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COMMENTARY
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Key Points:
- Unprecedented rates of change in the Earth system argue for more urgent action in support of a resilient global society
- Experts describe the meaning and impact of current and near-term change in four major domains
- We take an ensemble approach to highlight the similarities for actionable decision-making

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Toward a Resilient Global Society: Air, Sea Level, Earthquakes, and Weather

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Abstract Society's progress along the four corners of prepare, absorb, respond and adapt resilience square is uneven, in spite of our understanding of the foundational science and a growing sense that urgent action is needed. The resilience vignettes describe the meaning and impact of current and near-term change in four major domains: human health impacts from air pollution, coastal inundation from sea-level rise, damaging earthquakes in populated areas, and impacts from extreme precipitation. Given our understanding of the scientific principles, societal action, from preparation to adaption, will be critical in minimizing the negative impacts of change. The unprecedented rates of change in today's Earth system argue for urgent action in support of a resilient global society.

1. Introduction

Daily news reports bring harrowing testimonials by communities, aid organizations, and local officials of rapid environmental changes that are underway. Yet our society's response to these changes is slow and, in many cases, remains nonexistent. This inaction may reflect the perception that change is inherently slow and gradual, such as climate warming over several decades. The meaning of long-term change is embodied in the concept of sustainability, defined as a world where human needs are met equitably without harm to the environment, and without sacrificing the ability of future generations to meet their needs. However, changes are impacting human society more quickly in many areas, affecting wealthy nations and poor nations alike. This is captured by the complementary concept of resilience, which examines the ability of human society to prepare for, to absorb, to recover from, and to adapt to adverse events. Societal resilience forms the foundation of this connected set of scientific perspectives by experts that explore the changing domains of air quality, sea level rise, earthquakes, and extreme weather.

Resilience is variably defined in the science community, but we can use a four-sided square to examine societal value and progress. The resilience corners are Prepare, Absorb, Respond, and Adapt. While the corners are connected, each has different attributes:

1. **Prepare** is about understanding the changes and planning to minimize their impact.
2. **Absorb** is about dealing with adverse events; in essence, it is the realization of our preparations.
3. **Respond** represents our actions during and after an event, including local and regional support, and increasingly national and international support for impacted populations.
4. **Adapt** describes the actions we take to minimize the impacts of inevitable future events, based on our recent experiences.

Society's progress along the four corners of the Resilience Square is uneven, in spite of our understanding of the foundational science and a growing sense that urgent action is needed. In the resilience vignettes below, experts describe the meaning and impact of current and near-term change in four major domains: human health impacts from air pollution, coastal inundation from sea level rise, damaging earthquakes in populated areas, and impacts from extreme precipitation. Whereas the scientific focus of each vignette differs, we take an ensemble approach to highlight the similarities for actionable decision-making. Given our understanding of the scientific principles, societal action, from preparation to adaption, will be critical in minimizing the negative impacts of today's environmental changes. Moreover, today's unprecedented rates of change in the Earth system argue for more urgent action in support of a resilient global society.

2. Air: The Health Threat of Air Pollution—Susan Anenberg

About 70 years after the Donora, Pennsylvania, smog disaster in 1948 and the London *pea soup* of 1952, how has society progressed in its ability to anticipate, prepare for, and become more resilient to the public health threat of air pollution? Air pollution is the leading environmental health risk factor (Stanaway et al., 2018) with over 90% of the global population breathing air that exceeds the World Health Organization (WHO) guidelines for fine particulate matter ($PM_{2.5}$; (Health Effects Institute, 2018). Air pollution levels soared to catastrophic levels in India, China, and other parts of the world in the last decade, prompting the use of terms such as *Airmageddon* and *Airpocalypse*. Rising air pollution is not just a local problem, however; it affects public health on a global scale without regard to national boundaries. In recent years, the WHO and other intergovernmental organizations have responded by elevating air pollution on the world's environmental, health, and development agendas (World Health Organization, 2016).

The global picture obscures a more nuanced story that is characterized by divergent national actions and consequences. Whereas air pollution has been worsening in some parts of the world, criteria pollutant emissions in the U.S. dropped 73% from 1970 to 2017, while gross domestic product rose 262%, population rose 59%, vehicle miles traveled rose 189%, and energy consumption rose 44% (U.S. Environmental Protection Agency, 2017). The U.S. exemplifies countries that put in place effective air quality management programs, resulting in dramatic improvements in air quality and the numbers of days with *unhealthy* air throughout the country. Nevertheless, air pollution remains a top 10 risk factor in most countries of the world (including the U.S.), regardless of socioeconomic level. For example, nearly all cities in Asia and Africa have levels of $PM_{2.5}$ that exceed the WHO guideline (World Health Organization, 2018). This statistic is concerning given that half the world's population today lives in urban areas, growing to two thirds by 2050 (United Nations, 2014). Nearly all of that increase is expected in Asian and African cities.

How can countries and cities with poor air quality learn from past experiences of the international community? Exporting elements of the U.S. air quality management to other countries has clear advantages, including ground-based monitoring networks to track pollution levels and setting national ambient air quality standards. But countries in earlier stages of air quality management may want to look beyond air pollution and also consider the interrelatedness of air quality with climate change (Figure 1). The historical model of U.S. air quality management has focused largely on end-of-pipe emission controls, for example, scrubbers on coal-fired power plants, and diesel particulate filters and catalytic converters on vehicles. These technological approaches that remove air pollutants from tailpipe and smokestack emissions are quite effective in reducing health-harmful air pollutant emissions monitored by the U.S. Environmental Protection Agency but do not bring down greenhouse gas emissions. They also miss opportunities to improve quality of life in other ways: expanding urban green space, encouraging physical activity from active transportation, reducing traffic and traffic accidents, and avoiding gas and electricity costs by improving energy efficiency, to name a few. A broader view of environmental quality and public health goals highlights the need for looking beyond technological fixes and toward more transformational approaches that include other societal benefits.

To become more resilient to air pollution, we must consider potential feedbacks of climate change on air quality. New research indicates that future climate change may bring air quality *penalties*, making it harder to attain air quality standards through anthropogenic emission controls. A warmer, hotter world may lead to increased photochemical production of ground-level ozone pollution, which is associated with respiratory disease and premature mortality (US Global Change Research Program, 2016). While the literature has been more mixed on how climate change may influence $PM_{2.5}$, recent studies project that lengthening and intensifying wildfire seasons and drying soil conditions may lead to increases from smoke and soil dust. Since $PM_{2.5}$ has a strong association with premature mortality and is considered the dominant contributor to the air pollution disease burden, even small increases in concentration would result in substantial public health impacts. If the U.S. follows a high greenhouse gas emissions scenario, wildfires may dominate the $PM_{2.5}$ mortality burden by the end of the century (Ford et al., 2018), and health impacts from soil dust could be among the most costly climate change damage categories throughout the country (Achakulwisut et al.,

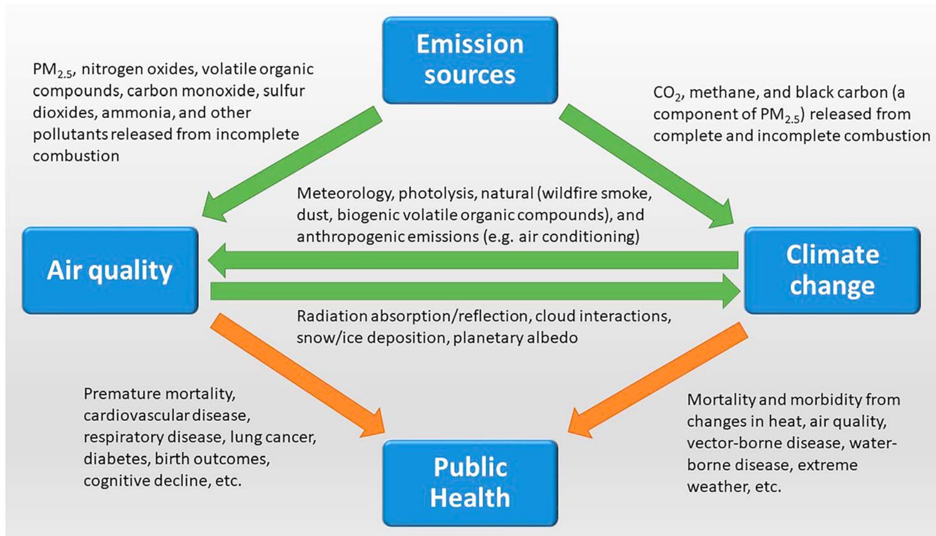

Figure 1. Key interconnections between emission sources, air quality, climate change, and public health.

2019). With these climate-induced increases in *natural* pollution sources, it could be harder to achieve clean air goals in many locations, even if anthropogenic emission controls are successful. Mitigating anthropogenic air pollution emissions now may not be enough to protect future air quality and public health without simultaneously controlling greenhouse gas emissions.

The interconnectedness of air quality and the climate system presents an opportunity for the world to achieve multiple benefits simultaneously. Greenhouse gases and health-harmful air pollutants are released when fuel is burned to produce electricity, propel vehicles, heat homes, and manufacture products. Any mitigation approach that burns less fuel will reduce both air pollutant and greenhouse gas emissions—a win-win-win for the Earth's air quality, climate system, and public health. Increasing energy efficiency for buildings, using electricity from zero emissions sources like solar and wind, and displacing motor vehicle trips with walking, cycling, and public transportation will burn less fuel, leading to climate, air quality, and public health cobenefits.

Transformative actions that unlock these opportunities of a low-carbon infrastructure are often more expensive and politically challenging than end-of-pipe emission controls, requiring major investments by local and national governments. Cities built around motor vehicles are challenging to transform into people-centric, carbon-neutral, sustainable communities. Fragmented governance structures at urban, national, and international scales also separate decision-making around transportation, energy, environment, and health, despite their many interconnections. Governments also lack complete information on which to base decisions. Most of the world is still lacking ground-based air pollution measurements (World Health Organization, 2018), limiting our ability to track the global progress on air quality. Going a step further, governments at all levels lack information about the air quality and public health consequences of alternative policy choices. With more understanding of local air pollution health impacts, cities may be further motivated to reduce greenhouse gases to achieve local and short-term benefits. As the benefits of air quality regulations dramatically outweigh the costs (Office of Management and Budget, Office of Information and Regulatory Affairs, 2017), including health impacts of air pollution under modern climate warming changes the calculus that society must weigh when deciding among greenhouse gas mitigation approaches.

Since the Industrial Revolution, humanity has profoundly altered the chemical composition of the Earth's atmosphere. What will the makeup of the world's air be in 2030? 2050? 2100? Will the world use lessons from the past, incorporate new information about the interconnectedness of air pollution and the climate system, and become more resilient in the future? We may not yet know what the future will bring, but the composition of our world's air may look very different.

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3. Sea Level: Translating Scientific Knowledge Into Resiliency in the Age of Coastal Inundation—Andrea Dutton

The abstract nature of the potential impacts of invisible greenhouse gases expressed in degrees of global warming does not always lend itself to effective communication on the urgency with which we need to address the warming of our planet. In contrast, sea level rise (SLR) offers more visually striking impacts of anthropogenic climate change. Rising seas are poised to impact heavily populated coastlines, coastal economies, and resources around the globe. It is clear that SLR has accelerated in step with postindustrial warming and will continue so in the future (Church et al., 2013; Sweet et al., 2017). Yet uncertainties in the physics of ice sheet response create a large spread in future sea level rise projections that are heavily relied upon for coastal planning. Here I argue that (1) the certainty of future SLR on its own is enough to prompt action to increase the resiliency of coastal communities; (2) becoming resilient requires us to account for the cascade of effects introduced by ongoing SLR and to account for processes that operate on multiple timescales; and (3) that the most critical step in translating scientific knowledge into resiliency is to overcome the social, psychological, and political barriers that currently impede the implementation of solutions.

Sea level rise is one of the major threats posed by anthropogenic global warming. Coastal communities at risk are understandably stymied by the array of sea level rise pathways that are depicted in comprehensive reports, such as the Intergovernmental Panel on Climate Change (Church et al., 2013) and the National Climate Assessment (Sweet et al., 2017; Figure 2). The spread of SLR projections that are the primary planning tool for coastal planning conveys the impression that there is large uncertainty, which, in turn, is frequently used as an excuse for inaction. Conversations often follow a narrative whereby the stakeholders ask the paired questions of "How much? and "How fast?" and scientists deliver probabilistic responses that are often interpreted as "we just don't know." This conversation desperately needs to be flipped on its head. Instead of asking leading questions that highlight the uncertainty that is largely driven by limitations in our understanding of dynamic polar ice sheet retreat, we need to focus on the certainty that sea level is going to continue to rise (Church et al., 2013; Sweet et al., 2017). Reconstructions from past warm periods have estimated that global mean sea level can be expected to rise by at least 6 m in response to 1–3 °C of warming over preindustrial background temperatures (Dutton et al., 2015). Even if this estimate is off by several meters, the implication is that nuisance flooding from high tides—which has doubled in the U.S. in the last 30 years (Sweet et al., 2018)—is only the first step on a long journey of coastal retreat. Additionally, observations that SLR continues to accelerate (Nerem et al., 2018), largely in response to melting from Greenland and Antarctic ice sheets, argue that linear projections of the average rate of SLR over the last century underestimate the impacts. These findings alone provide compelling evidence that we need to act quickly to adapt and plan for rising sea levels.

Although the long-term signal of SLR due to thermal expansion and land-based ice melt is important for future projections, coastal communities must also be aware of short-term (subdecadal to multidecadal) variability in the rate of SLR from ocean dynamics, such as the strength of winds and currents, and the effects of ocean-atmosphere interactions, such as the El Niño Southern Oscillation. Areas experiencing accelerated rates of SLR on the scale of years to decades have been referred to as *hot spots* (Sallenger et al., 2012; Valle-Levinson et al., 2017); for example, sea level in the southeast U.S. rose by >10 cm in only 5 years from 2011 to 2015 (Valle-Levinson et al., 2017). For comparison, a century of SLR at the current global average rate of SLR would result in about 30 cm of SLR. Hence, infrastructure adaptations along the U.S. east coast and other areas that are subject to such accelerations need to account for the heightened potential for short-term accelerations that are superimposed on the slower rise of sea level from warming of the atmosphere and ocean.

The threat of SLR is often oversimplified when only considering the impacts of water rising and flooding infrastructure in low-lying coastal areas. The scale and diversity of flow-on effects of SLR also include saltwater intrusion of freshwater aquifers, health issues arising from contaminated and/or standing floodwaters, reduced capacity for storm water runoff during rainfall events, loss of coastal resources through erosion and habitat loss, economic impacts to communities including industries such as tourism, real estate, and coastal industries such as shipping and fisheries, and social inequality arising from vulnerable communities that lack the resources to adapt. Some of these domino effects can be predicted, but we should also expect impacts due to rising seas farther inland, beyond just coastal communities. For example, risks to critical

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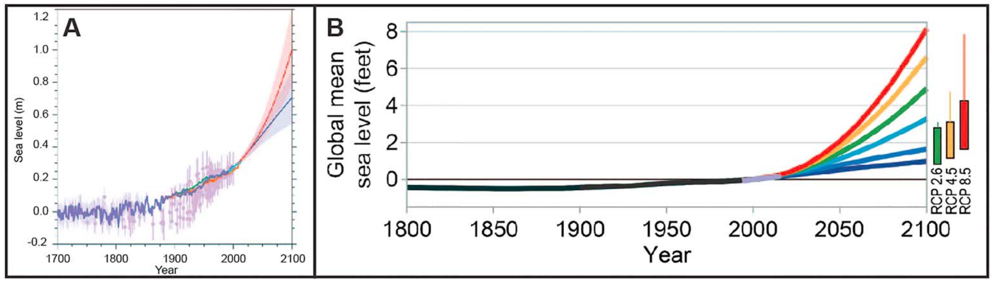

Figure 2. Projections of future sea level rise from (a) the Intergovernmental Panel on Climate Change 5th Assessment Report (Church et al., 2013) and (b) the National Climate Assessment Report (Vol. I; Sweet et al., 2017).

infrastructure from more frequent flooding pose a threat to areas and people that may not experience direct flooding.

Despite the urgent messages from climate science and despite warnings in a trove of scientific reports, the urgency to address climate change and SLR has somehow failed to prompt sufficient action, leaving many communities to tackle the impacts of these threats on their own. Today, a majority of Americans acknowledge that global warming is happening, but far fewer are willing to accept that they will be directly harmed by it (Howe et al., 2015). Take, for example, the public opinion maps for Florida, where SLR threatens the entire state's economy, but where a willingness to accept that global warming may impact them mostly reflects political party affiliation (Figure 3). Is the scientific community somehow failing to translate the urgency of these threats? More likely, complex social factors are interfering with an unequivocal message, including organized misinformation campaigns that influence the perceptions of the American public (Brulle, 2014). Hence, the most important step in achieving societal resiliency in the face of rising sea levels is to find more effective means to motivate action, so that we can keep ahead of rising seas as we enter this new age of coastal inundation and retreating coastlines.

4. Earthquakes: Seismic Hazard Assessment for Improved Resilience—Christine Goulet

The Southern California Earthquake Center (SCEC) community conducts and coordinates fundamental and applied research on earthquakes using southern California (SoCal) as a natural laboratory. It advances earthquake system science by gathering information from seismic and geodetic sensors, geologic field observations, and laboratory experiments and synthesizing knowledge of earthquake phenomena through system-level, physics-based modeling. The integration of advanced technologies and computational products allows sophisticated seismic hazard assessment, a key ingredient to seismic risk and community resilience. The benefits of this integration go beyond the science, affecting design practice and policy decisions, and support improved seismic safety and resilience, as illustrated below by a few key products and outcomes.

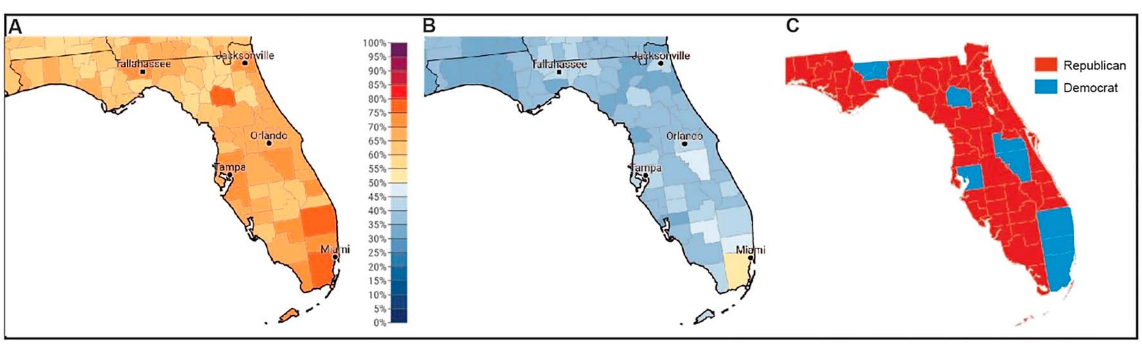

Figure 3. (a) Public opinion estimate maps showing the percent of adults who think global warming is happening (data from 2018; Howe et al., 2015). (b) Public opinion estimate maps showing the percent of adults who think global warming will harm them personally (Howe et al., 2015). (c) Florida election maps for the 2016 Presidential race (https://www.politico.com/2016-lection/results/map/president/florida/).

Figure 4. One of the key messages of the Great ShakeOut Earthquake Drills (ShakeOut.org/messaging).

In 2008, scientists from various organizations teamed up to develop simulations for a hypothetical magnitude 7.8 earthquake on the southern San Andreas Fault (Graves et al., 2008). The results from the simulations were used to assess the state of emergency response and preparedness in SoCal in the case of a large but plausible earthquake. Outcomes estimate as many as 1,800 deaths and over 53,000 casualties from injury. More than 18 million square meters of building space would be rendered unusable due to damage or complete collapse. Water distribution would take months to come back to normal, leading to other public health issues. Overall, economic losses would exceed $190 billion (~1% of U.S. GDP). The results were startling and presented a bleak picture of what could happen if such an event were to occur. Evaluation of impacts from this scenario revealed that existing disaster plans were inadequate, even for Los Angeles (LA), a city at the forefront of emergency preparedness. The LA Mayor's Office took notice and created the LA Seismic Safety Task Force. The Taskforce published their summary report *Resilience by Design* (Mayoral Seismic Safety Task Force, 2014), which recommended, among other measures, the fortification of the water distribution system, the retrofitting of buildings with high collapse risk, and the enhancement of reliability of telecommunication networks. The city also created a new position for a resilience officer. Key seismic recommendations were also integrated into the Resilient LA plan to improve the city resilience across the board (Resilient Los Angeles, 2018).

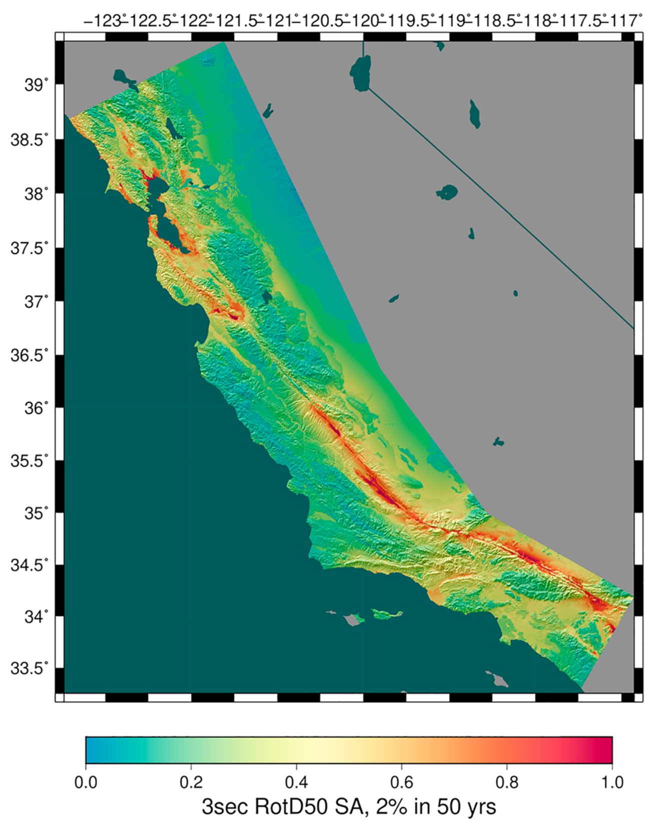

Figure 5. CyberShake map for 0.33-Hz (3 s) spectral acceleration for 2% in 50-year probability of exceedance. The composite map was produced by combining the 3-D southern California map (Study 15.4), the central California map (Study 17.3), and the northern California map (Study 18.8). In aggregate, the combined map includes 650 million seismograms representing ground motions at 1,673 sites; it took over 175 million core-hours of processing time to complete using NCSA Blue Waters and OLCF Titan, the two largest open-science supercomputers available at the time.

Following the release of the ShakeOut Scenario, an annual earthquake preparedness exercise, called the *Great ShakeOut Earthquake Drills*, was initiated by SCEC to encourage all aspects of preparedness and mitigation, reaching millions of participants all around the world. One of the key messages is *Drop, Cover, and Hold On*!, meant to encourage individuals to develop the automatic response to protect themselves under a sturdy piece of furniture when they feel earthquake shaking (Figure 4). The drills serve as an opportunity for families, schools, neighborhoods, workplaces, and other organizations to think about securing their space, anchoring furniture, and heavy art pieces and to prepare earthquake kits including dry and canned food, water, medication, and other supplies that can be used in the wake of an earthquake. The exercise (www.shakeout.org) turned 10 years old in 2018 and is now conducted annually with over 60 million participants each year, reaching other countries, including Iran, Turkey, Mexico, Italy, New Zealand, Canada, and Japan, with websites in several languages.

Another recent development is the Uniform California Earthquake Rupture Forecast 3 (UCERF3) model (Field et al., 2014), which describes earthquake sources in terms of their location and geometry, their slip rate, and the magnitudes they might produce over time. This model has become the basis of most design and building code applications for the complex California fault systems and guided the seismic hazard

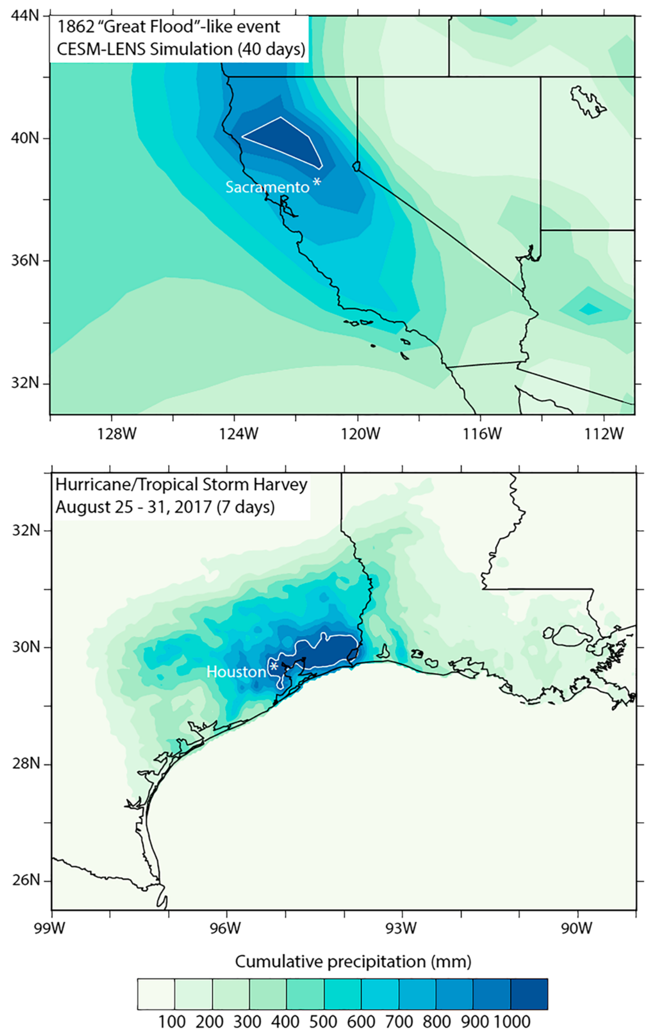

Figure 6. Simulated and observed *megafloods*. (a) Simulated 40-day cumulative precipitation associated with long-duration extreme (200-year return interval) precipitation events in the CESM-LENS preindustrial simulation (1,800-year control run; see Swain et al., 2018, for methodological details (http://www.cesm.ucar.edu/projects/community-projects/LENS/data-sets.html). A storm sequence capable of generating precipitation of this magnitude would be comparable to that which produced California's Great Flood of 1862. (b) Observed 7-day cumulative precipitation (PRISM; http://www.prism.oregonstate.edu) generated by Hurricane Harvey as it made landfall and subsequently stalled (at tropical storm strength) over southeastern Texas in late August 2017, producing torrential rainfall and subsequently devastating flooding across the Houston metropolitan area. In both (a) and (b), areas inside the white contour depict regions where cumulative precipitation exceeds 1 m.

estimates for California that led to a reduction of earthquake insurance rates.

In addition to individual scenario simulations, a physics-based computational Probabilistic Seismic Hazard Analysis platform combines earthquake rupture forecasts with fault rupture simulation and wave propagation codes to provide ground motion shaking estimates for engineering design (Figure 5). These CyberShake simulations (Jordan et al. 2018) were used to inform the Earthquake Early Warning system being implemented in California, and CyberShake maps are the basis for a new LA urban seismic hazard map (Moschetti et al., 2017, 2018) being developed by the USGS. Risk-targeted earthquake response (MCE_R) spectra using a combination of empirical approaches and the CyberShake model (Crouse et al., 2018) are available as a design tool for public use (https://data2.scec.org/ugms-mcerGM-tool_v18.4/).

These real world examples illustrate that there are several paths to achieve improved resilience. To engage a broad community, it is not sufficient to characterize the hazard, but it is also necessary to quantify impacts for society stakeholders. The knowledge transfer from science to engineering and policy is critical for tangible impacts. Societal resilience is broader than government planning at the city or county level and requires the engagement and education of individuals, industry, and local organizations. Collaborative research on earthquakes is ongoing, and as we further our knowledge and improve the modeling of physical processes, we will continue to grow the impact on earthquake resilience.

5. Weather: Is Society Ready for Precipitation Whiplash?—Daniel Swain

California, a region known for devastating wildfires and legal battles over scarce water, might seem a strange place for a case study on the societal risks posed by catastrophic flood events. But there is dramatic evidence from California's early statehood that the region is susceptible to greater inundation than widely believed: the *Great Flood of 1862*. The product of an extraordinary weeks-long sequence of storms, this deluge (Figure 6) transformed California's Central Valley into a vast inland sea at least 35 km wide and 500 km long—resulting in disastrously high flows on essentially every river, creek, and stream from Oregon to the Mexican border (Engstrom, 1996). The scope and duration of inundation was so severe, in fact, that certain towns were abandoned for months; even the state capitol of Sacramento was temporarily relocated to San Francisco (M D Dettinger & Ingram, 2013).

Is California's Great Flood a fluke, so unlikely an event as to be beyond the considerations of natural hazard planning? Recent evidence suggests otherwise. Coastal river sediment records indicate that this event is not unprecedented in recent Earth history (Malamud-Roam et al., 2006). Moreover, projections indicate that climate change could dramatically increase the likelihood of recurrence on human-relevant timescales, with a cumulative likelihood rising as high as 50% over the next 40 years (Swain et al., 2018). But not just the risk of the flood-related climate hazard is increasing: California's human demographics have changed radically over the past century and a half. In 1862, California was home to only 400,000 people; today, nearly 40 million people reside in the state. Housing for millions of Californians exists within probable inundation zones during extreme flood events, as do centers of agricultural activity and global information technology hubs (J. Mount et al., 2018). California's extensive water conveyance and storage network is actively managed using hundreds of pieces of potentially flood-vulnerable infrastructure, ranging from massive dams in the

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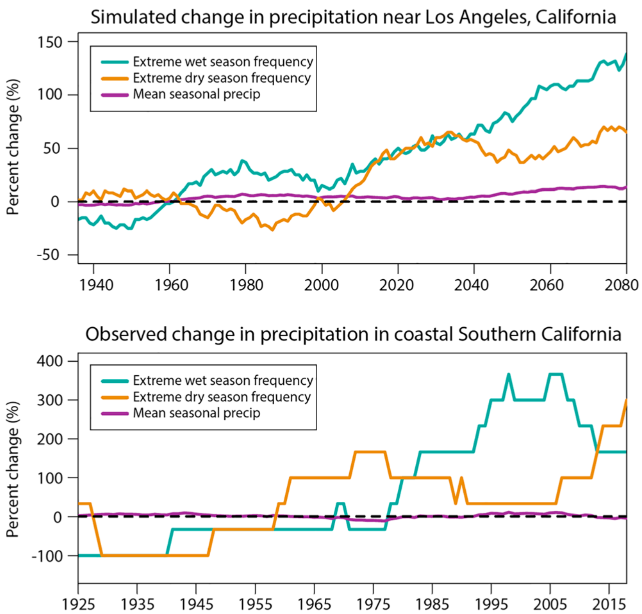

Figure 7. Simulated and observed changes in regional mean versus extreme precipitation. (a) Simulated change over time (across 40 ensemble members) in frequency of very wet (blue curve) and very dry (brown curve) November–March *rainy seasons*—as well as the relative change in mean seasonal precipitation (purple curve)—for a grid box near Los Angeles, California, as simulated in the CESM Large Ensemble experiment (CESM-LENS) under an RCP 8.5 greenhouse gas emission scenario. (b) Same as (a), but using observed precipitation for California's *South Coast Drainage* (which encompasses Los Angeles) from NOAA's divisional climate dataset (nClimDiv; www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php) and using an October–March rainy season definition. In both (a) and (b), the climatological period used to calculate precipitation baselines is 1921–1980, all curves are plotted using a 30-year moving average, and precipitation exceeding (falling below) the 95th (5th) quantile for seasonal baseline values qualifies as a *very wet* (*very dry*) season.

Sierra Nevada foothills to humble earthen levees in the Sacramento/San Joaquin Delta. Indeed, a report by the U.S. Geological Survey and the State of California concluded that a flood of comparable magnitude to that in 1862 would likely overwhelm California's flood defenses and cause unprecedented societal disruption, becoming one of the most expensive natural disasters in history (Porter et al., 2011; Wing et al., 2016).

While a modern California megaflood remains a hypothetical risk, recent events underscore that seemingly implausible worst case scenarios do happen. When Hurricane Harvey made landfall along the Gulf Coast of Texas and stalled over Houston in 2017, focusing rain directly over the sprawling metropolitan area for nearly a week, the resulting flood disaster was estimated to have a return interval as high as 2000 years in a stationary climate (Emanuel, 2017; Figure 6). At one point, nearly 30% of the surrounding region was underwater and hundreds of thousands were displaced; over 100 deaths were attributed to the storm, and total damages were estimated at $125 billion (Blake, 2018). This outcome, however, was not surprising to the meteorologists, hydrologists, and urban planners who had long anticipated such an event (Zhang et al., 2018)—and climate studies suggest that global warming has already increased the likelihood of Harvey-like flood events in the area by more than a factor of 3 or more (Emanuel, 2017; Risser & Wehner, 2017).

Many of the dangers posed by extremes are predictable, yet we are still underestimating the risks in most practical contexts. Recent work, for instance, has shown that flood hazard maps used to inform contingency planning, zoning, and insurance premiums for the federalized U.S. National Flood Insurance Program woefully underestimate the risk of inundation (Oliver et al., 2018). But even more realistic contemporary estimates of flood risk often fail to account for the fact that the climate itself is changing and that the risk of extreme precipitation is increasing. Thus, a key 21st challenge emerges: how can we best make use of cutting-edge climate science information in public policy and water management to improve societal resilience in an era of increasing hydroclimatic extremes?

While the theoretical basis and empirical evidence for human-caused global warming are well established, considerable uncertainty remains with respect to precipitation projections at regional scales (Deser et al., 2014). Indeed, natural (internal) climate variability can temporarily mask anthropogenic trends in regional precipitation, even on multidecadal timescales (Deser et al., 2012). This notion of *irreducible uncertainty* in regional climate (Hawkins et al., 2016) has been met with a certain level of dismay in policy and decision-making circles, where such projections inform climate adaptation measures. However, persistent uncertainty in regional mean precipitation trends may actually be masking more robust, higher-confidence changes at opposite ends of the hydroclimatic spectrum. While the projected increase in global mean precipitation is modest (around 3%/°C; Kharin et al., 2013), much larger increases in extreme precipitation events are expected (5–10%/°C; Donat et al., 2016; Neelin et al., 2017; Pendergrass et al., 2017). This divergence between global mean and regional extreme precipitation occurs because the former is constrained by the global atmospheric energy budget (Pall et al., 2007; Pendergrass & Hartmann, 2013), while the latter scales more closely with the exponential increase in atmospheric water vapor as the atmosphere warms (O'Gorman & Muller, 2010). Recent work points to an ominous rule of thumb: the heavier the precipitation, the larger the increase in relative frequency in a warming world (e.g., Giorgi et al., 2019).

Despite this increase in the expected frequency of heavy downpours, many regions are not expected to become substantially wetter on average. In fact, climate models suggest that increases in wet extremes will be variably offset by decreases in the frequency of light to moderate precipitation (Thackeray et al., 2018). This *compensation effect* is likely to yield an increase in the number of dry days across highly populated continental zones (Polade et al., 2014), the overall frequency of dry spells (Diffenbaugh & Giorgi, 2012), and sudden *whiplash* transitions between wet and dry extremes (Dong et al., 2018; Pendergrass et al., 2017; Swain et al., 2018). Figure 2 illustrates this evolution toward increasing variability in a particular location. In Southern California, for instance, the frequency of very wet (>95th percentile) and very dry (<5th percentile) years is projected to increase considerably (by 50–100% or more) even as mean precipitation changes only slightly in the coming decades (by less than 20%). Indeed, real-world observations suggest that such a pattern may already have begun to emerge (Figure 7).

Rising temperatures and increasing atmospheric evaporation will further amplify the effect of precipitation variability, potentially increasing the duration and intensity of drought (Diffenbaugh et al., 2015; Overpeck, 2013; Trenberth et al., 2013). Indeed, the increasing risk of future *megadrought* may be driven primarily by persistent warmth and temperature-driven aridity, as opposed to decreases in precipitation (Cook et al., 2015). Thus, shifts in the temporal and spatial character of the hydrologic cycle could become far more consequential than changes in its mean state (Donat et al., 2016; Dong et al., 2018; Pendergrass et al., 2017; Polade et al., 2017; Swain et al., 2018).

The success of climate-related public policy interventions, particularly those aimed at adapting to the increased risks from changing climate, hinge on decision-making that is informed by data with a sufficient degree of spatiotemporal granularity and regional context. Similarly, investing in an infrastructure that is truly *climate resilient* will depend on the understanding that incremental changes in mean climate belie far greater changes in the frequency of unprecedented extreme events (Diffenbaugh et al., 2017; Huang et al., 2018; Pendergrass et al., 2017; Swain et al., 2018).

California provides a good *on the ground* perspective. The state's annual average precipitation has changed little during the historical period (e.g., Seager et al., 2015), and climate models generally project modest and/or uncertain changes in regional mean precipitation even in a much warmer world (Neelin et al., 2013). Yet model simulations also depict a statistically robust increase in the frequency of extremely wet and dry periods (Berg & Hall, 2015; M. Dettinger, 2016; Dong et al., 2018; Swain et al., 2018). *Little mean change*" and *large increase in extremes* can thus both be technically correct interpretations of climate model projections—creating a high risk of *maladaptation* to future changes depending on which aspect is emphasized in decision-making. This physical reality means that decision-makers must explicitly consider climate extremes when planning for the future, instead of preparing only for the expected changes in *average* climate conditions.

To support the needed kind of nuanced decision-making, scientists and decision-makers must work together to bridge lingering gaps between research and practice. Scientists must develop and employ new methods and metrics that recognize subtle regional and seasonal variations in the coupled Earth system, moving beyond longitudinal and annual averages. Sustained conversations between scientists and users of climate information, from urban planners to civil engineers to wildland firefighters, can yield scientific metrics with greater practical relevance and ultimately ensure that climate complexity is fully integrated into societal - decision-making.

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