protection).

- *Advance* creates new land by building seaward and upward. It includes land reclamation above sea levels and polderisation, the gain of new low land with the construction of dike enclosures.
- *Ecosystem-based adaptation (EbA)* uses coastal ecosystems such as coral and oyster reefs, mangroves, marshes, and seagrass meadows as protective buffers that attenuate extreme water levels (surges, waves), reduce rates of erosion, and raise elevation or create new land by trapping sediments and building up organic matter and detritus (Pontee et al. 2016; Spalding et al. 2014; Temmerman et al. 2013).
- *Accommodation* involves implementing early warning systems for floods and floodproofing and elevating houses. It does not prevent coastal impacts but reduces the vulnerability of coastal residents, infrastructure, and human activities.
- *Planned or managed retreat* reduces exposure to coastal impacts by moving people, infrastructures, and human activities out of the exposed coastal area (Hino et al. 2017)—or by avoiding development of the coastal floodplain in the first place.

These physical responses are combined with or initiated through institutional arrangements such as regulations for design heights for dikes, building codes for floodproofing homes, monetary incentives for risk management (e.g., subsidized insurance), or the timely provision of information through flood early warning systems.

Advantages and Disadvantages

All types of response options have advantages and disadvantages and thus have complementary roles to play in an integrated response to SLR. Hard protection measures need less space and their effectiveness is more predictable than EbA approaches, which exhibit high natural variability in time and space (Narayan et al. 2016; Pinsky et al. 2013; Quataert et al. 2015).

Advantages of EbA measures for protecting the coast include their contribution to other ecosystem services, such as carbon sequestration or improved water quality, and to conservation and related goals. Furthermore, EbA approaches may autonomously maintain their effectiveness over time by naturally adapting to rising sea levels by raising land and migrating inland, provided sufficient sediment and inland space are available. In practice EbA measures are often combined with hard defenses.

Advance is widely practiced around coastal cities where land is scarce and valuable. Globally, about 34,000 km^2 of land has been gained from the sea during the last 30 years, with the biggest gains in Dubai, Singapore, and China (Donchyts et al. 2016; Martín-Antón et al. 2016). Over longer timescales, this has occurred around nearly all major coastal cities to some degree, even if only for the creation of port and harbor areas.

Accommodation measures such as floodproofing have high benefit-cost ratios: implementing them is less expensive than doing nothing. Early warning systems for coastal floods and storms have one of the highest benefit-cost ratios and should be universally adopted. However, these measures alone are effective only for current conditions and small rises in sea level; if SLR rises substantially they will need to be combined and/or replaced with other approaches.

It is also important to note that protection always leaves a residual risk—ESL events can exceed protection standards—and hence flood damage cannot necessarily be completely prevented. For example, a global analysis of flooding of coastal megacities under SLR found fewer but bigger flood disasters (Hallegatte et al. 2013). Only retreat and advance can avoid residual risks if ground is sufficiently high or can be reclaimed, or at least these options can buy time until residual risks reach unacceptable levels—and new adaptation decisions are necessary.

Different Adaptation Responses in Different Contexts

Coastal areas are diverse and there is no “silver bullet” adaptation. Rather, adaptation will vary in time and space depending on the context.

Context-Specific Examples

In deltas and sedimentary lowlands, especially urban areas, rates of human-induced subsidence may exceed climate-induced SLR by an order of magnitude. The most urgent response needed in this context is to mitigate human-induced subsidence. While in some cities such as Tokyo subsidence has been stopped by reducing the pumping of ground water, the problem continues at alarming rates of 3 to 17 cm/year in other Asian megacities such as Bangkok, Jakarta, and Manila (Kaneko and Toyota 2011) and is likely to emerge in other susceptible cities.

For cities and densely populated low-elevation areas, hard protection will continue to play a central role in adaptation. Many cities around the world are protected by hard defense infrastructure and if there is limited space and large human assets (e.g., buildings, infrastructure) are at risk, hard protection should be continued for the coming decades, at least until more is known about possible high-end SLR, which may require a change in adaptation strategy.

Development should be steered away from coastal floodplains to avoid future damages and/or the need for further adaptation investments.

Planned retreat does not yet need to be implemented widely but must be considered in the longer term if protection ceases to be affordable or feasible (Nicholls et al. 2013). However, if major coastal floods cause significant damage, it makes sense to consider opportunities for retreat instead of rebuilding. If safe land is available, development should be steered away from coastal floodplains to avoid future damages and/or the need for adaptation investments.

Economic Considerations

In most cases, it is technologically feasible to protect cities against multiple meters of sea level rise. Providing global protection for densely populated coasts would require investments during the 21st century on the order of \$2.8–\$13.4 trillion[2] under an SLR scenario that is consistent with the Paris Agreement (i.e., RCP2.6) and \$4.4–\$18.2 trillion under unmitigated greenhouse gas emissions (i.e., RCP8.5), considering capital and maintenance costs of coastal dikes, river dikes, and storm surge barriers (Nicholls et al. 2019). While this is a lot of money, the benefit-cost ratios of protecting cities

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[2] Amounts are in US dollars and are not discounted.

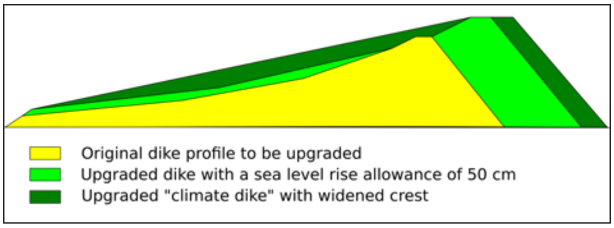

FIGURE 2 Profile of a German "climate dike," which includes a sea level rise allowance of 50 cm and a widened dike crest to allow for future upgrades. Adapted from MELUR-SH (2012).

(i.e., the cost of avoided damages divided by the cost of protection) are generally high (Lincke and Hinkel 2018). Further, the required investment is only a small fraction of local GDP (Diaz 2016; Hinkel et al. 2013; Lincke and Hinkel 2018). Economically productive cities should therefore be able to afford protection.

For rural and sparsely populated coasts, understanding of the future is less clear and the range of adaptation options appears more constrained. Hard coastal protection is less economically feasible because benefit-cost ratios are often less than one (Lincke and Hinkel 2018) and the required annual investments in coastal protection can amount to several percent of GDP, in particular for small island states (Diaz 2016; Wong et al. 2014). An alternative strategy is to protect rural coasts through EbA measures. Where sediment budgets and human activity allow, land can be elevated through managed morphodynamics; for example, controlled flooding of low-lying areas in deltas can raise land surfaces through flood-deposited sediments (Amir et al. 2013).

Designing and Planning Adaptation Responses

Many coastal decisions with time horizons of decades to over a century—for example, concerning critical infrastructure, coastal protection works, city planning—are being made today and factoring in SLR, even with the large uncertainty about it (figure 1), can improve these decisions.

Guiding Principles

Two guiding principles are specifically relevant for such decisions (Hinkel et al. 2019). The first calls for increasing flexibility by delaying or splitting decisions into multiple steps. For example, in the federal state of Schleswig Holstein in Germany coastal dikes that are upgraded are equipped with a wider crest than necessary (figure 2), allowing further raising of the dikes if SLR turns out to be higher than anticipated (MELUR-SH 2012). In the Netherlands sediment-based instead of hard measures are used for coastal protection, because the former provide the flexibility to increase protection (e.g., by applying more sand) as the consequences of SLR and other changes unfold, without the need to decide today on the construction of hard measures that would last decades (Kabat et al. 2009).

The second, related principle concerns adaptive decision making, which means that SLR monitoring systems are established to identify future decision points when a new strategy may need to be implemented. An important prerequisite for this approach is that the monitoring system can detect sea level signals (e.g., an acceleration in SLR) sufficiently early for implementation of adequate responses (Haigh et al. 2014; Stephens et al. 2018).

One approach that illustrates this second principle is dynamic adaptive policy pathways (Haasnoot et al. 2013), or simply adaptation pathways. This approach has, for example, been integrated in national guidance for coastal hazard and climate change decision making in New Zealand (Lawrence et al. 2018).

Even when no long-term SLR-related decisions are immediately needed, it is beneficial to prepare a long-term strategy to ensure that options, and sufficient time to implement them, are available even in the case of high SLR estimates (Hinkel et al. 2019).

Stakeholders' Risk Tolerance

There is no objective way to provide SLR information for adaptation planning, because the range of SLR relevant to a decision depends on the risk tolerance of the relevant stakeholders (Hinkel et al. 2019). As such, the IPCC SLR ranges do not necessarily provide the required information. Risk-tolerant stakeholders may prefer an adaptation response based on the 66 percent range of SLR in the latest IPCC report cited above (i.e., up to 1.1 m of SLR by 2100). Stakeholders with a lower risk tolerance should also consider SLR above this range because there is a 17 percent chance that global mean SLR will exceed 1.1 m under the RCP8.5 scenario by 2100.

Studies using and combining multiple lines of evidence—such as observations, paleo records, model sensitivity studies, scenario studies, and expert judgment—provide higher SLR estimates. For example, in the United Kingdom the so-called H++ scenario range extends to about 2 m SLR by 2100 (Lowe et al. 2009; Nicholls et al. 2014) (figure 1) and has been considered in coastal adaptation planning for London (i.e., the Thames Estuary 2100 project; Ranger et al. 2013) and for nuclear power station design (Wilby et al. 2011). While the confidence in these estimates is lower than for those of the IPCC, the higher estimates should be taken into account in decision making when stakeholders have a low risk tolerance (Hinkel et al. 2015).

Social Challenges in Implementing Adaptations

Implementation of adaptations raises social concerns that can be much more difficult to deal with than many of the biophysical and technical issues reported above (Esteban et al. 2019; Hinkel et al. 2018).

For example, financing the upfront investment in an adaptation is often prohibitively difficult, because the benefits of protection are public goods stochastically (i.e., benefits are felt only when a flood occurs) dispersed across diverse actors over a long period of time. In such situations beneficiaries may be unwilling to pay taxes or levees for uncertain benefits, and politicians do not have strong incentives to realize such long-term projects because of short electoral cycles and reputational risks that arise if investments are made and no flood occurs for a long time (Bisaro and Hinkel 2018). For these and related reasons, many parts of the world are not adapted to today's ESL regimes let alone those under SLR.

For urban areas, advance can be a way to overcome the financing gap, because upfront investments in protection can be recuperated within a few years through real estate revenues generated from newly created land. But this approach raises equity issues associated with access to the new land (Bisaro et al. 2019).

Retreat is often politically contested because of vested coastal interests (e.g., of the tourism and real estate sectors), difficult questions around equity and compensation (e.g., for forfeited property), and adverse outcomes such as disruption of livelihoods and loss of culture and identity (Hauer et al. 2019; Siders et al. 2019).

While EbA seems to be an attractive solution, the large-scale implementation required to address SLR in rural areas is a huge challenge, not least because coastal ecosystems currently experience the highest rates of human destruction. For example, annual global losses of mangroves and corals are 1–3 percent and 4–9 percent, respectively—much larger than for tropical forests (0.5 percent) (Duarte et al. 2008). The major driver is human development such as the conversion of mangroves into agriculture, shrimp farming, and industrial uses that provide short-term profits (Li et al. 2014). Maintaining wetlands and raising land through sediment management in river deltas also conflict with trends such as river-dam construction, which, if continued, could lead to a decline in sediment supply of up to 83 percent by 2100 (Dunn et al. 2019).

> *Coastal adaptation will be much easier and more likely to be successful when combined with stringent mitigation.*

The extent to which these and other conflicts can be resolved and adaptation advanced depends on the extent to which governance arrangements are in place or can be established to mitigate conflicts between different interests (e.g., development versus ecosystem conservation). Areas that have long been dealing with coastal risks and extreme sea levels, such as Northwestern Europe, China, and Japan, will find it easier to implement appropriate responses, and are already doing so, as governance arrangements are already in place. However, for many other places, SLR is a new phenomenon, preparation for it is generally less advanced, and new governance arrangements are required to address it.

Conclusions

The scale of the SLR challenge is immense and strong mitigation efforts are needed to avoid multiple meters of SLR within the next few centuries, which will be unmanageable for many coastal regions of the world. But even with such efforts, sea levels will continue to rise for decades and centuries to come. Thus coastal adaptation is essential in any future, but it will be much easier and more likely to be successful when combined with stringent mitigation. The important thing is to start exploring long-term adaptive strategies *now* if they are not already initiated.

Diverse adaptation measures are available and, depending on the coastal setting, quite different options will be selected. Protection appears likely in many urban contexts, but should be combined with other measures as much as possible, and residual risk needs to be considered. In the longer run, retreat appears likely in many less developed areas; there is a need for more analysis of this and other options. Research is needed to determine to what extent ecosystem-based approaches are effective in different areas.

Irrespective of technical considerations, coastal adaptation is much more constrained by economic, financial, and other social factors. Long before technical limits to coastal adaptation are reached, societies will probably be economically unable or socially unwilling to invest in such adaptation. This points to the need for research on appropriate governance structures for mitigating social conflicts around these issues to ensure progress on adaptation.

Importantly, such constraints will have a greater impact on poorer and rural areas, exacerbating inequalities between rich and poor coastal communities. Richer and more densely populated areas are likely to be well protected behind hard structures, while poorer and less densely populated areas are not likely to be able to afford investments in coastal protection and so will suffer ever more frequent damages from ESL events and eventually have to retreat from the coast. These social and economic issues should be discussed extensively in international climate change negotiations.

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Stratospheric geoengineering would come with benefits but also risks and concerns. More research is needed.

Benefits and Risks of Stratospheric Solar Radiation Management for Climate Intervention (Geoengineering)

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Alan Robock

Climate intervention (geoengineering) is being considered as a response to global warming. I discuss the scheme that has been studied the most: creation of a permanent sulfuric acid cloud in the stratosphere to reflect sunlight, mimicking large volcanic eruptions. It is impossible to do today, as the technology remains to be invented, and I discuss the engineering challenges and costs. Even if it becomes possible, stratospheric geoengineering would come with benefits but also risks and concerns. Quantifying these benefits and risks requires more research.

Introduction

Global warming is a real threat to human and other life on Earth. The question is what to do about it. The answer, as explained, for example, in the recommendations of a US National Research Council report on climate intervention (NRC 2015), is mitigation (leaving fossil fuels in the ground), adaptation, and attempts to remove carbon dioxide from the atmosphere. However, despite decreasing costs for solar and wind power, current mitigation pledges are not expected to keep global warming under 2°C above preindustrial global average surface air temperatures (e.g., Robiou du Pont and Meinshausen 2018). Therefore, there have been suggestions to consider schemes to reflect sunlight to cool Earth.

Definition of Terms

Ideas for removing carbon dioxide from the atmosphere or reflecting sunlight to cool Earth used to be called geoengineering or climate engineering, but the favored term nowadays (e.g., AGU 2018; NRC 2015) is climate intervention. In this article, the word "geoengineering" appears as a legacy of previous nomenclature.

Solar radiation management proposals include use of stratospheric aerosols to block sunlight, mimicking volcanic eruptions.

The definition of climate intervention is "deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Shepherd et al. 2009, p. 1). It is conventionally separated into carbon dioxide removal (CDR) and solar radiation management (SRM, also called albedo modification), which have completely different technologies, benefits, risks, governance, and ethics. This paper deals with SRM, and mostly with proposals to use stratospheric aerosols to block sunlight, mimicking volcanic eruptions.

UN Framework Convention on Climate Change

The 1992 United Nations Framework Convention on Climate Change, signed and ratified by the United States, says,

> The ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent *dangerous anthropogenic interference* [DAI; emphasis added] with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[1]

At the time, DAI did not have a specific definition. Enacting the Convention has been done by annual Conferences of the Parties (COPs). The third COP in Kyoto (1997) produced a protocol that was ineffective, as it required only developed (but not developing) countries to mitigate. It was not until COP15 in Copenhagen in 2009 that the world agreed to define DAI as global average surface air temperature greater than 2 K above preindustrial temperatures. At COP21 in Paris in 2015 various nations made voluntary pledges to reduce their emissions to try to prevent DAI, and an aspirational goal of keeping global warming under 1.5 K was also discussed.

A Combined Approach

Because the world is not moving rapidly to prevent DAI (e.g., Tollefson 2019) at either the 1.5 K or 2 K level, SRM—together with rapid conversion of the world's energy system and large-scale CDR, such as in the Representative Concentration Pathway 2.6 (van Vuuren et al. 2011)—is now being assessed as a possible additional response (e.g., MacMartin et al. 2018).

This paper discusses how SRM could be done technically, the research that needs to be done, the ethics and governance of such research, and potential benefits, concerns, and risks of SRM.

Geoengineering Methods and Costs

The technology for SRM does not yet exist (Smith and Wagner 2018). The two techniques that have been studied the most and seem the most practical involve either creating a sulfuric acid cloud in the stratosphere to simulate what large volcanic eruptions do occasionally, or brightening low clouds over the ocean (Robock et al. 2013). Brightening the surface (e.g., Oleson et al. 2010) is not considered to be effective on a global basis, and reflectors in space (e.g., Angel 2006) are unworkable and expensive. Much research is needed to tell whether it is possible to brighten marine clouds in a controlled way (NRC 2015), but stratospheric aerosol clouds do cool Earth after volcanic eruptions (Robock 2000), so I focus on that scheme here.

While balloons, artillery, and even towers have been suggested to get sulfur dioxide (SO_2, the precursor gas to sulfuric acid clouds created by volcanic eruptions) into the stratosphere (figure 1), the cheapest and most straightforward method would be with airplanes (Robock et al. 2009). However, it is not possible to retrofit current airplanes with the bigger engines or longer wings needed to do the job (Smith and Wagner 2018).

NAS, NAE, and IOM (1992) made the first quantitative estimates of the cost of putting gases or particles into the stratosphere to simulate volcanic eruptions; subse-

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[1] Available at https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf.

quent updates were rather rough estimates (McClellan et al. 2012; Robock et al. 2009). Now two teams have produced estimates that include the costs of developing new airplanes to inject particles (or their precursors) into the stratosphere (de Vries et al. 2020; Janssens et al. 2020; Smith and Wagner 2018). Such an aircraft could be operated remotely to save energy and weight by not having a pilot onboard (de Vries et al. 2020).

To estimate the cost, it is necessary to first decide how thick a cloud to create. Scenarios have been modeled to keep surface temperatures from changing until the end of the 21st century despite business-as-usual greenhouse gas emissions (Niemeier and Timmreck 2015; Tilmes et al. 2018), but those are model exercises and not meant to suggest an actual deployment.

Here, I choose a scenario where the climate still overshoots the preindustrial average by 1.5 or 2 K (e.g., Jones et al. 2018; Tilmes et al. 2016), and SRM would be applied for a limited time, as illustrated in John Shepherd's "napkin diagram" (Long and Shepherd 2014; figure 2). This scenario would require radiative forcing of about -2 W m^{-2} (Tilmes et al. 2016), which is also what would be required to offset half the climate change that would result from doubling atmospheric CO_2. Accounting for aerosol growth as SO_2 is continuously injected into an existing stratospheric cloud, the scenario would require about 12 teragrams (Tg; 1 Tg = 1 million tons) of sulfur (S) per year (Niemeier and Timmreck 2015).

If larger negative radiative forcing from stratospheric aerosols were required, the costs would go up nonlinearly, because additional SO_2 emissions would cause existing aerosol particles to grow larger, making them less effective at scattering per unit mass and likely to fall out of the stratosphere faster (Heckendorn et al. 2009). For example, a radiative forcing of -4 W m^{-2} would require 27 Tg S per year (Niemeier and Timmreck 2015).

Table 1 shows estimated costs based on four papers, scaling up from the cost of putting 1 Tg of material into the stratosphere per year. Volcanic stratospheric clouds are produced by injections of SO_2, so that might be the gas of choice, but some have suggested H_2SO_4 to reduce growth of aerosol particles (e.g., Pierce et al. 2010). However, it is not known if it is possible to produce sulfate droplets of the desired size distribution.

The price of the materials would probably not be a limiting factor, as sulfur is plentiful. Other substances have been suggested—such as calcium carbonate, aluminum oxide, or even diamonds (Keith et al. 2016), all of which might cause less ozone depletion—but there have been no studies of their practicality.

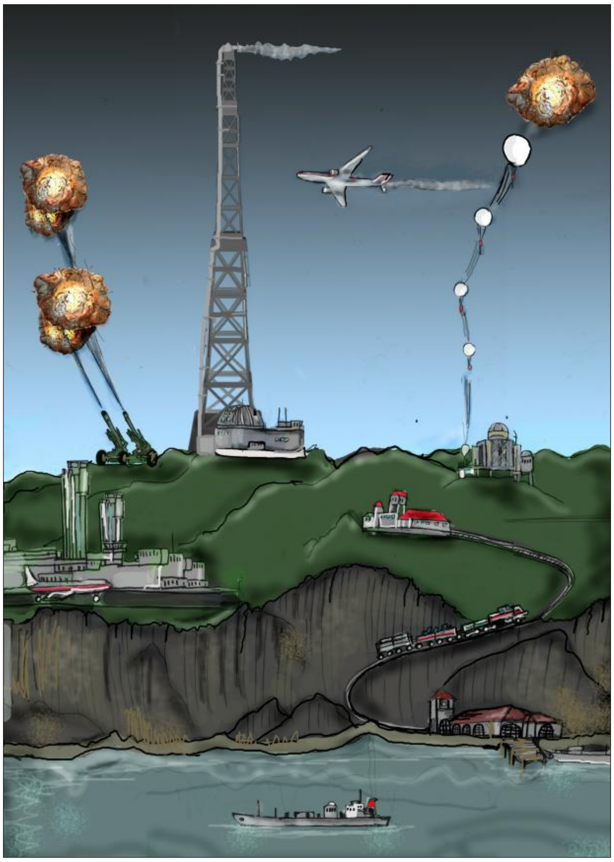

FIGURE 1 Proposed methods of stratospheric aerosol injection. Supplies would be delivered by ship and taken by train up the mountain. Then airplanes would fly them up, or they could be shot in artillery shells, sprayed from a tall tower, or delivered by balloons. A mountaintop location would require less energy for lofting to the stratosphere. Drawing by Brian West. Reprinted with permission from Robock et al. (2009).

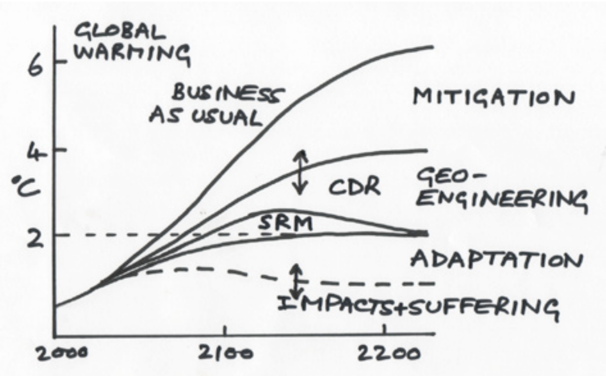

FIGURE 2 The "napkin diagram" originally drawn by John Shepherd on a napkin at the Asilomar International Conference on Climate Intervention Technologies in 2010. CDR = carbon dioxide removal; SRM = solar radiation management. Available at http://jgshepherd.com/wp-content/uploads/2011/01/Napkin-diagram.pdf and used by permission. Formally published as figure 87.1 in Long and Shepherd (2014).

TABLE 1 Annual cost in billions of US dollars to produce -2 W m^{-2} using sulfur flown into the lower stratosphere, which would require 12 teragrams (Tg) of sulfur (S) per year (Tg S/yr; Niemeier and Timmreck 2016), based on four analyses. Smith and Wagner (2018) propose lofting liquid sulfur and burning it in the stratosphere to produce SO_2, but the other estimates include the costs of lofting SO_2 or H_2SO_4; SO_2 (64 g/mole) would require 24 Tg/yr, and H_2SO_4 (98 g/mole) would require 37 Tg/yr. The cost of construction of the airplanes is amortized over 20 years. Of the three H_2SO_4 options considered in de Vries et al. (2020), the cheapest is used here. Payload costs for SO_2 and H_2SO_4 are from de Vries et al. (2020).

	SO_2	H_2SO_4
Robock et al. (2009)	107	172
McClellan et al. (2012)	42	72
Smith and Wagner (2018)	17	69
de Vries et al. (2020)	34	54

To summarize, there is currently no way to do stratospheric climate intervention. However, designs of airplanes to loft sulfur into the stratosphere suggest that under a credible SRM scenario it would cost \$20–\$200 billion per year. Research and development to see if that is even practical remain to be done.

Research

Ethics and Governance

While the NAS concludes that "Albedo modification at scales sufficient to alter climate should not be deployed at this time," the authoring committee also recommended that "an albedo modification research program be developed and implemented that emphasizes multiple-benefit research that also furthers basic understanding of the climate system and its human dimensions" (NRC 2015, pp. 9, 10). This raises the question of whether such research is ethical (Robock 2012a).

Arguments for and against SRM Research

Although deployment of SRM may never be part of a portfolio to deal with global warming (Pierrehumbert 2019; Robock 2012b), a decision to deploy should be informed by knowledge of its potential benefits and risks. The National Academies of Sciences, Engineering, and Medicine (NASEM), as part of a major initiative on America's Climate Choices, have a committee working on such a research plan, to be published in 2020.[2]

Arguments against SRM research include a slippery slope to deployment or diversion of resources that could be better spent on something more valuable. Arguments in favor of such research include the need to know what would happen in order to avoid the risk of deployment in ignorance of potential consequences, the discovery of "showstoppers" that would reduce the likelihood of deployment, and the integral role of modeling research for climate intervention to improve climate models used for other purposes.

The National Research Council (NRC 2015), American Meteorological Society (AMS 2013), and American Geophysical Union (AGU 2018) all agree with previous strong recommendations for geoengineering research (e.g., Betz 2012; GAO 2011; Keith et al. 2010).

Indoor vs. Outdoor SRM Research

SRM research can be separated into indoor and outdoor (Robock 2012a). Indoor research consists of climate modeling of various SRM scenarios as well as analysis of analogs, such as volcanic eruptions, with climate models and study of observations. It may also involve technological development of nozzles or aircraft that could be used for deployment.

Outdoor research, which involves injecting salt particles into marine clouds or various substances into the stratosphere, requires governance, including review of potential environmental impacts, monitoring of the experiments, and sanctions if the researchers break the rules (e.g., Shepherd et al. 2009). The NASEM committee that is planning a research agenda is also looking at research governance approaches, and the Keutsch group at Harvard, which is planning an outdoor Stratospheric Controlled Perturbation Experiment (SCoPEx), has established an external advisory committee as a form of governance research.[3] But there are no national or international governance structures.

Perhaps outdoor research that involves the development of ships or planes designed for deployment, but

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[2] Information on the project for Developing a Research Agenda and Research Governance Approaches for Climate Intervention Strategies That Reflect Sunlight to Cool Earth is available at http://nas-sites.org/americasclimatechoices/new-study-reflecting-sunlight/.

[3] https://projects.iq.harvard.edu/keutschgroup/scopex-governance

does not involve spraying, can be done without governance to show how difficult and expensive it might be. Any spraying requires governance. Outdoor experiments that go beyond trying to build the equipment to brighten clouds or produce stratospheric aerosols need to be scientifically justified: What can be learned from them that cannot be learned from modeling and analogs?

Climate Modeling

Modeling is a major part of indoor research on climate change. Unlike other science, the system under study is the entire Earth, with no separate control and experimental versions. Any test of stratospheric SRM would have to be at full-scale implementation for decades to obtain statistically significant responses (because of the chaotic nature of the climate system, a large signal is needed to overcome the noise; Robock et al. 2010). Therefore, "laboratory research" relies on computer programs that simulate the behavior of the Earth system. They use the fastest computers in the world and have been tested by simulations of past climate and with weather forecasting.

Some experts argue that outdoor research is needed because they do not have confidence in imperfect computer models. But concerns about global warming are based on computer simulations of future climate changes in response to possible scenarios of human behavior and emissions of greenhouse gases and particles.

National and International Programs

The current international cooperative project on modeling of future climate is the Coupled Model Intercomparison Project Phase 6 (Eyring et al. 2016). It includes the Geoengineering Model Intercomparison Project (GeoMIP), in which 19 climate modeling groups have simulated how the climate would respond to reduced insolation, creation of a stratospheric aerosol cloud, or brightened marine clouds to reduce climate change from various global warming scenarios. GeoMIP (Kravitz et al. 2011) has produced more than 85 peer-reviewed publications, and results from experiments with the latest models (Kravitz et al. 2015) as well as those from previous experiments continue to be analyzed. Analysis has mostly focused on climate elements, but impacts also need to be studied, including those on agriculture and ecosystems (e.g., Trisos et al. 2018). There is no organized research program to support either the modeling or analysis of the experiments, but it is planned as part of the NASEM program.

Beyond the GeoMIP-specified research, new experiments, some labeled as GeoMIP Testbeds, are being conducted. These include the Stratospheric Aerosol Geoengineering Large Ensemble (GLENS) project (Tilmes et al. 2018). In addition, the Geoengineering Modeling Research Consortium (www.cgd.ucar.edu/projects/gmrc) has been initiated to coordinate testbed and other model simulations.

The Open Philanthropy Project funds the Developing Country Impacts Modelling Analysis for SRM (DECIMALS) project (www.srmgi.org/decimals-fund) to use local expertise to examine impacts in less developed countries. Eight DECIMALS teams are using output from GeoMIP and GLENS simulations to analyze impacts on agriculture, drought, dust storms, and the spread of cholera in Argentina, Bangladesh, Benin, Indonesia, Iran, Ivory Coast, Jamaica, and South Africa. Such work supports research capacity building and helps those who might be affected by SRM to have a voice in future research and implementation decisions.

What can be learned from outdoor experiments that cannot be learned from modeling and analogs?

In the United States there are many national centers (e.g., NCAR, the NOAA Geophysical Fluid Dynamics Laboratory, NASA Goddard Institute for Space Studies, NASA Goddard Space Flight Center, and the DOE with its new Earth system modeling efforts) with the resources to conduct relevant, needed research. In particular, NCAR has global climate modelers, land surface experts, cloud experts, and people working on impacts.

Business-as-usual research does not provide many resources for studying climate intervention (Necheles et al. 2018). Private funding is the largest source for global geoengineering research—$6 million in 2018; government funding fell from almost $6 million in 2014 to $2 million in 2018.

Deployment Scenarios

The impacts of any stratospheric SRM will depend on the amount of aerosols created and the timing and location of their deployment. So far only simple

FIGURE 3 Spectacular image of the June 22, 2019, eruption of Raikoke volcano in the Kuril Islands, from the International Space Station. Available online at https://earthobservatory.nasa.gov/images/145226/raikoke-erupts.

deployments have been studied, such as spraying aerosol precursors in the tropics (GeoMIP) or subtropics (GLENS) to produce globally averaged temperature targets or gradients. Many scenarios are extreme—such as balancing four times current CO_2 (GeoMIP G1) or business-as-usual greenhouse gas emissions until the end of the 21st century (GLENS; Niemeier and Timmreck 2015) to obtain a large signal in the climate response as compared to natural climate variability—and are not proposed as realistic.

Future research is planned with scenarios that might involve credible deployments, such as balancing overshoot scenarios to keep global warming at less than 1.5–2.0 K above preindustrial temperatures (e.g., Tilmes et al. 2016). In addition, research into the use of actual impacts on, for example, agricultural production, water availability, or human health as metrics, rather than global average temperatures, is in its infancy.

So far, sulfate aerosols, produced by either SO_2 gas injection or sulfate aerosol direct injection (e.g., Vattioni et al. 2019), have been the major type studied. Other types have been suggested, but study of them is just beginning (e.g., Keith et al. 2016). Given experience with sulfate aerosol clouds from volcanic eruptions and the availability of sulfur, the latter will probably remain the chemical of choice, but the engineering of sulfate aerosol particle production and the engineering, benefits, and risks of other chemicals deserve further study.

Analogues

The best analogue for stratospheric geoengineering is volcanic eruptions that inject sulfur into the stratosphere. Eruptions such as Eyjafjallajökull in 2010, which produced only tropospheric emissions, do not cause climate change as the aerosols have a lifetime of about a week rather than a year for the stratosphere. The last large eruption (defined as a stratospheric injection of 5 Tg SO_2) was that of Mount Pinatubo in the Philippines (17 Tg SO_2) in 1991, but there have been smaller ones since then, such as that of Nabro (1.3 Tg SO_2) in 2011 (Bourassa et al. 2012).

NASA (2018) has a plan to make observations following the next large volcanic eruption, using balloons immediately and airplanes later. A threshold of 1 Tg SO_2 would call for launching regular balloon flights, but the plan was not implemented after the June 2019 Raikoke eruption (figure 3), which emitted about 1.4 Tg SO_2 into the stratosphere (Simon Carn, Michigan Technological University, personal communication, June 24, 2019).

The NASA plan, once implemented, will allow observation of future eruptions not only to enhance understanding of the impacts of volcanic eruptions—the largest natural cause of climate change—but to observe how SO_2 converts into aerosols, how the aerosols grow and are transported, and how they affect ozone as well as UV and diffuse radiation at ground level. In the meantime, the same balloon instruments can monitor the background stratosphere to provide information about its composition and processes.

Summary

To produce $-2\ \text{W m}^{-2}$ radiative forcing—enough to counter about half of the warming from doubling CO_2 or to keep global warming less than 2 K above the preindustrial level for an aggressive overshoot scenario—would cost \$20–\$200 billion per year based on current simplistic analyses. But research is needed into engineering to see if it is even possible, as the technology currently does not exist.

In addition, there are varying potential benefits, risks, and concerns associated with stratospheric solar radiation management (table 2). Recent scenarios that include more sulfur injection than originally considered and detailed analysis of the impacts (Eastham et al. 2018) suggest that the risk of additional acid rain and snow needs to be evaluated.

Table 2 is not meant to be used by just comparing the number of items on each side. Benefit number 1 is that if SRM could be implemented, it would reduce many of the impacts of global warming. The question is whether society would be willing to live with all the risks to get this benefit. Some of these risks appear to be difficult to

TABLE 2 Potential benefits, risks, and concerns of implementing stratospheric climate intervention, updated from Robock (2016).

Benefits	**Risks or Concerns**
1. Reduce surface air temperatures, which could reduce or reverse negative impacts of global warming, including floods, droughts, stronger storms, sea ice melting, and sea level rise 2. Increase plant productivity 3. Increase terrestrial CO_2 sink 4. Beautiful red and yellow sunsets 5. Unexpected benefits 6. Prospect of implementation could increase drive for mitigation	*Physical and biological climate system* 1. Drought in Africa and Asia 2. Perturb ecology with more diffuse radiation 3. Ozone depletion 4. Continued ocean acidification 5. Additional acid rain and snow 6. May not stop ice sheets from melting 7. Impacts on tropospheric chemistry 8. Rapid warming if stopped *Human impacts* 9. Less solar electricity generation 10. Degrade passive solar heating 11. Effects on airplanes flying in stratosphere 12. Effects on electrical properties of atmosphere 13. Affect satellite remote sensing 14. Degrade terrestrial optical astronomy 15. More sunburn 16. Environmental impacts of injection technology (e.g., local pollution, noise, CO_2 emissions) *Aesthetics* 17. Whiter skies 18. Make stargazing more difficult *Unknowns* 19. Human error during implementation 20. Unexpected consequences *Governance* 21. Cannot stop effects quickly 22. Commercial control 23. Whose hand on the thermostat? 24. Societal disruption, conflict between countries 25. Conflicts with current treaties 26. Moral hazard: the prospect of its effectiveness could reduce drive for mitigation *Ethics* 27. Military use of technology 28. Moral authority: do humans have the right to do this?

address (Robock 2012b). They include the difficulty of global agreement on how to set the planetary thermostat, lack of a system to determine those who would suffer and how to compensate them, rapid climate change if stratospheric injection is quickly terminated, and unexpected consequences.

Research shows that it may be possible to control regional climates (e.g., Tilmes et al. 2018), but does not show that temperature and precipitation can be controlled at the same time. As research progresses, with different scenarios, materials, and objectives, it will be interesting to reconsider table 2 in the future, add new issues that come up, remove items that have been addressed, and determine whether enough information is available to decide whether to implement SRM. If it is determined that SRM is still too risky, this will be important input to societal efforts to work much harder on mitigation.

Acknowledgment

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Dialogue, negotiation, principle, and equity are all components of concerted efforts to address climate change.

EES Perspective

Engineering and Ethics in the Anthropocene

Elke U. Weber

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Climate change, a statistical and increasingly physically evident reality, is a global phenomenon that intersects with the discipline and practice of engineering in important ways, as documented by the articles in this issue. It is not a new phenomenon, but has struggled for the attention of the public, professionals and their organizations, and politicians and policymakers, for a long list of reasons that are psychological, economic, evolutionary, and political (Weber 2015, 2016, 2017).

Background

The French scientist Jean-Baptiste Fourier (1824) first described the physical mechanisms of the greenhouse effect that gives rise to climate change in the early 19th century. In 1861 John Tyndall at the Royal Institute in London determined which gases in the atmosphere trap heat and calculated expected increases in global temperature with surprising accuracy.

More recent prescient observers include the late geochemist Wally Broecker, who in 1975 warned about a planetary crisis if humans continued to emit large amounts of carbon dioxide into the atmosphere. And in 1987 NASA scientist Jim Hansen testified on climate change before Congress.

This column is produced in collaboration with the NAE's Center for Engineering Ethics and Society to bring attention to and prompt thinking about ethical and social dimensions of engineering practice.

Engineering as a discipline and profession will be affected by the physical, ecological, social, and political impacts associated with climate change and the response to it (or lack thereof). It has a stake in the current technoeconomic energy infrastructure and in any energy transition toward decarbonization. This includes existing possibilities in oil and gas exploration as well as future jobs and other engineering opportunities in renewables and abatement technologies.

Ethical and Related Considerations

Engineering advances are integral to the detection of climate change (Parkinson 2020). From rain gauges to weather radars and satellites, engineers provide tools to increase the predictability of water resources crucial to human well-being (Lettenmaier and Lund 2020; Sorooshian et al. 2020). Engineers also apply science and engineering principles to design solutions that help people thrive under changing local conditions, from engineering roads, buildings, and pipelines on impermanent Arctic permafrost to adapting to a melting tundra (Schnabel et al. 2020).

It is important to bear in mind that engineering advances in general tend to interact with sociological and psychological considerations and processes. In the engineering psychology class I teach I use signal detection theory, developed by both engineers (Peterson et al. 1954) and psychologists (Tanner and Swets 1954) after World War II, to make this point.

The ability to distinguish a signal/target from background noise in uncertain information environments depends not only on the quality of the engineered physical detection device (e.g., the d-prime of the radar system being used) but also on the motivations of the observer (e.g., a desire to avoid either misses or false alarms and thus the selection of a criterion for identifying a stimulus as either a signal or noise). This suggests that engineers could benefit from being more aware of the users as well as the economic and social impacts of their innovations. Portfolio-based water management that aims to align management options with the behaviors of water users, system managers, and regulators (Lettenmaier and Lund 2020) is a promising example of such an approach.

Responses to climate change raise a plethora of ethical questions, increasingly considered by institutions such as the UN Intergovernmental Panel on Climate Change (IPCC) in their evaluations of response options (Kolstad et al. 2014). Many options concern distributional issues related to the impacts of climate change and/or the costs of adapting to or mitigating it.

Impacts and the ability to afford the costs of action differ between the developed and developing world and between rich and poor communities in all countries. Such equity considerations are raised by Hinkel and Nicholls (2020) in the context of adaptation to sea level rise, but they pervade every aspect of climate change impacts and action.

> *The ability to distinguish a signal/target from background noise in uncertain information environments depends in part on the motivations of the observer.*

One important ethical debate, often masquerading as an economic one by posing it as a question about the appropriate discount rate, concerns governments' and other organizations' willingness to take responsibility for tackling climate change now versus passing it on to future generations (see Stern 2006 and Nordhaus 2007 for contrasting views on this).

Philosophy and ethics also comment on the role of skepticism to keep the science of climate change honest (Keira 2015) rather than as a tool of vested interests that fight policies designed to increase public welfare (Hoggan 2010).

Limitations of Technological Innovation

One reason climate change is a wicked problem (Grundman 2016) is that mitigation and adaptation require coordinated action on multiple fronts. Technological innovation—the domain of engineering—is one such front and a necessary ingredient for the majority of the 15 climate stabilization "wedge" strategies described by Pacala and Socolow (2004) to keep CO_2 concentrations under 500 ppm for the next 50 years. But it is only one front, and must be coordinated with political action, social innovation, and action by individuals, communities, institutions, and firms.

Simply put, there is no silver bullet—only silver buckshot (Lettenmaier and Lund 2020; Weber and Bell 2014), requiring sustained and integrated action over time. Unfortunately, even professional decision makers typically stop looking for solutions to a problem after one has been implemented—the so-called "single action bias" documented among doctors and farmers (Weber 2015).

Engineering solutions help to reduce energy intensity, increase energy efficiency, and create renewable sources of energy that are cost effective and safe. But such innovation will not suffice. Rapid Switch, a project headquartered at Princeton's Andlinger Center for Energy and the Environment with partners across the globe, addresses the unprecedented need for both speed and scale in the technological and socioeconomic changes required to confront the climate crisis.

To many people, mitigation technologies present a moral hazard by appearing to encourage the continued use of fossil fuels.

It is becoming increasingly obvious that the silver buckshot needed for speed and scale will involve engineering and institutional innovation in negative emissions technology, parts of which are known as carbon capture and storage, discussed by Wilcox (2020). All but one of the IPCC (2018) scenarios that may restrict average global temperature increases by 2100 to 1.5°C or 2°C require substantial use of this technology. This makes it all the more surprising how little attention and money are allocated to R&D on these technologies, exemplifying perhaps a collective ambivalence to them. On the one hand, climate mitigation experts and modelers argue that these technologies will be needed soon and at major scale and that they do not preclude decarbonization efforts but must operate in parallel to them. On the other hand, to many other segments of society, negative emissions technologies present a moral hazard by appearing to encourage the "wrong" thing, continued use of fossil fuels (Anderson and Peters 2016).

The idea of purchases of carbon offsets elicits the same ambivalent response. Carbon offsets are a very effective way of creating and paying for CO_2 sinks as long as properties such as "additionality" and lack of "leakage" are guaranteed (Palmer 2016), but they evoke the medieval indulgences sold by the Catholic Church, absolving sinners for a price. Thus, while proponents view high-quality offsets as an asset that supports carbon-fighting projects, critics see them as a license to pollute.

Principled versus Pragmatic Stances

Ambivalence about negative emissions technologies and carbon offsets raises questions about the pros and cons of either taking a principled and often moral stance on such issues versus being pragmatic and open to technological-social-political-economic solutions that work but may trade off on one value to satisfy another. Multiple goals that are often in partial conflict are a fact of life.

A principled stance introduces a hierarchy into a goal structure and refuses to make certain "taboo" trade-offs between goals (e.g., no price on human life, no use of nuclear power under any circumstances). A pragmatic stance looks for compromises and trade-offs to achieve something like the greatest good across goals.

People and groups differ in their goals, and agreements and solutions need to be found in either cooperative or competitive contexts. Negotiation theory teaches ways to find win-win solutions in such situations, and requires a willingness to creatively explore goal conflict and for each side to compromise on objectives less important to them to achieve gains on objectives of greater importance.

A dogmatic approach may be counterproductive by taking response options prematurely off the table, but standing up for valued principles in an uncompromising way can create sorely needed social counterweights to the all-too-ready sacrifice of societal goals or moral values for short-term profit or expediency.

Questions

Discussions of "geoengineering" (e.g., Robock 2020) tend to treat the topic as a concern for the future. No doubt, there are significant issues of unintended consequences and governance to be worked out for technologies like stratospheric solar radiation management. Society needs to determine how best to balance different types of errors of judgment that can be committed in this arena, whether they are errors of commission ("sorcerer's apprentice" concerns about unforeseen negative consequences) or of omission (failure to aggressively pursue research on risk management strategies that may be necessary in the medium future) (Spranca et al. 1991).

But let me be provocative and state something that should be obvious but is rarely mentioned: It seems rather late to worry about the ethics of engineering the climate now!

Humans have been (inadvertently) engineering current and future climate for multiple decades, as increases in population, industrial output, and other human activity have driven up energy consumption that, satisfied by fossil fuels, has generated rapid increases in greenhouse gas emissions. These effects have earned the current geological age the name "Anthropocene," to acknowledge the fact that human activity has become a dominant influence on the global climate and environment.

Does it matter that this geoengineering has occurred for the most part without full intention and awareness? Should society not seek and encourage broad-based social dialogue about the ethics of current actions and inactions, especially when asked to do so by growing numbers of its young members around the world? What responsibilities come with humans' ability to shape the future of planet Earth? What are the potential contributions and/or responsibilities of professional individuals and organizations in this context? One corollary of the silver buckshot reality is that all members and levels of society have a role to play.

Dialogue and Collaboration for the Future

Ten years ago the American Psychological Association convened a task force to determine the contributions that different subdisciplines of psychology can make to establish the impacts of global warming on human mental health, well-being, and decision making and to design better ways to adapt to or mitigate climate change risks (APA 2009). Following my membership on the task force, I engaged in a multiyear scientific collaboration with two engineers and a legal scholar to diagnose and remove barriers to more sustainable infrastructure design by engineers and architects (e.g., Klotz et al. 2018; Shealy et al. 2016). Encouraged by the possibilities, we recently convened an international expert panel that produced a report on the joint contributions of behavioral science, architecture, and engineering toward sustainable design (Klotz et al. 2019).

Similar efforts could enhance awareness of climate change impacts and help determine effective ways of channeling expertise toward climate change solutions in a much broader range of professional disciplines and settings.

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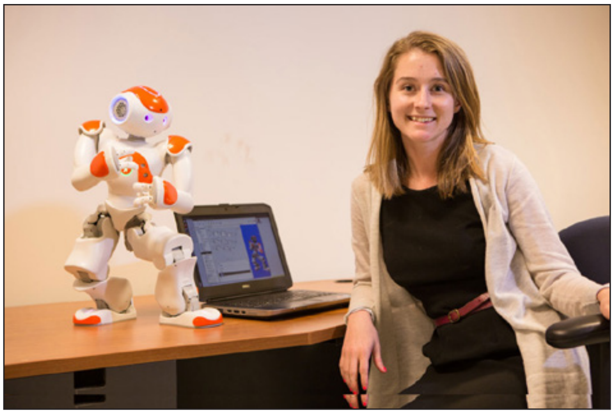
An Interview with . . .

Amy LaViers, Assistant Professor of Mechanical Science and Engineering, Robotics, Automation, and Dance Lab, University of Illinois at Urbana-Champaign



Amy LaViers with a small humanoid NAO robot in her lab at the University of Virginia, 2014. Image by Stacey Evans.

RON LATANISION (RML): We're delighted to talk with you today, Amy. Let's start by learning a little about your interest in both engineering and dance.

AMY LaVIERS: I always had an interest in both things. When I was looking at colleges, I looked for places that had a strong engineering program and places that had a strong dance program, never thinking I would combine the two interests the way that I have. I was just following the thread of what excited me and what I wanted to continue doing in college.

Then I got to study both things side by side. On the last Thursday of my junior year I had two classes: automatic control and a dance writing seminar. In the morning was the last lecture for automatic control; it was a notoriously hard class we all had to take—I was very confused in that class. That day the instructor showed us an MIT unrideable bicycle. Usually when you ride a bike, you turn the handlebar and the front wheel rotates; on this bike, they switched that and made the back wheel rotate from the front handlebars. This changes the system, making it take years to practice to learn to ride this bike. That example really resonated with me. All of a sudden, I completely understood this course that had been so mysterious to me: I could imagine a bike that I couldn't balance on and the difference between an unstable position—when it's related to my body—and a more stable one.

That afternoon I went to dance writing class and we watched a video of Twyla Tharp, the famous choreographer who has worked with both modern and ballet dance styles. She talked in this interview about the stability of different home positions in dance. In ballet, you can put the heels together and point the toes out and it creates a very unstable moment, it's a little wobbly. But if you need to lift one leg from that position, it doesn't affect you as much as when you stand with your two feet parallel and right under your hip bones—that's the home position in modern dance. It's very stable and easy to stand like that, but if you need to pick up one foot, you disrupt that stability and have to shift your weight in order to create space to lift the foot.

She talks about the inherent stabilities of these different home positions and how that leads to different patterns and movement. For me that was a moment of 'oh my gosh, that's what we've been studying in my control class.' That's when I decided I would love to use the mathematics I was learning in my engineering coursework to study different styles of motion. And that's what I'm working on today, in the context of robotics.

RML: Have you danced professionally or in a performance?

DR. LaVIERS: I never know how to answer that question. I've been paid to perform, to dance, but I've paid much more for dance lessons than I've been paid to dance. In terms of how professional I am, I think that's the best way I can explain it.

As part of my research, group members and collaborators perform regularly, including on professional stages,

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This conversation took place January 15, 2020. It has been edited for length and clarity.

Kate Ladenheim performs “Babyface” at the 2019 Dance NOW Festival, Joe’s Pub, Public Theater, New York. The robotic wings, developed in residency with Dr. LaViers’ lab, create an onstage hyperfeminine cyborg character to explore the experience of the feminine gender in technology. Their motion and interaction modalities required students in the lab to think about choreography and embodiment. Image by Yi-Chun Wu.

such as the Dance Now Festival at Joe’s Pub at the Public Theater in New York City. Thus, in that sense, I still actively perform dance as part of my profession.

CAMERON FLETCHER (CHF): When you say you’re performing on stages in New York, do you mean dancing with your body or having robots perform movements?

DR. LaVIERS: Both.

CHF: Together?

DR. LaVIERS: Together.

RML: What is an example?

DR. LaVIERS: My lab has an artist in residence named Kate Ladenheim, and she has collaborated with us to create a pair of robotic angel wings that she wears onstage to perform—they’re a physical metaphor for the ways technology often requires women to perform an ideal of gender. Kate wears a machine and sort of becomes an on-stage cyborg, using the physical machine as a way to bring scenes of technology on stage and push against what the expectations might be of an angelic woman.

It’s been a great project for my lab, in particular thinking about what should be the connection between the performer and the machine? We’ve been working on breath sensors that create both a conscious and unconscious boundary between the performer and the wings. Of course, there’s also the question of how we attach the wings to her body. There are a lot of technical challenges that come up in that artistic expression.

CHF: I see that one of your research areas is security and defense. What kinds of work are you doing that are related to dance for security and defense?

DR. LaVIERS: The broad goal of the lab is in thinking about how movement expresses information and in trying to create artificial systems that have more complex information-rich movement. In defense that idea applies in a few ways.

For a DARPA project I worked on, we were thinking about a movement specification language that would be platform invariant, the idea that I could take one sequence of commands and apply it to a host of robots.

One reason I think I convinced DARPA that dance is an important part of answering that question is through my study of the Laban/Bartenieff Movement System, a movement taxonomy that underpins the movement notation system called *Labanotation*.

I see the Laban system as a way of understanding people’s perceptual signposts for perceiving intent in movement. Imagine you have a corps of dancers on stage and there is the idea that they are all moving in unison. That’s a perceptual phenomenon that we all experience: “Look at that group of 30 distinct individuals moving in unison.” In fact, never will you see 30 perfectly mechanically similar people on stage doing exactly the same thing. It just seems like they are doing the same thing. The idea of imitation or moving in unison or doing the same thing is a perceptual feature of people.

How did those people get to the point where you think they are dancing in unison? They use strategies, choreographic taxonomies, body-based language, and years of training to get to that point and to change their motion such that it looks like it’s the same.

We use that idea to think about what it means for two distinct robots to take the same movement command and do “the same thing.” It’s not actually possible, but perceptually it is—if people think it’s the same, then we are starting to align our movement taxonomy or our programming language to people's perception of movement.

In one experiment we have a group of people use a shorthand version of Labanotation to label a human movement phrase choreographed in response to stimuli. We video the sequence and use their labeling to create the movement with a robot.

Then new participants, who were not part of the first part of the experiment, watch the original human and three distinct robots, a large two-arm Rethink Robotics Baxter robot that cannot translate or move in space, a small Softbank NAO humanoid, and a mobile KUKA youBot with one arm and a mobile base. We ask the participants, Are these robots doing the same thing as the original human?

From this we have recently developed a teleoperation system for rapid response to dynamic unknown environments and offering operators joint-space control. As opposed to telling a robot at each joint "do this" or "do that," we use the large gross movement ideas from the Laban system to quickly create many joint angles moving at once based on higher-level commands like "move forward."

RML: I'm beginning to understand that, from a military point of view, you can program robots to do a lot of things, such as patrol or identify targets, but they can't do it with this ease of motion that you, and perhaps DARPA, think would be more useful. Is that a general framework for the interest of DARPA in this work?

DR. LaVIERS: Yes, I think so. As part of the grant, I interviewed soldiers who work with PackBots. They said that some of the things they want to be able to do with the robot involve translating the base and moving and articulating the arm at the same time. This is a more complex movement. It would be helpful if a soldier could translate intent to a robot as easily as he could shout to another human counterpart how to do these movements.

We're working on creating a language set for generating movement rapidly on the fly, which is really important for use in unknown environments. The physical hardware can do it. It's the interface between the human and the robot that can't rapidly disseminate those commands in the same natural way.

There's also not a sense of the right way to take an old program from the '80s and put it on a current robot. Computers struggle with that a bit, but there's a lot more interoperability of programs on different pieces of computer hardware than with robots. As a broader, more foundational piece, there's also thinking about what's the right way to do that for articulated machines with distinct physical morphologies.

Movement score notated in Motif, a shorthand notation system that uses symbols common to Labanotation, created by Amy LaViers. The score indicates four movements described through the lenses of spatial direction, movement quality, modes of shape change, and body landmarks. Dr. LaViers has also used Motif for robotic motion on a variety of robotic platforms using the same specification. Image by Amy LaViers.

RML: In your work with graduate students, do they typically have interests as broad as yours? Are they more computer science oriented?

DR. LaVIERS: I try to have students from many ends of the spectrum present in the lab. Part of the way I do that is I offer independent studies and collaborations with students who are not in mechanical engineering. They may be in dance, or from kinesiology or neuroscience.

For the students who are doing a thesis with me and graduating from my department, I think what makes them most successful is having a background of some kind in what I call intense movement or embodied investigation. We've had rock climbers, Frisbee players, runners, classically trained Indian dancers, and ballet dancers. These are people who have spent a lot of time with their body; they value its physical intelligence and the expertise needed to give a correction to somebody or to change the strategy you're using to, say, reach up from one rock hold to the next. Those students do the best.

Robotics is really popular and a lot of students want to work with the lab, but a lot of students are not the right fit to work with the lab. I show students initial semester-long projects, for example, or some way to try out the lab. For example, we have a weekly writing hour and a weekly movement hour in addition to our lab meetings that are unusual in my field. Those events can be challenging for students who have a very different idea about what engineering is than I have. I think it's push and pull in terms of both recruiting students and making sure they understand how unusual the lab is when they join.

We are all creating and choreographing movement profiles every day.

CHF: What have you learned from your students who have the intensive experience of using their bodies in "nondance" ways like rock climbing and Frisbee?

DR. LaVIERS: I work to have everyone realize that we are all creating and choreographing movement profiles every day—that is, in my view, a "baby form" of dancing. Even if we're all sitting around a table, I'm moving in a way that's designed to make you think I know what I'm talking about. That's a small act of choreography and a small act of dance right there.

We went to a rock climbing gym and a climber showed us how it's done. There's a lot of choreography there. For example, you try a series of hand holds and if one doesn't work what's the reason? It could be a bodily reason because your arm doesn't reach far enough so you have to create a different path. That's a form of dance, adjusting spatial pathway. Let's say there's a hand hold that's sort of far away, and you use a mental image of "punching up" to it, adjusting the quality of your intent. That's a movement strategy that a choreographer might ask a dancer to use to get the right texture in a moment or a certain part of a piece.

This is the lens I see the world through. To me, all those things are based on changes in movement that are perceivable to other human beings.

CHF: So for you it's a continuum, it's not a matter of separate categories of movement.

DR. LaVIERS: It's definitely not a matter of separate categories of movement. In fact, what's so great about dance is that everyone has their own mental image of it. If you study dance at a university, those faculty—like choreographers in New York City—are trying to come up with new movement profiles that you would not associate with dance and that you've never seen on stage.

I recently saw a piece by Kimberly Bartosik, a former Merce Cunningham dancer. She's working with gyrating, very physical, heavy, quick movements that hit hard and aggressively. It seems painful. You watch the dancers and think, 'How can they physically do it?' She's creating a new texture that people haven't seen before. That's what dance is. It's not about selecting from a canon—"here are the dance moves and here are the nondance moves." It's "how do I take this body and create a new idea that people have not seen on stage?"

Another example is Yvonne Rainer, one of the more famous postmodern choreographers. She put on stage something that looks so utterly pedestrian that people were shocked, they thought, 'How can walking around on stage be an expression of art?' But it turned out to be one of the greatest expressions of art. It's about innovating and finding new movement profiles.

You can also go to a class where they will teach you moves A, B, C, D, E, F. But dance as a field, dance as a cutting-edge intellectual pursuit, is not that.

RML: When you watch a professional athlete, a lot of what they do—I don't know if I would call it dance, but it certainly has dance characteristics. For example, if you watch the footwork involved for a first baseman, readying himself to catch the ball from an infielder, it's like ballet.

I think also of gymnastics. You're probably closer to gymnastics with the kinds of things you could presumably prepare a robot to do as a means of examining gymnastics movement.

It occurs to me that there are a lot of areas that your work could impact, such as medicine or health care. Movement for artificial limbs, for example. Have you thought about any of that in terms of the work you're doing?

DR. LaVIERS: I often tell my students that we all perceive pattern and motion. With these moments in baseball that you're comparing to ballet, I think what you're seeing is human grace and coordination and harmony and physical movement that has been practiced and perfected for a particular moment in a particular context and it just looks beautiful and right.

RML: We don't necessarily think of athletics as being graceful, but it's better if you can watch in slow motion. There seems to be a lot of dance and athleticism required to make a good first baseman.

DR. LaVIERS: One question we're thinking a lot about is what it means to look graceful. That's a qualitative term that we apply to many different physical situations and I don't know what defines it. Figuring it out involves asking questions about what looks graceful and what doesn't. For an upcoming study we're going to look at "robot movement A" and "robot movement B" and ask "Which of these is more graceful?" We also see grace in animals, in all sorts of natural creatures, but we rarely have quantitative models for what generated that movement—hence the advantage of using robots to study a question like this.

I'm really interested in understanding what differentiates natural movement and artificial movement and understanding the benefits of both. In health care, that could translate into things like rehabilitation or having a better model for how people move under normative healthy circumstances. We also think about the caregiving setting; for one project we thought about having teams of robots care for people in their homes, particularly older adults.

My lab's contribution has been about ways to create systems whose movement changes in a new context, communicates an internal state. If you're reaching for your reading glasses on a Saturday afternoon, the way you move to get them is different from running to get aspirin because someone is about to have a heart attack. We want to create robotic systems that are externally reflective of those very different internal states.


Catie Cuan (left) and Amy LaViers (right) perform "Trio," an excerpt from Time to Compile, at the 2018 Dance NOW Festival, Joe's Pub, Public Theater, New York; Ishaan Pakrasi (not shown) is operating the robot. Catie is an artist and graduate student in robotics at Stanford University and was the lab's artist in residence 2017–18; Ishaan completed a master's thesis in the lab at UIUC. The piece explored the feelings of frustration that occur both in programming a machine and in being a woman working in engineering. Image by Yi-Chun Wu.

RML: With your interest in computation and mechanical engineering and dance and so on, it seems like all the ingredients, all the infrastructure, to do important work on artificial limbs.

DR. LaVIERS: We haven't looked at artificial limbs yet, but a lot of the same ideas underpin that area.

RML: Your undergraduate training was at Princeton, is that correct?

DR. LaVIERS: Yes. I studied mechanical and aerospace engineering and dance. You can't major in dance—to my parents' great relief. But when I was there, there was a program in theater and dance; now dance is its own program and you can get a certificate, which is like the equivalent of a minor at Princeton.

RML: Then you got your master's and PhD in electrical and computer engineering at Georgia Tech. I don't know the Laban/Bartenieff Institute of Movement Studies. Could you tell us a little about it?

DR. LaVIERS: It's based in New York City but they have programs all over the world that train certified movement analysts; I did my training in New York and Belgium. It's a 2-year certification program that I did in modular chunks, like 2½ weeks at a time, over the course of 2 years.

The Laban/Bartenieff Movement System is more like a dance degree than an engineering degree, but is probably somewhere between those two. It's very analytical. For example, there are movement scales that traverse various Platonic solids, so you have to think about the progression and balance of those forms. As soon as I got my faculty position at UVA, I started that program because I knew it was an area that I'd been leveraging in my research but needed a deeper, proper exposure to.

> *In 50 years we will have so much more respect for what natural systems can do.*

One of the areas we study is the Effort System, a way of categorizing different qualities of movement—a 'flick' versus a 'punch' versus a 'slash.'

RML: Do you envision your life as that of both an academic and a dancer? How do you balance your two interests?

DR. LaVIERS: I think my ultimate choice would be a joint appointment with a dance department and an engineering department. Both can be pursued with a university—or without a university. I don't know what the ideal mix of activities is for myself, but for now the university's a beautiful place to do this work.

RML: How did you become associated with the DARPA programs? Did you respond to an RFP?

DR. LaVIERS: I responded to their young faculty award (YFA) call in 2014 or 2015. As an assistant professor I had visited DARPA program managers who might be interested in my work and been encouraged to apply for the YFA.

RML: Where would you say your work is at this point in terms of your own objectives and in terms of DARPA's interest? Have you had any of your products in the field?

DR. LaVIERS: Not yet. But they renewed my grant for a third year, and I'm working on some follow-on projects to move toward understanding new adaptations. One of the ideas was to compare today's robots and look for a natural correlate to the movement capacity of these machines from an information-theoretic point of view, rather than traditional measures of torque, force, speed, and precision.

Through these lenses robots can outpace their natural counterparts. That has been true for many decades. But for something information rich and complex, there are a lot of ways that natural systems still outperform artificial systems. From very different viewpoints—not Newton's viewpoint, I would say, but from a Shannon information theory viewpoint—I wondered what might be a natural correlate to robots.

One program manager at DARPA is very interested in using this viewpoint to compare artificial and natural systems. For the natural correlate, it may be the tiny *C. elegans* worm. Quantitative models of its motion are richer, requiring more complexity, more numbers to describe a pose, than for typical modern robots.

C. elegans has only 302 neurons and persists in dynamic unknown environments throughout its life. We are really curious about that. Why do *C. elegans* know how to do stuff that machines can't do?

RML: As you are speaking, another thought occurs to me. This year, we're celebrating the 50th anniversary of *The Bridge*. When you look at the past 50 years, you can see just how amazing the transformation in engineering and technology has been in such a short period of time. The internet, robots, all the things that we take as a given today have emerged. Thinking about robots, their applications, the technology of building them, their capacity for movement, and other capacities, where do you think this field will be in the next 50 years? Do you have a vision of what the future will be for robots?

DR. LaVIERS: Well, I'm a contrarian at heart. My answer to this question points in the direction opposite of where I think everyone else is.

In my honest opinion, in 50 years we will have so much more respect for what natural systems can do. There are Boston Dynamics videos of a robot doing a back flip and people are going crazy about how this was solved. But that machine does a back flip off a box of a very particular height onto a surface with a very particular friction with a very particular lack of wind. I think in a few decades we're going to have to come to grips with how incredible it is that humans can do back flips in so many environments—in the dark or in the light, in the rain, from a high point or a low point, on a full stomach or an empty stomach….

I think we underestimate the capacity for movement of natural systems because as mechanical engineers we're fixated on measures of movement like force, torque, and precision. We see those as the way to measure movement. It's true that, on those measures, robots outperform most natural systems, although there are some really interesting natural systems with crazy movement profiles.

But the lens of dance encourages us to think about not just how well, how hard, how fast can you do this one thing but how many different things can you do and how much control do you have over every choice you make as you move through space. I think in a few decades we'll understand the challenge of robotics better than we do today. I think there's been a lot of overhyped promise from the technical community as well as media and related communities. Look at self-driving cars. I think the claims about what we can do in 5–10 years in that space have been irresponsible, coming from a lack of respect for how incredible nature is.

These things go in swings. I think right now there's a lack of deference to observation of natural systems, that I hope robotics will have in the coming decades.

RML: I see the contrarian in your thinking, but I think you're right. I think it's good to balance all the pluses and minuses.

CHF: Amy, it sounds like you're forging this very interesting dynamic marriage of two fields that often are not put together. I'm wondering where you see your work going in say 10 or 20 years. What's the natural extension of your thinking and exploration?

DR. LaVIERS: That's a good question and a harder one to answer. Some of that depends on what opportunities I'm given, being at that critical tenure moment. I think that could change a lot. Someone like me who doesn't do the traditional disciplinary thing faces a special challenge in finding the right home for my work.

I think of disciplines like lenses. If dance is blue and engineering is red and what I'm doing is purple, it's never going to look as red to the red people and it's never going to look as blue to the blue people as it could if it weren't purple.

What I'm curious about and want to be able to understand better in 10 years is this question of natural systems and their movement, where they may excel in ways we don't completely understand. I'm fascinated by this. When you put a human body on stage next to a robot, that difference is highlighted even more because humans are so expressive.

There are labs sprouting up that are centrally interested in how the performing arts can help robotics.

We're trying to understand what that means—what is grace? What is expression? What does it mean to do the tango versus a pas de deux in ballet? They look different. Qualitatively, we can see that, but quantitatively modeling what is different about the two is the first question I'm interested in. I want to understand dance and how we move and how we change our profile. In the next 10 years, I might have 1 percent of that answer.

CHF: The word that comes to mind as I listen to you describe your efforts and interests is groundbreaking. Have you talked with colleagues who are doing anything like this, aside from the people in your lab?

DR. LaVIERS: A lot of people. There are many dancer-engineers and other artist-engineers, and part of my life is helping to amass this community of people who are thinking in a similar way. We do workshops at conferences or symposiums where we invite like-minded people. Some people who do very similar work are Ken Goldberg, Thecla Schiphorst, and Michael Neff. Among people my age, like Elizabeth Jochum, Kristin Carlson, Naomi Fitter, Kate Sicchio, Heather Knight, and Guy Hoffman, there are labs sprouting up that are centrally interested in how the performing arts can help robotics.

CHF: Very cool. You are in on the ground floor. Good for you.

RML: This has been a terrific conversation, Amy. Thank you for joining us this afternoon. I wish you all sorts of good luck in moving your work forward. I like what you're doing, it's very transformative. Congratulations and much good luck.

DR. LaVIERS: Thank you both so much.

NAE News and Notes

Class of 2020 Elected

In February the NAE elected 87 new members and 18 international members, bringing the total US membership to 2,309 and the number of international members to 281.

Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate,… the engineering literature," and to "the pioneering of new and developing fields of technology, making major advances in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

A list of the newly elected members and international members follows, with their primary affiliation at the time of election and a brief statement of their principal engineering accomplishments. Election of new NAE members is the culmination of a yearlong process. The ballot is set in December and the final vote for membership is in January.

New Members

Lilia A. Abron, chief executive officer, president, and founder, PEER Consultants, PC, Washington. For leadership in providing technology-driven sustainable housing and environmental engineering solutions in the United States and South Africa.

Eleanor Allen, chief executive officer, Water for People, Englewood, CO. For leadership and advocacy in making clean water and sanitation systems accessible to people around the world.

David J. Allstot, professor, electrical engineering and computer science, Oregon State University, Corvallis. For research and commercialization of mixed-mode integrated circuits and systems.

Robert O. Ambrose, division chief, Software, Robotics, and Simulation Division, NASA Johnson Space Center, Houston. For advances in dexterous space robotics, and for leadership in human-robotic teaming in space operations.

Saeed D. Barbat, executive technical leader, safety research and innovation, Ford Motor Co., Dearborn, MI. For leadership in automotive safety and contributions to the science of crashworthiness, occupant protection, and biomechanics.

Peter J. Basser, senior investigator, Section on Quantitative Imaging and Tissue Sciences, National Institutes of Health, Bethesda, MD. For development of diffusion tensor MRI and streamline tractography, transforming the characterization of brain disorders and visualization of nerve fiber pathways.

Barbara A. Bekins, research hydrologist, US Geological Survey, US Department of the Interior, Menlo Park, CA. For contributions to characterizing subsurface microbial populations related to contaminant degradation.

Stacey F. Bent, professor, Department of Chemical Engineering, Stanford University, Stanford, CA. For contributions to materials surface chemistry and its application across technology platforms from energy to electronics.

Thomas Berson, chief security advisor, Salesforce.com Inc., San Francisco. For contributions to cybersecurity in the commercial and intelligence communities.

Stephan R. Biller, vice president, Watson IoT, IBM Corp., Durham, NC. For leadership and advancement of manufacturing technologies and innovations based on the Internet of Things and digital data.

Charles F. Bolden Jr., president, Bolden Consulting Group LLC, Alexandria, VA. For leadership and development of US human spaceflight and space operations programs, and for revitalizing fundamental aeronautics research.

Alison K. Brown, president and chief executive officer, NAVSYS Corp., Colorado Springs. For contributions to research and development of precision navigation and timing technologies.

Marilyn A. Brown, Regents' Professor and Brook Byers Professor of Sustainable Systems, School of Public Policy, Georgia Institute of Technology, Atlanta. For bridging engineering, social and behavioral sciences, and policy studies to achieve cleaner electric energy.

Graham V. Candler, McKnight Presidential Professor, aerospace engineering and mechanics, University of Minnesota, Minneapolis. For development and validation of computational models for high-fidelity simulation of supersonic and hypersonic interactions.

Reginald DesRoches, William and Stephanie Sick Dean of Engineering, George R. Brown School of Engineering, Rice University, Houston. For research and design of resilient infrastructure systems to mitigate damage from natural disasters and other extreme conditions.

Joel Emer, senior distinguished research scientist, NVIDIA, Westford, MA. For quantitative analysis of computer architecture and its application to architectural innovation in commercial microprocessors.

Horacio D. Espinosa, James and Nancy Farley Professor of Mechanical Engineering, Northwestern University, Evanston, IL. For contributions bridging nanoscale experimentation and atomistic simulations.

John C.C. Fan, president, chief executive officer, and chair of the board, Kopin Corp., Westborough, MA. For innovation and entrepreneurship in electronic materials and devices for displays.

Margaret M. Faul, vice president, drug product technologies, Amgen, Newbury Park, CA. For technical leadership in the development of marketed medicines and leadership in enabling technologies, pharmaceutical standards, green chemistry, and sustainability.

Karl N. Fleming, president, KNF Consulting Services LLC, Spokane, WA. For contributions to probabilistic risk assessment methods and their application to enhance the safety of nuclear power facilities.

Gene A. Frantz, cofounder and chief technical officer, Octavo Systems, Sugar Land, TX. For leadership in the development and commercialization of digital signal microprocessors.

Paul L. Freedman, chief executive officer, LimnoTech, Ann Arbor, MI. For development and application of science-based computer models for watershed assessment, remediation, and management.

Rajeev Gautam, president and chief executive officer, performance materials and technologies, Honeywell, Morris Plains, NJ. For business and technical leadership in the oil, gas, and petrochemicals industry.

Eric Gebhardt, managing director, KCK-US, Houston. For development and utilization of advanced electric generation technologies including gas and wind turbines.

Thomas R. Giallorenzi, senior technical fellow, Communication Systems-West, L3Harris, Salt Lake City. For innovation and entrepreneurship in civilian and military communication networks and systems.

Robert B. Gilbert, department chair and professor, Civil, Architectural, and Environmental Engineering, University of Texas, Austin. For advancing the use of reliability analyses, risk assessment, and risk-based decision making for complex engineering projects.

Kenneth E. Goodson, Davies Family Provostial Professor and senior associate dean, Department of Mechanical Engineering, Stanford University, Stanford, CA. For developments in microprocessor thermal management and nanoscale heat conduction.

Kenneth C. Hall, Julian Francis Abele Professor, Department of Mechanical Engineering and Materials, Duke University, Durham, NC. For development of unsteady aerodynamic and aeromechanics theories and analysis for internal and external aerodynamic flows.

Vicki L. Hanson, executive director and chief executive officer, Association for Computing Machinery, New York City. For contributions to the design of accessible systems, and for leadership in the computer science and engineering community.

Latonia M. Harris, scientific director, pharmaceutical development and manufacturing science, Janssen Pharmaceutical Companies of Johnson & Johnson, Malvern, PA. For leadership in biomanufacturing of a breakthrough immunotherapy biotherapeutic, and for outreach activities in STEM education.

Susan J. Helms, principal and owner, Orbital Visions LLC, Colorado Springs. For accomplishments in civil and military space programs.

Susanne V. Hering, founder and president, Aerosol Dynamics Inc., Berkeley, CA. For advances and commercialization in aerosol measurements and instrumentation.

Susan S. Hubbard, associate laboratory director and senior scientist, earth and environmental sciences, Lawrence Berkeley National Laboratory, Berkeley, CA. For contributions to hydrogeophysics and biogeophysics and the geophysics of permafrost.

Omar Ishrak, chair and chief executive officer, Medtronic, Minneapolis. For contributions to diagnostic ultrasound, and for leadership in medical technology innovation and globalization.

Dana (Keoki) Jackson, chief engineer and vice president of engineering and program operations, Lockheed Martin Corp., Bethesda, MD. For developing human and technological aerospace capabilities for national security, and for promoting global technology cooperation.

Mrdjan Jankovic, senior technical leader, Ford Research and Advanced Engineering, Ford Motor

Co., Dearborn, MI. For contributions to nonlinear control theory and automotive technology.

Sallie Ann Keller, division director, Social and Decision Analytics Division, and professor of public health sciences, Biocomplexity Institute & Initiative, University of Virginia, Charlottesville. For development and application of engineering and statistical techniques in support of national security and industry.

Ioannis G. Kevrekidis, Bloomberg Distinguished Professor, Department of Chemical and Biomolecular Engineering, Johns Hopkins University, Baltimore. For research on multiscale mathematical modeling and scientific computation for complex, nonlinear reaction, and transport processes.

Ronald Klemencic, chair and chief executive officer, Magnusson Klemencic Associates (MKA), Seattle. For innovation in the design of high-rise buildings worldwide, and for research and design guidelines to advance structural engineering practices.

Tamara G. Kolda, distinguished member of the technical staff, informatics and systems assessments, Sandia National Laboratories, Livermore, CA. For contributions to the design of scientific software, including tensor decompositions and multilinear algebra.

Julia A. Kornfield, professor, chemical engineering, California Institute of Technology, Pasadena. For developing megasupramolecules for antimisting fuel additives and light-adjustable intraocular lenses to improve cataract surgery outcomes.

Paul E. Krajewski, director, global research and development, General Motors Co., Warren, MI. For development and implementation of lightweight automotive materials.

Steven L. Kramer, professor, civil and environmental engineering, University of Washington, Seattle. For contributions to geotechnical earthquake engineering, including liquefaction, seismic stability, and seismic site response.

Thomas R. Kurfess, chief manufacturing officer, Oak Ridge National Laboratory, TN. For development and implementation of innovative digital manufacturing technologies and system architectures.

James F. Kurose, distinguished professor, College of Information and Computer Science, University of Massachusetts, Amherst. For contributions to the design and analysis of network protocols for multimedia communication.

Sarah Kurtz, professor, materials science and engineering, University of California, Merced. For contributions to the development of GaInP/GaAs photovoltaic cells and leadership in solar cell reliability and quality.

Mark G. Lauby, senior vice president and chief engineer, North American Electric Reliability Corp. (NERC), Atlanta. For the development and application of techniques for electric grid reliability analysis.

Fei-Fei Li, Sequoia Capital Professor, computer science, Stanford University, Stanford, CA. For contributions in building large knowledge bases for machine learning and visual understanding.

Charles M. Lieber, Joshua and Beth Friedman University Professor, chemistry and chemical biology, Harvard University, Cambridge, MA. For contributions at the intersection of nanoelectronics, materials design, and neuroscience.

Eugene Litvinov, chief technologist, business architecture and technology, ISO New England, Holyoke, MA. For development of optimization mathematics for new electricity markets and innovative applications for electric grid control, visualization, and planning.

Chen-Ching Liu, American Electric Power Professor, Electrical and Computer Engineering Department, Virginia Tech, Blacksburg. For contributions to computational methods for power system restoration and cybersecurity.

Susan S. Margulies, Wallace H. Coulter Chair Professor, biomedical engineering, Georgia Tech and Emory University, Atlanta. For elaborating the traumatic injury thresholds of brain and lung in terms of structure-function mechanisms.

Thomas L. Marzetta, Distinguished Industry Professor, electrical and computer engineering, New York University Tandon School of Engineering, Brooklyn. For contributions to massive multiple-input multiple-output antenna arrays in wireless communications.

Paul F. McKenzie, chief operating officer, CSL Behring, King of Prussia, PA. For delivering breakthrough medicines, modernizing process development and manufacturing, and integrating modern engineering concepts in pharmaceutical industries.

Muriel Médard, Cecil H. Green Professor, electrical engineering and computer science, Massachusetts Institute of Technology, Cambridge. For contributions to the theory and practice of network coding.

Lelio H. Mejia, senior principal engineer, Geosyntec Consultants, Oakland, CA. For the evaluation, design, and construction of embankment dams and foundation systems and contributions to geotechnical earthquake engineering.

Russell D. Meller, vice president, research and development, Fortna Inc., Louisville, CO. For contributions to large-scale distribution center design and operation.

James A. Momoh, chair and chief executive officer, Nigerian Electricity Regulatory Commission, Abuja. For the development of electric grid optimization techniques and implementation of advanced technology and policy for emerging electric grids in Africa.

Paulo J.M. Monteiro, Roy W. Carlson Distinguished Professor, civil and environmental engineering, University of California, Berkeley. For contributions to the science and nanotechnology of concrete for sustainable construction and durable structures.

Jayathi Y. Murthy, Ronald and Valerie Sugar Dean and Distinguished Professor, Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles. For the development of unstructured solution-adaptive finite volume methods for heat, mass, and momentum transport.

Laura E. Niklason, professor of anesthesiology and biomedical engineering, Yale University, New Haven, CT. For cardiovascular tissue engineering, lung regeneration, and biomedical imaging.

Jorge Nocedal, Walter P. Murphy Professor, industrial engineering and management sciences, Northwestern University, Evanston, IL. For contributions to the theory, design, and implementation of optimization algorithms and machine learning software.

Ellen Ochoa, retired director, NASA Johnson Space Center, Boise, ID. For service as an astronaut, a technical leader in government, and an optical scientist/engineer.

Sara N. Ortwein, former president, XTO Energy Inc., Magnolia, TX. For engineering leadership in the upstream sector of the oil and gas industry.

Per F. Peterson, William S. Floyd and Jean McCallum Floyd Chair in Engineering, nuclear engineering, University of California, Berkeley. For experimental and analytical research contributions for the design and development of passive safety systems for advanced nuclear reactors.

Francisco F. Roberto, technical specialist/manager for process technology and innovation, technical services/processing and metallurgy, Newmont, Englewood, CO. For advancing biotechnical applications for environmentally responsible mine production.

Anne K. Roby, executive vice president, Linde PLC, Ridgefield, CT. For developments in oxidation processes, and for leadership in technological developments, safety, and business growth in global industrial gas companies.

Ahmadreza Rofougaran, chief technology officer, co–chief executive officer, and founder, Movandi Corp., Irvine, CA. For the development of radio system-on-a-chip technology for wireless networking.

Mark E. Russell, vice president of engineering, technology, and mission assurance, Raytheon Co., Waltham, MA. For leadership in developing radar systems for enhanced national security and safety.

Amarpreet S. Sawhney, chair and chief executive officer, Instylla Inc., Waltham, MA. For development of innovative medical devices that have impacted millions of patients.

Alexander A. Shapiro, Russell Chandler III Chair and professor, School of Industrial and Systems Engineering, Georgia Institute of Technology, Decatur. For contributions to the theory, computation, and application of stochastic programming.

Peter W. Shor, Morss Professor of Applied Mathematics, Massachusetts Institute of Technology, Cambridge. For pioneering contributions to quantum computation.

Gwynne Shotwell, president and chief operating officer, SpaceX, Hawthorne, CA. For bringing affordable, commercially competitive space transportation to NASA and the US National Security Space Launch.

Nancy R. Sottos, Donald B. Willett Professor of Engineering, materials science and engineering, University of Illinois, Urbana-Champaign. For contributions to the design and applications of self-healing and multifunctional materials.

Michael A. Sutton, distinguished professor, mechanical and biomedical engineering, College of Engineering and Computing, University of South Carolina, Columbia. For creation of digital image correlation-based measurement technology and its dissemination through commercialization and applications in industry.

Maria C. Tamargo, professor, physical chemistry and inorganic chemistry, City College of New York. For forging the way toward an inclusive science and engineering research community, and for contributions to molecular-beam epitaxy of semiconductor materials.

Russell H. Taylor, John C. Malone Professor, Department of Computer Science, Johns Hopkins

University, Baltimore. For contributions to the development of medical robotics and computer-integrated systems.

Mark E. Thompson, professor of chemistry and materials, University of Southern California, Los Angeles. For development of highly efficient electrophosphorescent materials for organic light emitting devices used in displays and lighting worldwide.

Rudolf M. Tromp, research staff member, IBM Research Division, IBM Thomas J. Watson Research Center, Yorktown Heights, NY. For contributions to development and commercialization of nanoscale characterization methods, and their application in materials science.

Leung Tsang, professor, electrical engineering and computer science, University of Michigan, Ann Arbor. For contributions in wave scattering and microwave remote sensing theories for satellite missions.

Kerry J. Vahala, Ted and Ginger Jenkins Professor of Information Science and Technology and Applied Physics, California Institute of Technology, Pasadena. For research and application of nonlinear optical microresonators to the miniaturization of precision time and frequency systems.

Richard A. Vaia, senior scientist, emergent materials systems, Air Force Research Laboratory, Dayton, OH. For aerospace applications of polymeric nanomaterials, and for technical leadership in materials for national defense applications.

Steven H. Walker, chief technology officer, Lockheed Martin Corp., Bethesda, MD. For leadership of national security R&D at the Defense Advanced Research Projects Agency and the US Air Force.

Charles W. Wampler II, senior technical fellow, Chemical and Materials Systems Laboratory, General Motors Global R&D, Warren, MI. For leadership in robotic systems in manufacturing, mathematical methods for robot motion and machine design, and traction battery modeling.

Kenneth E. Washington, chief technology officer, Ford Motor Co., Dearborn, MI. For leadership in nuclear safety, information systems and high-performance computing, space research, and automotive technologies.

Dick K.P. Yue, Philip J. Solondz Professor, mechanical and ocean engineering, Massachusetts Institute of Technology, Cambridge. For contributions to ocean engineering and innovation of OpenCourseWare to make higher education freely available worldwide.

Jie Zhang, founder, chief scientist, and chair, GeoTomo, Houston. For advances in earthquake seismology, geophysical imaging, and medical technology.

New International Members

Eduard Arzt, chief executive officer and scientific director, INM – Leibniz Institute for New Materials, Saarland University, Saarbrücken, Germany. For research on mechanical properties and development of bio-inspired functional surfaces for medical adhesives and novel gripping systems.

Günter Blöschl, professor of hydrology and water resources, Institute of Hydraulic Engineering and Water Resources, Vienna University of Technology (TU Wien), Austria. For international leadership in the prediction and management of extreme hydrological events.

Daeje Chin, chief executive officer, SkyLake Investment Co., Seoul. For innovations and industry leadership in semiconductor technology.

Raffaello D'Andrea, professor, Department of Mechanical and Process Engineering, ETH Zürich. For contributions to the design and implementation of distributed automation systems for commercial applications.

Zhonghan John Deng, chief executive officer/chair, Vimicro Group, Zhongxing Microelectronics Co. Ltd., Beijing. For development of the world's first CMOS single-chip web camera and China's Surveillance Video and Audio Coding (SVAC) national video standard.

Igor Emri, professor of mechanics, University of Ljubljana, Slovenia. For contributions to the testing and modeling of time-dependent materials, and to novel sound and vibration isolation materials.

Claudia Anna-Maria Felser, director, Max Planck Institute for Chemical Physics of Solids, Dresden. For the prediction and discovery of engineered quantum materials ranging from Heusler compounds to topological insulators.

Pawan K. Goenka, managing director, Mahindra & Mahindra Ltd., Mumbai. For leadership and expansion of Mahindra's automotive business in India, and for contributions in automotive engine lubrication.

Susan T. Harrison, professor, chemical engineering, University of Cape Town, South Africa. For leadership in biochemical engineering and its application to mining and environmental remediation.

Chennupati Jagadish, distinguished professor, electronic materials engineering, Australian National University, Canberra. For contributions to nanotechnology for optoelectronic devices.

Wolfgang Marquardt, chair, Forschungszentrum Jülich GmbH, Germany. For contributions to process systems engineering and large-scale computations, and for national leadership in science/technology policy and management.

Roberto Meli Piralla, research professor emeritus, Engineering Institute, National Autonomous University of Mexico (UNAM), Mexico City. For advancing the preservation of historic structures and improving the seismic safety of concrete, masonry, and adobe structures worldwide.

Michael V. Sefton, University Professor and Michael E. Charles Professor of Chemical Engineering, University of Toronto. For advances in biomaterials and tissue engineering through cell microencapsulation, and for leadership of large-scale research initiatives.

Abigail J. Sellen, deputy director and principal researcher, Microsoft Research Cambridge, United Kingdom. For contributions that ensure consideration of human capabilities in the design of computer systems.

Essam Abdel Aziz Sharaf, professor, Department of Public Works, Cairo University, Giza. For leadership to modernize transportation systems in Egypt and the Middle East through scholarship, advocacy, and public policy.

Guaning Su, president emeritus, Nanyang Technological University, Singapore. For contributions to regional security and defense, and for academic leadership.

Viola Vogel, professor, health sciences and technology, ETH Zürich. For elucidation of how proteins work as nanoscale mechanochemical switches, and applications to bioengineering and medicine.

Rabab K. Ward, professor emeritus, electrical and computer engineering, University of British Columbia, Vancouver. For innovative applications of signal processing to industrial and bioengineering problems.

NAE Newsmakers

Frances H. Arnold, Linus Pauling Professor of Chemical Engineering, Bioengineering, and Biochemistry, California Institute of Technology, has been **named to the Pontifical Academy of Sciences**, a scientific academy under the auspices of the Pope and based in Vatican City. The academy was established in 1936 by Pope Pius XI with the goal of promoting "the progress of the mathematical, physical, and natural sciences." As a member of the academy, Arnold will be invited to attend academy meetings and participate in study groups focused on scientific issues.

Hari Balakrishnan, professor of computer science, Massachusetts Institute of Technology, is among the newly selected **2020 class of IEEE fellows**. The rank of fellow is bestowed on IEEE senior members whose work has advanced innovation in their field and furthered the IEEE mission to foster the development of technology to benefit society. Professor Balakrishnan's citation reads "for contributions to the design and application of mobile sensing systems."

Jack J. Dongarra, University Distinguished Professor, Innovative Computing Laboratory, University of Tennessee, Knoxville, will receive the **2020 IEEE Computer Pioneer Award** in May during the IEEE Computer Society Board of Governors meeting. The award honors the vision of those whose efforts resulted in the creation and continued vitality of the computer industry and whose main contribution was made at least 15 years earlier.

Dorota A. Grejner-Brzezinska, professor and Lowber B. Strange Endowed Chair and associate dean for research, College of Engineering, Civil, Environmental, and Geodetic Engineering, Ohio State University, has been **appointed to the President's Council of Advisors on Science and Technology** (PCAST). She is one of a few academics appointed thus far to the 16-member panel. The director of OSTP stated that academic voices will play a critical role in advising the president on matters central to US science and technology efforts.

The International Association of Advanced Materials (IAAM) conferred the title of **Researcher of the Year 2020** on **Herbert Gleiter**, professor, Institute of Nanotechnology, Karlsruhe Institute of Technology, for his decades of research advancing materials to global excellence. The citation reads "For his contributions to research in nanoscience and physics that influenced the rise of nanoscience and nanotechnology around the world." The award was presented during the 30th Assembly of IAAM in Singapore, October 31–November 4, 2019.

AIME Honorary Membership was conferred on **Jessica E. Kogel**, associate director of mining, National Institute for Occupational Safety and Health, during the MineXchange2020 SME Annual Conference & Expo in Phoenix February 23–26.

Raymond J. Krizek, Stanley F. Pepper Professor of Civil Engineering, Northwestern University, has been honored by ASCE as the winner of the **2020 Outstanding Projects and Leaders (OPAL) Award for Education**. He is recognized for his accomplishments in research and excellence in furthering the quality of civil engineering education.

James C. Liao, president, Academia Sinica (Taiwan), has been elected to the **World Academy of Sciences**, recognized for using metabolic engineering, synthetic biology, and systems biology to construct microorganisms to produce next-generation biofuels and to study the obesity problem in humans. And in Copenhagen in December, he was awarded the **2019 Novozymes Award for Excellence in Biochemical and Chemical Engineering** for his contributions to science that can help develop fuels and chemicals from renewable resources.

Bruce E. Logan, Kappe Professor of Environmental Engineering, Pennsylvania State University, and **Joseph Sifakis**, Verimag Laboratory, Bâtiment IMAG, Université Grenoble-Alpes, are among the 29 **foreign members elected to the Chinese Academy of Engineering** in 2019.

Asad M. Madni, independent consultant and retired president, chief operating officer, and CTO, BEI Technologies Inc., was awarded an **Honorary Fellowship** by the UK Council of the **Royal Aeronautical Society** (RAeS), the highest award conferred by the society. It is awarded to "those whose career, leadership, inspiration, and impact mark them out as among the most eminent, widely recognized, and influential aerospace professionals of their generation."

Perry L. McCarty, Silas H. Palmer Professor Emeritus, Department of Civil and Environmental Engineering, Stanford University, and **George P. Peterson**, independent consultant, have been **inducted into the Engineering and Science Hall of Fame** in Dayton, Ohio. Dr. McCarty was cited for leadership in the development of environmental engineering and the treatment of water and wastewater, and Mr. Peterson was cited for development and deployment of advanced composite materials and manufacturing technologies.

Richard A. Meserve, senior of counsel, Covington & Burling LLP, was awarded the **Eisenhower Medal** by the American Nuclear Society at its annual meeting November 18 in Washington. The medal is given "in recognition of outstanding leadership in public policy for nuclear science and technology or outstanding contributions to the field of nuclear nonproliferation."

Shuji Nakamura, CREE Distinguished Professor, Materials and professor of electrical and computer engineering, Materials Department, University of California, Santa Barbara, has been awarded the **2019 Leigh Ann Conn Prize for Renewable Energy**. The biennial award, bestowed by the University of Louisville, is meant to "acknowledge, publicize, and disseminate outstanding ideas and achievements in research related to the sciences, engineering, technology, and commercialization of renewable energy." Professor Nakamura was chosen for his part in unlocking the technology that led to the birth of the white LED, which has resulted in both energy efficiency and significant savings to consumers. And at the annual meeting of the National Academy of Sciences in April, Professor Nakamura will receive the **2020 Award for the Industrial Application of Science**. He was selected for the triennial award, which this year focuses on sustainability, for his "pioneering discoveries, synthesis, and commercial development of Gallium nitride LEDs and their use in sustainable solid-state light sources, which are reducing greenhouse gas emissions while also reducing costs to those adopting these techniques."

Howard A. Stone, Donald R. Dixon '69 and Elizabeth W. Dixon Professor, Department of Mechanical and Aerospace Engineering, Princeton University, has been named a **fellow of the National Academy of Inventors**.

Kathryn D. Sullivan, senior fellow, the Potomac Institute, is the recipient of the **2020 DRI Nevada Medal of Science**. She will receive the award in May.

Sharon L. Wood, dean, Cockrell School of Engineering, University of Texas at Austin, received the **2020 Pinnacle Award** at the 25 Influential Women in Energy lunch March 4 in Houston. She was selected for her dedication to the advancement of architectural and environmental engineering.

2019 EU-US Frontiers of Engineering Hosted by Royal Swedish Academy of Engineering Sciences

The EU-US Frontiers of Engineering symposium was held in Stockholm November 18–20, 2019, at the Royal Swedish Academy of Engineering Sciences (IVA)—the first engineering science academy in the world. The NAE partnered with the European Council of Applied Sciences, Technologies, and Engineering (Euro-CASE) to carry out the event with organizational support for the EU side provided by IVA. **Michael Tsapatsis**, Bloomberg Distinguished Professor of Chemical Engineering and Materials Science at Johns Hopkins University, and Pontus Johnson, professor of network and systems engineering at the Royal Institute of Technology, cochaired the symposium.

The meeting brought together approximately 60 engineers, ages 30 to 45, from US and European universities, companies, and government labs for a 2½-day meeting to hear about leading-edge developments in four topics: 5G and the Internet of Things, smart manufacturing, materials engineering enabled by advances in imaging, and systems approaches to a clean environment. Participants were from the United States and 11 EU countries: Czech Republic, Denmark, Finland, France, Germany, Hungary, Romania, Slovenia, Sweden, Switzerland, and the United Kingdom.

We take for granted the ability to call friends, send text messages, browse the internet, and use apps to stream video and play games via smartphones. But as the demands of society and industries evolve, there is a need to improve the technology—for example, to provide higher speeds for faster downloads and increased reliability to avoid dropped calls. Speakers in the session on 5G and the Internet of Things (IoT) described the underlying technology of 5G and how it is being used in various IoT applications. Specifically, they discussed the use of 5G for vehicular communication in the automotive and transportation sector, how 5G networks can be used for manufacturing and production, and a future where 5G supports 4K video,

EU-US FOE attendees at the Royal Swedish Academy of Engineering Sciences (IVA). Photo courtesy of IVA.

augmented reality, and the Internet of Everything.

Smart manufacturing integrates sensors, advanced robotics, information technology, and AI so that production tools constantly gather data, monitor production processes, and perform real-time optimization. And the use of cognitive computing allows for inference and reasoning about data to improve the end product, the ultimate goal being self-monitoring and self-optimization of the end-to-end manufacturing process. The first speaker in this session talked about the challenges of enabling smart manufacturing in the glass industry, with a focus on product deployment, state-of-the-art services, privacy, and sustainability. The second speaker discussed "synthesis for robotics," which encompasses new approaches for automating robot design and programming from high-level specifications. This was followed by a presentation on metal additive manufacturing (AM), which offers benefits in design versatility and customization but is hindered by a lack of process control, process repeatability, and part quality verification that may be alleviated by intelligent methods for feed-forward control, models, and hardware. The final speaker focused on addressing safety requirements in optimizing controls and the importance of considering human factors when doing so.

The organizers of the session on Materials Engineering Enabled by Advances in Imaging noted that advanced imaging techniques are essential for exploring the complexity of devices at the nanoscale, as the scale of materials required for technological advances has shrunk. Applications require both an understanding of the processes that take place during materials synthesis, processing, and device functioning, and correlation of the impacts of different materials' structures on a device's physical and chemical behavior and performance. Speakers in this session described a range of techniques used in multidimensional imaging as well as novel developments in the fields of light, electron, X-ray, ion, in situ, and scanning probe microscopies for the micro- and nanostructural study of complex materials systems.

The final session was on systems approaches to a clean environment. Because feedbacks and interactions underpinning environmental issues span many different scientific fields, addressing such challenges benefits from a systems approach. The talks covered the economic case for combating climate change; research on net-zero emissions energy systems, which focuses on the challenges, technological solutions, and R&D priorities of eliminating CO_2 emissions associated with difficult-to-decarbonize services (e.g., long-distance freight transport, air travel, and highly reliable electricity); Sweden's implementation of roadmaps for a fossil-free, competitive future that supports the dual goals of growth and reduced emissions; and how engineering-based research can illuminate the physical and societal links between policy actions and their impacts on people and their health and well-being.

Abstracts of the papers can be accessed in the List of Sessions for the 2019 EU-US FOE at www.naefrontiers.org.

In addition to the formal sessions, a poster session preceded by flash poster talks was held on the first afternoon, as both an icebreaker and an opportunity for participants to share information about their research and technical work. On the first evening, the group had dinner in IVA's historic banquet hall, which reflects the neoclassical style typical of the late 1800s and early 1900s. An a capella group from the Natural Sciences Programme of Kungsholmens Gymnasium entertained the guests with a medley of Swedish folk and Lucia songs. On the second afternoon the group enjoyed a tour of the Nobel Prize Museum where docents provided insights on the many exhibits related to Alfred Nobel and Nobel laureates and their achievements. This was followed by dinner at Eriks Gondolen, which afforded beautiful views of the city, delicious Swedish cuisine, and an opportunity for fellowship.

Financial support for the symposium was provided to the NAE by The Grainger Foundation and National Science Foundation. We also thank Michael Tsapatsis for his service as US cochair for the 2017 and 2019 EU-US Frontiers of Engineering symposia.

The next EU-US FOE will be held October 19–21, 2020, at Nokia Bell Labs in Murray Hill, New Jersey. **Vahid Tarokh**, Rhodes Family Professor of Electrical and Computer Engineering at Duke University, will serve as US cochair.

The NAE has been holding Frontiers of Engineering symposia since 1995, and the EU-US FOE since 2010. For more information about the symposium series or to nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at the NAE Program Office at JHunziker@nae.edu. The FOE website is www.naefrontiers.org.

Mirzayan Fellow Joins Program Office

REKHA BALACHANDRAN is a postdoctoral research fellow at Purdue University School of Health Sciences studying the effects of manganese exposure on cell signaling pathways in mammalian cell lines and in neurons of different lineages derived from human-induced pluripotent stem cells. She earned her PhD at the University of Illinois at Urbana-Champaign with an emphasis on neurotoxicology and chronobiology; her dissertation work examined the effects of circadian disruption on attention and impulsive behavior. She earned her MS in biological engineering, studying the metabolic burden imposed by synthetic gene circuits. In her graduate studies, Rekha sought different avenues to learn more about policy and regulatory landscape; for example, as an intern at USDA's National Institute of Food and Agriculture, she worked on developing policy briefs and strategies regarding emerging global bioeconomies. Rekha is a member of the Society of Toxicology and the Developmental Neurotoxicology Society (DNTS), and was webmaster for DNTS for the last 2 years. She is keen on learning how to work toward keeping policy and regulatory affairs at par with the speed at which technology is developing. She can be reached at balachandran.rekha@gmail.com.


Rekha Balachandran

Message from NAE Vice President Corale L. Brierley

I am pleased to report that more than 780 members, friends, and organizations invested over $5.5 million in new cash, pledges, and planned gifts in 2019. Thank you!

Philanthropy underpins our mission to advance the well-being of the nation by promoting a vibrant engineering profession and advising the federal government on matters involving engineering and technology. You, our members and friends, play a vital role in ensuring a dynamic and proactive NAE. You help ensure that the engineers of tomorrow—today's girls and boys, young women and men—are engaged and equipped to take on the most pressing challenges facing our country and the world.

Private support derived from annual contributions from individuals, corporations, and foundations, and spendable income from endowments funded about 68% of the NAE's work in 2019. The NAE's EngineerGirl and Grand Challenges Scholars Program for developing engineering talent, Frontiers of Engineering for sustaining engineering excellence, and Center for Engineering Ethics and Society for ensuring the integrity of the profession—all rely on funding from our members and friends. Your generosity enables the NAE to serve the engineering community, young people, policymakers, and the public.

This year as we recognize our Annual, Golden Bridge, Einstein, and Heritage Societies, we also announce the addition of three new giving societies: the Abraham Lincoln Society, Benjamin Franklin Society, and Marie Curie Society. We are thrilled to have these new societies to recognize and thank our generous donors.


Corale L. Brierley

Romig Challenge Update

In 2019 Al and Julie Romig established a $100,000 giving challenge for NAE members elected since 2015. All first-time and upgraded gifts counted toward the challenge, allowing members to double the impact of this gift. Sixty-seven members qualified for the challenge, nearly 14% of the 481 members from the classes of 2015–2019. Those members contributed a total of $235,193.35 to the NAE, which helped provide mission-critical funding.

Onward

In our rapidly changing world, the NAE helps solve the complex challenges facing people and society today and in the coming decades. Your ongoing philanthropic investment ensures a solid foundation from which to sustain important projects and spearhead inspiring new programs. Thank you for your continued support.

Corale L Brierley

Corale L. Brierley

PS Keep an eye out for the 2019 *Annual Report*, which will be available online this summer. It will provide information on our three new giving societies and a listing of those donors.

For more information about ways to give, please contact:

Radka Nebesky, Director of Development
202.334.3417 or RNebesky@nae.edu

Lauren Bartolozzi, Associate Director of Development
202.334.3258 or LBartolozzi@nae.edu

2019 Honor Roll of Donors

We greatly appreciate the generosity of our donors. Your contributions enhance the impact of the National Academy of Engineering's work and support its vital role as advisor to the nation. The NAE acknowledges contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

Lifetime Giving Societies

We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the academies as advisor to the nation on matters of science, engineering, and medicine.

The Einstein Society

In recognition of members and friends who have made lifetime contributions of $100,000 or more to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

$1 million and above

Bruce and Betty Alberts
Richard and Rita Atkinson
Norman R. Augustine
Craig and Barbara **Barrett**
Jordan* and Rhoda **Baruch**
Stephen D. Bechtel, Jr.
Arnold and Mabel **Beckman***
Leonard Blavatnik
Harry E. Bovay, Jr.*
Donald L. Bren
Harvey V. Fineberg and Mary E. Wilson
Bernard M. Gordon
Cecil H. Green*
Michael and Sheila Held*
William R. and Rosemary B. **Hewlett***
Ming and Eva **Hsieh**
Irwin and Joan **Jacobs**
Robert L. and Anne K. James
Kenneth A. Jonsson*
Fred Kavli*
Daniel E. Koshland, Jr.*
Tillie K. Lubin*
Whitney and Betty MacMillan
John F. McDonnell
George P. Mitchell*
The Ambrose Monell Foundation
Gordon and Betty **Moore**
Philip and Sima Needleman
Peter O'Donnell, Jr.
Robert* and Mayari **Pritzker**

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*Deceased

Richard L. and Hinda G. Rosenthal*
Martine A. Rothblatt
Jack W. and Valerie Rowe
Fritz J. and Dolores H. Russ Prize Fund of the Russ College of Engineering and Technology at Ohio University
Dame Jillian Sackler
Raymond and Beverly Sackler*
Bernard and Rhoda Sarnat*
Leonard D. Schaeffer
Sara Lee and Axel Schupf
James H. and Marilyn Simons
John and Janet **Swanson**
Anthony J. Yun and Kimberly A. Bazar

$500,000 to $999,999

Rose-Marie and Jack R. Anderson*
John and Elizabeth **Armstrong**
Kenneth E. Behring
Gordon Bell
Elkan R.* and Gail F. Blout
Carson Family Charitable Trust
Charina Endowment Fund
Ralph J.* and Carol M. Cicerone
James McConnell Clark
Henry David*
Richard Evans*
Eugene Garfield Foundation
Theodore Geballe
Penny and **Bill George**, George Family Foundation
Christa and Detlef Gloge
William T.* and Catherine Morrison Golden
Alexander Hollaender*
Thomas V. Jones*
Cindy and **Jeong Kim**
Ralph and Claire **Landau***
Asta and **William W. Lang***
Ruben F.* and Donna **Mettler**
Dane* and Mary Louise **Miller**
Oliver E. and Gerda K. Nelson*
Gilbert S. Omenn and Martha A. Darling
Shela and **Kumar Patel**
William J. Rutter
Henry and Susan **Samueli**
Herbert A. and Dorothea P. Simon*
Raymond S. Stata
Roy and Diana Vagelos
Andrew and Erna* **Viterbi**
Alan M. Voorhees*
Anonymous (1)

$250,000 to $499,999

The Agouron Institute
W.O. Baker*
Warren L. Batts
Elwyn* and Jennifer **Berlekamp**
Daniel Branton
George* and Virginia **Bugliarello**
Clarence S. Coe*
Rosie and Stirling A. Colgate*
W. Dale and Jeanne C. **Compton***
Lance and Susan **Davis**
David and Miriam Donoho
Ruth and Victor Dzau
Dotty and **Gordon England**
George and Christine Gloeckler
Jerome H.* and Barbara N. Grossman
John O. Hallquist
John L. Hennessy
Chad and Ann **Holliday**
William R. Jackson*
Anita K. Jones
Mary and **Howard*** **Kehrl**
Kent Kresa
Robin K. and Rose M. **McGuire**
Janet and **Richard M.*** **Morrow**
Clayton Daniel and Patricia L. **Mote**
Ralph S. O'Connor*
Kenneth H. Olsen*
Ann and **Michael Ramage**
Simon Ramo*
Anne and **Walt Robb**
Matthew L. Rogers and Swati Mylavarapu
Stephen* and Anne Ryan
H.E. Simmons*
Judy Swanson
Marci and **James J. Truchard**
Ted Turner
Leslie L. Vadasz
Martha Vaughan*
Charles M.* and Rebecca M. **Vest**
Wm. A. Wulf
Anonymous (1)

$100,000 to $249,999

John and Pat **Anderson**
Laura E. and John D. Arnold
Holt Ashley*
Nadine Aubry and John L. Batton
Francisco J. and Hana Ayala
William F. Ballhaus, Sr.*
David Baltimore
Thomas D.* and Janice H. **Barrow**
H.H. and Eleanor F. Barschall*
Donald and Joan Beall
Daniel and Frances **Berg**
Diane and Norman Bernstein
Bharati and **Murty Bhavaraju**
Chip and Belinda **Blankenship**
Erich Bloch*
Barry W. Boehm
Gopa and **Arindam Bose**
David G. Bradley
Lewis M. Branscomb
Sydney Brenner*
Malin Burnham
Ursula Burns and Lloyd Bean

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*Deceased

Chau-Chyun and Li-Li **Chen**
John and Assia **Cioffi**
Paul Citron and Margaret Carlson Citron
A. James Clark*
G. Wayne Clough
Barry and Bobbi Coller
John D. Corbett*
Ross and Stephanie **Corotis**
Ruth David and Stan Dains
Roman W. DeSanctis
Robert* and Florence **Deutsch**
Nicholas M. Donofrio
Paul M. Doty*
Charles W. Duncan, Jr.
George and Maggie Eads
Robert and Cornelia **Eaton**
The Eleftheria Foundation
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Emanuel and Peggy Epstein
Thomas E. Everhart
Olivia and **Peter Farrell**
Michiko So* and Lawrence Finegold
Tobie and **Daniel J.*** **Fink**
Delbert A. and Beverly C. Fisher
George and Ann **Fisher**
Robert C.* and Marilyn G. **Forney**
Harold K.* and Betty **Forsen**
Edward H. Frank and Sarah G. Ratchye
William L. and Mary Kay **Friend**
Christopher Galvin
William H. and Melinda F. **Gates III**
Nan and **Chuck Geschke**
Jack and Linda Gill
Martin E. and Lucinda **Glicksman**
Avram Goldstein*
Robert W. Gore
Paul and Judy **Gray**
Corbin Gwaltney
Margaret A. Hamburg and Peter F. Brown
William M. Haney III
Wesley L. Harris
George* and Daphne **Hatsopoulos**
Jane E. Henney and Robert Graham
Lyda Hill
Jane Hirsh
Michael W. Hunkapiller
Jennie S. Hwang
M. Blakeman Ingle
Richard B. Johnston, Jr.
Trevor O. Jones
Thomas Kailath
Yuet Wai and Alvera Kan
John and Wilma **Kassakian**
Leon K. and Olga **Kirchmayer***
Frederick A. Klingenstein
William I. Koch
Gail F. Koshland
Jill Howell Kramer
John W. Landis*
Janet and Barry Lang
Ming-wai Lau
Gerald and Doris **Laubach**
David M.* and Natalie **Lederman**
Bonnie Berger and **Frank Thomson Leighton**
Thomas M. Leps*
Frances and **George Ligler**
R. Noel Longuemare, Jr.
Asad M., Gowhartaj, and Jamal **Madni**
Davis L. Masten and Christopher Ireland
Roger L. McCarthy
Michael and Pat McGinnis
William W. McGuire
Burt* and Deedee McMurtry
Marcia K. McNutt
Rahul Mehta
G. William* and Ariadna Miller
Ronald D. Miller
Stanley L. Miller*
Sanjit K. and Nandita **Mitra**
Sharon and **Arthur Money**
Joe and Glenna Moore
David* and Lindsay Morgenthaler
Narayana and Sudha **Murty**
Jaya and **Venky Narayanamurti**
Ellen and **Philip Neches**
Norman F. Ness
Ronald and Joan **Nordgren**
Susan and **Franklin M. Orr, Jr.**
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Charles and Doris **Pankow***
Larry* and Carol **Papay**
Jack S. Parker*
Arogyaswami J. Paulraj
Edward E. Penhoet
Allen E.* and Marilynn **Puckett**
Richard F. and Terri W. **Rashid**
Alexander Rich*
Arthur D. Riggs
Ronald L. Rivest
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Maxine L. Savitz
Walter Schlup*
Wendy and **Eric Schmidt**
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Harold C. and Carol H. Sox
Robert F. and Lee S. **Sproull**
Georges C. St. Laurent, Jr.
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F. William Studier
Thomas and Marilyn Sutton
Charlotte and **Morris Tanenbaum**
Peter and Vivian **Teets**
Hemant K. and Suniti **Thapar**
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Jean D. Wilson
Ken Xie
Tachi and Leslie Yamada
Adrian Zaccaria
Alejandro Zaffaroni*
Peter Zandan
Janet and Jerry Zucker
Anonymous (3)

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*Deceased

Golden Bridge Society

In recognition of NAE members and friends who have made lifetime contributions totaling $20,000 to $99,999. Boldfaced names are NAE members.

$75,000 to $99,999

Paul F. Boulos
Kristine L. Bueche
Josephine Cheng
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Robert E. Kahn
Paul and Julie **Kaminski**
Rita Vaughn and **Theodore C.* Kennedy**
Johanna M.H. Levelt Sengers
Jane and **Norman N. Li**
John Neerhout, Jr.
Roberto Padovani

$50,000 to $74,999

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Corbett Caudill
William Cavanaugh
Selim A. Chacour
The Crown Family
Gerard W. Elverum
Louis V. Gerstner Jr.
Priscilla and **Paul E.* Gray**
Kathryn S. and **Peter S. Kim**
Richard A. Meserve
James K. and Holly T. **Mitchell**
Darla and **George E.* Mueller**
Jane and **Alan R. Mulally**
Cherry A. Murray
Cynthia J. and **Norman A.* Nadel**
Robert M. and Marilyn R. **Nerem**
Cathy and **Paul S.* Peercy**
Ellen and **George A.* Roberts**
Mendel Rosenblum and **Diane Greene**
Linda S. Sanford
Leo John* and Joanne **Thomas**
David W. Thompson
Sheila E. Widnall
A. Thomas Young
Elias A. Zerhouni

$20,000 to $49,999

Andreas and Juana **Acrivos**
Rodney C. Adkins
Alice Merner Agogino
Clarence R. Allen
Valerie and **William A. Anders**
John C. Angus
Seta and **Diran Apelian**
Frances H. Arnold
Ruth and **Ken Arnold**
Kamla* and **Bishnu S. Atal**
Ken Austin*
Clyde and Jeanette **Baker**
William F. Banholzer
David K. Barton
Becky and Tom **Bergman**
R. Byron Bird
Diane and **Samuel W.* Bodman**
Mark T. Bohr
Rudolph Bonaparte
Kathleen and **H. Kent Bowen**
Corale L. Brierley
James A. Brierley
Lenore and **Rob Briskman**
Andrei Z. Broder
Rodney A. Brooks
Alan C. Brown
Andrew and Malaney L. **Brown**
Harold Brown*
Robert L. Byer
François J. Castaing
Sigrid and **Vint Cerf**
Joe H. and Doris W.L. **Chow**
Vinay and **Uma Chowdhry**
Joseph M. Colucci
Rosemary L. and **Harry M. Conger**
Kay and **Gary Cowger**
Natalie W. Crawford
Malcolm R. Currie
Glen T. and Patricia B. **Daigger**
David and Susan **Daniel**
Pablo G. Debenedetti
Carl de Boor
Mary and **Raymond Decker**
Tom and Bettie **Deen**
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James J. Duderstadt
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Bruce and Pat **Finlayson**
Edith M. Flanigen
Samuel C. Florman
G. David Forney, Jr.
Douglas W. and Margaret P. **Fuerstenau**
Elsa M. Garmire and Robert H. Russell
Richard L. and Lois E. **Garwin**
Arthur and Helen **Geoffrion**
Paul H. Gilbert
Eduardo D. Glandt
Arthur L. and Vida F. **Goldstein**
Mary L. Good*
Joseph W. Goodman
Kathy and **Albert G. Greenberg**
Delon Hampton
Eli Harari
Janina and **Siegfried Hecker**
Robert and Darlene **Hermann**

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*Deceased

David and Susan **Hodges**
Edward E. Hood, Jr.*
Lee Hood and Valerie Logan Hood
Evelyn L. Hu and **David L. Clarke**
J. Stuart Hunter
Ray R. Irani
Wilhelmina and **Stephen Jaffe**
Lean H. Jamieson
Edward G.* and Naomi **Jefferson**
George W. Jeffs*
Kristina M. Johnson
Frank and Pam **Joklik**
Howard* and Evelyn **Jones**
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Albert S. and Elizabeth M. **Kobayashi**
Robert M. and Pauline W. **Koerner**
Demetrious Koutsoftas
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Lester C.* and Joan M. **Krogh**
Ellen J. Kullman
Louis J. and M. Yvonne DeWolf **Lanzerotti**
David C. Larbalestier
Cato and Cynthia **Laurencin**
Yoon-Woo Lee
Burn-Jeng Lin
Jack E. Little
Robert G. Loewy
Thomas* and Caroline **Maddock**
Thomas J. Malone
John C. Martin
James F. Mathis
Robert D. Maurer
Dan and Dalia* **Maydan**
James C. McGroddy
Kishor C. Mehta
James J. Mikulski
Susan M. and **Richard B. Miles**
Duncan T. Moore
Van and Barbara **Mow**
Matt O'Donnell
Claire L. Parkinson
Aliene and **Thomas K. Perkins**
Lee* and **Bill Perry**
Donald E. Petersen
Julia M. Phillips and John A. Connor
Dennis J. Picard
Leonard and Diane Fineblum **Pinchuk**
John W. and Susan M. **Poduska**
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Srilatha and **Prabhakar Raghavan**
Joy and **George Rathmann***
Buddy Ratner and Cheryl Cromer
Kenneth and Martha **Reifsnider**
Richard J.* and Bonnie B. **Robbins**
Bernard I. Robertson
Mary Ann and **Thomas Romesser**
Howie Rosen and Susan Doherty
William B. and Priscilla **Russel**
Vinod K. Sahney
Steve* and Kathryn **Sample**
John M. Samuels, Jr.
Jerry Sanders III
Robert E.* and Mary L. **Schafrik**
Donna and **Jan Schilling**
Ronald V. Schmidt
Fred B. Schneider and Mimi Bussan
William R. Schowalter
Martin B. and Beatrice E.* **Sherwin**
Megan J. Smith
Alfred Z. Spector and Rhonda G. Kost
David B. and Virginia H. **Spencer**
Henry E. Stone
Yongkui Sun
Gaye and **Alan Taub**
Rosemary and **George Tchobanglous**
Daniel M. Tellep
Matthew V. Tirrell
James A. Trainham and Linda D. Waters
John R. Treichler
Raymond Viskanta
Robert and Robyn **Wagoner**
David Walt and Michele May
Daniel I. Wang
Albert R.C. and Jeannie **Westwood**
David and Tilly **Whelan**
Willis S. White, Jr.
George M. Whitesides
John J. Wise
Edgar S. Woolard, Jr.
Israel J. Wygnanski
Yannis C. Yortsos
William and Sherry **Young**
Teresa and Steve **Zinkle**
Anonymous (1)

Heritage Society

In recognition of members and friends who have included the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine in their estate plans or who have made some other type of planned gift to the Academies. Boldfaced names are NAE members.

Gene M.* and Marian **Amdahl**
Betsy Ancker-Johnson
John C. Angus
John and Elizabeth **Armstrong**
Norman R. Augustine
Jack D. Barchas
Harrison H. and Catherine C. **Barrett**
Stanley Baum
Clyde J. Behney
C. Elisabeth Belmont
Daniel and Frances **Berg**
Paul Berg
Elkan R.* and Gail F. Blout
Enriqueta C. Bond
Daniel Branton
Robert and Lillian Brent
Corale L. Brierley
James A. Brierley
Lenore and **Rob Briskman**
Kristine L. Bueche
Dorit Carmelli
Peggy and Thomas Caskey
A. Ray Chamberlain
Linda and Frank Chisari

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*Deceased

Rita K. Chow
Paul Citron and Margaret Carlson Citron
John A. Clements
D. Walter Cohen*
Morrel H. Cohen
Stanley N. Cohen
Graham A. Colditz and Patti L. Cox
Colleen Conway-Welch*
Ross and Stephanie **Corotis**
Ellis and Bettsy Cowling
Barbara J. Culliton
Malcolm R. Currie
Glen T. and Patricia B. **Daigger**
David and Susan **Daniel**
Peter N. Devreotes
Gerard W. Elverum
Dotty and **Gordon England**
Emanuel and Peggy Epstein
Tobie and **Daniel J.* Fink**
Robert C.* and Marilyn G. **Forney**
William L. and Mary Kay **Friend**
Arthur and Helen **Geoffrion**
Paul H. Gilbert
Martin E. and Lucinda **Glicksman**
George and Christine Gloeckler
Christa and Detlef Gloge
Joseph W. Goodman
Chushiro* and Yoshiko Hayashi
John G. Hildebrand and Gail D. Burd
John R. Howell
Nancy S. and Thomas S. Inui
Richard B. Johnston, Jr.
Anita K. Jones
Jerome Kagan
Diana S. and **Michael D. King**
Norma M. Lang
Marigold Linton and Robert Barnhill
Daniel P. Loucks
Ruth Watson Lubic
R. Duncan* and Carolyn Scheer Luce
Thomas* and Caroline **Maddock**
Asad and Taj **Madni**
Pat and Jim McLaughlin
Jane Menken
Sharon and **Arthur Money**
Van and Barbara **Mow**
Guido Munch
Mary O. Mundinger
Philip and Sima Needleman
Norman F. Ness
Ronald and Joan **Nordgren**
Gilbert S. Omenn and Martha A. Darling
Bradford W. and Virgina W. **Parkinson**
Zack T. Pate
Neil and Barbara Pedersen
Frank Press*
James J. Reisa, Jr.
Emanuel P. Rivers
Richard J.* and Bonnie B. **Robbins**
Eugene* and Ruth Roberts
Julie and **Alton D. Romig, Jr.**
James F. Roth
Esther and Lewis* Rowland
Sheila A. Ryan
Paul R. Schimmel
Stuart F. Schlossman
Rudi* and Sonja Schmid
Susan C. Scrimshaw
Kenneth I. Shine
Arnold and Constance **Stancell**
H. Eugene Stanley
Rosemary A. Stevens
John and Janet **Swanson**
Esther Sans Takeuchi
Paul* and Pamela Talalay
Walter Unger
John C. Wall
Patricia Bray-Ward and David C. Ward
Robert and Joan **Wertheim**
Maw-Kuen Wu
Wm. A. Wulf
Tilahun D. Yilma
Michael and Leslee Zubkoff
Anonymous (4)

Annual Giving Societies

The National Academy of Engineering gratefully acknowledges the following members and friends who made charitable contributions to the NAE, and NAE members who supported the Committee on Human Rights, a joint committee of the three academies, during 2019. The collective, private philanthropy of these individuals has a great impact on the NAE and its ability to be a national voice for engineering. We acknowledge contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

Julie and Alton "Al" D. Romig, Jr. gave $100,000 to fund a challenge for members elected since 2015. Members who participated in the Julie and Al Romig Challenge for the classes of 2015–19 are noted with the ♦ symbol.

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*Deceased

Catalyst Society

$50,000+

Nadine Aubry and John L. Batton
Ming and Eva Hsieh
Jennie S. Hwang
Thomas M. Leps*
Robin K. and Rose M. McGuire
Arogyaswami J. Paulraj
Wendy and Eric Schmidt
Hemant K. and Suniti Thapar◆
Katherine K. and John J. Tracy
Marci and James J. Truchard
Anonymous (1)

Friend
John F. McDonnell

Rosette Society

$25,000 to $49,999

John and Pat Anderson
Jeffrey Dean
James O. Ellis, Jr. and Elisabeth Paté-Cornell
Dotty and Gordon England
John O. Hallquist
Wesley L. Harris
Richard F. and Terri W. Rashid
Mendel Rosenblum and Diane Greene◆
Jonathan J. Rubinstein
Henry and Susan Samueli
Anonymous (1)

Challenge Society

$10,000 to $24,999

John and Elizabeth Armstrong
Gordon Bell
Barry W. Boehm
Gopa and Arindam Bose
Paul F. Boulos
Chau-Chyun and Li-Li Chen
Josephine Cheng
Priscilla and Sunlin* Chou
Joe H. and Doris W.L. Chow◆
Joseph M. Colucci
Glen T. and Patricia B. Daigger
Ruth David and Stan Dains
Lance and Susan Davis
Nicholas M. Donofrio
Gerard W. Elverum
Thomas E. Everhart
Martin E. and Lucinda Glicksman
Robert W. Gore
Paul and Judy Gray
Michael W. Hunkapiller
Kristina M. Johnson
Kent Kresa
David C. Larbalestier
Frances and George Ligler
Kiran Mazumdar-Shaw◆
Clayton Daniel and Patricia L. Mote
Larry* and Carol Papay
Cathy and Paul S.* Peercy
Julie and Alton D. Romig, Jr.
John M. Samuels, Jr.
Jerry Sanders III
Linda S. Sanford
Richard J. Stegemeier
James M. Tien and Ellen S. Weston
Adrian Zaccaria

Charter Society

$1,000 to $9,999

Linda M. Abriola
Ilesanmi and Patience Adesida
Rodney C. Adkins
Kyle T. Alfriend
Montgomery and Ann Alger
Richard C. Alkire
John C. Angus
Frances H. Arnold
Ruth and Ken Arnold
R. Lyndon Arscott
Aziz I. Asphahani
Amos A. Avidan
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Mary Baker◆
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Harrison H. and Catherine C. Barrett
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David K. Barton
Tamer Basar
Steven Battel◆
Arden L. Bement, Jr.
Craig and Karen Benson
Daniel and Frances Berg
Thomas and Becky Bergman
Elwyn* and Jennifer Berlekamp
Bharati and Murty Bhavaraju
Mark and Kathy Board
Mark T. Bohr
Rudolph Bonaparte

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*Deceased
◆Romig Challenge

Anjan and Francy Bose
Craig T. Bowman
Frank Bowman
Lewis M. Branscomb
Corale L. Brierley
James A. Brierley
Andrei Z. Broder
John H. Bruning
George* and Virginia Bugliarello
Antonio J. Busalacchi
Wesley G. Bush◆
Cleopatra Cabuz
Stuart K. Card
Robert P. Caren*
François J. Castaing
Corbett Caudill
Selim A. Chacour
Don B. Chaffin
Weng C. Chew
Dianne Chong◆
Vinay and Uma Chowdhry
James J. Coleman
Harry E. Cook*
Stuart L. Cooper
Kay and Gary Cowger
Magnus G. Craford
Natalie W. Crawford
Robert L. Crippen
Steven L. and Karen L. Crouch
David and Susan Daniel
L. Berkley Davis
Carl de Boor
Pablo G. Debenedetti
Tom and Bettie Deen
Hariklia Deligianni◆
George E. Dieter
Stephen W. Director
Ali H. Dogru
Jean-Jacques Dordain◆
Albert A. Dorman
Fiona M. Doyle◆
Elisabeth M. Drake
E. Linn Draper, Jr.
James J. Duderstadt
Susan T. Dumais
Richard E. Emmert
Paul England◆
John V. Evans
Thomas V. Falkie*
Olivia and Peter Farrell
Hans K. Fauske
Robert E. Fenton
Leroy (Mike) M. Fingerson
Bruce and Pat Finlayson
Edith M. Flanigen
Samuel C. Florman
Maria Flytzani-Stephanopoulos*
G. David Forney, Jr.
Robert C.* and Marilyn G. Forney
Eric R. Fossum
John S. Foster, Jr.
Efi Foufoula-Georgiou
Katharine G. Frase
William L. and Mary Kay Friend
Douglas W. and Margaret P. Fuerstenau
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Calendar of Meetings and Events

March 1–31	Election of NAE officers and councillors
March 10	NAE regional meeting: Engineering Therapies for the Future North Carolina State University, Raleigh
March 13	2020 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education Presentation Stanford University
April 1	NAE regional meeting University of Arizona, Tucson
April 28	NAE Convocation on Systems Engineering
April 30	NAE regional meeting Rensselaer Polytechnic Institute, Troy, NY
May 14–15	NAE Council meeting
May 20	NAE regional meeting: Human/Robot Interaction Amazon and University of Washington, Seattle
May 28	NAE regional meeting Medtronic, Minneapolis, MN
June 7–9	Workshop on Sharing Exemplary Admissions Practices That Promote Diversity in Engineering Irvine, CA
June 22–24	Japan-America Frontiers of Engineering Irvine, CA

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

ALI S. ARGON, 90, Quentin Berg Professor Emeritus, Massachusetts Institute of Technology, died December 21, 2019. Professor Argon was elected in 1989 for major contributions to the understanding of deformation and fracture of engineering materials through the application of mechanics to microstructure.

YUAN-CHENG B. FUNG, 100, professor emeritus of bioengineering, University of California, San Diego, died December 15, 2019. Professor Fung was elected in 1979 for contributions to the theory of elasticity and aeroelasticity, and applications to bioengineering.

HÉCTOR GARCÍA-MOLINA, 65, professor, Stanford University, died November 25, 2019. Dr. García-Molina was elected in 2003 for contributions to distributed-information systems.

IRVIN GLASSMAN, 96, Robert H. Goddard Professor of Mechanical and Aerospace Engineering Emeritus, Princeton University, died December 14, 2019. Dr. Glassman was elected in 1996 for contributions as researcher, author, editor, and educator in combustion and propulsion.

SIMON MIDDELHOEK, 88, professor emeritus, Delft University of Technology, died January 8, 2020. Dr. Middelhoek was elected a foreign member in 1996 for contributions to magnetic thin-film storage devices and micromechanics for sensors and actuators.

T.W. FRASER RUSSELL, 85, Allan P. Colburn Professor Emeritus, University of Delaware, died November 29, 2019. Dr. Russell was elected in 1990 for introduction of reaction engineering principles and continuous processing to the manufacture of thin-film electronic materials and for contributions to two-phase flow.

GARY K. STARKWEATHER, 81, architect, Microsoft Corporation, died December 26, 2019. Mr. Starkweather was elected in 2004 for the innovative application of optical technologies to computing, including the invention of the laser printer.

JOHN F. WELCH, JR., 84, retired chair and CEO, General Electric Company, and former chair (1986–90), NAE Council, died March 1, 2020. Mr. Welch was elected in 1983 for leadership in developing engineered plastics and for increasing national recognition of the importance of technology and innovation.

Invisible Bridges

Deep Unlearning

Guru Madhavan is the Norman R. Augustine Senior Scholar and director of NAE programs.

There's a clear line between content analysis and cussing. IBM's Watson crossed that line. While preparing for *Jeopardy!*, the famous "question-answering" system ingested a smorgasbord of content, including the *Urban Dictionary*, a sourcebook of slang. Watson was "learning"—and learned to swear.[1] The engineers were nonplussed. What to do about the expletives? Simple: just block, ban, censor. Control the input, control the output. End of story.

But is it?

A doubleness seems to define much of what we try to do with artificial intelligence: while we want machines to learn as humans do, we can filter their input to privilege one perspective over another. What machines learn is in part a function of what else they could learn.

With this capacity come many conveniences. Our devices are companionable. Their status updates keep us in the "now." Search engines have become "searching" engines, ever active without a command. We drive electrons with our thumbs and voice to summon a ride share or get turn-by-turn directions. Looking for movies to stream? Seamless. Podcasts? Delivered. Designer pizza or Ethiopian stew? Enjoy. Remixed 1970s funk? Here you go (and you might also like 1990s Trip Hop). Set your smart thermostat? Cool. Execute a precision strike on a foe? Bam.

Out of this mining and mingling emerges the AI version of being swept by currents of data akin to pollen gliding in the winds. We have empowered—and come to expect—greedy algorithms to conduct our work. In doing so, in important ways we have elbowed humans from the equation. This may be an unstated strategy in engineering, but every technological push forward evokes a social pushback. Langdon Winner termed this "mythinformation"—the hype to the public about artificial intelligence (AI) confronting the public's distrust of AI. Writing in 1984, Winner observed that AI's "present course is influenced by…the absent mind" (p. 596).

Think about humans' ability to understand what we are reading, let alone learning. "Dark patterns" online make us interpret one thing when what's being said is entirely different. Similarly, "deepfake" visuals are a reality. Profitability or manipulation in all forms affect how we provide judicial reasoning, make loan decisions, determine policy recommendations, interpret scientific results, and process content online. We have come to rely on systems that may identify a love letter as a legal contract and automated translators that don't understand the language they are translating. Isn't this evidence of an excess faith in statistics for sensemaking? What we have is a capability trap, and we don't know how to admit it even amid growing unease surrounding AI.

Back in the 1970s, AI leaders Marvin Minsky and Seymour Papert (1971) discussed the split between refining technical capacity (the "power strategy") and ways of calculating, classifying, interpreting, and using information (the "knowledge strategy"). In their words, this is "a more sophisticated kind of 'trade-off' that we do not yet know how to discuss."

Adapting Somerset Maugham's thoughts on writing a good book, there are three rules to develop useful learning. But no one knows what they are. That's because AI learning lacks a necessary counterpoint that informs human intelligence.

*

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

[1] A related discussion can be found in Rouse (2017), p. 8.

Practical concepts can be made sense of in dualities: good and bad, rise and decay, charging and discharging, statics and dynamics, health and disease, liberalism and conservatism…. Be it for power or knowledge, the obsessive focus on *learning* in AI misses something.

Why does an opposite for learning matter? Assigning dominance to one purpose—learning without a counterbalance—may be detrimental. Polarities need to be thought through and managed well. An opposite cannot simply be ignored.

Barry Johnson (2014) uses the example of breathing to illustrate the importance of dualities. Inhaling delivers oxygen; exhaling flushes out carbon dioxide. These are positive effects. The negative result of too much inhaling at the expense of exhaling is excess carbon dioxide; greater emphasis on exhaling than on inhaling supplies too little oxygen. These breathing contrasts are coupled and cannot be ignored as they are tied to another chief polarity: life and death.

Aim for informed unlearning: understand what unlearning is and should be, and how it could guide fruitful learning.

In this framing, the antidote for all the learning-by-doing in AI is not learning-by-not-doing but rather *unlearning*-by-doing. The question is how to make Watson unlearn from input rather than just to exclude it. Until that is understood and addressed, all our efforts in deep learning—however much depth is claimed—might sound triumphant but are ultimately shallow.

Any AI system that doesn't take unlearning into account is hardly a revolution; it's not even a reaction. One might argue that AI does unlearn all the time. For example, it will analyze lots of images and then make guesses about whether what it is seeing is a cat; if it isn't a cat, it "unlearns" and tries again. Not quite.

A starting point for serious AI would be to aim for *informed unlearning*: understand what unlearning is and should be, and how it could guide fruitful learning.

Both biological and cultural evolution present unlearning as an activity of renewal and reinforcement. Consider ecdysis, the process key for reforming protective structures—snakes shed skin, penguins molt, and so on. The process is inconvenient but essential. Consider depression. In one sense, what previously motivated an individual doesn't have the same effect. Components of cognitive behavioral therapy, a form of treatment for depression, center on unlearning certain thoughts, beliefs, and attitudes in favor of learning new coping mechanisms. These examples are representations of evolutionary fitness and readiness.

Engineering reminds us that contrary concepts can coexist and be constructive. With all kinds of trade-offs, when has engineering design ever worked without an opposing force? Engineering advances through learning and unlearning, although only the learning components are emphasized. The result has, alas, led to a business and policy boom to create more "learning systems" that foster higher performance and quality. This idea is incomplete, but it is a common desire in manufacturing, education, and health care.

A high-level demonstration of how learning interacts with unlearning comes from Japanese technology firms, which have "an almost fanatical devotion to learning," as Ken-ichi Imai and colleagues (1985) point out. Epson, the firm recognized for its printers, is known for having a next-generation model—that's at least 40 percent better—ready by the time a "new" model is launched (Imai et al. 1985, p. 346). This meant Epson needed a different kind of learning practice among its employees: to become effective generalists, they needed to gain and at once apply an engineering and business sense to the product. Epson complemented this by embracing polarities, approaching "a new product idea from two opposing points of view. One idea is pitted squarely against another even when developing the next generation model of a successful product already on the market," as Imai and colleagues note. "This approach opens the door for unlearning to take place and helps to maximize flexibility within the development process" (Imai et al. 1985, p. 361).

At Honda, unlearning is practiced through what's called the "rugby approach" (Imai et al. 1985, p. 353). This is different from a relay, where product development proceeds in sequence, individuals are responsible only for their piece of work, and they transfer control to the next unit; the quality of work at one state depends on the quality in its previous state. In a rugby model, the whole team "runs" together, coordinating their actions to get the ball to the goal. The method produces vigorous unlearning to depart from the relay-like hierarchies of most businesses and gain new advantages. This unlearning also creates a robust learning environment, akin to the way evolutionary selection and variation work at many levels, from an individual's competency to a team's capability to a market-generated preference.

Unlike Epson, though, where polarity was appreciated in advance, Honda had the choice of just modifying the current version of its Civic or building a wholly new concept. The latter would require unlearning of design practices that Honda had put in place. As Imai and colleagues (1985, p. 361) put it: "What used to work in the past is no longer valid, given the changes in the external environment. To adapt to these changes, the challenge is to retain some of the useful learning accumulated from the past and, at the same time, throw away that portion of learning which is no longer applicable."

This is *routine unlearning*, where previously learned habits passively fade away. New learning replaces or refines what was learned earlier. But for AI, and all "learning organizations," more is needed.

Wiping is a form of unlearning that over time works in two ways: through the "push" or pressure (as from a federal directive) to cease an action, or the "pull" or motivation provided by new information (as in a different delivery method for a medical treatment). Both these approaches, according to Rosemary Rushmer and Huw Davies (2004, p. ii11), are "deliberate and directed attempts at wiping out past learning; one using force, the other appealing to persuasion based on convincing evidence."

A third approach is undirected and unpredictable, and is perhaps the most valuable. This so-called *deep unlearning*, write Rushmer and Davies, involves a "new way of being and understanding that reflects a radical break with the past. This can be triggered by a sudden action, comment, or event; a single moment in which our lives are changed forever. This can be experienced when we are suddenly confronted with a major and substantial gap between what we see or hear and how we believed the world to be." Unlike passive or smooth unlearning, Rushmer and Davies (1984, p. ii11) add, "the unlearner falls fast, far, and hard. The person that lands at the bottom is never the same as the person that began the descent." This is hard change, necessary change, and useful change, and it fundamentally alters every aspect of how we learn.

*

Unlearning isn't easy; it's harder than learning. And more learning or abruptly ceasing to learn doesn't mean unlearning is automatically happening. It's a conscious practice in which we concurrently establish new connections as we relinquish old aspects. Try learning a new language, and the ones you already know keep interfering.

Material insights for learning and unlearning could come from a venerable Japanese tradition, very different from making printers and cars. The Ise Jingū shrine is about 2,000 years old. Every 20 years, continuing a practice initiated in 690 AD, people tear down the wooden shrine and rebuild it from scratch. The unique belief of this ritual called Shikinen Sengū is that "repeated rebuilding renders sanctuaries eternal."[2] The 30-odd events involved in Shikinen Sengū consume eight years; timber preparation alone takes four years. Reporting on this esteemed custom, one writer noted: "The renewal of the buildings and of the treasures has been conducted in the same traditional way ever since the first Shikinen Sengū had been performed 1300 years ago. Scientific developments make manual technology obsolete in some fields. However, by performing Shikinen Sengū, traditional technologies are preserved."

Unlearning is a trainable virtue. The process may be technically inconvenient but it is culturally essential.

In a deeper sense, while Shikinen Sengū could be taken as a case study in cultural transmission across generations, it also serves as a stellar motivation for learning and unlearning. The periodic disassembly and reassembly of the shrine is not destruction or inefficiency; it's a cultural process of renewal, one that might simultaneously privilege both knowledge and ignorance. Shikinen Sengū illustrates that unlearning is a trainable virtue. The process may be technically inconvenient but it is culturally essential.

We are told that learning is limitless. Does this mean we should simply keep acquiring information without a conscious effort to remove and renew? And there's a bigger challenge: how to overcome individual and insti-

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[2] Quotations are from Edahiro (2013). Also discussed in Nuwer (2014).

tutional resistance to unlearning that promotes rigidity, complacency, and intransience. This is precisely a scenario where AI systems can provide an advantage by pairing deep learning with deep unlearning.

Just as there's no stalemate between light and darkness, there shouldn't be tension between learning and unlearning. Only with that appreciation can the current artificial intelligence become a different AI: accountable intelligence.

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