

DOCKETED

Docket Number:	17-IEPR-09
Project Title:	Climate Adaptation and Resiliency
TN #:	221158
Document Title:	Well Under 2 Degrees Celsius Fast Action Policies to Protect People and the Planet from Extreme Climate Change
Description:	Report of the Committee to Prevent Extreme Climate Change Chairs: V. Ramanathan, M. L. Molina, and D. Zaelke
Filer:	Raquel Kravitz
Organization:	California Energy Commission
Submitter Role:	Commission Staff
Submission Date:	9/13/2017 9:45:40 AM
Docketed Date:	9/13/2017

Well Under 2 Degrees Celsius:

Fast Action Policies to Protect People and the Planet from Extreme Climate Change

Report of the Committee to Prevent Extreme Climate Change

Chairs:

V. Ramanathan, M. L. Molina, and D. Zaelke

Climate Policy Success

Pull Third Lever: ACE

(Atmospheric Carbon Extraction)

- Forest Degradation Reversal & Afforestation
- Soil Restoration and Eco-System Management
- CO₂ Direct Air Capture, Storage, & Utilization

Pull Two Levers: Carbon & SLCPs

- Lever 1 - Decarbonize the global economy with renewables
- Lever 2 - Cut short-lived climate pollutants to maximum extent possible (black carbon, methane, tropospheric ozone, & HFCs)

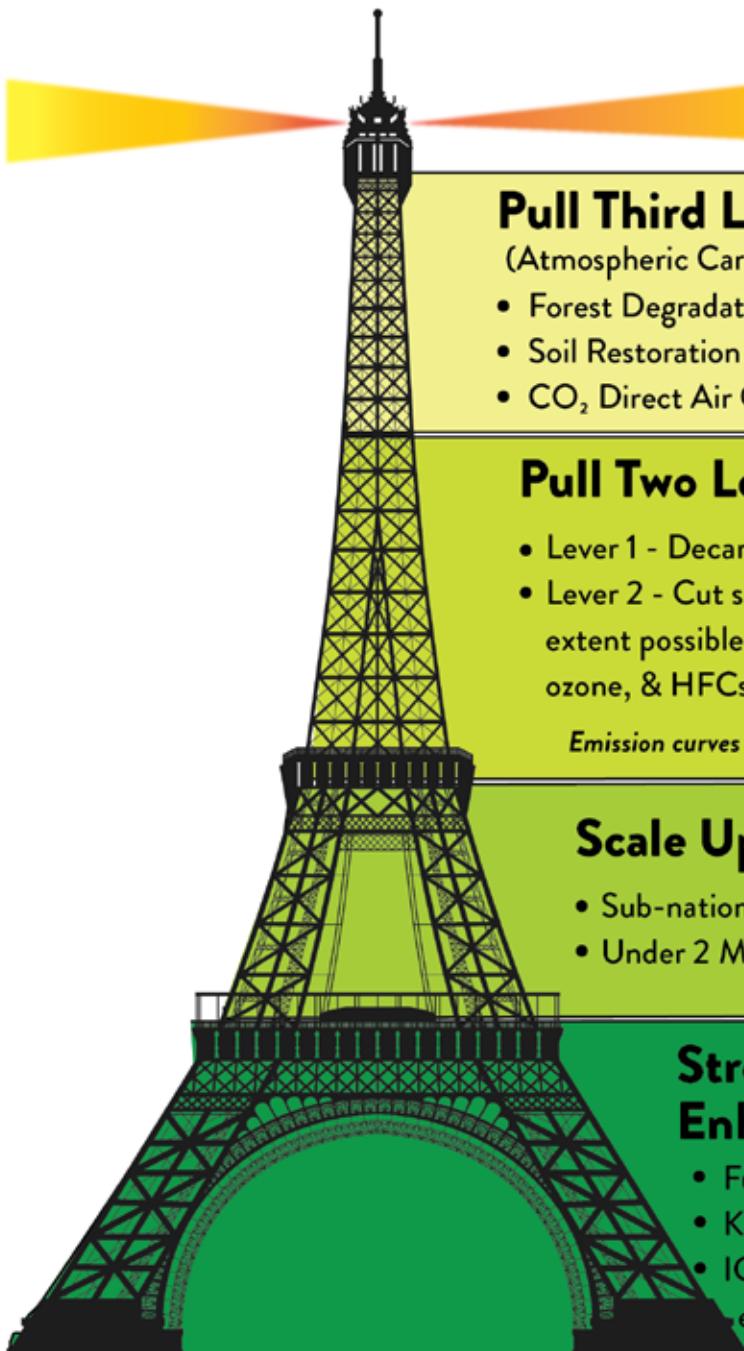
Emission curves have to bend to negative emission trends by 2020

Scale Up Subnational Governance

- Sub-national and city-scale climate action plans
- Under 2 MOU commitments

Strengthen Paris Agreement & Enhance Sister Agreements

- Fully Implement NDC mitigation pledges
- Kigali HFC Amendment to the Montreal Protocol
- ICAO & IMO efforts on shipping and aircraft emissions



This report should be referred as: Ramanathan, V., Molina, M.J., Zaelke, D., Borgford-Parnell, N., Alex, K., Auffhammer, M., Bledsoe, P., Collins, W., Croes, B., Forman, F., Gustafsson, Ö., Haines, A., Harnish, R., Jacobson, M., Kang, S., Lawrence, M., Leloup, D., Lenton, T., Morehouse, T., Munk, W., Picolotti, R., Prather, K., Raga, G., Rignot, E., Shindell, D., Singh, AK, Steiner, A., Thiemens, M., Titley, D.W., Tucker, M.E., Tripathi, S., Victor, D., & Xu, Y., Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Changes, 2016.

The Committee to Prevent Extreme Climate Change (CPECC) Co-Chairs:

V. Ramanathan, M.J. Molina, D. Zaelke

Task Force Members:

1. **Ken Alex**, California Governor's Office
2. **Max Auffhammer**, UC Berkeley
3. **Paul Bledsoe**, Bledsoe & Associates
4. **Nathan Borgford-Parnell**, IGSD
5. **William Collins**, UC Berkeley
6. **Bart Croes**, California Air Resources Board
7. **Fonna Forman**, UC San Diego
8. **Örjan Gustafsson**, Stockholm University
9. **Andy Haines**, London School of Hygiene & Tropical Medicine
10. **Reno Harnish**, UC San Diego
11. **Mark Jacobson**, Stanford University
12. **Shichang Kang**, Chinese Academy of Sciences
13. **Mark Lawrence**, IASS Potsdam
14. **Damien Leloup**, Scripps
15. **Tim Lenton**, University of Exeter
16. **Tom Morehouse**, Former Acting Assistant Secretary of Defense, Operational Energy
17. **Walter Munk**, Scripps Institution of Oceanography
18. **Romina Picolotti**, CEDHA
19. **Kim Prather**, UC San Diego
20. **Graciela Raga**, National Autonomous University of Mexico
21. **Eric Rignot**, UC Irvine
22. **Drew Shindell**, Duke University
23. **AK Singh**, Retired Air Marshal & Former Commander in Chief of Indian Air Force
24. **Achim Steiner**, Oxford University
25. **Mark Thiemens**, UC San Diego
26. **David W. Titley**, Retired Rear Admiral United States Navy
27. **Mary Evelyn Tucker**, Yale University
28. **Sachi Tripathi**, IIT Kanpur
29. **David Victor**, UC San Diego
30. **Yangyang Xu**, Texas A&M

High Level Summary

The Paris Agreement is an historic achievement. For the first time, effectively all nations have committed to limiting their greenhouse gas emissions and taking other actions to limit global temperature change. Specifically, all nations agreed to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels,” and achieve carbon neutrality in the second half of this century.

The climate has already warmed by 1°C. The problem is running ahead of us, and under current trends we will likely reach 1.5°C in the next fifteen years and surpass the 2°C guardrail by mid-century. The Paris Agreement and supporting climate policies must be strengthened substantially within the next five years to bend the emissions curve down faster, stabilize climate change, and prevent catastrophic warming. Until now, no specific plan or policy roadmap has been proposed to provide a realistic and reasonable chance of limiting global temperature to safe levels and preventing unmanageable climate change. This report provides such a plan—an outline of specific science/policy pathways that serve as the building blocks for a three-lever strategy to limit warming to well under 2°C. We have framed the plan in terms of four building blocks and three levers which are implemented through 10 solutions.

The first building block would be fully implementing the nationally determined mitigation pledges under the Paris Agreement of the UN Framework Convention on Climate Change (UNFCCC). In addition, several sister agreements that provide targeted and efficient mitigation must be strengthened. Sister agreements include the Kigali Amendment to the Montreal Protocol to phase down HFCs, efforts to address aviation emissions through the International Civil Aviation Organization

(ICAO), and maritime black carbon emissions through the International Maritime Organization (IMO). HFC measures, for example, can avoid as much as 0.5°C of warming by 2100 through the global phasedown of HFC refrigerants within the next few decades, and substantially more through parallel efforts to improve energy efficiency of air conditioners and other cooling equipment.

For the second building block, numerous sub-national and city scale climate action plans have to be scaled up. One prominent example is California’s Under 2 MOU signed by over 165 jurisdictions from 33 countries in six continents covering a third of world economy. The goal of this Memorandum of Understanding is to scale up California’s target of 40% reductions in CO₂ emissions by 2030 and 80% reductions by 2050. Another prominent example is the climate action plans by over 52 cities and 65 businesses around the world aiming to cut emissions by 30% by 2030 and 80% to 100% by 2050. There are concerns that the carbon neutral goal will hinder economic progress; however, real world examples from California and Sweden since 2005 prove that economic growth can be decoupled from carbon emissions and the data for CO₂ emissions and GDP reveal that growth in fact prospers with a green economy.

The third building blocks consist of two levers that we need to pull as hard as we can: one for drastically reducing emissions of short-lived climate pollutants (SLCPs) beginning now and completing by 2030, and the other for decarbonizing the global economy by 2050. Pulling both levers simultaneously can keep global temperature rise below 2°C through the end of the century. If we bend the CO₂ emissions curve such that global emissions peak in 2020 and decrease steadily thereafter until reaching zero in 2050, there is less than a 20% probability of exceeding 2°C. This call for

bending the CO₂ curve by 2020 is one major new proposal of this report. Many cities and jurisdictions are already on this pathway thus demonstrating its scalability. Achieving carbon neutrality and reducing emissions of SLCPs would also drastically reduce air pollution globally including all major cities thus saving millions of lives and over 100 million tons of crops lost to air pollution each year. In addition, these steps would provide clean energy access to the world's poorest three billion who are still forced to resort to 18th century technologies to meet basic needs such as cooking.

For the fourth and the final building block, we are adding a third lever, ACE (Atmospheric Carbon Extraction, also known as Carbon Dioxide Removal, or "CDR"). This lever is added as an insurance against surprises (due to policy lapses, mitigation delays or non-linear climate changes) and would require development of scalable measures for removing the CO₂ already in the atmosphere. The amount of CO₂ that must be removed will range from negligible, if the emissions of CO₂ and SLCPs start to decrease by 2020 and carbon neutrality is achieved by 2050, to a staggering one trillion tons, if CO₂ emissions continue to increase until 2030, and the carbon lever is not pulled until after 2030. This issue is raised because the NDCs (Nationally Determined Contributions) accompanying the Paris Agreement would allow CO₂ emissions to increase until 2030. We call on economists to assess the cost-effectiveness of reducing carbon and SLCPs emissions beginning in 2020 compared with delaying it by ten years and then being forced to pull the third lever to extract one trillion tons of CO₂.

The fast mitigation plan of requiring emissions reductions to begin by 2020, which means that many countries need to cut now, is urgently needed to limit the warming to well under 2°C. Climate change is not a linear problem. Instead, we are facing non-linear climate tipping points that can lead to self-reinforcing and cascading

climate change impacts. Tipping points and self-reinforcing feedbacks are wild cards that are more likely with increased temperatures, and many of the potential abrupt climate shifts could happen as warming goes from 1.5°C in 15 years to 2°C by 2050, with the potential to push us well beyond the Paris Agreement goals.

Where Do We Go from Here?

We have almost run out of time to address climate change. With unchecked business-as-usual emissions, global warming has a 50% likelihood of exceeding 4°C and a 5% probability of exceeding 6°C, raising existential questions for most especially the poorest three billion people. Dangerous to catastrophic impacts on health of people including generations yet to be born, on the health of the ecosystem, and on species extinction have emerged as major justifications for mitigating climate change well below 2°C. We must act now, and we must act fast and effectively. This report sets out a specific plan for reducing climate change in both the near- and long-term. With aggressive urgent actions, we can protect ourselves. Acting quickly to prevent catastrophic climate change by decarbonization will save millions of lives, trillions of dollars in economic costs, and massive suffering and dislocation to people around the world. This is a global security imperative, as it can avoid the migration and destabilization of entire societies and countries and reduce the likelihood of environmentally driven civil wars and other conflicts.

Staying well under 2°C will require a concerted global effort. We must address everything from our energy systems to our personal choices to reduce emissions to the greatest extent possible. The health of people for generations to come and the health of ecosystems crucially depend on an energy revolution beginning now that will take us away from fossil fuels and toward the clean renewable energy sources of the future.

10 Scalable Solutions to Bend the Curve

Achieving success will require the global mobilization of human, financial, and technical resources. For the global economy and society to achieve such rapid reductions in SLCPs by 2030 and carbon neutrality and climate stability by 2050, we will need multi-dimensional and

multi-sectoral changes and modification, which are grouped under Ten Scalable Solutions in the table below. We have adapted the solutions with some modifications from the report: Bending the Curve written by fifty researchers from the University of California system. These solutions, which often overlap, were in turn distilled from numerous publications and reports.

Science Solutions

1. Show that we can bend the warming curve immediately by reducing SLCPs, increasing energy efficiency, and replacing current fossil fuel energy systems with carbon neutral technologies

Societal Transformation Solutions

2. Foster a global culture of climate action through coordinated public communication and education at local to global scales.
3. Build an alliance among science, religion, health care, and policy to change behavior and garner public support for fast mitigation actions.

Governance Solutions

4. Build upon and strengthen the Paris Agreement, and strengthen sister agreements like the Montreal Protocol's Kigali Amendment to reduce HFCs.
5. Scale up subnational models of governance and collaboration around the world to embolden and energize national, regional, and international action. California's Under 2 MOU and climate action plans by over 50 cities are prime examples.

Market- and Regulation-Based Solutions

6. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO₂ and SLCPs emissions.
7. Develop and strengthen direct regulatory measures—including rebates and efficiency and renewable energy portfolio standards—to complement market-based policies.

Technology-Based Solutions

8. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, mini-grids, smart-grids, building efficiency, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes. Available technologies are already sufficient to pull the CO₂ lever half-way (40%) by 2030. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and generate the electricity 100% by renewables.
9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50%, reduce black carbon emissions by 90%, and eliminate high-GWP HFCs ahead of the schedule in the Kigali Amendment while fostering energy efficiency.

Atmospheric Carbon Extraction Solutions

10. Regenerate damaged natural ecosystems and restore soil organic carbon. Expand with urgency research and development of approaches and measures for atmospheric carbon extraction, as well as carbon capture, utilization, and storage.

Aggressive mitigation actions have already begun

The four building blocks to be implemented through the 10 solutions may appear ambitious and formidable, but there are numerous living laboratories ranging from cities such as Stockholm to a large state like California, the sixth largest economy in the world, already embarked on mitigation actions such as 40% reductions in CO₂ emissions by 2030 and 50% to 80% reductions in SLCPs. CO₂ emissions curves in the US and EU have already started to bend since 2005. G7 and G20 countries have agreed to accelerate access to renewables. The world now adds more renewable power capacity annually than it adds (net) capacity from all fossil fuels combined. By the end of 2015, there was enough installed renewable capacity in place to supply an estimated 23.7% of global electricity demand, with hydropower providing about 16.6%. There is also more hope for increased public support due to religious declarations – including the Pope's environmental encyclical, *Laudato Si'*, as well as inter-faith declarations on climate change – calling on their billions of followers to commit to a low-carbon future through renewable energy. Businesses are also stepping up. Twenty-five worldwide business networks speaking for 6.5 million companies from over 130 countries have pledged to help foster a low-carbon and climate resilient economy. We are not starting from a blank page. The climate change mitigation train has already left the station. All we have to do is scale up what is already happening in many parts of the world.

Three Fast Actions the World Can Take to Immediately Begin Bending the Curve

1. Immediately end all fossil fuel subsidies and expand incentives for renewables.
2. Ratify and quickly implement the Kigali Amendment to the Montreal Protocol to phase down HFCs, while pursuing parallel efforts to improve appliance efficiency by at least 30%.
3. Reduce methane from oil and gas production and distribution and reduce black carbon from diesel engines.

Table of Contents

1. The Building Blocks Approach	7
2. Major Climate Disruptions: How Soon and How Fast?	10
3. What Are the Wild Cards for Climate Disruption?	12
4. Dealing with Uncertainty and the Problem of the “Fat Tail”	16
5. What Are the Impacts on Social Systems?	18
6. How Much Time Do We Have to Protect Nature and Humanity?	21
7. The Two Lever Approach: What Do We Need to Do and When?	24
8. Adding a Third Lever	27
9. Building Blocks for the Three Lever Approach	29
10. In Pursuit of the Common Good: Where Do We Go from Here?	39
11. References	41



1. The Building Blocks Approach

The 2015 Paris Agreement, which went into effect November 2016, is a remarkable, historic achievement. For the first time, effectively all nations have committed to limit their greenhouse gas emissions and take other actions to limit global temperature and adapt to unavoidable climate change. All Nations agreed to hold “the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels” and “achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century” (UNFCCC, 2015). Nevertheless, the initial Paris Agreement has to be strengthened substantially within five years if we are to prevent catastrophic warming; current pledges place the world on track for up to 3.4°C by 2100 (UNEP, 2016).

Until now, no specific policy roadmap exists that provides a realistic and reasonable chance

of limiting global temperatures to safe levels and preventing unmanageable climate change. This report is our attempt to provide such a plan—an outline of specific solutions that serve as the building blocks for a comprehensive strategy for limiting the warming to well under 2°C and avoiding dangerous climate change (Figure 1).

The first building block is the full implementation of the nationally determined mitigation pledges under the Paris Agreement of the UN Framework Convention on Climate Change. The next building blocks are: 1) the global sister agreements, such as the Kigali Amendment to the Montreal Protocol to phase down HFCs, which can provide additional targeted, fast action mitigation; 2) sub-national agreements such as California’s Under 2 MOU signed by 136 jurisdictions from 30 countries on six continents; and 3) climate action plans for carbon neutrality being implemented by 52 cities and 65 businesses around the world. The third building block is targeted measures to reduce

emissions of short-lived climate pollutants (SLCPs), beginning now and fully implemented by 2030, along with major measures to fully decarbonize the global economy, causing the overall emissions growth rate to slow in 2020 and stop by 2050. Such a deep de-carbonization would require an energy revolution similar to the Industrial Revolution that was based on fossil fuels. The final building blocks are scalable and reversible carbon dioxide (CO_2) removal measures, which can begin removing CO_2 already emitted into the atmosphere.

Such a plan is urgently needed. Climate change is not a linear problem. Instead, climate tipping points that can lead to self-reinforcing, cascading climate change impacts. Tipping points are more likely with increased temperatures, and many of the potential abrupt climate shifts could happen as warming goes from 1.5°C to 2°C , with the potential to push us well beyond the Paris Agreement goals.

We are running out of time to address these concerns. We must act now, and we must act fast. Reduction of SLCPs will result in fast, near-term reductions in warming, while present-day reductions of CO_2 will result in long-term climate benefits. This two-lever approach—aggressively cutting both SLCPs and CO_2 —will slow warming in the coming decades when it is most crucial to avoid impacts from climate change as well as maintain a safe climate many decades from now. To achieve the near-term goals, we have outlined solutions to be implemented immediately. These solutions to bend down the rising emissions curve and thus bend the warming trajectory curve follow a 2015 assessment by the University of California under its Carbon Neutrality Initiative. The solutions are clustered into categories of social transformation, governance improvement, market- and regulation-based solutions, technological innovation and transformation, and natural and ecosystem management.

Additionally, we need to intensely investigate and pursue a third lever—ACE (Atmospheric

Carbon Extraction). While many potential technologies exist, we do not know the extent to which they can be scaled up to remove the requisite amount of carbon from the atmosphere in order to achieve the Paris Agreement goals, and any delay in mitigation will demand increasing reliance on these unproven technologies.

Yet, there is still hope. Humanity can come together, as we have done in the past, to collaborate towards a common goal. We have no choice but to tackle the challenge of climate change. We only have the choice of when and how: either now, through the ambitious plan outlined here, or later, through radical adaptation and societal transformations in response to an ever-deteriorating climate system that will unleash devastating impacts—some of which may be beyond our capacity to fully adapt to or reverse for thousands of years.



Figure 1: Four building blocks to achieve climate policy success.



2. Major Climate Disruptions: How Soon and How Fast?

"Without adequate mitigation and adaptation, climate change poses unacceptable risks to global public health."

WHO, 2016

The planet has already witnessed nearly 1°C of warming, and another 0.6°C of additional warming is currently stored in the ocean to be released over the next two to four decades. The impacts of this warming on extreme weather, droughts, and floods are being felt by society worldwide to the extent that many think of this no longer as climate change but as climate disruption. Consider the business as usual scenario:

15 years from now: In 15 years, planetary warming will reach 1.5°C above pre-industrial global mean temperature. The last time the planet was this warm was about 115,000–130,000 years

ago. The impacts of this warming will affect us all yet will disproportionately affect the Earth's poorest three billion people, who are primarily subsistence farmers that still rely on 18th century technologies and have the least capacity to adapt. They thus may be forced to resort to mass migration into city slums and push across international borders. The existential fate of low-lying small islands and coastal communities will also need to be addressed, as they are primarily vulnerable to sea-level rise, diminishing freshwater resources, and more intense storms. In addition, many depend on fisheries for protein, and these are likely to be affected by ocean acidification and climate change. Climate injustice could start causing visible regional and international conflicts. The risk of passing tipping points increases.

30 years from now: By mid-century, warming is expected to exceed 2°C, which would be unprecedented with respect to historical records

of at least the last one million years. Such a warming through this century could result in sea-level rise of as much as 2 meters by 2100, with greater sea-level rise to follow. A group of tipping points are clustered between 1.5°C and 2°C (Figure 2). The melting of most mountain glaciers, including those in the Tibetan-Himalayas, combined with mega-droughts, heat waves, storms, and floods, would adversely affect most everyone on the planet.

80 years from now: In 80 years, warming is expected to exceed 4°C, increasing the likelihood of irreversible and catastrophic change. The 2°C and 4°C values quoted above and in other reports, however, are merely the central values with a 50% probability of occurrence. There is a 5% probability the warming could be as high as 6°C due to uncertainties in the magnitude of amplifying feedbacks (see Section 4). This in turn could lead to major disruptions to natural and social systems, threatening food security, water security, and national security and fundamentally affecting the great majority of the projected 10 billion inhabitants of the planet in 2100.



3. What Are the Wild Cards for Climate Disruption?

Generally, increasing the concentrations of greenhouse gases in the atmosphere increases its radiative forcing (the difference between the amount of energy entering the atmosphere and leaving) and thus increases the global temperature. However, climate wild cards exist that can alter the linear connection with warming and anthropogenic emissions by triggering abrupt changes in the climate. Some of these wild cards have not been thoroughly captured by the models that policymakers rely on the most. These abrupt shifts are irreversible on a human time scale and will create a notable disruption to the climate system, condemning the world to warming beyond that which we have previously projected. These climate disruptions would divert resources from needed mitigation and upset mitigation strategies that we have already put in place.

1. Unmasking Aerosol Cooling: The first such wild card is the unmasking of an estimated 0.7°C

(with an uncertainty range of 0.3°C to 1.2°C) of committed warming by reducing cooling aerosols. Aerosol air pollution is a major health hazard with massive costs to public health and society, including contributing to about 7 million deaths (from household and ambient exposure) each year. While some aerosols, such as black carbon and brown carbon, strongly absorb sunlight and act as powerful climate pollutants, others reflect sunlight back into space, which cools the climate. The net impact of all manmade aerosols is negative, meaning that about 30% of the warming from greenhouse gases is being masked by co-emitted air pollution particles. As we reduce greenhouse gas emissions and implement policies to eliminate air pollution, we are also reducing the concentration of aerosols in the air. Aerosols last in the atmosphere for about a week, so if we eliminate air pollution without reducing emissions of the greenhouse gases, the unmasking alone would lead to an estimated

0.7°C of warming within a matter of decades. We must eliminate aerosol emissions due to their health effects, but we must simultaneously mitigate emissions of CO₂, other greenhouse gases, and black carbon and co-pollutants to avoid an abrupt and very large jump in the near-term warming beyond 2°C.

2. Tipping Points: It is likely that as we cross the 1.5°C to 2°C thresholds we will trigger so called “tipping points” for abrupt and nonlinear changes in the climate system with catastrophic consequences for humanity and the environment. Once the tipping points are passed, the resulting impacts will range in timescales from: disruption of monsoon systems (transition in approximately a year), loss of sea-ice (approximately a decade for transition), dieback of major forests (nearly half a century for transition), reorganization of ocean circulation (approximately a century for transition), to loss of ice sheets and subsequent

sea-level rise (transition over hundreds of years). Regardless of timescale, once underway many of these changes would be irreversible.

Recent modeling work shows a “cluster” of these tipping points could be triggered between 1.5 and 2°C warming (Figure 2) including melting of land and sea-ice and changes in high-latitude ocean circulation (deep convection). This is consistent with existing observations and understanding that the polar regions are particularly sensitive to global warming and have several potentially imminent tipping points. The Arctic is warming nearly twice as quickly as the global average, which makes the abrupt changes in the Arctic more likely at a lower level of global warming. Similarly, the Himalayas are warming at roughly the same rate as the Arctic and are thus also more susceptible to incremental changes in temperature. This gives further justification for limiting warming to no more than 1.5°C.

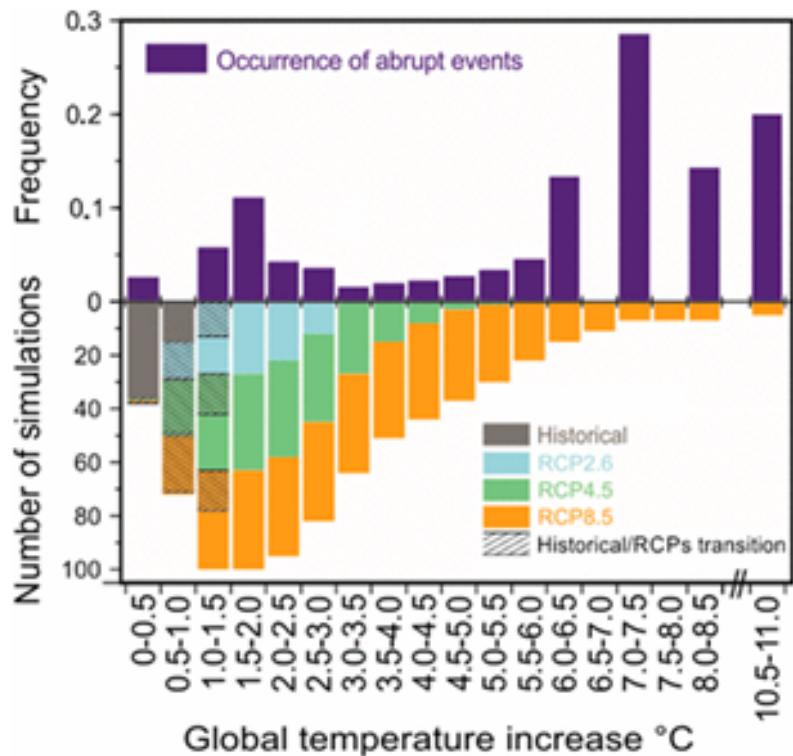


Figure 2: The occurrences of abrupt events (purple bars) show a cluster between 1.5°C and 2°C global temperature increase and again above 6°C. Source: Drijfhout et al., 2015.

While all climate tipping points have the potential to rapidly destabilize climate, social, and economic systems, some are also self-amplifying feedbacks that once set in motion increase warming in such a way that they perpetuate yet even more warming. Declining Arctic sea-ice, thawing permafrost, and the poleward migration of cloud systems are all examples of self-amplifying feedback mechanisms, where initial warming feeds upon itself to cause still more warming acting as a force multiplier.

3. Unstable Melting of Marine-Based Sectors of Ice Sheets: During the Eemian period (115,000 to 130,000 years ago), the earth was approximately 1.5°C warmer than present temperatures. This caused significant portions of the Greenland ice sheet and most of the marine-based portions of the west Antarctic ice sheet to melt, resulting in 6 to 9 meters of sea-level rise. The time scale of this staggering rise in sea-levels is unknown, but this paleo-record along with the recent discovery of unstable melting of the Amundsen sector of west Antarctic and the melting of Greenland glaciers has raised concern about the probability of a 2-meter sea-level rise by the end of this century.

4. Himalayan and Tibetan Glaciers and the Asian Monsoon: More than 80% of the glaciers in this region are retreating. A primary source of water for these glaciers is precipitation from the South Asian monsoon, which has decreased by about 7% during the last fifty years. Many studies have attributed the weakening monsoon to the reduction of solar radiation, known as “global dimming,” due to aerosol pollution. Further, the deposition of black carbon (from diesel combustion and biomass cooking among other sources) on glaciers and snowpack is decreasing the snow’s albedo, contributing to surface warming and melting. The combination of warming by greenhouse gases, weakening monsoons due to aerosol dimming, and surface melting driven by black carbon deposition is creating an unstable situation for this so-

called “Water Tower of Asia,” which provides headwaters for most of the major river systems in Asia.

5. Loss of Arctic Summer Sea-Ice: Arctic summer sea-ice, which has already retreated by 40%, could disappear abruptly when the 1.5°C threshold is crossed in 15 years. As the Arctic warms, the sea-ice melts and exposes the darker ocean water beneath, which allows for greater absorption of solar radiation, increasing the ocean’s temperature and acting as a force multiplier. Furthermore, the persistently warmer water hinders significant ice growth in winter, which can also impact the amount of sea-ice that melts during the summer. The increased climate forcing from the loss of Arctic summer sea-ice between 1979 and 2011, if averaged globally, is equivalent to 25% of the forcing from CO₂ over the same period.

6. Collapse of Arctic Permafrost and Other Soil Carbon Stores: Permafrost is soil that stays below freezing temperatures for at least two consecutive years. Arctic permafrost contains three times as much carbon as there is in the atmosphere, and the thawing of the permafrost over land and subsea has the potential to release large quantities of this trapped carbon as both CO₂ and methane. The thawing of permafrost will not necessarily result in an abrupt shift in the climate, but even a release of 1% of the carbon stored in permafrost could double the rate of warming. By the end of the century carbon release from permafrost could add an estimated 0.1–0.3°C of warming and even greater and irreversible increases for centuries to come. While the Arctic region contains the largest stores of soil carbon on earth, warming temperatures are also expected to deplete soil carbon stocks outside of permafrost regions. By 2050, increasing temperatures could trigger global soil carbon losses equivalent to 12 to 17% of expected emissions under a BAU scenario.

7. Poleward Retreat of Extra-Tropical Cloud Systems: Though clouds enhance the greenhouse

effect by trapping heat, they also reflect an enormous amount of solar radiation and nearly double the albedo of the planet. Their albedo effect dominates over their greenhouse effect, balancing out to a net cooling of about -25 Wm^{-2} (compared with the 1.6 Wm^{-2} forcing from CO_2 and total current forcing of 3 Wm^{-2}). More than two-thirds of this cooling is from the extensive extratropical cloud systems, which are found poleward of about 40° and are associated with jet streams and storm tracks. Satellite data reveal that these cloud systems are retreating poleward in both hemispheres, which has led to an increase in the solar radiation reaching the extratropics, further amplifying warming. Thus, the Arctic warming is amplified by two large feedbacks: first is the decrease in albedo from the retreating sea-ice, which is then further amplified by the decrease in albedo from the shrinking storm track clouds.



4. Dealing with Uncertainty and the Problem of the ‘Fat Tail’

Climate change projections are quantified on their likelihoods of occurrence. Our understanding of the climate system is more refined in some areas than in others, but this does not detract from the overall assessments and projections for future changes to the climate. Climate models will continue to improve their treatment of many physical, dynamical, and chemical processes, particularly those dealing with clouds, aerosols, ice sheet dynamics, and the carbon cycle. But the complexity and interconnectedness of climate and human systems means that humanity will never fully dispel all uncertainties about the exact rate, magnitude, or implications of the changes we are affecting on our world through climate change.

Despite these uncertainties, the observed changes in our climate system and the ability of the climate models to simulate these changes and even predict the changes in many instances give us more than enough certainty to act. As warned

by a team of retired admirals and generals from the U.S. in a report on climate change,

“Speaking as a soldier, we never have 100 percent certainty. If you wait until you have 100 percent certainty, something bad is going to happen on the battlefield.”

However, the uncertainties cut both ways and there is one type of climate uncertainty that should inspire us to act with incredible urgency: the uncertainty of the “fat tail.”

The feedbacks mentioned in the above section, and others not discussed here, give rise to a wide spread probability distribution of warming for a given forcing from increased CO₂ and other climate pollutants. For example, a doubling of CO₂ has a projected central value of warming of 3°C. The 90% probability distribution, however, includes warming as low as 2°C and as large as

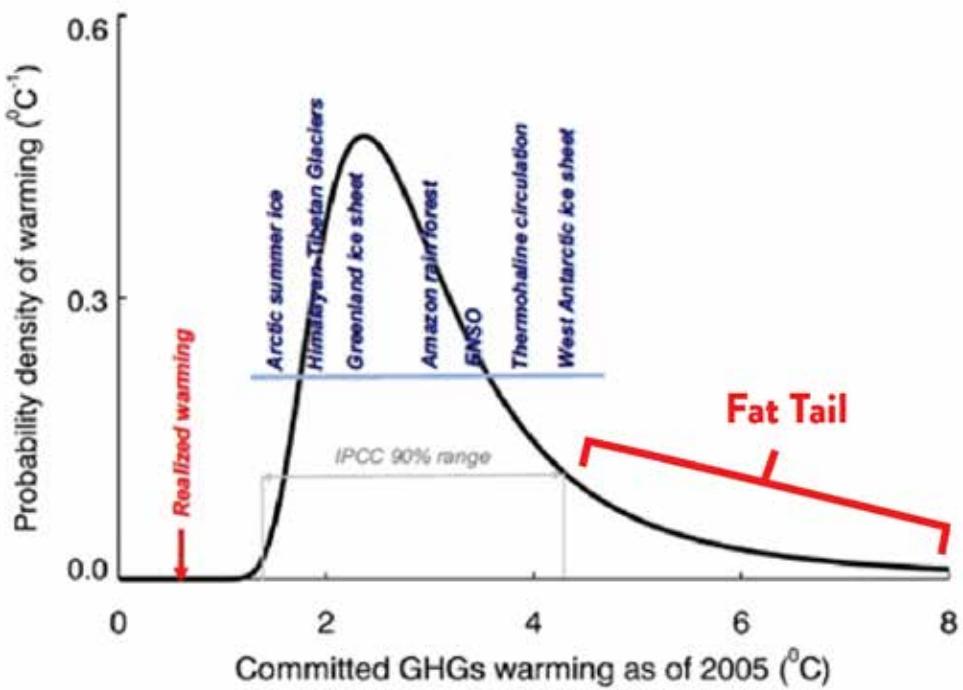


Figure 3: The figure shows a central estimate of warming of about 2°C with a 20% probability of being more than 3°C and a 5% chance of being more than 4°C . The results shown above were estimated by keeping the concentrations of GHGs fixed at their 2005 levels and zeroing out emissions of all aerosols. Such a scenario could result if stringent air pollution were enacted to clean the air of particulates immediately and emissions of GHGs were allowed to decrease slowly to zero by 2100. For the end of the century projection of 4°C warming, there is a non-trivial 1% to 5% probability the warming could be as large as 6°C to 8°C . Source: Ramanathan & Feng, 2008.

4.5°C . On the lower side, there is a less than 1% chance that the warming seen under a doubling of CO_2 will be less than 1.5°C . However, on the upper limit, there is a 1% to 5% probability the warming could be as large as 6°C to 8°C , which is referred to as the “fat tail.” Such warming would pose an existential threat to most of the global population.

In the context of warming and greenhouse gases, the “fat tail” indicates there exists a larger range of possible temperatures far warmer than 2°C compared to the range of possible temperature cooler than 2°C . With each incremental increase in temperature, this central value gets shifted farther towards the warmer temperature range, and with it the “fat tail” shifts

in the same manner, which means that even greater temperatures exist within the realm of possibility, even if it is a small chance.

Put in perspective, how many people would choose to buckle into an airplane seat if they knew there was a 1 in 20 to 1 in 100 chance of the plane crashing? Most of us would undoubtedly stay home. The calculated odds of dying in a plane crash are closer to 1 in 11 million, which is why it is such a popular and safe form of transportation. If a 1 in 100 chance of dying in a plane crash would be enough to end air travel shouldn't it also be enough to end the use of fossil fuels and heroically slow climate change?



5. What Are the Impacts on Social Systems?

Damages due to climate change have already been detected and, in the future, are expected to disproportionately affect the poorest and most vulnerable. Coastal archaeology provides us with some understanding of how past societies have responded to the impacts of rapid climate change and can serve as analogues for our present-day societal responses to anthropogenic global warming. A number of studies of coastal societies that existed more than 4,000 years ago indicate that there are climatic thresholds to cultural tolerances, and that abrupt, unpredictable climate change can have devastating consequences on human populations by disrupting food production, forcing repeated human dispersal, and causing conflict and realignment of social and trade networks.

Limiting global average temperature rise to well under 2°C, aiming for no more than 1.5°C, over

pre-industrial temperatures will not eliminate the negative impacts of anthropogenic climate change, but it would significantly reduce the rate of temperature increase, the intensity of climate impacts and the risks to society. This is critical for both providing societies time to adapt to changes and slowing, if not avoiding, the worst predicted impacts of climate change. Actions that would bring immediate relief to the rapidly changing climate are vital for survival. With mounting evidence of past impacts, we still have a good deal to learn about how climate change will affect communities. What follows is a list of issues being discussed among social scientists, policy experts, and political leaders.

National and International Security: Climate change poses security risks “because it degrades living conditions, human security, and the ability of governments to meet the basic needs of their populations” (U.S. DOD, 2015). Climate

change is a direct cause of resource conflicts in countries with weak capacities and governance challenges. The conflicts in Syria and Darfur are partially attributed to droughts that caused massive agriculture failures, which in turn led to mass displacements and migration. One estimate suggests that sea-level rise of one meter could displace almost 50% of Bangladeshi citizens.

Sustainable Development: The 17 Sustainable Development Goals (SDGs) and their 169 targets strive to eliminate poverty and hunger, improve health, expand access to clean modern energy, protect the planet, and ensure all people enjoy peace and prosperity. The current and near-term impacts of climate change will cause multiple complex impacts on human health, infrastructure, society, and the environment and thereby threaten to undermine the success of the SDGs if not put them entirely out of reach. Climate change is a multiplier of the obstacles faced in achieving the SDGs.

For example, increased extreme weather events combined with reduced crop production due to climate change can put entire food systems at risk. This threatens the SDGs related to food security, health (through increased malnutrition), and poverty (due to losses of traditional livelihood). Agricultural failures can also lead to massive impacts on social systems.

In 2015, extreme weather-related events were reported to have displaced just over 19 million people, with an average of approximately 25 million people displaced each year since 2008. While the impacts of extreme, individual climate-driven disasters are relatively clear, the “cumulative impacts from small, recurrent disasters over time can equal or even exceed those from larger catastrophes” (World Bank, 2013). In addition to the direct impacts described above and the indirect impacts such as increased food prices and food insecurity, these smaller climate-related hazards tend to exacerbate other stressors, reinforce poverty, and compound the hardships endured by poor communities.

Public Health: Between the millions of premature deaths resulting from fossil fuel combustion—directly from air pollution and indirectly from increases in climate change-related extremes such as heat waves, droughts, floods, and forest fires—there is good evidence that “without adequate mitigation and adaptation, climate change poses unacceptable risks to global public health” (WHO, 2016). Morbidity and mortality due to heat stress alone is now common all over the world, and extreme heat events are responsible for more deaths annually than hurricanes, lightning, tornadoes, floods, and earthquakes combined.

Climate Justice:

“We have to realize that a true ecological approach always becomes a social approach; it must integrate questions of justice in debates on the environment, to hear both the cry of the earth and the cry of the poor.”

Pope Francis, *Laudato Si*, 2015

Roughly 50% of the climate warming pollution is from the wealthiest one billion of humanity while the poorest three billion contribute 5% or less. Yet these poorest three billion will suffer the worst consequences of climate change since they are forced by poverty to rely on 18th century technologies for meeting basic needs such as cooking. The World Bank estimates that more than 100 million people could be forced into extreme poverty within 15 years when the warming reaches 1.5°C. About 10% of the global population is at risk of forced displacement due to climate change. The impacts on mass migration, trafficking, and breakdown of social structure among the poorest three billion must be assessed urgently, and preventive measures must be put into place. The poorest three billion will be significantly more impacted by the climate change impacts occurring over the next 30 years than those in the long term, for the simple reason that they may not survive to see those long-term effects. In this context, speed is essential for achieving climate justice, as “justice delayed is justice denied.”

Box 1: Health co-benefits of climate change mitigation policies

Well-designed policies to reduce the emissions of GHGs and the SLCP black carbon, can also improve human health by reducing air pollution as well as increases in physical activity (through increased walking and cycling) and dietary change. A recent study of the sources of PM_{2.5} worldwide suggests that 25% of urban ambient air pollution from PM_{2.5} is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 22% from unspecified sources of human origin, and the remainder from dust and natural sources.

A growing number of studies have quantified the air pollution benefits of climate change mitigation policies. The recent report of the International Energy Agency projects that under a “central scenario,” “premature deaths attributable to outdoor air pollution increase to 4.5 million in 2040 (from around 3 million today), while premature deaths due to household air pollution fall to 2.9 million (from 3.5 million today)” due to reducing use of solid biomass as a cooking fuel. Under a ‘Clean Air Scenario’ maximizing deployment of existing air pollution reduction technologies, annual outdoor air pollution deaths declined to 2.8 million and deaths due to household air pollution to 1.3 million by 2040 with the largest benefits in developing economies, notably China and India. Although a 7% increase in investment is required between 2016 and 2040, amounting to about USD \$5 trillion, these costs are offset by the resulting health and other co-benefits.

Policies (particularly in urban areas) to increase the uptake of low carbon transport, including petrol/electric hybrids and electric vehicles and investment in public transport, can reduce fine particulate air pollution and increased active travel (walking and cycling), bringing additional benefits of increased physical activity. The balance of health co-benefits depends on background levels of air pollution, physical activity patterns, and the risk of road traffic injuries. In the case of London, the health co-benefits are likely to result particularly from increased physical activity and greatly outweigh the increased risks of injury and death. In a city like Delhi the benefits of reduced air pollution may be relatively larger. There is the potential to reduce costs to the health system due to common conditions related to sedentary lifestyle such as diabetes, heart disease, and stroke. The benefits of active travel also exceed the increased risks of air pollution exposure in all but the most heavily polluted cities. Better design of transport infrastructure can reduce injury risks and increase walking and cycling.

The food and agriculture sectors are major contributors to GHG emissions and are responsible for up to 30% of emissions if land use change is included. They are also a major driver for land use and freshwater demands. At the same time, poor diets are responsible for a large disease burden worldwide including by increased risks of a range of common non-communicable diseases. A recent systematic review has shown how dietary change can potentially provide benefits for both the environment and health, particularly in Western countries where most studies have been located. The systematic review outlined 14 common dietary patterns, which aimed to be more sustainable than comparison diets, with resulting reductions as high as 70±80% of GHG emissions and land use, and 50% of water use (20±30%). The environmental benefits were generally proportional to the magnitude of reduction of livestock-based foods. Dietary shifts also yielded modest benefits in all-cause mortality risk.

Taking into account the health and other co-benefits of climate change mitigation policies can potentially make them more attractive to decision makers, and when these benefits are included in economic valuations, they frequently more than offset the extra costs of these policies.



6. How Much Time Do We Have to Protect Nature and Humanity?

At what warming level does climate change become catastrophic? Is it at 1.5°C, 2°C, 3°C, or 4°C? A correlated question is: How do we define “catastrophic”? Even a one-meter sea-level rise (which is assured given the current atmospheric concentrations of pollutant gases) would be catastrophic for small island nations like the Federated States of Micronesia and the Maldives and low-lying coastal nations such as Bangladesh. The sort of multiyear drought that recently impacted California would be catastrophic for much of the poorest three billion. Heat waves and floods that have become more frequent over the last few decades are already killing thousands in many nations, including in developed nations. We are fully aware of such limitations of defining “catastrophic”.

In what follows, we will build upon the Paris Agreement and discuss the time we have left to mitigate climate change to well below 2°C. We assume this to mean limiting the warming to a

range between 1.5°C to 2°C. In addition, we are making a proposal of “Well Under 2 Celsius.” The climate forcing of CO₂ and all other anthropogenic greenhouse gases as of 2010, however, is 3 Wm⁻², which is sufficient to warm the planet by 2°C or more (Figure 3). So how can we keep the warming well under 2°C?

There is one way to get out of this quandary. Of the 3 Wm⁻² greenhouse forcing, about 1.2 Wm⁻² is from gases with atmospheric lifetimes of approximately one decade or less (methane, tropospheric ozone, and HFCs). These gases are collectively known as short-lived climate pollutants (SLCPs). In addition, black carbon, which has a lifetime of only one week, has a net positive forcing of 0.4 Wm⁻² after accounting for the cooling effects of co-emitted organic carbon particles.

The short atmospheric lifetimes of SLCPs means that reducing them will reduce their

forcing within a decade. If we mitigate the emissions of these SLCPs making maximum use of available technologies, we can reduce their positive forcing by as much as 0.8 Wm^{-2} and reduce the warming by as much as 0.6°C by 2050.

This could cut the rate of global average warming in half by 2050 and, the rate of Arctic warming by two-thirds, as well as reduce total warming in the high-altitude Himalayan-Tibetan Plateau by at least half.

Beyond 2050, further warming can be mitigated by making the planet carbon neutral

(net zero emissions of CO_2) but only if actions are taken by 2020 to aggressively reduce CO_2 emissions. The Paris Agreement, on the other hand, allows CO_2 emissions to increase until 2030 and decline afterwards. A substantial portion (20–40%) of emitted CO_2 remains in the atmosphere for centuries to millennia. This long lifetime combined with ocean thermal inertia means that cutting CO_2 emissions will not produce considerable climate benefits for several decades. As of 2010, we have emitted 2 trillion tons of CO_2 . At BAU emission rates, we will have emitted the third trillionth ton by 2035. That would commit the planet to 2°C warming

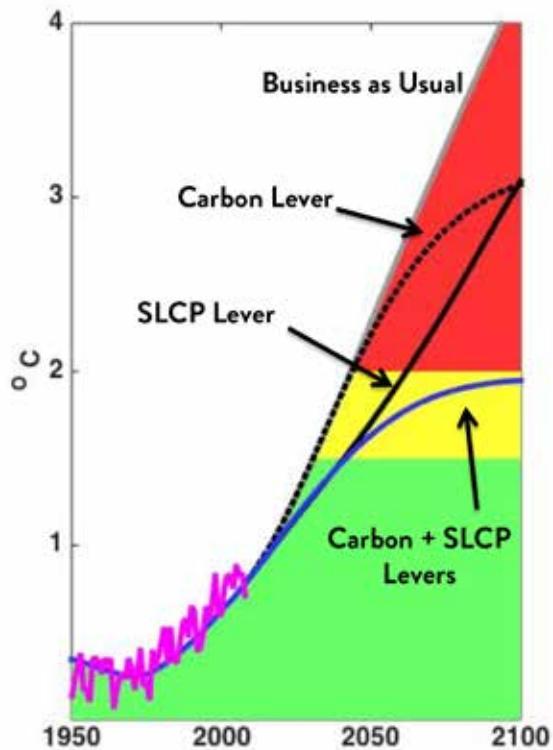


Figure 4. Possible warming trajectories under different mitigation strategies: BAU, mitigation of only CO_2 (Carbon Lever), mitigation of only SLCPs (SLCP Lever), and mitigation of both CO_2 and SLCPs (Carbon + SLCP Levers). The temperature estimates shown are anomalies relative to the 1900–1910 mean and are based on the central value of climate sensitivity. The pink line represents observations from 1900 to 2011. Source: Ramanathan and Xu, 2010 & Hu et al., 2013.

by 2035 from CO₂ alone (assuming it will take about 40 years to reduce the emissions to zero from 2035), meaning that if we wait until 2035 to act, we will have already committed the planet to more than 2°C warming. If we continue with BAU until we witness 2°C warming in 2050, we will emit the fourth trillionth ton by 2055. By then the warming would be locked in at more than 3°C. These estimates of warming are only 50% probability events. The 10% to 20% probability would project warming double the 50% probability warming values. The bottom line is that we must decarbonize as fast as possible.

In sum, long-lived CO₂ and SLCPs are key levers for slowing climate change that can and must both be pulled immediately to achieve our climate goals. The climate impact of each of the two levers operates on fundamentally different timescales. By mitigating the emissions of SLCPs by 2030 and by beginning the carbon neutrality pathway in 2030 and completing it by 2050, we may be able to bend down the warming curve to keep warming below 2°C throughout the rest of the century (Figure 4). However, the graph shows only a 50% probability of achieving this goal. There is still a 10–20% probability of the warming exceeding 3°C by 2100. To decrease the probability of exceeding 2°C to less than 20%, we have to start on the carbon neutrality pathway by 2020, i.e. emissions of CO₂ begin to decrease by 2020. A 10-year delay in beginning carbon neutrality as envisioned in the Paris Agreement would necessitate the removal of as much as one trillion tons of CO₂ from the air during the second half of this century.



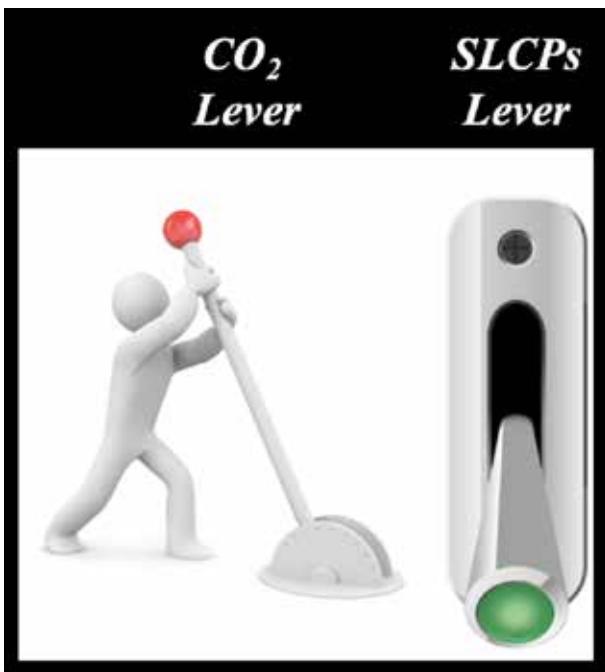
7. The Two Lever Approach: What Do We Need to Do and When?

Bending the Curve: We need to bend the rising curve of projected emissions of pollutants. As explained earlier, we have two key levers to pull: the SLCP lever and the carbon lever. The SLCP lever is essential for slowing near-term warming (the next three decades), and slowing the self-amplifying feedbacks, especially in the Arctic. Both levers are essential for slowing long-term warming (beyond 2050). This two-lever strategy is also justified by ethical and equity considerations.

The SLCP lever: In addition to slowing the self-reinforcing feedbacks, the SLCP lever addresses the ethical/equity issue of intra-generational equity. This concerns primarily the fate of the poorest three billion who until now had very little to do with the climate pollution. The poorest three billion are often the most vulnerable to the impacts of climate change and the least capable of adaptation. As explained in the previous

section, we need measures that can be deployed and scaled within a matter of years and provide climate relief within decades or less.

In 2011, the UNEP/WMO Assessment identified 16 technical and policy measures which, if deployed at scale by 2030, can reduce black carbon emissions by ~77% and methane emissions by ~38% (Table 2). Most of the control measures for reducing black carbon and methane can be implemented today with existing technologies and often with existing laws and institutions, including through enhancement and enforcement of existing air quality regulations. HFCs are now being phased down under the Montreal Protocol as a result of the landmark Kigali Amendment in 2016 (Box 2). The Montreal Protocol could potentially avoid up to 0.5°C by 2100 as the control mechanisms are strengthened next decade, and potentially significantly more through parallel efforts to



improve energy efficiency of air conditioners and other cooling equipment.

Together, these SLCP measures would avoid up to 0.6°C of projected warming by 2050 and 1.2°C by 2100. SLCP measures would cut the rate of warming in 2050 in half, giving societies and natural systems, including glaciers, ecosystems such as coral reefs and the Amazon, managed agriculture, and rivers, urgently needed time to adapt to unavoidable changes.

In addition to climate benefits, reducing SLCPs provides strong collateral benefits for public health and food security. For example, black carbon is a component of aerosol particles, a harmful air pollutant, so the reduction of sources of particulate matter and black carbon will reduce their climate impact as well as improve air quality. Cutting emissions of SLCPs could save an estimated 2.4 million lives per year currently lost to outdoor air pollution and likely millions more from indoor air pollution. In addition, it would cut global crop losses by around 52 (30–140) million tons a year, which represents an increase of up to 4% of the total annual crop production.

The Carbon Lever: The effects of CO₂ on climate and ecosystems last thousands of years, affecting generations yet to be born. Thus, the rationale for pulling this lever is based on intergenerational equity, which is at the core of the sustainability of nature and sustainability of humanity. It has been estimated (IPCC-AR5) that cumulative emission of 3.7 trillion tons of CO₂ (or one trillion tons of carbon) will result in a warming of 2°C (50% probability). Since we have already emitted 2 trillion tons of CO₂ by 2010, we have to limit cumulative CO₂ emissions from 2010 through the rest of the century to 1.7 trillion tons of CO₂. The current annual rate of emissions is 38 billion tons of CO₂ or 50 billion tons of CO₂e (if we include other greenhouse gases). These emission rates imply that we must immediately work to bend the emissions curve (i.e. negative emission trends) by 2020 and achieve carbon neutrality by 2050.

However, making rapid changes in total CO₂ emissions will be challenging because a large portion of CO₂ emissions comes from sources with long replacement timescales (e.g., power plants). Significantly reducing emissions from these sources is achievable in the near-term but in some cases would require early sunsetting of existing facilities that would strand assets. It would also require significantly increasing investments in deployment of clean energy technologies and supporting infrastructure such as long-distance transmission.

Researchers at Stanford University have outlined pathways to deep cuts in CO₂ by employing 80% renewable energy (water, wind, and sunlight) for global energy needs across the electricity, transportation, commercial, and industrial sectors by 2030 and 100% by 2050. Theoretically, this can be achieved if all end uses of energy are converted to electricity and hydrogen fuel. Such technologies have currently been deployed at limited scales in California, Denmark, Germany, and elsewhere. In addition, 52 cities with populations ranging from 100,000 to

13 million, 63 businesses, and several universities have become living laboratories for ambitious climate mitigation programs that include carbon neutrality goals. Use of renewables and other low carbon energy sources are increasing rapidly. Catalyzed by falling prices, renewables accounted for about 50% of all new power generation in the world (primarily in China, Japan, Germany, and the United States) in 2014, representing an investment of about \$270 billion. Scaling up by 2030 will require society's deep commitment.

There are concerns that the carbon neutral goal will hinder economic progress. Case studies from California and Sweden, which are already on a carbon neutral pathway, contradict such claims. These case studies reveal that between 2000 and

2014, California and Sweden grew their GDPs by nearly 30% while their CO₂ emissions declined, about 30% for Sweden and 5% for California. The evidence is growing that economic growth can be decoupled from carbon emissions. Other concerns have been raised about carbon neutral goals potentially harming the poor by limiting their access to energy. There are about 3 billion who still lack access to sufficient energy to meet their basic needs, often because the infrastructure to support expanded energy access is lacking. For these poorest three billion, decentralized power through, for example, village scale microgrids relying on solar power, wind, and biogas would be far more effective for providing access to modern forms of energy.

Box 2: The Kigali Amendment to the Montreal Protocol – The SLCP Lever in Action

The 2016 Kigali Amendment to the Montreal Protocol will essentially eliminate the warming caused by HFCs, one of the six main greenhouse gases, using a treaty with the experience and expertise to ensure a fast, effective, and efficient phasedown. The Montreal Protocol fully implements the principle of 'common but differentiated responsibilities' by having developed countries undertake their control measures first and then pay the full incremental cost of compliance for developing countries through the Multilateral Fund. It is the only treaty in the world with universal membership, including for its four previous amendments.

Under the Kigali Amendment, most developed countries start in 2019 with a freeze in HFC consumption, which caps future growth, and an immediate 10% reduction. The progressive group of developing countries, which includes China, freeze in 2024, with India, the Gulf States, and a few other countries freezing in 2028. The early action by developed countries and the ambitious group of developing countries ensures a fast market transition, which means that the transition of those in the last group almost certainly will be much faster than their formal date. Even on the original phase down schedule, the Kigali Amendment will avoid ~90% of the warming HFCs otherwise would have caused by 2100.

Historically, the market for new environmentally friendly substitutes has moved ahead of the Montreal Protocol control schedules, and recent studies calculate that countries can reduce their HFC emissions by as much as 99% by 2030 by simultaneously transitioning to already available low-GWP alternatives and super-efficient appliances. A simultaneous transition to super-efficient air conditioners could double the climate benefit of either action alone and would avoid (or free up for other uses) an amount of electricity equal to the production of between 680 and 1,587 medium-sized peak-load coal power plants by 2030 and between 1,090 and 2,540 by 2050.



8. Adding a Third Lever

The two-lever strategy assumes a central value of climate sensitivity of 3°C warming for a doubling of CO₂. What does that mean? To reduce the probability of exceeding the 2°C warming from 50%, to less than 20%, we must employ a third lever: managing CO₂ after it has been emitted, for example, by capturing, utilizing, and storing it, and by removing it from the ambient atmosphere, known as atmospheric carbon extraction (ACE), or Carbon Dioxide Removal (CDR).

The main ACE measures under consideration are afforestation (including urban forestry), capturing, utilizing, and storing CO₂, bioenergy combined with carbon capture and sequestration (BECCS), soil organic carbon management, biochar, direct air capture, enhanced weathering and ocean liming, and ocean fertilization with iron. It is very likely that one or more of these techniques could eventually be used to significantly reduce the amount of

anthropogenic CO₂ in the atmosphere (i.e., removing a cumulative amount of up to hundreds of Gt CO₂), although the development of the necessary technologies and vast infrastructures would likely take several decades. Furthermore, BECCS, other than from waste biomass, is not carbon neutral in the critical near-term period when we are at risk of accelerating the self-amplifying feedback mechanisms and passing critical tipping points. Immediate analysis needs to be done to determine which BECCS technologies are carbon neutral or negative in the critical near-term period, and which are only neutral or negative in the longer term.

Given the short-timescales to keep global warming well below 2°C aiming for 1.5°C, it is not clear how much ACE will be able to contribute in the near term. However, given the very real chance of a substantial overshoot of the Paris Agreement goals and the incumbent impacts, not pursuing ACE options may result

in policymakers eventually considering radical geoengineering options such as injecting particles into the stratosphere or other forms of large-scale solar radiation management (also known as planetary albedo modification). While these proposed techniques may be able to reduce climate risks in some regions, they are very poorly understood and could introduce novel climate and environmental risks, including a rapid temperature increase if such techniques were to be implemented and then interrupted abruptly at a future time. Furthermore, given their regionally heterogeneous impacts they would present an extremely large governance challenge.

Given the urgency, it is critical to support ongoing research and staged deployment of CO₂ removal techniques, and to deepen our scientific understanding of and albedo modification techniques to support informed decision-making in the future. This research needs to include technical, engineering and natural as well as social science aspects in order to be most effective in guiding policy development. It should also address aspects ranging from development of effective governance and regulation, to our societal perspective on the relationships between humans and their environments, to more concrete economic aspects, particularly considering the investments needed to scale up any of the CO₂ removal techniques and whether it would be more prudent to make the same investment directly in decarbonizing energy and production.



9. Building Blocks for the Three Lever Approach

Achieving climate success will require the mobilization of human, financial, and technical resources at a global scale. Some of the building blocks for this are already available using existing treaties, regulations, and technologies, including the four building blocks for the Three Lever Approach.

Building Block 1: Fully implement the pledged Nationally Determined Contributions (NDCs) under the Paris Agreement and strengthen sister agreements.

The 2015 Paris Agreement was a landmark achievement, with 190 countries submitting intended NDCs by the end of 2016, in which each committed to greenhouse gas reductions, indicating a significant level of interest and expectation that this Agreement will produce tangible results. However, recent analysis indicates that even if all unconditional and conditional

NDC pledges are achieved, projections indicate only a 66% probability of maintaining global temperatures at 3°C over pre-industrial temperatures by the end of the century (UNEP, 2016).

The commitments of the Paris Agreements can be immediately strengthened and supported by addressing specific emissions and emissions sectors through targeted multilateral sister agreements and by expanding subnational models of governance and collaboration around the world to embolden and energize national and international action. (Bottom up efforts will be especially important during the Trump Administration in the US.) Scaling up these initiatives can drive greater ambition and provide a down payment for climate mitigation using targeted tools and expertise.

- Strengthen the ambition of current and pending sister agreements over time to achieve even greater climate benefit. The current HFC phasedown could be accelerated for quicker elimination of HFCs and thus lesser warming impact from the pollutants. Fast implementation and parallel efforts to improve energy efficiency of air conditioners and other cooling equipment could potentially double available climate mitigation.
- Eliminate use of heavy fuel oil (HFO) in the Arctic through the International Maritime Organization.
- Develop new, targeted agreements to address specific emissions or sectors such as regional emissions of black carbon and PFCs from the aluminum sector.

Table 1. Selected Sister Agreements

Kigali HFC Amendment to the Montreal Protocol	The Kigali Amendment to the Montreal Protocol, passed in October 2016, will phase down consumption and production of HFCs and will help avoid most of the 0.5°C of warming that would occur if HFC production continued as currently projected.
International Civil Aviation Organization Ruling on Aircraft Emissions	In October 2016, ICAO agreed to cap net CO ₂ emissions from the aviation industry by 2035 to 2020 levels, becoming the first sector to act. Any emissions growth after 2020 needs to be offset.
International Maritime Organization Ruling on Shipping Emissions	IMO is beginning to act on reducing black carbon emissions from the maritime shipping industry. In early 2015, the organization published a report assessing abatement technologies to reduce emissions. IMO also has passed mandatory measures regarding the fuel efficiency of ships, which will reduce both CO ₂ and black carbon emissions.

Building Block 2: Scale up subnational models of governance

State- and city-level jurisdictions can set the standards and the pace for national actions by serving as living laboratories for renewable technologies, regulatory-based (“command and control”) strategies, and market-based solutions. California, for example, has many successful strategies other state- and city-level jurisdictions can emulate. Building cross-sector collaborations among urban stakeholders is critical because creating sustainable cities is a key to global change. One example is the Under 2 MOU (Memorandum of Understanding), which brings together “136 jurisdictions

from 32 countries and 6 continents,” that have “commit[ted] to either reducing their greenhouse gas emissions 80–95% below 1990 levels by 2050 or achieving a per capita emissions target of less than 2 metric tons by 2050.” National and subnational leaders must promote international action and cooperation for unilateral climate policies, such as California’s climate mitigation mandate under the Global Warming Solutions Act of 2006 (also known as AB 32), the American Clean Energy and Security Act of 2009, the Short-Lived Climate Pollutants Act of 2016 (SB 1383), and the proposed AB 262 (Buy Clean California Act). State-level climate policy should also

encourage innovation and commercialization of technologies and solutions that can replace fossil fuels and concurrently enable the poorer nations of the world to achieve economic growth with zero and low-carbon technologies.

- Accelerate the impact of cities on climate mitigation through: municipal and regional Climate Action Plans; green infrastructure projects such as urban forestry and localized microgrids of renewable energy; smart mobility planning and improved mass transit systems to encourage cities to be less auto-centric; incentivizing passive house developments, including photovoltaic retrofits and net-zero energy technology for buildings, and super-efficient cooling appliances and equipment

Building Block 3: Pull the carbon and SLCP levers

Immediately begin decarbonizing the global economy with mature renewables, low- or no-carbon technologies, and aggressively support and promote innovation.

- Promote immediate and widespread use of mature clean technologies such as photovoltaics, wind turbines, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes; this could achieve a 30% to 40% reduction in fossil fuel CO₂ emissions by 2030 relative to BAU.
- Create efficient incentives to businesses and individuals to reduce CO₂ and SLCPs through market-based instruments, such as cap and trade or carbon pricing. This will require high-quality emissions inventories and monitoring and enforcement mechanisms. Economic theory and empirical evidence (such as the experience

with European, California, and New England carbon markets) tell us that market approaches may be the most cost-effective in many circumstances. A central market mechanism should be to remove subsidies for fossil fuels and other emissions-intensive activities, while simultaneously expanding subsidies for low-emissions technologies. Current subsidies provide carbon-intensive fuels an economic advantage over low-carbon fuels and thereby promote carbon pollution. Direct regulatory measures—such as rebates, efficiency standards, and renewable energy portfolio mandates—may be most effective for high-emissions sectors not covered by market-based policies. Regulatory measures are historically the choice for air pollution, including black carbon and tropospheric ozone.

- Promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency. Smart grid and microgrid technology make possible the increasing penetration of intermittent solar and wind generation resources, the emergence and integration of plug-in electric vehicles into the grid infrastructure, and a proactive response to the increasing demand for enhanced grid resiliency, thereby meeting the challenging environmental goals associated with climate change, air quality, and water consumption. The evolution of this technology represents a paradigm shift. In addition, energy storage is a vital enabling technology that holds the key to both transitioning away from fossil fuels for our vehicular needs and managing the intermittency of renewables on the electric power grid. Over the past five years, electric vehicles have been entering the market, and storage technologies are being tested now on various grid applications, mainly driven by innovations in lithium-ion batteries and hydrogen.

Table 2: Select Decarbonization Measures

Energy System	
Electric Grid	Achieve a more reliable and resilient electric grid with at least 90% of all new generation capacity by 2030 from distributed and renewable technologies, such as those listed above.
End-use Devices	Expand electrification of highly efficient end-use devices, especially lighting, electric vehicles, machinery, and plug-load appliances.
Storage	Support development of lower cost energy storage for applications in transportation, resilient large-scale and distributed micro-scale grids, and residential uses.
Storage	Support research and development of a portfolio of new energy storage technologies, including batteries, super-capacitors, compressed air, and hydrogen and thermal storage, as well as advances in heat pumps, efficient lighting, fuel cells, smart buildings and systems integration. These innovative technologies are essential for meeting the target of an 80% reduction in CO ₂ emissions by 2050.
Transport System	
Electrification	Transition from fossil to zero-carbon, locally-sourced transportation fuels, such as hydrogen to power fuel cell-powered electric vehicles and low-carbon grid electricity to power battery electric vehicles, to meet the carbon reduction required from the light-duty and goods movement transportation sectors (medium and heavy-duty vehicles, locomotives and ships).
Fuels	Support research and development of environmentally friendly renewable fuel solutions for heavy-duty transport, such as algal-based biofuels.
Building Efficiency	
Lighting	Replace all incandescent, metal halide, and fluorescent lighting fixtures with LED lighting. This can reduce energy consumption from lighting by 40%.
Lighting	Support investments, research, and development in next-generation intelligent and more efficient 200 lumens per Watt LED lighting products.
Cooling and Heating	Replace existing residential and commercial air conditioning units with super-efficient systems using low-GWP refrigerants, while improving building design to keep cool such as white roofs
Cooling and Heating	Deploy heat pumps and systems coupled with solar thermal and solar power generation. Residential natural gas consumption can be reduced by 50% or more. To accelerate this goal, we recommend deploying an incentive program of rebates comparable to those for energy efficiency appliances.

Sustainable agricultural practices and maintaining natural ecosystems is also an essential component of decarbonizing the global economy, and is vital to global food security, and human health. Agriculture accounts for 10 to 15% of global GHG emissions (60% of nitrous oxide and 50% of methane emissions). Agriculture and residues from natural ecosystems can contribute to renewable energy production through the conversion of organic waste streams to bio-based products and fuels. Globally, food waste reduction programs that recover energy from food that is not consumed has the potential to reduce 20% of the current 50 billion tons of emissions of CO₂ and other greenhouse gases and, in addition, meet the recently approved sustainable development goals by creating wealth for the poorest 3 billion.

- The over-use of nitrogen fertilizers is estimated to be the largest portion of direct agricultural soil management-related nitrous oxide emissions in most countries. Global agricultural nitrous oxide emissions are expected to increase by 35 to 60% by 2030 in association with increased fertilizer nitrogen use and manure production. Therefore, the efficient application of nitrogen-based fertilizers should be encouraged worldwide to mitigate GHG emissions. Appropriate fertilizer nitrogen use also increases crop biomass to help restore, maintain, and increase soil organic carbon.

Immediately make maximum use of available technologies combined with regulations to eliminate high-GWP HFCs, reduce methane emissions by 50%, and reduce black carbon emissions by 90% by 2030. Immediately implementing and globally scaling-up technology and policy solutions to address SLCPs will avoid up to 0.6°C of warming by 2050 and 1.2°C by 2100. In addition to the

climate and health benefits, this solution will provide access to clean cooking for the poorest 3 billion people who spend hours each day collecting solid biomass fuels and burning them indoors for cooking.

- HFCs will be phased down under the Montreal Protocol under the Kigali Amendment of October 2016. Moreover, several recent studies have shown that emissions of HFCs could be quickly phased out and their warming virtually eliminated by 2030 by using low-GWP alternatives already available on the market. With a rapid transition away from high-GWP HFCs, an additional 39–64 Gt CO₂e can be avoided from future buildup of HFC banks. The climate benefits of phasing out HFCs could be more than doubled in some sectors through parallel efforts to increase energy efficiency of air conditioners and other appliances and equipment during this switch in refrigerants.
- The specific technological measures for reducing methane and black carbon are described in the table below. These measures were developed by an international panel and reported in a UNEP WMO Report, 2011.

Table 3: Select Measures for Curbing Black Carbon and Methane Emissions

Methane Measures	
Extraction and transport of fossil fuels	Extend pre-mine degasification and recovery and oxidation of CH ₄ from ventilation air from coal mines
	Extend recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from production of oil and natural gas
	Reduce gas leakage from long-distance transmission pipelines
Waste Management	Separate and treat biodegradable municipal waste through recycling, composting and anaerobic digestion as well as landfill gas collection with combustion/utilization
	Upgrade primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control
Agriculture	Control methane emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs, but also researching methods to reduce methane from enteric fermentation
	Promote healthy low-meat diets
Black Carbon Measures (affecting BC and other co-emitted compounds)	
Transport	Require diesel particle filters for road and off-road vehicles
	Eliminate of high-emitting vehicles in road and off-road transport
	Promote active transport
Residential	Replace coal by coal briquettes in cooking and heating stoves
	Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood-burning technologies in the residential sector in industrialized countries
	Introduction of clean-burning biomass stoves for cooking and heating in developing countries
	Leapfrog to inexpensive portable induction cookstoves
Industry	Replace traditional brick kilns with vertical shaft kilns and Hoffman kilns
	Replace traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries
Agriculture	Ban open field burning of agricultural waste

Building Block 4: Pull the third lever of atmospheric carbon extraction

Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon through afforestation, reduced deforestation, sustainable grazing strategies, efficient application of fertilizer, and restoration of soil organic carbon, including through the use of organic amendments, such as biochar or compost. The potential for carbon mitigation from afforestation, reduced deforestation, and restoration of soil organic carbon is about 8 to 12 Gt per year. Other strategies to extract CO₂ from the air include biochar, enhanced weathering and ocean liming, ocean fertilization with iron, and direct air capture. Because they are scalable and reversible, these strategies are sometimes described as “soft-geoengineering.” In addition, other strategies include carbon capture, utilization, and storage, or CCUS, such as the process for capturing CO₂ at the smoke stack of power plants and cement plants and turning it into calcium carbonate to use as building materials.

Supporting the Building Blocks with a Global Strategic Campaign

The building blocks are there, but how do we create the political and social momentum to support the substantial changes needed to achieve them? To successfully deploy these building blocks and create strong public support for these technology and policy solutions, we will also need a comprehensive strategy that engages and mobilizes all of societies resources to achieve this momentous task. A global strategic campaign must support the four building blocks. Some elements of this strategy should include:

Engagement with strategic constituents and a broad ally base to foster a deeper global culture of climate collaboration, as action will be difficult to implement without buy-in from

key stakeholders. A diverse support base sends a strong message that all communities have something to lose from climate change and are willing to work together to tackle this challenge. These stakeholders include:

- The military is an important constituency that can help mobilize both public and political action; it was instrumental in the U.S. in convincing the administration to require agencies to develop short-term mitigation and long-term mitigation plans. Further, the military needs to both build infrastructure and plan for operations to last for at least 30 years, so it has a vested interest in climate mitigation and adaptation.
- The medical community can similarly influence both public and political action. There is a growing recognition in the medical community of the imminent threat climate change and air pollution pose to public health. For example, in 2015 the Lancet Commission concluded, “the effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health.”
- Industry, particularly the energy industry.
- The world’s top carbon emitters, both individuals and institutions, contribute about 60% of the world’s greenhouse gas emissions. This target audience is easy to reach as they have readily available access to information technologies, and we must work to engage them in these issues.

To bring these diverse communities together, it is important to design venues where stakeholders, community and religious leaders, and researchers and scholars from all academic disciplines can converge around concrete problems. These will provide safe spaces for collaboration, instigating collective action to mitigate climate disruption. Within these venues, collaborators can outline policies and

projects that are likely to lead to success. This includes building upon and learning from past successes like the Montreal Protocol and the California programs (Table 5), as well as smaller scale ideas that are ready to be taken to the next level.

Coordinated public communication and education at local and global scales to foster a global culture of climate action. Public support and awareness of the need and tools for taking heroic actions are still lacking. Major initiatives are needed to both foster that public support and change social attitudes and behavior. This will require, for example:

- A stronger education and communication strategy, working to educate policymakers, corporate CEOs, civil society leaders, and citizens around the world, as well as to draw in climate change skeptics and address false information and narratives. Top-down action will be difficult to implement without substantial support from the general public.
- Integrated curricula at all levels of education, from kindergarten to graduate levels, to educate a new generation about climate change impacts and solutions. Following this education, the fundamental transformation is a change in our attitudes and a willingness to change some of our behaviors towards each other and towards nature, understanding how our social systems intersect with our natural systems.
- A global citizen movement is a crucial element needed to force governments and private industry to restrict warming to well below 2°C. To protect our climate and prevent catastrophe, average people must become advocates of fast climate action.

The actions that underpin the building blocks described in this section can be distilled into

10 Scalable Solutions which we have adapted from the pioneering work of more than 50 researchers in the Bending the Curve report and earlier research, which are listed in the table and figure below.

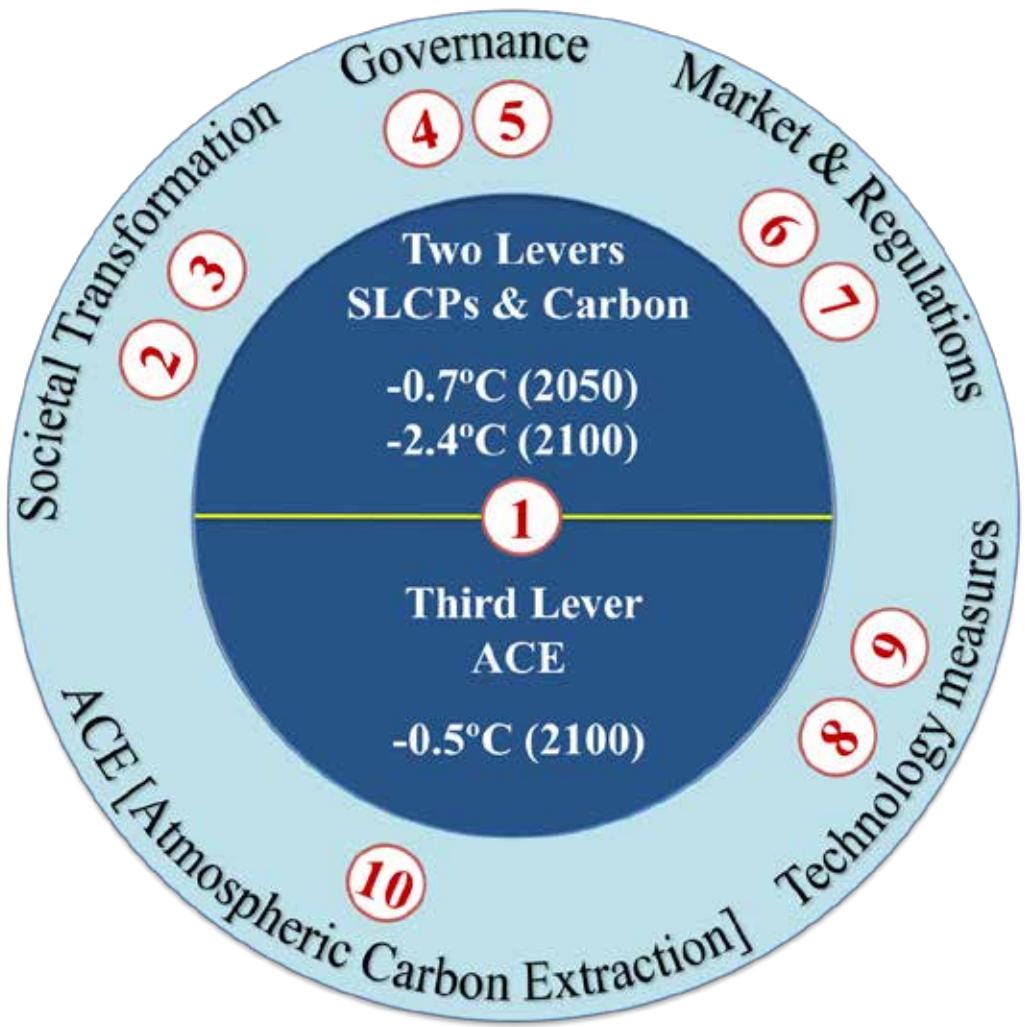


Figure 5: Scalable solutions for climate policy success highlighting the climate benefits from carbon neutrality (Carbon Lever), SLCPs (SLCP Lever), and Atmospheric Carbon Extraction (ACE Lever) mitigation. Adapted with modifications from Ramanathan et al., 2015.

Table 4: Ten Scalable Solution

Science Solutions
1. Show that we can bend the warming curve immediately by reducing SLCPs, and long-term by replacing current fossil fuel energy systems with carbon neutral technologies.
Societal Transformation Solutions
2. Foster a global culture of climate action through coordinated public communication and education at local to global scales.
3. Build an alliance among science, religion, health care, and policy to change behavior and garner public support for drastic mitigation actions.
Governance Solutions
4. Build upon and strengthen the Paris Agreement. Strengthen sister agreements like the Montreal Protocol's Kigali Amendment to reduce HFCs.
5. Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action. California's Under 2 MOU and climate action plans by over 50 cities are prime examples.
Market- and Regulations-Based Solutions
6. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO ₂ emissions.
7. Target direct regulatory measures-such as rebates and efficiency and renewable energy portfolio standards-for high emissions sectors not covered by market-based policies.
Technology-Based Solutions
8. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency.
9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50%, reduce black carbon emissions by 90%, and eliminate high-GWP HFCs ahead of the schedule in the Kigali Amendment while fostering energy efficiency.
Atmospheric Carbon Extraction Solutions
10. Regenerate damaged natural ecosystems and restore soil organic carbon. Urgently expand research and development for atmospheric carbon extraction, along with CCUS.



10. In Pursuit of the Common Good: Where Do We Go from Here?

We conclude by considering the fundamental question: will society rise to the climate challenge or give up hope before it is too late? Given the existential threats BAU emissions presents to many ecosystems, jurisdictions, and societies, it is imperative that we accept the challenge and effectively address climate change this century. We are quickly running out of time to prevent hugely dangerous, expensive, and perhaps unmanageable climate change. That is a central conclusion of this report.

Yet political leaders, corporations, civil society, and the general public for the most part are acting as if we do have plenty of time, not yet aware of the urgency of the climate crisis.

Climate change is an extremely urgent challenge and we need to act now to accelerate our solutions to reach global scale as fast as possible.

The good news is that it is still not too late to prevent disastrous climate changes.

This report sets out a specific plan for limiting climate change in both the near- and long-term. With aggressive, urgent action, we can still protect ourselves. We also have many examples in our recent past proving that humanity can mobilize to achieve collective environmental objectives (Table 5).

As discussed above, staying well under 2°C will require a concerted global effort. We must address everything from our energy systems to our personal choices in order to reduce emissions to the greatest extent possible. Decarbonization must happen immediately and rapidly for our best chance to stay well under 2°C, and even with heroic action, removing existing carbon from the atmosphere will almost certainly be necessary to achieve this goal.

This report describes a detailed plan to restrict warming to well under 2°C and provides a path toward true climate protection, with the possibility,

although difficult, of limiting warming to 1.5°C. Acting quickly, by 2020, to prevent catastrophic climate change will save millions of lives, trillions of dollars in economic costs, and massive suffering and dislocation to people around the world. Acting quickly to slow self-amplifying

feedbacks and prevent runaway climate change is a global security imperative that can avoid the destabilization of entire societies and countries and reduce the likelihood of environmentally driven civil wars and other conflicts.

Table 5: Examples of Environmental Successes

Montreal Protocol	<p>In the mid-1980s, scientists realized the ozone layer above Antarctica was disappearing due to the rapid rise in the production and usage of CFCs (chlorofluorocarbons). Recognizing the threat to human health, countries signed the Montreal Protocol to phase out these chemicals in 1987. Today the Montreal Protocol has phased out nearly 100 ozone-depleting substances by nearly 99% and has set the ozone layer on a path to recovery by 2065. In the U.S., the treaty will prevent over 280 million cases of skin cancer, 1.5 million skin cancer deaths, and 45 million cataracts. Because ozone-depleting substances are also powerful greenhouse gases, the Montreal Protocol also avoided the equivalent of 135 billion tons of CO₂ between 1990 and 2010, earning recognition as the most successful environmental treaties in history. When early boycotts against CFCs and early national measures are included, the avoided warming is equal to the warming currently caused by CO₂ today. Absent the 2016 Kigali Amendment and parallel control measures at national and regional level, the carbon budget associated with a 66% probability of limiting warming to 2°C would have been reduced by 30 to 60%.</p>
Air Quality Improvements in California, New York City, and London	<p>Recognizing the harmful effects of air pollution, particularly to human health, various cities and states have taken on air quality control measures over the last few decades. Since the 1960s, California has been highly successful in reducing air pollution, cutting emissions of ozone precursor gases, PM_{2.5}, air toxics, and black carbon by as much as 90% despite large increases in population, number of vehicles, and diesel fuel consumption. In New York City from 2008 to 2014, annual averages of PM_{2.5}, NO₂, and NO levels, all of which threaten public health, declined by 16–24%, and SO₂ declined by nearly 70%. In London, NOx emissions fell by nearly 40% from 2005 to 2013. Across the U.S., the Clean Air Act (passed in 1970 and amended in 1990) has led to \$10-95 in health benefits for each \$1 spent on pollution control measures.</p>
The Convention on Long-range Transboundary Air Pollution	<p>LTARP has resulted in drastic reductions of air pollutants in the United Nations Economic Commission for Europe region (Europe, the U.S., Canada, the Central Asian republics, and Israel). From 1990 to 2006, SO₂ and NOx emissions, both of which contribute to acid rain, fell by 70% and 35% in the EU, respectively and 36% and approximately 25% in the U.S., respectively. PM₁₀, which is a public health threat, levels declined by nearly 30% in the EU.</p>

11. References

- Alley R., et al. (2015). Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More. *Ann. Rev. Earth Planet. Sci.* 43:207–231.
- Ault T.R., et al. (2016). Relative impacts of mitigation, temperature, and precipitation on 21st Century megadrought risk in the American Southwest. *Science Advances* 2(10): e1600873.
- Bahadur R., et al. (2012). Solar absorption by elemental and brown carbon determined from spectral observations. *Proc. Nat'l. Acad. Sci.* 109(43):17366–17371.
- Barriopedro D., et al. (2011). The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* 332(6026):220224.
- Bender M. F. A.-M., et al. (2012). Changes in extra-tropical storm track cloudiness 1983–2008: observational support for a poleward shift. *Climate Dynamics* 38:2037–2053.
- Bolch T., et al. (2012). The state and fate of Himalayan glaciers. *Science* 336(6079):310–314.
- Boos W. R. and Storelvmo T. (2016). Near-linear response of mean monsoon strength to a broad range of radiative forcings. *Proc. Nat'l. Acad. Sci.* 113:1510–1515.
- Cai Y., et al. (2016). Risk of multiple climate tipping points should trigger a rapid reduction in CO₂ emissions. *Nature Climate Change*, 6: 520–525.
- Campos A., et al. (2012). Analysis of disaster risk management in Colombia: a contribution to the creation of public policies. Bogotá, Colombia: The World Bank and GFDRR.
- Climate and Clean Air Coalition (CCAC) (2016a). Integrated Assessment of Short-Lived Climate Pollutants in Latin America and the Caribbean: Summary for Decision Makers. Nairobi: UNEP.
- Climate and Clean Air Coalition (CCAC) (2016b). Short-lived Climate Pollutants in Countries' Intended Nationally Determined Contributions, A Scientific Advisory Panel Briefing Note.
- Crowther T.W., et al. (2016) Quantifying global soil carbon losses in response to warming. *Nature* 540:104-108.
- Dasgupta P., et al. (2015). Climate Change and the Common Good: A Statement of the Problem and the Demand for Transformative Solutions. The Pontifical Academy of Sciences and the Pontifical Academy of Social Sciences.
- DeConto R. M. and Pollard D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature* 531:591–597.
- Department of Defense (DOD) (2015) National Security Implications of Climate-Related Risks and a Changing Climate.
- Drijfhout S., et al. (2015). Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proc. Nat'l Acad. Sci. USA.* 112:E5777–E5786.
- Dutrieux P., et al. (2014). Strong Sensitivity of Pine Island Ice-Shelf Melting to Climatic Variability. *Science* 343:174–178.
- Dutton A., et al. (2015). Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* 349:aaa4019.
- E.U. (2014). Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated gases and repealing Regulation (EC) No 842/2006.
- Favier L., et al. (2014). Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change* 4:117–121.
- Flynn H. C. and Smith P. (2010). Greenhouse Gas Budgets of Crop Production—Current and Likely Future Trends. International Fertilizer Industry Association, Paris, France.
- Francis J. and N. Skific (2015). Evidence linking rapid Arctic warming to mid-latitude weather patterns. *Philos. Trans. Roy Soc. A* 373(2045):20140170.
- Fujita K. and Niimura T. (2011). Spatially heterogeneous wastage of Himalayan glaciers. *Proc. Nat'l. Acad. Sci.* 108(34):14011–14014.
- Fuss S., et al. (2014). Betting on negative carbon emissions. *Nature Climate Change* 4:851

- Ganguly D., et al. (2012). Climate response of the South Asian monsoon system to anthropogenic aerosol. *Journal of Geophysical Research: Atmospheres* 117(D13):2156–2202.
- Ganguly D., et al. (2012). Fast and slow responses of the South Asian monsoon system to anthropogenic aerosols. *Geophysical Research Letters* 39(18).
- Gardelle J., et al. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience* 5(5):322–325.
- Gardner A. S., et al. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* 340(6134):852–857.
- Garschagen M., et al. (2016). World Risk Report. UNU-EHS.
- Gertler C. G., et al (2016). Black carbon and the Himalayan cryosphere: a review. *Atmospheric Environment* 125:404–417.
- Goswami B. N., et al. (2006). Increasing Trend of Extreme Rain Events Over India in a Warming Environment. *Science* 314(5804):1442–1445.
- Guo W., et al. (2015). The second Chinese glacier inventory: data, methods, and results. *J. Glaciology* 61(226):357–372.
- Gustafsson O. and Ramanathan V. (2016). Convergence on climate warming by black carbon aerosols. *Proc. Nat'l. Acad. Sci.* 113(16):4243–4245.
- Haberle S. G. and David B. (2004). Climates of change: Human dimensions of Holocene environmental change in low latitudes of the PEPII transect. *Quaternary International* 118119:165179.
- Hallegatte S., et al. (2013). Future flood losses in major coastal cities. *Nature Climate Change* 3:802–806. Hallegatte S., et al. (2016). Shock Waves: Managing the Impacts of Climate Change on Poverty. World Bank. Hansen J., et al. (2016). Global Temperature in 2015.
- Hinkel J., et al. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise, *Proc. Natl. Acad. Sci.* 111(9): 3292–3297.
- Holland D. M., et al. (2008). Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nature Geoscience* 1:659–664.
- Hope C. and Schaefer K. (2016). Economic impacts of carbon dioxide and methane released from thawing permafrost. *Nature Climate Change* 6:56–59.
- Hu A., et al. (2013). Mitigation of short-lived climate pollutants slows sea-level rise. *Nature Climate Change* 3:730–734.
- Immerzeel W. W., et al. (2010). Climate change will affect the Asian water towers. *Science* 328(5984):1382–1385.
- Immerzeel W. W., et al. (2012). Hydrological response to climate change in a glacierized catchment in the Himalayas. *Climatic Change* 110(3–4):721–736.
- Internal Displacement Monitoring Centre (2016). Global Report on Internal Displacement 2016: SUMMARY.
- International Civil Aviation Organization (ICAO), Press Release (2016). Historic agreement reached to mitigate international aviation emissions.
- International Energy Agency (IEA) (2016). World Energy Outlook 2016.
- International Maritime Organization (IMO) (2015). Investigation of Appropriate Control Measures (Abatement Technologies) to Reduce Black Carbon Emissions from International Shipping.
- IPCC (2001) Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, 2001.
- IPCC (2007). Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.
- IPCC (2011). Managing the Risks of Extreme Events and Disasters to Advance Climate Change and Adaptation (SREX).

- IPCC (2013). Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
- IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability: Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
- Jacob T., et al. (2012). Recent contributions of glaciers and ice caps to sea level rise. *Nature* 482(7386):514–518.
- Jacobson M. Z., et al. (2015). 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy & Environmental Science* 8:20932117.
- Jarrett J. et al. (2012) Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *Lancet* 379(9832):2198–2205.
- Ji Z., et al. (2015). Simulation of carbonaceous aerosols over the Third Pole and adjacent regions: distribution, transportation, deposition, and climatic effects. *Climate Dynamics* 45(9–10):2831–2846.
- Joughin I., et al. (2014). Marine ice sheet collapse potentially under way for the Thwaites Glacier basin, West Antarctica. *Science* 344:735–738.
- Kääb A., et al. (2012). Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* 488(7412):495–498.
- Kang S., et al. (2010). Review of climate and cryospheric change in the Tibetan Plateau. *Environmental Research Letters* 5(1):015101.
- Kang S., et al. (2015). Dramatic loss of glacier accumulation area on the Tibetan Plateau revealed by ice core tritium and mercury records. *The Cryosphere* 9(3):1213–1222.
- Kang S. C. and Cong Z. Y. (2016). Atmospheric black carbon and its effects on cryosphere. *Advances in Climate Change Research*.
- Karagulian F. et al. (2015). Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. *Atmospheric Environment* 120:475–483.
- Kelley C. P., et al. (2015). Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proc. Nat'l. Acad. Sci.* 112(11):3241–3246.
- Kennett D. J., et al. (2007). Human responses to Middle Holocene climate change on California's Channel Islands. *Quaternary Science Reviews* 26(34):351367.
- Kreft S., et al. (2015). Global Climate Risk Index 2016: Who Suffers Most from Extreme Weather Events? Weather-related Loss Events in 2014 and 1995 to 2014.
- Kriegler E., et al. (2009). Imprecise probability assessment of tipping points in the climate system. *Proc. Nat'l. Acad. Sci.* 106:5041–5046.
- Lam N. L., et al. (2012). Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps. *Envnl. Science & Technology* 46(24):13531–13538.
- Lau K. M. and Kim K. M. (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical Research Letters* 33(21):L21810.
- Lau N.-C. and Nath M. J. (2014). Model Simulation and Projection of European Heat Waves in Present-Day and Future Climates. *J. Climate* 27:3713–3730.
- Lemoine D., and Traeger C. P. (2016). Economics of Tipping the Climate Dominoes. *Nature Climate Change* 6:514–519.
- Lenton T. M. (2012) Arctic climate tipping points. *AMBIO* 41:10–22.
- Lenton T. M., et al. (2008). Tipping elements in the Earth's climate system. *Proc. Nat'l. Acad. Sci.* 105:1786–1793.
- Levy H., et al. (2013). The roles of aerosol direct and indirect effects in past and future climate change. *J. Geophysical Research: Atmospheres* 118(10):4521–4532.
- Li C., et al. (2016). Sources of black carbon to the Himalayan–Tibetan Plateau glaciers. *Nature Communications* 7:12574.

- Li X., et al. (2015). Mechanisms of Asian Summer Monsoon Changes in Response to Anthropogenic Forcing in CMIP5 Models. *J. Climate* 28(10):4107–4125.
- Li Y., et al. (2016). Impacts of black carbon and mineral dust on radiative forcing and glacier melting during summer in the Qilian Mountains, northeastern Tibetan Plateau. *The Cryosphere Discuss.*
- Lin L., et al. (2016). Sensitivity of precipitation extremes to radiative forcing of greenhouse gases and aerosols. *J. Geophysical Research Letters* 43(18):9860–9868.
- Liu S. Y., et al. (2006). Glaciers in response to recent climate warming in Western China. *Quaternary Sciences* 26(5):762–771.
- Lontzek, T. S., et al. (2015). Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change* 5:441–444.
- Lugber G. and McGeehin M. (2008). Climate change and extreme heat event. *American Journal of Preventative Medicine* 35(5):42935.
- Mayewski P. A., et al. (2013). West Antarctica's Sensitivity to Natural and Human-forced Climate Change Over the Holocene. *J. Quaternary Science* 28(1):40–48 (2013).
- McKay N. P., et al. (2011). The role of ocean thermal expansion in Last Interglacial sea level rise. *Geophysical Research Letters* 38(14):L14605.
- Meehl G. A. and Tebaldi C. (2004). More intense, more frequent, and longer lasting heatwaves in the 21st century. *Science* 305:994–997.
- Molina M., et al. (2009). Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO₂ emissions. *Proc. Nat'l. Acad. Sci.* 106(49):20616–20621.
- Neckel N. et al. (2014). Glacier mass changes on the Tibetan Plateau 2003–2009 derived from ICESat laser altimetry measurements. *Environmental Research Letters* 9(1):014009.
- Nitschke M., et al. (2011). Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. *Environmental Health* 10(42).
- Norris J. R., et al. (2016). Evidence for climate change in the satellite cloud record. *Nature* 536:72–75.
- OECD (2007). Ranking the World's Cities Most Exposed to Coastal Flooding Today and in the Future: Executive Summary. OECD, Paris, France.
- Pal, J. S. and Eltahir, E. A. B. (2015). Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change* 6:197–200.
- Paolo F. S., et al. (2015). Volume loss from Antarctic ice shelves is accelerating. *Science* 348(6232):327–331. Pistone K., et al. (2014). Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proc. Nat'l. Acad. Sci.* 111(9):3322–3326.
- Pope Francis (2015). Laudato Si': On Care for Our Common Home [Encyclical]. Qiu J. (2008). China: the Third Pole. *Nature* 454:393–396.
- Rahmstorf S. and Coumou D. (2011). Increase of extreme events in a warming world, *Proc. Nat'l. Acad. Sci.* 108(44):17905–17909.
- Ramanathan V. and Carmichael G. (2008). Global and regional climate changes due to black carbon. *Nature Geoscience* 1:221–227.
- Ramanathan V. and Feng Y. (2008). On avoiding dangerous anthropogenic interference with the climate system: formidable challenges ahead. *Proc. Nat'l Acad. Sci. USA* 105(38):14245–14250.
- Ramanathan V., et al. (1985). Trace Gas Trends and Their Potential Role in Climate Change. *J. Geophysical Research* 90(D3):5547–5566.
- Ramanathan V., et al. (2001). Aerosols, Climate, and the Hydrological Cycle. *Science* 294(5549):2119–2124.
- Ramanathan V., et al. (2005). Atmospheric brown clouds: impacts on South Asian climate and hydrological cycle. *Proc. Nat'l. Acad. Sci.* 102(15):5326–5333.

- Ramanathan V., et al. (2015). Bending the Curve: Executive Summary. University of California.
- Rignot E., et al. (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. *Geophysical Research Letters* 31: L18401.
- Rignot E., et al., (2011) Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophysical Research Letters* 38(5):L05503.
- Rignot E., et al. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Letters* 41:3502–3509.
- Rogelj J., et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change* 5:519–527.
- Rogelj J., et al. (2015). Impact of short-lived non-CO₂ mitigation on carbon budgets for stabilizing global warming. *Envnl. Research Letters* 10(075001):1–10.
- Schleussner C.-F., et al. (2016a). Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proc. Nat'l. Acad. Sci.* 113(33):9216–9221.
- Schleussner C.-F., et al. (2016b). Differential climate impacts for policy-relevant limits to global warming: the case of 1.5C and 2C. *Earth System Dynamics* 7:327–351.
- Schoof C. (2007). Ice sheet grounding line dynamics: steady states, stability, and hysteresis. *J. Geophys. Res.* 112:F03S28.
- Schuur E. A. G., et al. (2015). Climate change and the permafrost carbon feedback. *Nature* 520:171–179. Serreze M. C. and Barry R. G. (2011). Processes and impacts of Arctic amplification: a research synthesis. *Global Planetary Change* 85–96.
- Shah N., et al. (2015). Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Air Conditioning. Lawrence Berkeley National Laboratory.
- Shindell D., et al. (2017) A climate policy pathway for near- and long-term benefits. *Science* 356(6337):493–494.
- Shindell D. and Faluvegi G. (2009). Climate response to regional radiative forcing during the twentieth century. *Nature Geoscience* 2:294–300.
- Shindell D., et al. (2012). Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science* 335(6065):183189.
- Sillmann J., et al. (2015). Climate emergencies do not justify engineering the climate. *Nature Climate Change* 5:290–292.
- Sinha A., et al. (2015). Trends and oscillations in the Indian summer monsoon rainfall over the last two millennia. *Nature Communications* 6:6309.
- Straneo F. and P. Heimbach (2013). North Atlantic warming and the retreat of Greenland's outlet glaciers. *Nature* 504:36–43.
- Sun X., et al. (2016) China's Air Pollution Rules: Compliance and Enforcement Lessons From Global Good Practice. *Environmental Law Institute* 46, 10958.
- Tainio M., et al. (2016) Can air pollution negate the health benefits of cycling and walking?. *Preventative Medicine* 87:233–236.
- UNEP (2011). Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers.
- UNEP (2015). Decision XXVIII/1: Further Amendment of the Montreal Protocol.
- UNEP (2016). The Emissions Gap Report 2016: A UNEP Synthesis Report.
- UNEP-WMO (2011). Integrated Assessment of Black Carbon and Tropospheric Ozone. Nairobi: UNEP.
- UN Office for Disaster Risk Reduction (UNISDR) & Centre for Research on the Epidemiology of Disasters (CRED) (2015). THE HUMAN COST OF WEATHER-RELATED DISASTERS 1995–2015.

- UN Framework Convention on Climate Change (UNFCCC) (2015) Paris Agreement.
- Velders G. J. M., et al. (2007). The importance of the Montreal Protocol in protecting climate. *Proc. Nat'l. Acad. Sci. U.S.A.* 104:4814–4819.
- Velders G. J. M., et al. (2009). The large contribution of projected HFC emissions to future climate forcing. *Proc. Nat'l. Acad. Sci. U.S.A.* 106:10949–10954.
- Velders G. J. M., et al. (2012). Preserving Montreal Protocol Climate Benefits by Limiting HFCs. *Science* 335(6071):922–923.
- Velders G. J. M., et al. (2014). Growth of climate change commitments from HFC banks and emissions. *Atmospheric Chemistry & Physics* 14:4563–4572.
- Wang X., et al. (2012). Using remote sensing data to quantify changes in glacial lakes in the Chinese Himalaya. *Mountain Research and Development* 32(2):203–212.
- Watts N., et al. (2015). Health and climate change: policy responses to protect public health. *The Lancet* 386(10006):18611914.
- Webster P. J., et al. (1998). Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophysical Research* 103(C7):14451–14510.
- Wheeler T. (2015). Climate Change Impacts on Food Systems. *Climate Change Impacts on Food Systems and Implications for Climate-Compatible Food Policies*, Chapter in: Climate change and food systems: global assessments and implications for food security and trade, Aziz Elbehri (editor). Food Agriculture Organization of the United Nations (FAO), Rome, 2015.
- White House (2014). Climate Action Plan: Strategy to Reduce Methane Emissions.
- White House Office of the Press Secretary (2016). FACT SHEET: Nearly 200 Countries Reach a Global Deal to Phase Down Potent Greenhouse Gases and Avoid Up to 0.5°C of Warming.
- Winkelmann R., et al. (2015). Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet. *Science Advances* 1:e1500589.
- Woodcock J., et al. (2009) Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet* 374(9705):1930–1943.
- World Bank (2013a). Building Resilience: Integrating Climate and Disaster Risk into Development.
- World Bank (2013b). Turn Down the Heat: Why a 4°C Warmer World Must be Avoided. Washington, DC.
- World Health Organization (WHO) (2014). Burden of disease from the joint effects of household and ambient air pollution for 2012.
- World Health Organization (WHO) (2016). Second Global Conference: Health and Climate, Conference Conclusions and Action Agenda.
- Xu, Y., et al. (2013). Estimating the radiative forcing of carbonaceous aerosols over California based on satellite and ground observations, *J. Geophysical Research: Atmospheres* 118(19):11148–11160.
- Xu Y., et al. (2013). The role of HFCs in mitigating 21st century climate change. *Atmospheric Chemistry and Physics* 13:60836089.
- Xu Y., et al. (2015). The importance of aerosol scenarios in projections of future heat extremes. *Climatic Change* 1–14.
- Xu Y., et al. (2016). Observed high-altitude warming and snow cover retreat over Tibet and the Himalayas enhanced by black carbon aerosols. *Atmospheric Chemistry & Physics* 16:1303–1315.
- Yao T., et al. (2012). Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change* 2(9):663–667.
- Yasunari T. J., et al. (2010). Estimated impact of black carbon deposition during pre-monsoon season from Nepal Climate Observatory–Pyramid data and snow albedo changes over Himalayan glaciers. *Atmospheric Chemistry & Physics* 10(14):6603–6615.

- You Q., et al. (2015a). Comparison of multiple datasets with gridded precipitation observations over the Tibetan Plateau. *Climate Dynamics* 45(3-4):791–806.
- You Q., et al. (2015b). Rapid warming in the Tibetan Plateau from observations and CMIP5 models in recent decades. *International Journal of Climatology*.
- Zaelke D., et al. (2012). Strengthening Ambition for Climate Mitigation: The Role of the Montreal Protocol in Reducing Short-Lived Climate Pollutants. *Rev. Eur. Comp. & Int'l. Envtl. Law* 231–242.
- Zhao L., et al. (2014). Glacier volume and area change by 2050 in high mountain Asia. *Global and Planetary Change* 122:197–207.