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Summary

Michael Oppenheimer and Jesse Anttila-Hughes begin with a primer on how the greenhouse effect works, how we know that Earth is rapidly getting warmer, and how we know that the recent warming is caused by human activity. They explain the sources of scientific knowledge about climate change as well as the basis for the models scientists use to predict how the climate will behave in the future. Although they acknowledge the large degree of uncertainty that surrounds predictions of what will happen decades or even centuries in the future, they also emphasize the near certainty that climate change has the potential to be extremely harmful to children.

Most children around the world will face hotter, more extreme temperatures more frequently. Higher temperatures will directly affect children's health by increasing the rates of heatstroke, heat exhaustion, and heat-related mortality. Excessive heat is also likely to affect children indirectly by disrupting agricultural systems, driving up prices, and increasing food scarcity.

Many of the world's children may see local demand for water outstrip supply, as shifting precipitation patterns dry out some regions of the world, make other regions wetter, and increase the frequency of both unusually dry periods and unusually severe rains. Mountain glaciers will recede further, significantly reducing storage of winter snows and thus springtime runoff, which has traditionally been used to water fields and recharge reservoirs. Melting ice will also raise sea levels, triggering direct physical threats to children through flooding and erosion and indirect threats through migration and expensive adaptation.

Climate change is also expected to make weather-based disasters more frequent and more damaging. This is particularly worrisome for children, not only because of the physical peril disasters pose but also because disasters can have debilitating long-term indirect effects on children. Damage to ecosystems from climate change may also harm children; for example, acidification the world's oceans will reduce food supplies, and disease-carrying insects will invade new areas in response to changing rains and temperatures.

In the face of such dire forecasts, Oppenheimer and Anttila-Hughes argue, climate change forces us to directly confront the value we put on future children's wellbeing. Fortunately, we have reason for hope as well as for concern: "History," they write, "has demonstrated time and again that humans can tackle uncertain threats in times of need."

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Understanding how humanity's accumulated greenhouse gas emissions will alter Earth's climate over the next few centuries requires a broad perspective, so climate change is usually discussed as a global issue. But understanding how climate change will affect children who live through it requires a narrower focus—one that pushes directly against the limitations of that global view. Geographic variation in climate change's effects over time, uncertainty stemming from scientific complexity, and, more than anything, the inherent impossibility of forecasting future human behavior combine to make climate change's eventual impacts on children both very different from place to place and extraordinarily difficult to predict with any certainty. Climate change will influence children's lives in few "global" ways. Rather, during the coming decades, children will face myriad interactions between changes in the climate and social, economic, and cultural forces.

A defining theme of this article is the need to balance high uncertainty in some areas with relative certainty in others. As we will show, we now have overwhelming evidence that human emission of greenhouse gases has already begun to change the climate and that it will continue to do so unless emissions are halted; hence we call this climate change *anthropogenic*, from the Greek for *human influenced*. Moreover, ample evidence indicates that we can expect many changes in the weather and the climate that will fall outside the range of human experience. Unless we reduce emissions drastically, those changes are expected to have pervasive impacts worldwide, including, in some cases, the destabilization or destruction of ecological and social systems. Thus the costs of inaction are high. At the same time, enormous uncertainty surrounds any forecast of specific outcomes of climate change. Which regions will be affected and in what ways, how quickly changes will occur, and how humans will respond are all impossible to know with certainty, given the complex natural and social forces involved. From a risk management perspective, the possibility of extremely negative outcomes means climate change has much in common with other large-scale global threats such as conflict between nuclear powers, wherein the potential for highly undesirable and irreversible outcomes is real but very difficult to predict with precision. We will return to this theme many times.

Origins of Understanding

The greenhouse effect is a prerequisite for life as we know it because without it, Earth would be much colder (by about 32° Celsius, or 57.6° Fahrenheit) and drier: a frozen desert. Nobel Prize–winning Swedish chemist Svante Arrhenius laid out the greenhouse "problem" in an 1896 paper. He showed that a rise in atmospheric concentrations of carbon dioxide—a by-product of combustion, caused by burning coal as an energy source in the emergent industrialized countries—would make the planet warmer, although he saw that warming as beneficial rather than problematic. Other notable nineteenth- and early-twentieth-century scientists also contributed to our understanding by linking earlier, natural changes in atmospheric carbon dioxide to the comings and goings of ice ages.

After Arrhenius, interest in the problem lagged until the 1950s, when a few scientists began exploring in detail how carbon dioxide traps infrared radiation. They provided the first credible estimates of the fraction of emissions that remain in the atmosphere rather than dissolving in the ocean. The advent of modern computing advanced weather forecasting and led to an interest in modeling the general circulation of the atmosphere. An offshoot of those studies examined the effect of carbon dioxide and, in the 1960s, produced the first computer-based models for estimating future climate change. By the 1970s, scientists had come to understand that the *cooling effect of particulate matter*, which is a by-product of dirty, fossil fuel combustion techniques, had been substantially offsetting the *warming effect of carbon dioxide*. The roles played by water vapor, clouds, and minor atmospheric gases other than carbon dioxide were also elaborated in great detail. By the late 1980s, the scientific consensus that carbon emissions would warm the climate was sufficient to become a major political issue, leading to the 1992 negotiation of the United Nations Framework Convention on Climate Change treaty, which was dedicated to stabilizing greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system." Today, carbon dioxide has increased by more than 40 percent from its preindustrial level because of the mining and burning of fossil fuels, the cutting and burning of forests, certain agricultural practices that emit greenhouse gases, and the output of certain industries, such as those that produce cement and halocarbon refrigerants.

The terms *climate* and *weather* are sometimes confused with each other, and that confusion can have serious implications. *Weather* denotes the actual behavior of Earth's oceans and atmosphere over a given short period; the term *weather* refers to the temperature, precipitation, wind, storminess, and so forth that we experience during any given day, week, month, or year. *Climate*, on the other hand, refers to the behavior of weather over longer periods, such as decades, from a statistical perspective (for example, annual mean temperature or mean daily maximum temperature, averaged for a geographic region). *Climate change* thus refers to an increase in *average global temperature*, along with all of the ways such an increase affects the characteristics of climate and weather.

Failure to differentiate between weather and climate can lead to serious misunderstandings. We easily recall weather, and that readiness of perception (or *availability*, as psychologists call it) often dominates our assessment of risk: If this winter is cold, what happened to global warming? If this summer is hot, we'd better hurry up and fix the problem! Obviously, such misunderstandings can be manipulated to fit political agendas, and we must act to decouple our understanding of the larger, global problem from the random weather experienced on any given day.

The Physical Problem

Concern about climate change has grown over the past 25 years. Today, thousands of climatological scientists and researchers across related fields are conducting research on topics ranging from the specifics of obscure climate processes to the likely impacts of climate change on everything from alpine ecosystems to financial markets. The pace of discovery and the growth in understanding have been sufficiently rapid, the breadth of impacts sufficiently wide, and the implications of social concern sufficiently broad that a major international organization was created to synthesize scientific evidence on climate change. The Intergovernmental

Panel on Climate Change, or IPCC, operates under the auspices of the United Nations Environment Programme and the World Meteorological Organization. Every six years or so, the panel publishes assessment reports that summarize the state of the research on climate change science, impacts, and policy.[1] Many other organizations, too, have assessed aspects of the problems inherent in climate change, resulting in projects ranging from the 2007 *Stern Review*—a UK government study emphasizing the economic benefits of early action against climate change—to the 2014 philanthropically funded American Climate Prospectus, which summarizes the expected economic risks of climate change in the United States.[2]

Perhaps the most important point about the science of climate change is that our knowledge arises from four very different sources: direct observations of the climate system and changes within it, including everything from almanac records to satellite-based imaging; paleoclimate evidence of Earth's climate in the distant past—for example, what we can deduce by examining air bubbles trapped in the Antarctic ice sheet by snow that fell hundreds of thousands of years ago, or by analyzing the chemical composition of fossilized marine animal shells trapped in sedimentary layers at the sea bottom for tens of millions of years; laboratory studies of the chemical and physical processes that take place in the atmosphere; and—perhaps most important for forecasting—numerical, computer-based models of climate circulation and other climate properties, which in many respects are similar to the meteorological models used for generating weather forecasts. Our understanding of climate change is based on all four of these sources, which together paint a consistent picture of carbon's current and future warming effects on the planet.

Scientists are nearly certain that climate change is occurring and has the potential to be extremely harmful. Climate change nonetheless has several unique characteristics that combine to present a very challenging mix for policy makers. Climate changes—both those already observed and those anticipated—will affect different countries and different regions very differently. But, eventually, the changes will affect humans in every nation on the planet; in no place will climate remain unchanged. Moreover, every country's carbon dioxide emissions affect the climate in every other country because carbon dioxide's long lifetime means that it achieves a nearly uniform distribution in the atmosphere. Thus climate change is a global commons problem at the largest conceivable scale; the atmosphere is an easily damaged, open-access resource whose preservation will demand increasingly active coordination across the full complexity of human social interactions. Climate change's global nature thus distinguishes it from almost every other major environmental policy problem—except, perhaps, the effects of ozone depletion or large-scale nuclear warfare.

Another implication of carbon dioxide's very long lifetime is that a significant fraction (about 25 percent) of today's emissions will remain airborne even a millennium from now unless we invent a technology to affordably capture and bury the carbon dioxide, meaning that many expected changes are effectively irreversible. Furthermore, the huge mass of the oceans is absorbing a large portion of the climate's thermal energy as Earth warms, and the resulting thermal inertia means that the effects of today's emissions will take several decades to appear.

Even if we could eliminate emissions entirely today, enough greenhouse gases have already been released to gradually warm the planet for the rest of the current century and beyond.

Policy makers will need an unusual degree of foresight, extraordinary powers of judgment, and a willingness to act without getting credit for the outcomes.

Climate change science is also rife with uncertainty. Even though scientists are increasingly certain about the general characteristics of global climate changes under certain emissions scenarios, extensive uncertainties remain when it comes to details of how the climate will respond at time and spatial scales relevant to humans. The answers to such questions as how fast the sea level will rise are so uncertain that scientists can offer policy makers only a very limited basis for making decisions, much less tell them with confidence how high to build a seawall. When combined with the fact that, in the coming years, humans will change their emissions behaviors in response to changes in energy supply and economic development, uncertainty about what will happen becomes daunting.

The combination of universality; effective irreversibility; lags between emissions, policy actions, and system responses; and general uncertainty means that policy makers will need an unusual degree of foresight, extraordinary powers of judgment, and a willingness to act without getting credit (or suffering opprobrium) for the outcomes. It's no wonder that many leaders have resisted grappling with climate change—all the more so because of the potential costs of reducing greenhouse gas emissions.

A natural question is whether all of climate change's impacts on children's wellbeing must necessarily be bad. Generally speaking, most scientists say climate changes will disrupt and damage both natural and human systems in most places around the world; the IPCC, for example, acknowledges eight risks associated with climate change, ranging from increases in rates of death and illness during periods of extreme heat to loss of rural livelihoods.[3] Certain regions are predicted to be more mildly affected, and cooler countries closer to the poles, such as Canada and Russia, may actually see a variety of benefits under climate change (at least temporarily), thanks principally to longer growing seasons and milder winters. However, those beneficial effects are expected to be dwarfed by a variety of negative impacts around the world, particularly in poorer countries, and especially after factoring in certain indirect effects of the increased stress that climate change will exert on socioeconomic systems.

Scholars have made strides in understanding how social and economic systems respond to climate changes, often using variability in historical weather patterns to provide insights into what future climate change might mean for human society. Readers who want to learn more about such research should consult a recent review by economists Melissa Dell, Benjamin Jones, and Benjamin Olken in the open-access *Journal of Economic Literature* or the Impacts, Adaptation, and Vulnerability section of the most recent IPCC report.[4]

In general, the fact that climate change's impacts are expected to be mostly negative reflects the speed and intensity with which human activity is expected to change the climate. Although the climate is constantly in flux, natural variations on such a large scale normally occur many times more slowly than the current rate of change. The rapid pace of anthropogenic climate change limits our ability to respond smoothly and gradually to changes in risk, and it hampers the efficacy of slow-moving policy options for mitigating climate risk—such as improving infrastructure or developing new technologies—thereby potentially forcing populations and food systems to change at speeds far faster than normal.

What Can Past Climates Tell Us about Climate Change?

Natural climate variation has arisen from (1) a host of small changes in the amount of light the sun emits, (2) fluctuations in the amount of volcanic dust in the atmosphere (which cools Earth by reflecting sunlight), and (3) a spectrum of other variations, including some that are chaotic and therefore unpredictable. Taken together, these factors have caused global average temperature to vary by a few tenths of a degree Celsius through the decades—less than the current level of human-influenced warming.

One lesson science can draw from the recent past stems from the effects of the El Niño Southern Oscillation, a suite of climatological changes tied to an increase in the surface temperature of the eastern tropical Pacific Ocean that occurs every three to seven years. El Niño and similar oscillations are associated with changes in weather patterns around the world, including changes of a few tenths of a degree in the global average temperature. Even that small a variation in the global climate is enough to seriously influence human wellbeing; strong El Niño events are associated with punishing droughts and heavy floods throughout the world, including in major agricultural regions like California and eastern Australia. One vivid albeit imperfect way of conceptualizing climate change's magnitude would be to think of a permanent shift in the global climate regime several times stronger than El Niño, though at a much slower pace.

We can extend our understanding of the climate further into the past by analyzing data related to the paleoclimate. Air bubbles trapped in ice that froze millennia ago, tree rings that capture growing-season conditions, microscopic fossils millions of years old buried beneath the ocean floor, and plentiful other data let scientists infer what the atmosphere and climate were like in ages past and to chart climate history. Scientists now know that the causes of natural, preindustrial climate changes included very gradual shifts in Earth's orbit and axis of rotation relative to the sun over tens and hundreds of thousands of years. Those cycles alter the pattern of sunlight that reaches Earth's surface and thereby affect the level of photosynthesis, the melting of ice sheets, and many other processes that determine both the amount of greenhouse gases in the atmosphere and, ultimately, the behavior of Earth's climate. In the past million years, at the climatic minimums of such cycles—which we call ice ages—glaciers covered much of the Northern Hemisphere, and global surface temperature averaged around 5°C (9°F) below its value during periods of peak warmth, called interglacials. The entirety of human civilization, starting at the dawn of agriculture, has taken place during the most recent interglacial.

Much earlier, about 65 million years ago, when the age of the dinosaurs came to an end, temperatures averaged 8–10°C (14.4–18°F) higher than today. About 55 million years ago, during the Eocene, global average temperature jumped relatively rapidly, to 12°C (21.6°F) higher than today, possibly because of unusually high atmospheric levels of methane, a potent greenhouse gas. During the period of sustained warmth 50 million to 55 million years ago, the Arctic latitudes were home to alligators, tapirs, and rain forests.[5] In other words, the projected warming for this century is modest in terms of the very long span of climate history but is comparable in magnitude to changes of the past million years that remade Earth's surface; in our case, however, changes are occurring much, much more quickly than the natural rate. Sea level also varies naturally, but the trend associated with global warming, about 6–8 inches of sea level rise over the past century, now exceeds natural variations. Eight inches may not seem like much, but it is sufficient to erode and permanently submerge about 60 feet landward from the typical US East Coast beach tide line.

Observed Global Changes

Earth's average temperature since the mid nineteenth century is known with fair precision. By that point, enough ground- and ship-based thermometers were in place and readings were being reported with sufficient reliability that scientists today can retrospectively establish a credible record of global average temperature by using modern analytic techniques; that record is supplemented by satellite-based measurements beginning around 1980. Similarly, global sea level measurements using tide gauges go back to the late nineteenth century and are supplemented by satellite-based observations of sea surface height beginning around 1990.

Together, our climatic records indicate that Earth's average temperature has gradually increased during the past century and a half by 0.85°C, or about 1.5°F. That increase has been uneven, with alternating intervals of one to three decades of above-average or (as was the case for the most recent 16 years) below-average warming or even complete cessation (1940–70), a natural consequence of the climate system's highly complex and variable nature. In the inland areas of continents, the warming observed so far has been greater than the global average because coastal areas experience the moderating effect of the oceans. Warming has also been greater than average in the northern polar regions, where melting sea ice increases the oceans' absorption of the sun's rays. Global mean sea level, meanwhile, has risen about 15–20 centimeters (6–8 inches) during the past century. Warming has melted the land ice of mountain glaciers and polar ice sheets and simultaneously caused the thermal expansion of water already in the oceans; both factors have raised the oceans' height.

Such changes in mean temperatures and sea levels are already worrisome. To provide context, a further 1°C increase in global average temperature above today's levels, which many scientists say is already inevitable, would put Earth clearly outside the range of global temperature experienced in the entire 10,000-year history of civilization. In addition—and critically important when considering impacts on humans and infrastructure—are changes in climatic extremes, which are expected to increase as the planet warms. The frequency of extremely hot days and nights has already surpassed the historical record, as have the frequency and duration of heat waves. Very cold days have become less common. Because more heat means more evaporation of water from the ocean surface to drive the hydrologic cycle, more land areas are seeing increases rather than decreases in the frequency and intensity of extreme precipitation. When the excess ocean vapor encounters conditions under which precipitation would normally occur, it adds to the moisture available for storms; and heavy rainfall, which causes damaging inland flooding, only becomes heavier. In addition, even minor changes in average sea level can produce major changes in the likelihood of coastal flooding, dangerously high tides, and storm surges, all of which have increased. For example, in the mid nineteenth century, a flood level of about four feet occurred about once every 10 years in New York Harbor. Since then, the local sea level has risen 1.3 feet. That seemingly small shift in average sea level means that the 10-year flood level now reaches 6.4 feet, topping the seawall that protects much of lower Manhattan.[6]

Scientists have documented many other phenomena in the past few decades consistent with unusual climate changes, ranging from rapid loss of mountain glaciers and ice caps known to be thousands of years old to migrations of species toward cooler climates, to changes in annual ecological cycles such as the flowering and fruiting of plants. Many of these changes are subtle for now, but together they paint a consistent picture of a planet that's warming with unprecedented speed. At the same time, scientists still can't prove that some of the climate's more complex behaviors—such as the rate of formation and the intensity of tropical cyclones or large-scale oscillations such as El Niño—have been altered by climate change, although they say changes are likely to occur in the future.

How Do We Know Humans Are Responsible?

A variety of evidence establishes that humans are the primary culprits causing climate change. Humans emit 35 billion metric tons of carbon dioxide into the atmosphere per year. Under natural conditions, Earth's ocean and land areas, including organic and inorganic material, emit about 20 times that amount, and they also naturally absorb an almost equal amount via dissolution in the ocean and photosynthesis. Without human interference, the gains and losses in the carbon cycle would be more or less in balance, and the amount of carbon dioxide in the atmosphere would vary very slowly over thousands of years. Human additions to the cycle can be absorbed only so fast, however, making it fairly straightforward to connect the recent, rapid buildup of carbon dioxide to human activity. The isotopes of atmospheric carbon dioxide (that is, heavy and light forms of carbon dioxide that carry different numbers of neutrons in their carbon atoms) carry distinctive fossil carbon signatures, making it easy to demonstrate the amount of carbon in the atmosphere that comes from fossil fuels versus the amount that comes from natural processes. Legal records for the major fossil fuel extraction companies dating back more than a century make total emissions from a supplier's perspective easy to calculate. Even the nearly uniform distribution of carbon dioxide in the atmosphere is broken slightly by a pattern of geographic variation that can be traced to the distribution of emission sources around the world. In sum, there is no doubt that humans have radically altered the carbon cycle.

It's harder to ascribe responsibility for changes in temperature and precipitation because human forcing is only one of many things that influence the climate's complex behavior. On a grand scale, observed average global temperatures have been increasing in time with emissions and in line with our understanding of climate. But that average state masks wide-ranging variability. Although scientists say they're certain that we're changing the climate overall, it's hard to show that any specific climatic event happens "because of" climate change. To infer that climate change bears some of the responsibility for a specific event or shift in the climate involves sophisticated statistical optimal-fingerprinting techniques, which compare observed geographic distribution of warming, precipitation, and other factors with climate models that either include or exclude the buildup of anthropogenic greenhouse gases and particulate matter. The optimal-fingerprinting method estimates the effect of an increase in greenhouse gases, thereby enabling scientists to calculate the odds that certain events, such as an unusual heat wave, would not have occurred in the absence of climate change. Simpler techniques compare the time series of observed warming with a model projection method that yields best estimates of how climate variables would have changed continent by continent or region by region. In both cases, models that account for increasing amounts of greenhouse gases substantially agree with what we've actually observed, whereas models that don't include rising greenhouse gases do not agree. Moreover, direct observations since about 1980 have ruled out the possibility that other factors might be responsible for climate change; compared with anthropogenic factors, neither variations in the sun's activity, which can slightly alter the amount of solar radiation reaching Earth, nor changes in the amount of volcanic particulates in the upper atmosphere, which can cool the planet after eruptions, have produced anything but small effects on the planet's temperature.

Projecting Future Climate and Scientific Uncertainty

To the best of our understanding, climate change's impacts on humans have so far been small and subtle compared with variations in other environmental factors that affect human welfare. Under business-as-usual scenarios whereby we continue to emit vast quantities of carbon dioxide, however, the impact of climate change is expected to grow markedly, eventually becoming a significant drag on human wellbeing all over the planet. To understand the full scope of the problem, we need to predict climate change decades into the future. The most reliable tools for such predictions are climate-modeling computer programs called atmosphere-ocean general circulation models (AOGCMs). These models solve complex systems of equations embodying the known physical and chemical laws that describe how the atmosphere and the oceans behave under the influence of sunlight, Earth's rotation, and changes in the chemical composition of the climate system, including emission of greenhouse gases. AOGCMs take as input the historical record of Earth's climate and make predictions subject to past constraints, thereby producing a long-term climate forecast not unlike weather forecasts provided daily by the world's meteorological organizations. Earth system models expand on AOGCMs by adding descriptions of how the ocean, atmosphere, and climate interact with surface vegetation.

Even the most advanced models can only approximate the climate's behavior, and they often disagree about specific aspects. That uncertainty stems from two sources. First, our understanding of the physical and biological world is incomplete and must be approximated in ways that compromise accuracy. Second, the equations that underpin AOGCMs must be solved numerically on computers with finite capacity, resulting in low (but rapidly improving) spatial and temporal resolutions on even the fastest computers. Together, those uncertainties mean that most models agree fairly well about large changes over long periods of time, but they disagree about smaller-scale changes. For example, projections of how mean temperature will change in an area the size of half of North America can be taken as fairly defensible—unlike projections of specific changes in a small area and a short time frame, such as the intensity of windstorms in Beijing in the winter of 2051.

Differences in how models project global mean temperature arise from a variety of sources, the most influential which is the modeling of feedback factors—complex responses to warming that either amplify or dampen the heat-trapping effect of greenhouse gases. For example, water vapor is a potent greenhouse gas, but it's so abundant in the air that direct human emissions don't alter its concentrations. However, the indirect effect of ocean surface warming that results from climate change causes more evaporation from the oceans and an even greater greenhouse effect, leading to increased warming, or a positive feedback. Similarly, about 30 percent of the sunlight that strikes Earth is reflected back into space under natural conditions without being absorbed—an effect called *albedo*. Changes in albedo lead to changes in the amount of solar energy that Earth absorbs, so changes that make Earth more or less reflective can influence warming. The clearest example involves ice: land-based glaciers and ice sheets—in particular, Arctic sea ice—reflect more light back into space than do the surfaces underlying them. As the planet warms and surface ice coverage shrinks, Earth will absorb more sunlight, thereby warming the planet further still and melting even more ice.

Clouds, too, make predictions more difficult. Sunlight is reflected from the tops of clouds, especially opaque clouds from which precipitation falls, thereby altering albedo. But clouds—especially cirrus clouds, which are high and thin—can also absorb infrared radiation, much like greenhouse gases. Because we poorly understand many aspects of cloud formation, it's hard to say how, on balance, cloud changes feed back into warming. As a result, each climate model represents cloud processes in a distinct way and thus produces a level of cloud feedback different from that of other models. Differences in cloud feedback are the main cause of disagreement among the models when it comes to projecting global mean temperature. However, there is consensus that cloud feedback would at least modestly amplify warming rather than help lessen it.

The uncertainty that various kinds of feedback cause in climate models, dominated by the uncertainty in cloud feedback, has been summarized by a gross property of each model called its *climate sensitivity*, or the amount of warming the model predicts if carbon dioxide concentrations were to double from their preindustrial levels. The range of model sensitivities is 1.5–4.5°C (2.7–8.1°F); that is, average projected future global warming is 3°C (5.4°F), with uncertainty ranging from 50 percent below to 50 percent above that value.

Differences in how models project global mean temperature arise from a variety of sources, the most influential which is the modeling of feedback factors—complex responses to warming that either amplify or dampen the heat-trapping effect of greenhouse gases. Those differences mean that estimated uncertainty increases when we make predictions that are regional rather than global, sometimes producing high geographic variability. For example, a moderate emissions scenario predicts that by the last two decades of this century, the globe will warm 1.2–2.7°C (2.2–4.9°F) compared with recent temperatures; the same model predicts average warming in the broad range of 1.7–4°C (3.1–7.2°F) in central North America and Asia, with a narrower range in Africa and South America. Predictions of mean precipitation increases vary even more, ranging from 0 percent to 3 percent and 3 percent to 9 percent, respectively, for North America and Asia, to minus 9 percent to plus 9 percent for Africa. The uncertainties make projections more or less meaningless for areas smaller than about 1,000 square kilometers (386 square miles, or about the size of San Diego). The uncertainties also affect shorter time scales. A 4°C (7.2°F) increase in average temperature in an American Midwestern state like Kansas would shift the temperature distribution enough to lead to dozens more days per year of dangerously high temperatures exceeding 35°C (95°F), but trying to predict how such local-scale changes would evolve from year to year is simply too complex a task for current models.

The comparison of observed warming with reconstructed weather data, discussed earlier, offers strong evidence that the models perform reasonably well for conditions not so different from today's—that is, when greenhouse gas concentrations in the atmosphere range from 280 to 400 parts per million. For concentrations beyond that range, paleoclimate data enhance the models' credibility; such data include correlations between atmospheric temperatures and greenhouse gas concentrations that we can infer from ancient ice cores retrieved from deep under the Antarctic and Greenland ice sheets. Not only are the *correlations* consistent with our understanding of how geophysical and climatological processes have evolved over time, but the *magnitude* of the changes is consistent with model-based estimates of how large the temperature difference should be between cold, glacial periods and warm, interglacial periods (like our current epoch). The warming that followed the most recent glaciation, which substantially remade Earth's surface, was about 3–5°C (5.4–9°F), comparable to the higher end of projections for warming by the year 2100.

We've shown that the climate's complexity makes prediction difficult. An even bigger problem is uncertainty about future emissions. To accurately estimate emissions would involve an unimaginable degree of foresight about future technologies, economies, cultures, and policies, including emission abatement policies. Science's answer has been to create hypothetical scenarios in the form of estimates of different, plausible ways that humanity might choose to increase or decrease carbon emissions over the next several decades—generally guided by economic, technical, and political experts. The highest emissions scenario is usually characterized as the likely outcome of business as usual, wherein countries carry on with using carbon-intensive fuel sources for decades. The lowest emissions scenario represents a world with strict climate policies and rapid attempts to drastically reduce emissions and prevent further changes. The differences between those two scenarios are sufficiently large that they have a far greater influence on the uncertainty of future temperature predictions than do model uncertainties themselves. Put differently, models disagree about the difference between temperature predictions in low-emissions scenarios by a little more than one degree over this century, but the difference between projected temperature in any one model between low- and high-emissions scenarios is on the order of three degrees.

The many sources of uncertainty in projecting the future climate could mean huge differences in the eventual impact on human lives. If change is relatively modest, then this century's warming would increase the global average temperature by about 2°C (3.6°F). Under this scenario, a child born in the United States in 2080 would experience a climate markedly different from the one children born today experience; 2080 would see hotter summers, more extreme precipitation, and various other changes outlined later in this article. But those effects pale in comparison to what we can expect if climate changes are substantial. A child born into a 2080 world that is 4°C (7.2°F) warmer would experience a global average temperature higher than anything seen in the past several million years of Earth's history. That scenario would produce a climate radically different from the one we currently live in. Serious droughts, extreme heat waves, and rising sea levels would expose children to a range of risks unprecedented in human experience.

Regime Shifts in Planetary Systems

Scientists see a significant chance that certain changes in the physical climate system could be so rapid, and their impact so widely distributed geographically, that they would radically alter human society. Examples include a multi-meter sea level rise from the melting of ice sheets; a rapid release of methane (a potent greenhouse gas) from melting Arctic ocean sediments and permafrost, that would in turn produce several extra degrees of warming; a shift from moist tropical forest to savannah in the Amazon, causing large losses of ecosystems and species and substantial warming feedback from release of carbon dioxide from soils and biota; and shifts in precipitation and temperature large enough to drastically reduce agricultural productivity.

These possibilities are relatively less likely than other, less extreme changes. But should they occur, their impact will be high. We likely won't face them in this century, but they are nonetheless plausible outcomes of extreme warming that policy makers should take into account. Low-probability but high-impact risks, such as those stemming from cancer-causing chemicals, nuclear accidents, or geopolitical missteps are often viewed as threatening enough to require major shifts in policy. While the risk of a 4°C rise in global average temperature is low, it is not zero, and some estimates put the likelihood of even a 6°C rise in temperature at greater than one percent by the end of the century under a business-as-usual scenario. From a risk management perspective, the threat of less likely but extremely damaging regime shifts may thus be even more important than the threat of more likely but less damaging outcomes.

How Will Children Be Vulnerable to Climate Change?

The many climate changes expected to occur in the coming century are expected to threaten children's wellbeing in a variety of both overt and subtle ways. Of particular concern are changes in environmental risk that could influence children's development both directly—through increasing levels of exposure to a given hazard—and indirectly: through intermediate effects on social and economic systems. For example, an increase in the number of heat waves threatens children directly by exposing them to higher temperatures, increasing their risk of heatstroke and other heat-related illnesses, and making it harder to learn, play, and exercise outdoors. Heat waves' indirect effects are more subtle. More heat waves will make crop failures more likely, driving up prices in market economies and potentially depriving children of food in rural parts of the world. Heat waves also interact with emissions from local industry and transportation systems to increase atmospheric concentrations of gases like ozone (the central component of smog) that harm children's health. And high temperatures increase rates of interpersonal violence such as murder and abuse, as well as group violence such as war.

Climate change's indirect effects are in many ways more worrisome than the direct ones because so much of children's wellbeing is conditioned by social and economic factors. The climate's influence on a child's life doesn't occur in isolation but, rather, in combination with specific social circumstances. For example, a middle-class child in the Midwestern United States might be well insulated from many of climate change's direct effects by technologies such as air conditioning and modern sanitation systems. The indirect effects, however, will include everything from changes to the global food system that threaten to raise prices and induce shortages, to geopolitical changes that occur because climate change destabilizes social relations, thereby increasing conflict and migration. Moreover, children will experience the indirect effects of climate change as people and institutions respond not only to actual changes but also to climate-driven risks—from governments' decisions about urban development to families' decisions about where to rear children. Such adaptive choices are difficult to predict because they will be influenced by complex political, economic, and social factors.[7]

Poverty and development add more complexity. Children in poor countries are particularly vulnerable and exposed to climate-driven threats such as crop failures, heat waves, and tropical storms, and they won't be able to draw on the more sophisticated adaptation mechanisms available to children in rich countries. Moreover, in developing countries, families tend to rely more directly on the environment for their livelihoods—particularly through agriculture, meaning that climate change may cause serious harm to family livelihoods. In their article in this issue, Rema Hanna and Paulina Oliva cover the threats that climate change poses to children in developing countries.[8]

Wherever children live, climate change is likely to affect their development in ways that last well into later life. In recent years, researchers such as Douglas Almond and Janet Currie, who is one of the editors of this issue, have amassed evidence demonstrating that even relatively mild disturbances to a child's developmental trajectory may have effects that last into adulthood, particularly when the disturbances occur during pregnancy and infancy.[9] Economists Sharon Maccini and Dean Yang, for example, have demonstrated that women in rural Indonesia who were born during wetter rainy seasons are taller, better educated, richer, and in better health than their counterparts born during drier rainy seasons.[10]

Lastly, some of the most psychologically important losses that children can expect to incur from climate change involve the destruction of aesthetic and cultural heritage. Although such losses are difficult to quantify, climate change is expected to submerge islands and coastlines, eradicate or permanently change a number of ecosystems, threaten many traditional ways of life, and combine with other human social forces to lead the world through what many biologists say is already the sixth mass extinction of species in Earth's history. Many of the changes will be irreversible, potentially leaving this century's children a world bereft of a host of iconic species, delicate ecosystems, and culturally relevant sites. Cultural practices that depend on the environment—such as skiing, camping, hunting, and fishing—are likely to be permanently altered in many areas, and they may disappear entirely from certain areas. Climate change will thus reshape the very cultural fabric in which children develop, albeit in ways we can't yet know for certain.

What Will Changes Relevant to Children Look Like?

Uncertainties and caveats aside, a variety of changes in the climate are expected to influence social and economic outcomes that are particularly relevant for children. Climate models agree that at high latitudes and in the interiors of continents, warming will be greater than the global mean change, whereas oceans will heat more gradually—much like the pattern that has already been observed. Similarly, the world as a whole will be wetter because of evaporation from the warmer ocean surface, but the excess moisture will be unevenly distributed and generally restricted to high latitudes and parts of the tropics. Broad areas at the historically arid horse latitudes (belts of high pressure roughly 30–35 degrees north and south of the equator) are expected to become even drier. Precipitation overall will become more variable: wet areas and periods will generally become wetter, and dry areas and periods drier, especially in the middle of continents. Ice will continue to melt worldwide; melting will reduce drinking water sources for areas like Lima, Peru, that depend in part on mountain glaciers for their water supplies, and it will increase sea level rise. Extremes of heat, precipitation, coastal flooding, and drought are all likely or very likely to continue to increase, and the strongest tropical cyclones (that is, hurricanes and typhoons) are more likely than not to grow even more intense. All of these factors can be expected to influence children's welfare over the next century in a variety of ways.

Changes in Temperature Distribution

The increase in average temperatures, including the higher likelihood of extremely hot days, is one of the most direct ways that children will be affected by climate change. Regional forecasts vary, but most children around the world will face hotter, more extreme temperatures more frequently in a variety of forms, ranging from heat waves to higher nighttime temperatures to warmer winters. Assuming that future population centers don't radically shift, a typical American family will experience 45–96 days above 35°C (95°F) each year, on average, if emissions don't abate during this century; that's somewhere from four to eight times as many as we've experienced in the past 30 years.[11] The higher temperatures will directly affect children's health and physiology in potentially serious ways, increasing the rates of heatstroke, heat exhaustion, and heat-related mortality and reducing children's basic ability to enjoy the outdoors. Health economists Joshua Graff Zivin and Jeffrey Shrader examine heat's effects on children's health and human capital in their article in this issue.[12]

Heat will also affect children indirectly in a variety of ways. For example, many crops are vulnerable to high temperatures, and even relatively small increases in heat exposure can cause huge reductions in crop health above certain threshold temperatures. Under business-as-usual warming scenarios, by the end of the century the United States may produce more than 50 percent less of such key crops as corn.[13] Higher temperatures will likely disrupt food systems, drive up prices, and increase scarcity, particularly when combined with increased stress on water supply due to population growth and drought. The changes may be particularly damaging in developing countries, where poor growing-season conditions can cause marked increases in death and illness among children.

Heat has other indirect effects that may be more subtle but are no less worrisome. Scientists from a range of disciplines have shown that increased temperatures and more-variable rains are broadly associated with increased rates of violent conflict, both interpersonally and societywide. A variety of mechanisms seem to explain those results, ranging from heat-wave-induced crop failures that lead to poverty and unrest to the physiological effects of high temperatures on aggressive behavior. In his article in this issue, Richard Akresh reviews that research.[14] More generally, many studies have found that the combined influence of higher temperatures on everything from crop productivity to the human body's ability to work means that economies grow less quickly than they otherwise would, which reduces GDP growth, especially in poorer countries. If that's true, then climate change will likely mean that children around the world will be less prosperous than they otherwise would.

Hydrologic Stress

A second defining aspect of climate change that will influence children's welfare is a global increase in hydrologic stress. Even without climate change, many areas of the world already face serious water shortages because of rapid population growth, migration into cities, increasing pollution, and other processes that have hugely increased global demand for water. Climate change will worsen the situation in three major ways. First, it will shift precipitation patterns around the world, drying out certain regions and making others wetter. Second, it will increase the variability of precipitation in many places, making both unusually dry periods and unusually severe rains more likely. Third, it will reduce the mass of mountain glaciers in ranges such as the Himalayas, the Rockies, and the Andes, significantly reducing storage of winter snows and thus springtime runoff, which has traditionally been used to water fields and recharge reservoirs.

As climate change interacts with increasing future water needs, much of the world's population may see local demand for water outstrip supply. Municipal water and sanitation systems will be increasingly stressed, increasing the cost of access to clean water for consumption and sanitation. Agricultural systems already threatened by more frequent extreme heat will see damage exacerbated by insufficient water, particularly in areas where crops are fed by rain rather than irrigation. Water scarcity will threaten a variety of water-intensive industrial processes such as power generation and, in the long run, may put serious pressure on people to migrate out of drier regions.

Technological advances such as heat-resistant genetically modified crops, cheaper ways to remove salt from seawater, and improved efficiency of water use could help avert those difficulties. But such technologies may not come to fruition fast enough.

Changes in Extreme Events and Hazards

Climate change is expected to alter the behavior of hydrometeorological and climatological disasters, partly because of the increased variability of precipitation and temperatures. More frequent extreme rainfalls will bring more flooding to many parts of the world, while in other areas, higher temperatures combined with decreased rainfall will raise the risk of drought. Extreme temperatures and hydrologic stress will cause more wildfires, and more-intense rains will cause more landslides in mountain areas. There is no consensus as to whether tropical cyclones—the large storms we call cyclones, typhoons, or hurricanes, depending on the ocean basin—will occur any more or less frequently, and the physics behind them is complex. But they will more likely than not increase in average intensity over the coming decades, with stronger, more damaging storms becoming more common in some areas.

The increased potential for large disasters is particularly worrisome for children, not only because of the physical peril they pose but also because a growing number of studies have found that disasters can have debilitating long-term indirect effects on children through everything from households' ability to earn a living and feed their children, to urban planning and infrastructure investment decisions that may fundamentally determine children's living environments. In her article in this issue, Carolyn Kousky reviews the expected impacts of increased natural hazards on children.

Sea Level Rise

Rising seas will increase both (1) long-term land loss, thus reducing the amount of land available for settlement, and (2) episodic coastal inundation. At current rates of sea level rise, for example, the portion of New York City at risk for a one-hundred-year flood will double under high emissions scenarios from just over 10 percent of the city today to 20 percent by 2100.[15] Rising sea levels are also expected to increase erosion and to interact with tropical and extratropical cyclones to worsen storm surges, all of which pose direct threats to children's wellbeing. Less directly, sea level rise will affect children by forcing coastal settlements to adopt expensive adaptive urban planning systems and infrastructure such as seawalls. Sea level rise will also increase the likelihood of large-scale migration and extremely costly relocation of urban centers.

Damage to Ecosystems

Damage to ecosystems is itself a result of climate change and in turn poses threats to children. Climate change is expected to reduce or fundamentally alter major ecosystem services provided by the planet, such as regeneration of soil, pollination of crops, and regulation of erosion. Many of those effects will have the potential to harm children's wellbeing indirectly—for example, by working with other factors to reduce agricultural yields or by increasing the cost of access to clean water. In less-developed countries, where more people depend on ecosystem services, the impacts promise to be more devastating than in wealthy countries.

Biodiversity loss caused by climate change will present further indirect threats to children's wellbeing. Biodiversity makes ecosystems resilient, and the stress that rapid climate change places on animal and plant species will further reduce ecosystem services such as pollination and pest control. More broadly, loss of biodiversity poses a serious threat to cultural heritage for children in many countries. Many threatened species with high aesthetic, cultural, patriotic, or religious value, such as polar bears or coral reefs, will face increased risk of extinction, potentially depriving future generations.[16]

One source of ecosystem damage that deserves special mention is the gradual acidification of the world's oceans, which has already begun under climate change. The oceans naturally absorb carbon dioxide from the atmosphere as part of the global carbon cycle. Carbon dioxide forms a mild acid, called carbonic acid, when dissolved in water, and adding anthropogenic carbon dioxide to Earth's climate has slowly begun to acidify the oceans. Acidification poses a major threat to the many invertebrates, including coral, that harvest calcium dissolved in seawater to form their shells. If it isn't slowed and eventually stabilized or reversed, the gradual increase in acidity would reduce calcium concentrations sufficiently to threaten populations of many ocean invertebrates, ranging from human food sources like lobsters and clams all the way down the food chain to the zooplankton that form the foundation of the ocean ecosystem. Coral reefs, which are home to much of the oceans' biodiversity and a critical habitat for commercially fished species, are at risk from both acidification and warming, as well as from several nonclimate threats. Unless we reduce emissions, more than half of fish species are expected to be harmed by ocean acidification alone during this century.

Climate-driven changes in Earth's ecosystems are also expected to influence key aspects of the complex disease interaction between humans and the natural environment. Disease vectors such as the *Anopheles* mosquito are expected to move to new areas in response to changing rains and temperatures, which would expose new populations to diseases ranging from malaria to dengue to chikungunya. Changes in the distribution and migration behaviors of birds and other animals are potentially more worrisome because these animals serve as frequent sources of diseases passed on to humans. Pandemic influenzas, for example, are believed to occur when different influenza viruses recombine in the same host; some evidence suggests that flu pandemics may be sparked partly by climate-driven shifts in migratory bird patterns.

Pollution

Air pollutants such as carbon monoxide and ozone have such harmful effects that the World Health Organization has named air pollution as the single greatest environmental health risk, and children are more vulnerable than adults. The major sources of greenhouse gas emissions typically also emit common air pollutants known to damage health; moreover, temperature and precipitation affect whether and how those emissions become smog. Economist Matthew Neidell and research analyst Allison Larr, in their article in this issue, review the pollution impacts of climate change.[17]

The Policy Response

Scientists and policy makers broadly agree that without large-scale international cooperation, economic development and technological progress on their own will not slow emissions enough to save us from large changes in the global climate, which creates a clear need for active international climate policies. Unfortunately, for many reasons, we haven't yet seen an adequate global policy response. The uneven global impacts of climate change and the unequal emission histories of developed versus developing nations produce political divides that have made it hard to find common ground on issues ranging from who should begin reducing emissions first to how much rich countries should pay poor countries not to increase deforestation (a secondary source of carbon dioxide emissions).

The long delay between emissions and their eventual impact on the climate means that effective climate policy must simultaneously satisfy a wide variety of global stakeholders today while maintaining a point of view sufficiently farsighted to incur nontrivial costs that will not show benefits for decades. Uncertainty and scientific complexity make the problem difficult for policy makers to deal with and the public to understand. Attempts to reach binding agreements, most notably the 1997 Kyoto Protocol, have had mixed results at best. Recent moves by the leaders of the United States, China, and certain other main greenhouse-gas-emitting nations indicate that those leaders have begun to see the matter as more pressing, but some nations with growing emissions, such as India, remain hesitant. The international agreement at the December 2015 Paris Climate Conference provides at least some promise that key emitter nations will take meaningful steps over the next five to ten years.

At this writing, there is relatively little indication that world leaders are considering world carbon emission trajectory changes of the size needed to achieve a two-degree target; economist Joseph Aldy, in his article in this issue, reviews the political aspects of climate change. We have nonetheless seen substantial progress in the broader field of climate policy. Policy makers and researchers generally divide the social response to climate change into two complementary halves: mitigation and adaptation. Mitigation policies seek to insulate society from climate change by preventing it via emission reductions—for example, by replacing fossil fuels with renewable energy or by reversing deforestation. Adaptation policies seek to protect society from climate changes that have already occurred or will occur; such policies can consist of anything from improving disaster response to making agricultural systems more drought resistant.

Most experts agree that limiting warming to no more than 2°C (3.6°F)—governments' chosen benchmark of danger—is technologically feasible and would likely serve to avoid many types of disruptive changes. That agreement implies that there's a limit on how much additional carbon can be emitted—that is, a carbon budget for the planet—before the 2°C target is exceeded. If humans stay within the carbon budget, adaptation will be feasible, although potentially costly. If the carbon budget is exceeded and if climate changes become sufficiently severe, policies could expand to include geoengineering projects intended either to reduce the carbon dioxide in the atmosphere or to reduce the average temperature. Such efforts could range from seeding the atmosphere with sulfate particles to increase albedo and thus cool the planet, to injecting billions of tons of carbon dioxide into old oil and gas deposits and other geologic formations—a process called *carbon capture and sequestration*. Albedo modification is widely regarded as a concept rather than an established technology, and it would be risky for several reasons, including the potential for unforeseen interactions with Earth's complex climate system. Many experts see albedo modification only as a last resort.[18]

Climate Change and Future Generations

It's easy to feel overwhelmed by the scope and scale of climate change as a problem. The uncertainty that stems from our incomplete knowledge about climate and our inability to forecast future human behavior suggests a practically unknowable future, in which potentially huge losses caused by climate change compete with technological advances, economic growth, and social and cultural shifts to determine children's welfare for the rest of the century. That said, history has demonstrated time and again that humans can tackle uncertain threats in times of need. The insurance industry exists to help us manage risks, and businesses in many industries perform risk analyses and adopt policies to reduce risks. On a larger scale, international frameworks are in place to manage global safety risks. International agreements adopted to reduce the risk of nuclear war constitute one such example; the Montreal Protocol prohibiting the manufacture of ozone-layer-destroying chemicals is another. Climate change has much in common with those uncertain but very real global threats. We must understand that scientific uncertainty about the specifics of a complex problem can go hand in hand with broad agreement about the overall riskiness of an outcome.

At the heart of the climate change problem lies a tension that forces us to directly confront the value we put on future children's wellbeing. The long lag between the emission of a greenhouse gas and its eventual warming effect means that costly decisions to reduce emissions today will bring benefits largely through reduced harm to future generations born many years hence. There is much debate over the best way to approach decisions when costs and benefits are distributed over time, and many deep philosophical and ethical issues surrounding how we justify those decisions are not easily settled. In their article in this issue, economists William Pizer, Ben Groom, and Simon Dietz review discounting and intergenerational decision making.

In the remainder of this issue, leading experts on the social effects of climate change examine issues relevant to climate change's impacts on children. In each case, readers can find ample cause for concern, as well as ample reason for hope that children's lives will continue to improve throughout the current century as they did during the previous one. Taken together, these reports make it clear that ensuring that children's futures are adequately protected from the hazards of climate change will require unprecedented effort, innovation, and coordination, suggesting that few of our decisions about any other issues will come close to having as strong an influence on children's lives.

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