

12ish Things to Know about Climate Science: a Primer for Policy-making

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This document attempts to present, in the simplest manner possible, the fundamental, high-level findings of climate science that are most relevant to the international climate change negotiations. For a comprehensive summary of climate science, see the Intergovernmental Panel on Climate Change's Fifth Assessment Report (AR5) at ipcc.ch/report/ar5/; the FAQs are particularly helpful and easy to read. For something in between, try the IPCC's Synthesis Report <http://ar5-syr.ipcc.ch/> or the four Summaries for Policy Makers.

0. Get the units straight

Greenhouse gas emissions are expressed in a variety of units. These are the most common:

Names	grams	kgs
Tonne, metric ton (t) ²	10 ⁶	10 ³
Teragram (Tg), million metric tons (MMT)	10 ¹²	10 ⁹
Gigaton (Gt), Petagram (Pg)	10 ¹⁵	10 ¹²

Depending on the context, emissions may also be denoted in terms of carbon (C) or carbon dioxide (CO₂). One ton of carbon is equivalent to 44/12 (~3.67) tons of carbon dioxide. (The atomic weights of carbon and oxygen are 12 and 16 respectively, so the molecular weight of CO₂ is 44.) Other greenhouse gases are often denominated in equivalent carbon dioxide (CO₂e) units, which are calculated by multiplying their mass by their Global Warming Potential (see next section).

An atmospheric concentration of 1 part per million (ppm) CO₂ is equivalent to 7.81 Gt of CO₂ (CDIAC). Current emissions rates from fossil fuel combustion and cement production are about 36 Gt of CO₂ per year (Le Quéré et al., 2015).

1. Different gases produce different warming effects.

If the Earth had no atmosphere, the average surface temperature would be about -18°C (Marshall & Plumb, 2008). The atmosphere acts as an insulator, allowing shortwave (visible) radiation from the sun to pass through and warm the surface, but absorbing some of the outgoing longwave (infrared) radiation emitted by the Earth. This greenhouse effect keeps the Earth's average surface temperature at about 15°C.

The most important greenhouse gases (GHGs) in Earth's atmosphere, in terms of their abundance and ability to trap heat, are water vapor, carbon dioxide, and methane. Comparing the

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² In the U.S., "tons of CO₂" can also refer to the American measurement of 1 short ton = 2000 pounds. These are not used internationally, however. The scientific literature also generally uses SI (metric) units.

relative impact of different greenhouse gases is not straightforward: each has a different capacity to trap heat and a different lifetime in the atmosphere. CO₂ is a very long-lived GHG: it will take many centuries for natural processes to remove just half the CO₂ humanity has emitted. Methane (CH₄), on the other hand, traps much more heat on a per-mass basis than CO₂ but is rapidly removed through a combination of bacterial action in soils and chemical processes in the atmosphere.

The **global warming potential** (GWP) is a measure of a gas's heat-trapping ability over a defined period of time; CO₂ is defined to have a GWP of one, and other gases' GWPs reflect their heat-trapping ability relative to an equal mass of CO₂. To compare emissions of different gases, the mass emitted is multiplied by the gas's GWP to produce a value in carbon dioxide equivalents (CO₂e). This is typically done using a 100-year timespan for GWP, but some argue that 20 years is a more appropriate metric for societal decision-making (e.g., Eco-Cycle, n.d., Chapin et al., 2014). As the IPCC notes, "The choice of time horizon is a value judgement because it depends on the relative weight assigned to effects at different times" (IPCC AR5 WG 1 Ch 8 p.711-712).

GWPs also do not easily capture the effects of other climate forcing agents, such as black carbon. Black carbon (soot) is not a gas (so, strictly speaking, not a GHG), but it is a powerful contributor to global warming at low altitudes by absorbing solar radiation. On the other hand, aerosols (fine particulates) at high altitudes can reflect more sunlight than they absorb, resulting in cooling (AR5 WG1 SPM).

	Atmospheric composition ³	Atmospheric lifetime	GWP (20 years)	GWP (100 years)	Increased radiative forcing (W/m ²)
CO ₂	398.55 ppm	centuries	1	1	1.68
CH ₄	722 ppb	decades	84-86	28-34	0.97
F-gases	~850 ppt	decades	3,700-7,000	1,300-4,700	0.18
Black carbon	varies	days	~1600	~460	0.05-0.8

Sources: Blasing, 2014; Tans and Keeling, 2015; IPCC AR5 WG1 Ch 8.7, Ch 7.5, TS Ch 3. Note that older GWP figures are commonly used by regulatory agencies, such as the USEPA and the Clean Development Mechanism, and in reporting national inventories.

2. The Earth's climate is highly dynamic

Over geologic time (i.e. millions of years), the Earth has seen extreme ice ages, hothouse eras (with palm trees and alligators inside the Arctic Circle), and everything in between. These climatic changes are responses to subtle variations in the Earth's orbit known as Milankovitch cycles. Milankovitch cycles produce relatively small changes in the amount and distribution of sunlight reaching the Earth, but are sufficient to kick-start powerful feedbacks within the climate system that alter the state of the climate (AR5 WG1 5.2). Additional factors influencing Earth's climate include variations in the Sun's energy output and volcanic eruptions, which can add both

³ Recent annual means. CO₂ is from 2014; other values from 2012.

heat-trapping carbon dioxide and radiation-shielding sulfur dioxide aerosols to the atmosphere (AR5 WG1 FAQ 11.2).

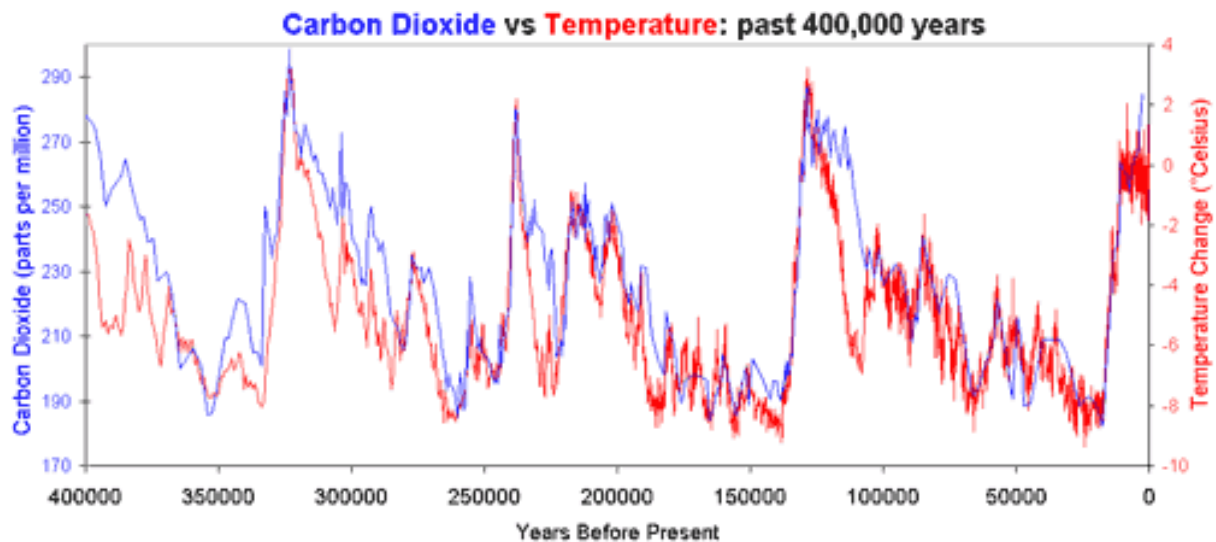


Figure 1: Vostok ice core records for carbon dioxide concentration and temperature change (Skeptical Science from Barnola et al., 2003 and Petit et al., 2000).

3. Feedback cycles dominate the climate.

The Earth's climate contains multiple positive and negative feedback cycles, including:

Atmospheric water vapor: Warm air holds more moisture than cold air. As the atmosphere warms, its water vapor content tends to increase. Water vapor has a powerful greenhouse effect, so the increased vapor content of the atmosphere causes more atmospheric warming.

Arctic sea ice: Sea ice, being white, reflects most sunlight back into space. As it melts, it reveals darker ocean water, which absorbs more sunlight, causing the ocean to warm and melt more ice.

Methane release: Large quantities of frozen methane are locked up in permafrost (particularly in Siberia and the Canadian Arctic) and as clathrates in ocean floor sediments (Schuur et al., 2015). As these areas warm, some of the methane is released into the atmosphere, where it amplifies warming. (for examples, see [ROV Hercules](#), [methane lakes](#))

Amazonian drying: Much of the rainfall in the Amazon and other rainforests is recycled. As deforestation proceeds in the Amazon, it reduces the evapotranspiration of water from the forest into the atmosphere. This process then reduces rainfall further downwind in the Amazon, leading to further drying and thus more tree mortality and forest fires, which result in the transfer of carbon from forest biomass to the atmosphere (Malhi et al., 2009).

Ocean CO₂ absorption: About 30% of the anthropogenic CO₂ released into the atmosphere is absorbed by the ocean via air-sea gas exchange (AR5 WG1 3.8). This partly explains why both

atmospheric concentrations of CO₂ and the warming it induces are much lower than if all CO₂ emitted were to stay in the atmosphere. The more CO₂ the atmosphere contains, the more of it the ocean will absorb. There are indications, however, that the rate of CO₂ uptake by the oceans is slowing down because of climatic changes – increasing winds and warmer surface waters (Le Quéré et al., 2010). Moreover, absorption of CO₂ by the oceans causes ocean acidification, a distinct problem from climate change (AR5 WG1 Box 3.2, FAQ 3.3).

CO₂ fertilization of plant growth: To plants and other photosynthetic organisms like algae, CO₂ is a nutrient, and, in general, higher levels of ambient atmospheric CO₂ lead to higher levels of CO₂ uptake, reducing CO₂ in the atmosphere (AR5 WG1 Box 6.3). However, the capacity of the biosphere to remove excess anthropogenic CO₂ in the atmosphere is variable and limited (e.g. Shaw et al. 2002), often because of the limited availability of soil nutrients such as nitrogen and phosphorus.

The Earth's climate, globally and locally, reflects the coupling of all these – and many other – positive and negative feedback cycles to each other and to external forcings such as orbital cycles, sunspot cycles, and volcanic eruptions.

In addition, other processes internal to the Earth system impact the rate of warming at Earth's surface. One important example is the Pacific Decadal Oscillation (PDO – also called the Interdecadal Pacific Oscillation). The PDO is a naturally occurring, irregular cycle of climate variability which switches phase approximately every 20 years (Mantua & Hare, 2002). The PDO can act to temporarily slow down or accelerate the rate of surface warming depending on its phase. When the PDO is in a “cool” phase, strong tradewinds bury warm, tropical waters deep in the Western Pacific, replacing them with cool waters upwelled from the deep Eastern Pacific. These cool waters absorb heat from the atmosphere and then are buried in turn, removing heat from the atmosphere. When the PDO switches to a “warm” phase, the tradewinds weaken and the deep warm waters of the western Pacific slosh back across the Pacific surface, releasing heat to the atmosphere. The “cool” phase PDO since 1999 largely explains the slowdown in surface air temperature growth of the last 15 years, but seems to be switching phase in 2015 (England et al., 2014).

4. Climate is not only about average temperature.

We use average surface temperature as an index to measure climate change, but no single location on Earth actually experiences average temperatures all the time. Moreover, different regions of the planet warm and cool at different rates: currently, high latitudes experience far greater rates of warming than low latitudes (but see below for “time of emergence”). In terms of what people and biophysical systems experience, a change in average temperature may be less important than a change in extremes: a small change in average temperature can greatly increase the number of very hot days or reduce the number of frost days, both of which can have important impacts.

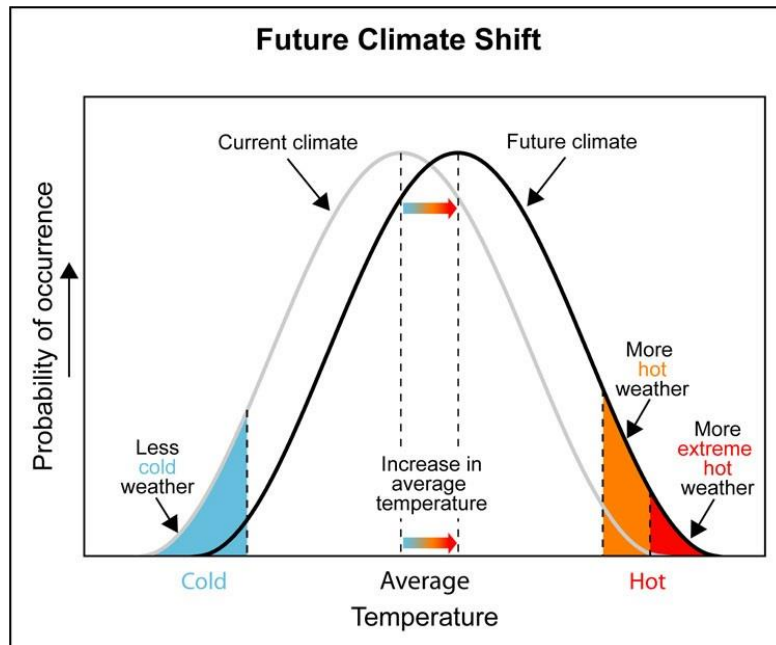


Figure 2: A small change in the average (e.g., temperature) can imply a large increase in the probability of extreme events (Southwest Climate Change Network).

Changes in temperature may be less important than changes in precipitation, which affect agriculture and drinking water availability, sea level (driven by thermal expansion of the oceans and glacial melting), wind and ocean currents, which can affect migrating species, etc. In general, climate change is expected to deliver more extreme climates: that is, wetter regions will get wetter and drier regions will get drier (AR5 WG1 7.6.2). However, the impacts on any one particular location are shaped by local factors (orography, atmospheric dynamics) and may be very different from the general trend.

5. Humans have adapted to the Holocene.

Human civilization, and in particular agriculture, developed over the last 10,000 years, during a relatively stable period known as the Holocene. In fact, some scholars think that human activity (in particular, rice cultivation – which generates methane – and deforestation – which generates CO₂) is responsible for maintaining relatively stable temperatures throughout the Holocene, which would have otherwise seen a gradual cooling trend (Ruddiman, 2003, 2007). The stability of the Holocene allowed us to build cities along shorelines, farm crops, develop irrigation and drinking water systems, etc. Humans can adapt to a huge variety of climates, but the built infrastructure, economy, knowledge and cultural practices tend to be specific to a particular local climate. Changing all these operations to a new “normal” climate could be daunting, depending on how different the new climate is. And if the climate becomes less stable than it is at present, or continues to change, it will be hard to know what climate to adapt to.

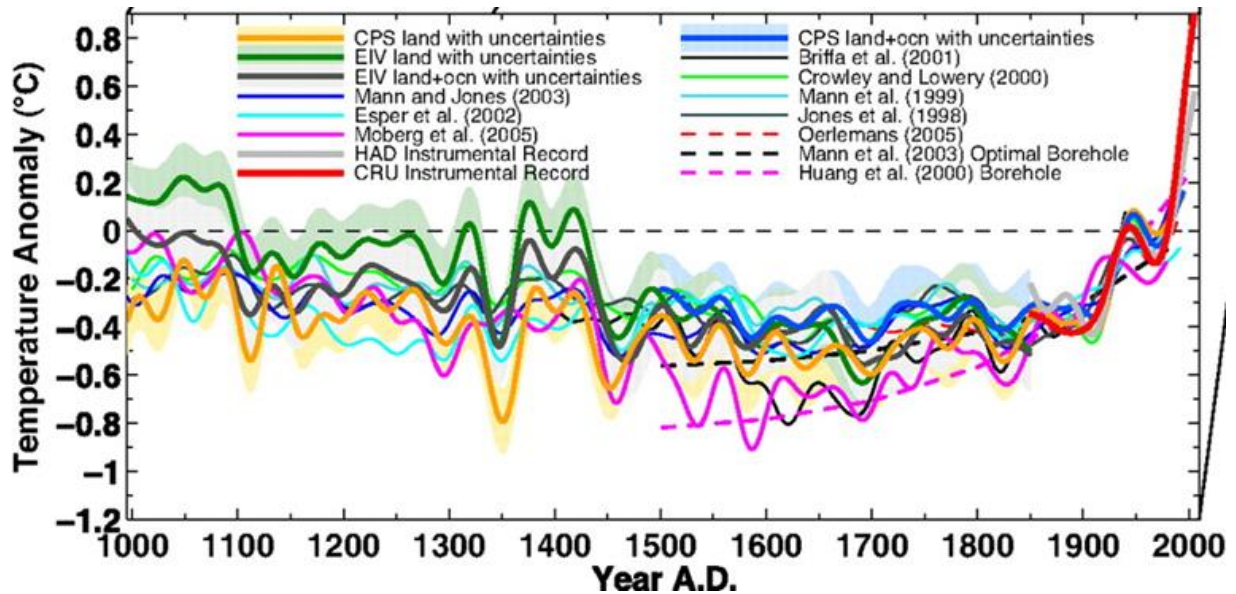


Figure 3: Northern Hemisphere surface temperature records from proxy reconstructions, aka the new “hockey stick” graph (Mann et al., 2008)

Under anthropogenic global warming (AGW), various scientists have calculated a “time of emergence” – a date at which a particular locale’s climate will no longer resemble its past climate. There are various formal definitions (Diffenbaugh & Scherer, 2011; Mora et al., 2013) but, in essence, the idea is to identify a date after which the coldest year will be warmer than the average pre-anthropogenic year. This date is much sooner in the tropics than in high latitudes because, although high latitudes are warming faster than the tropics, they also have a larger range of natural variability; so it takes longer for the temperature trend to emerge from the envelope of variability.

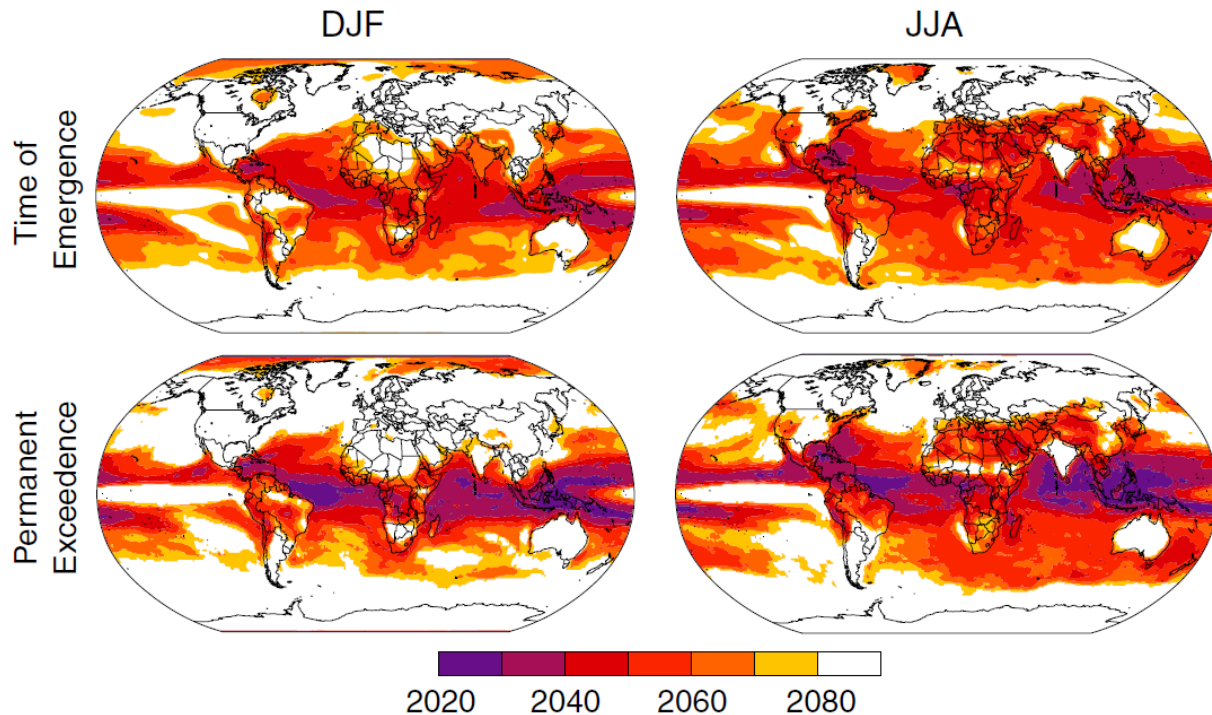


Figure 4: Time of emergence. *Top row*: decade of emergence from ensemble of climate models. *Bottom row*: decade of the last occurrence of a season that is cooler than the 1980–1999 maximum (Diffenbaugh & Scherer, 2011).

6. Temperature change has a linear relationship with cumulative emissions – so far.

Modeling and empirical results indicate that the increase in average surface temperatures since pre-industrial times has an approximately linear relationship with cumulative anthropogenic emissions of CO₂ (AR5 WG1 SPM E.8). In other words, **every additional quantity of CO₂ emitted to the atmosphere will result in additional warming, regardless of when it is released.** The implication, as long as this relationship holds true, is that to arrest climate change, humanity will have to eventually eliminate all its CO₂ emissions. To have a two-thirds chance of holding the Earth to a 2°C rise from pre-industrial times, we can emit no more than about 2900 gigatons (Gt) of CO₂, of which about 2150 were already emitted by 2011 (IPCC AR5 WG1 SPM 10). From 2011 to the time of this writing, ~155 more gigatons of CO₂ were added. This leaves a “carbon budget” of less than 600 Gt of CO₂ which can be emitted. If we want to have a better than two-thirds chance of remaining below the 2°C limit, or we want to hit a lower temperature target, then our total emissions must be further reduced. At current anthropogenic emission rates, we will use up our 2°C carbon budget in less than two decades. (For more background on these calculations, see Pearce, 2014.)

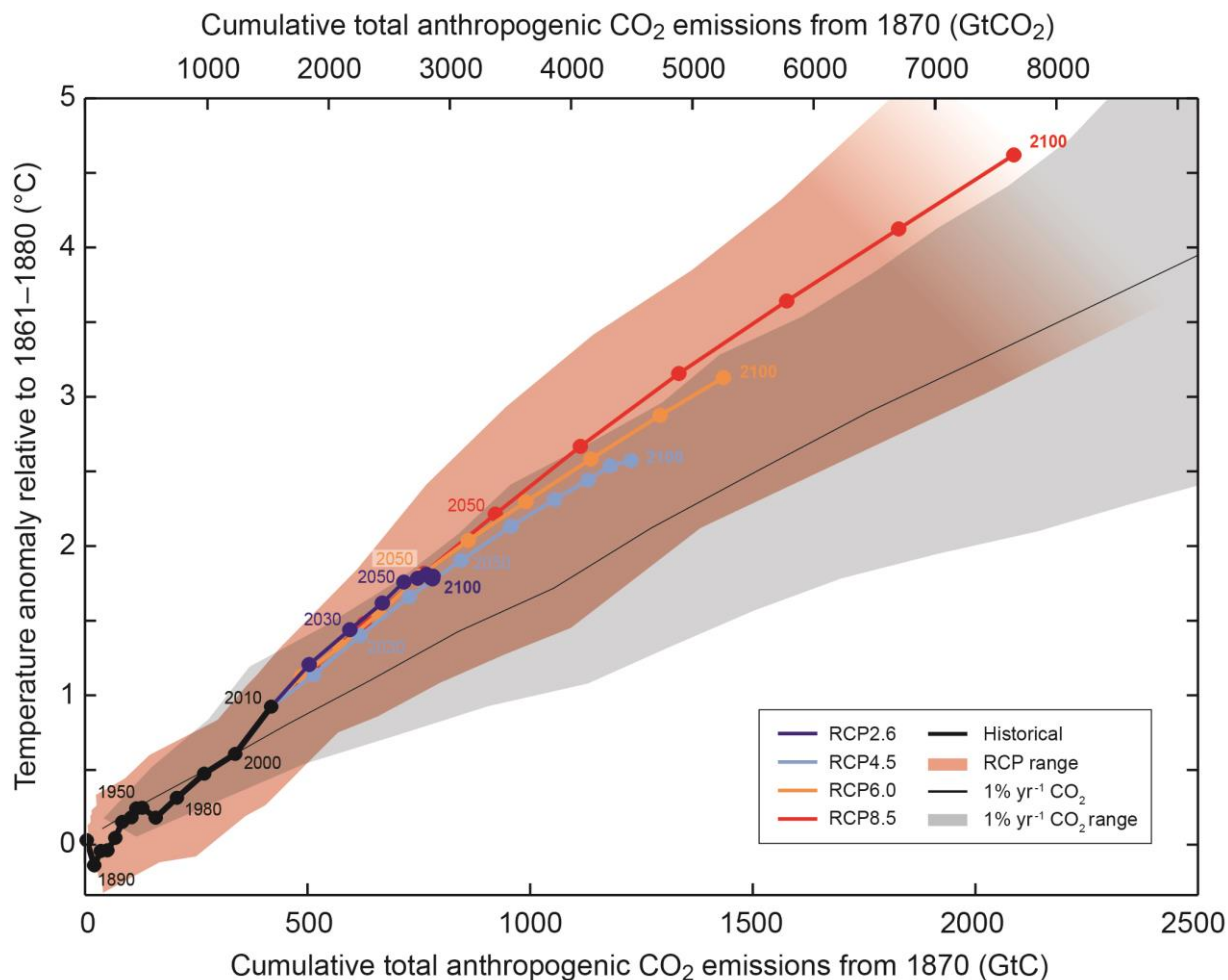


Figure 5: Global mean surface temperature increase as a function of cumulative total global CO₂ emissions (IPCC AR5 WG1 SPM.10).

7. Climate change is effectively irreversible.

Currently, the oceans absorb about 30% of anthropogenic CO₂ emitted to the atmosphere through equilibration; a smaller amount is removed through increased plant growth. Most of the rest remains in the atmosphere until it is removed through geological weathering, which takes tens to hundreds of thousands of years. (Note that this refers to long-term, cumulative change; there is considerable turnover on short timescales, as plants and microbes use CO₂ and then respire it again). On timescales relevant to society – a century or less – atmospheric concentrations of CO₂ will only go up, not down; and the additional heating from the higher concentrations is, from a societal perspective, permanent (AR5 WG1 12.5).

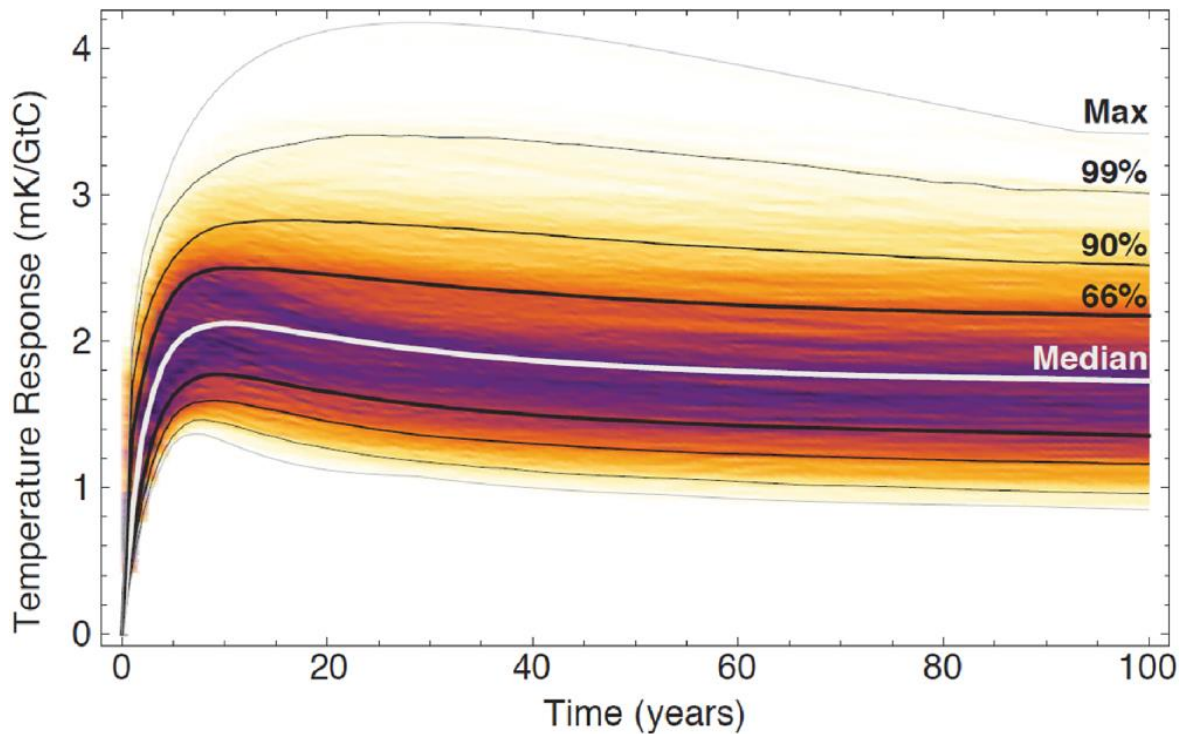


Figure 6: Temperature increase from an individual emission of carbon dioxide (CO₂) from 6000 model simulations. The colors represent the relative density of simulations in a given region of the plot (Ricke & Caldeira, 2014).

Temperatures will rise as CO₂ concentrations increase, and continue to rise even after CO₂ concentrations stabilize. CO₂ concentrations have increased from preindustrial levels of 280 ppm to around 400 ppm in 2015, and the Earth is currently about 0.85°C above preindustrial temperatures (IPCC AR5 WG1 2.4). By the time CO₂ has doubled to 560 ppm, temperatures will have risen 1°C to 2.5°C. This is known as the transient climate response (TCR). If at that point, anthropogenic emissions cease, it will take several centuries for the climate to settle into an equilibrium temperature (measured by the equilibrium climate sensitivity or ECS) of 1.5°C to 4.5°C above pre-industrial⁴ – as long as the climate system does not pass through any tipping points. (For more details, see IPCC AR5 WG1 Box 12.2).

⁴ The pre-industrial period is defined variously as ending in 1750 or 1850. The difference is not significant compared to recent changes in the climate system.

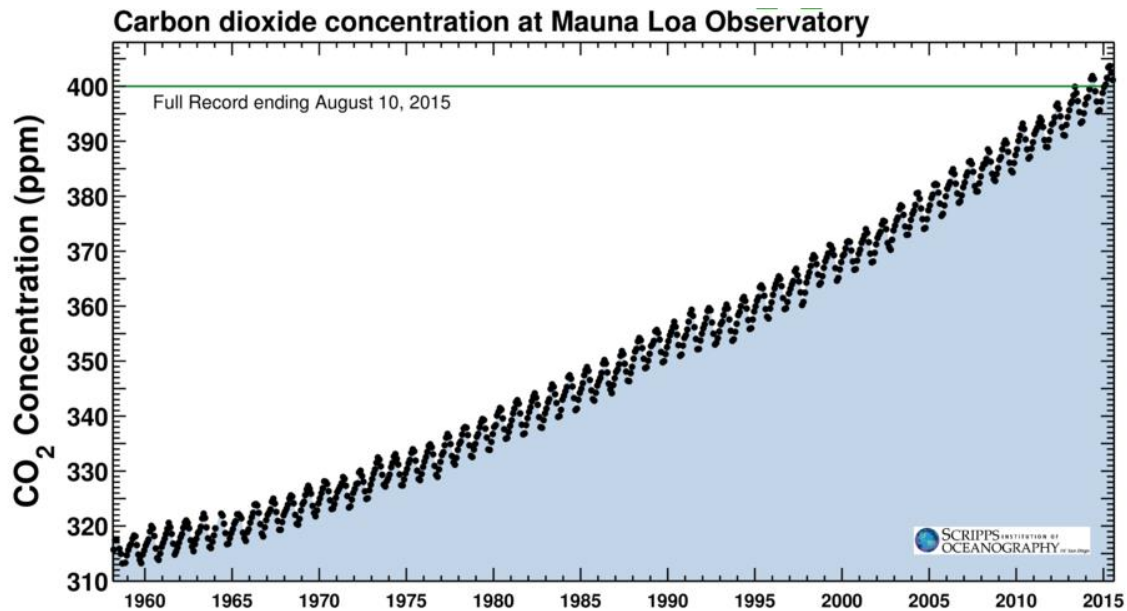


Figure 7: CO₂ concentration in the atmosphere (the Keeling Curve). Note the seasonal cycle due to Northern Hemisphere plant respiration (Scripps Institute of Oceanography).

8. The climate can change abruptly.

Discussing climate change in terms of averages can give a picture of a climate that changes smoothly and incrementally. That may be true for small variations in climate, but ice cores tell us that the climate has also changed abruptly in the past. For example, more than 20 rapid warming events (up to 8°C in as little as 4 decades) occurred during the last ice age (Dansgaard et al., 1993). Human societies would have a hard time adapting to such dramatic changes in temperature and the accompanying changes in precipitation, sea level rise, disease incidence, animal migration, etc. on such a short timeline.

Abrupt changes in the climate system may be caused by non-linearities known as tipping points. Examples of possible tipping points include the collapse of the West Antarctic Ice Sheet, massive melting of permafrost (and attendant discharge of significant quantities of methane and carbon dioxide), and the slowdown of thermohaline circulation in the Atlantic Ocean (Lenton et al., 2009). One way to think about the climate is as a metastable system: a large enough perturbation can knock it from one state to another, without any easy return path. This is why the IPCC warns that changes in the climate system may be irreversible, at least for many millennia.

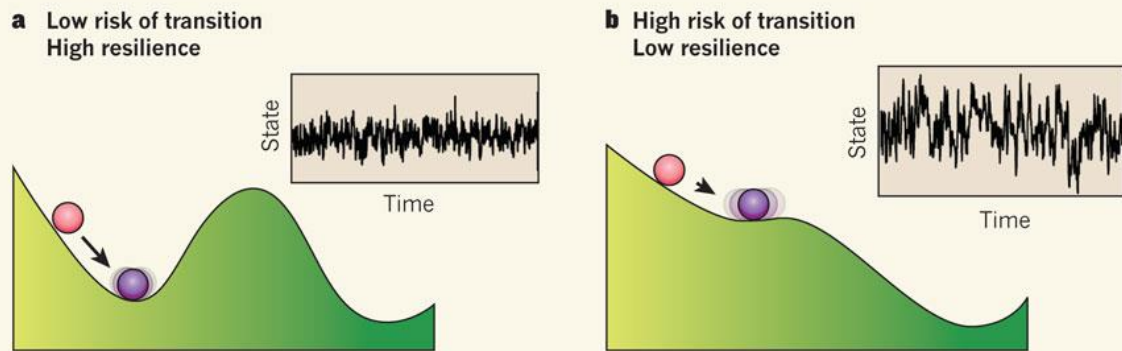


Figure 8: A system with metastable states. A resilient system (a) recovers quickly from disturbance and is unlikely to shift to an alternative state. A risky state (b) has a slower recovery from perturbation (arrow) and fluctuations in a stochastic (random) environment will tend to be larger and time-correlated (Sheffer, 2010).

9. Representative Concentration Pathways (RCPs)

One of the key uncertainties in predicting the future of climate change is how much anthropogenic emissions will be emitted. Unlike uncertainties in the physical system, emissions uncertainty stems from uncertainties about policy and economic choices that societies will make. The published literature contains thousands of different emissions projections, based on different assumptions about economic growth, policy choices, technological improvement, and other factors. The IPCC has developed 4 emissions trajectories, known as Representative Concentration Pathways (RCPs) to represent the spread of possible scenarios. Running different climate models on the same RCPs allows climate scientists to generate a distribution of possible climate responses to these emissions scenarios. Similarly, social scientists model various policy scenarios against standardized emissions pathways.

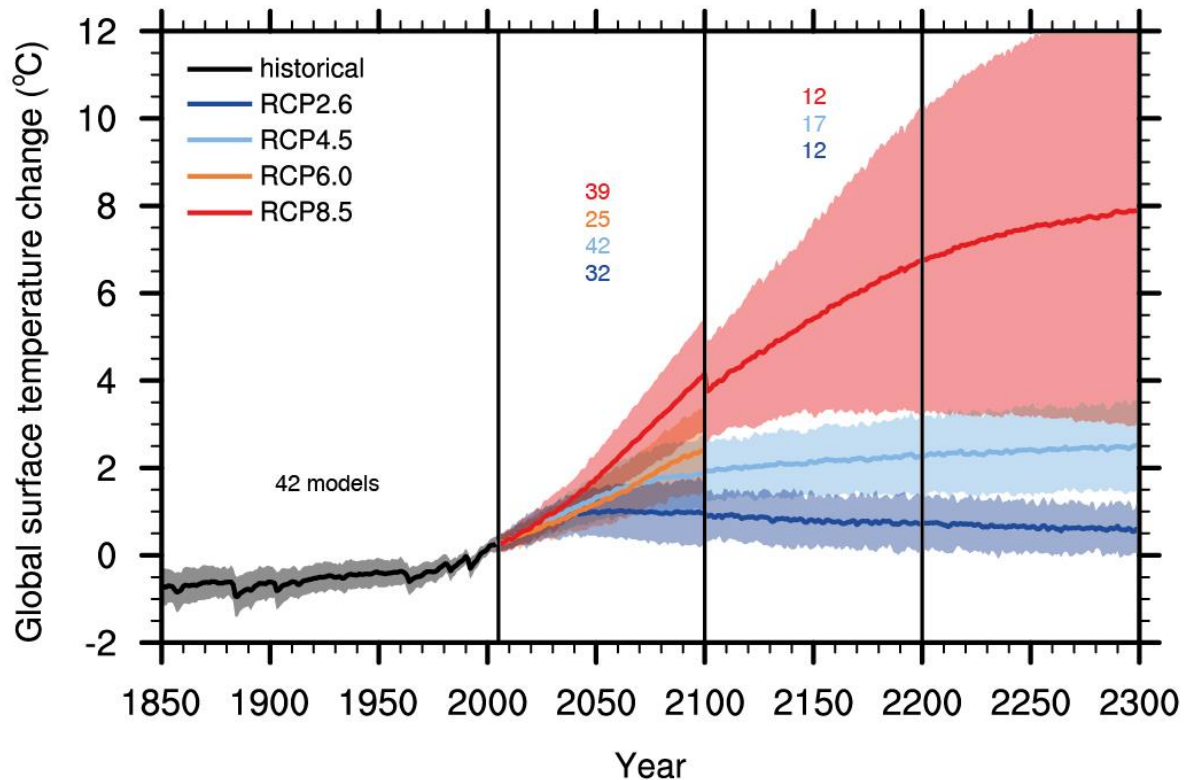


Figure 9: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and the 5 to 95% range across the distribution of individual models (shading). Numbers show number of models for each interval (IPCC AR5 WG1 12.5).

The four RCPs are named for the equivalent increase in atmospheric forcing in Watts/m^2 by the year 2100. RCP 8.5 (i.e., 8.5 W/m^2 above pre-industrial) is the “business as usual” scenario – it projects increasing emissions along the lines of historic emissions growth, and predicts average temperatures will rise 4.0°C – 6.1°C above preindustrial by 2100, and then continue rising. RCP 6.0 projects climate stabilization at 2.6°C – 3.7°C after 2100 with CO_2 concentrations of about 850 ppm. RCP 4.5 would result in climate stabilization between 2.0°C and 3.0°C around 650 ppm after 2100. Only RCP 2.6 is likely to stabilize the climate below 2.0°C ; it projects a decline in CO_2 concentrations from a peak of 490 ppm (Rogelj et al, 2012). Notably, all 3 of the lower scenarios require significant deployment of technologies that are not yet commercially available, such as carbon capture and storage (CCS), in addition to strong mitigation policies and reductions in population growth. RCP 2.6 relies heavily on carbon dioxide removal from the atmosphere through bioenergy-CCS (van Vuuren 2011). Over the past decade, the cumulative radiative forcing caused by anthropogenic greenhouse gas emissions, now totaling almost 3 W/m^2 , increased at a rate of $\sim 1.5\%/ \text{year}$ (Butler and Montzka, 2015). For more on RCPs, see Wayne, 2013.

Greenhouse Gas Emissions by Economic Sectors

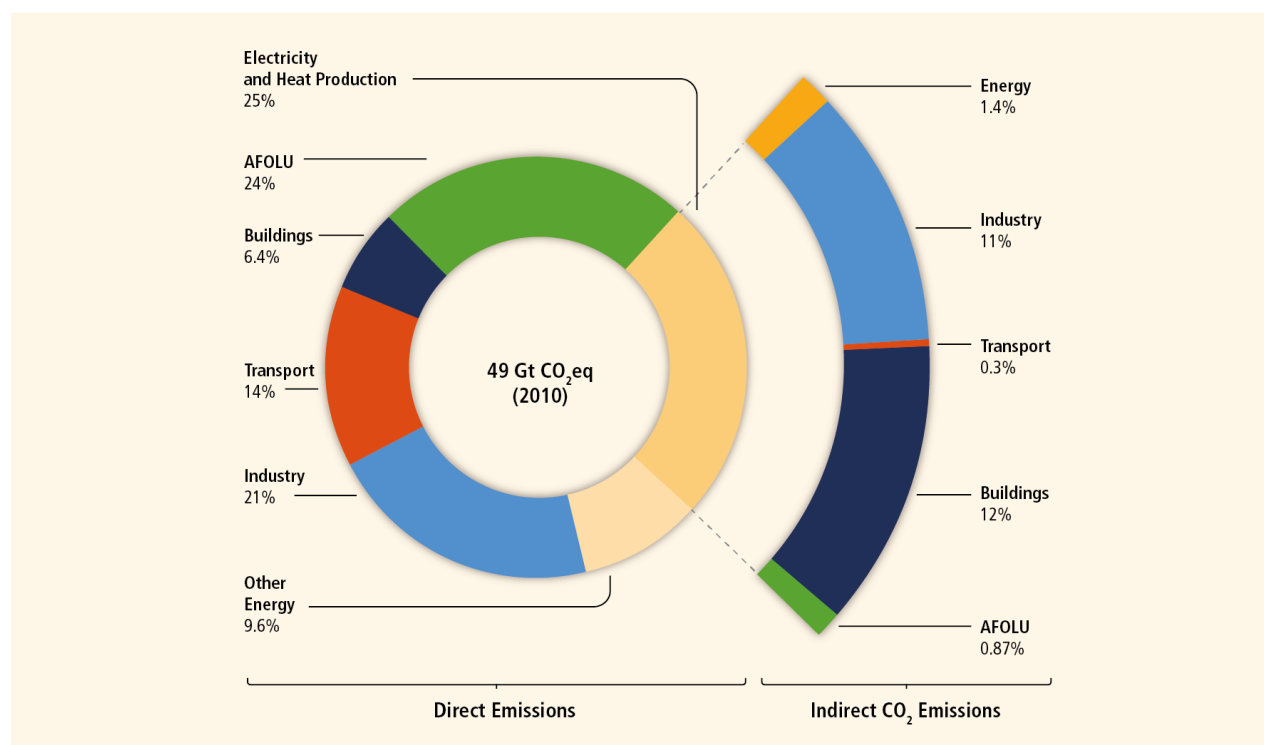


Figure 10: Total anthropogenic GHG emissions in 2010. Pull-out shows how indirect CO₂ emission shares (in % of total anthropogenic GHG emissions) from electricity and heat production are attributed to sectors of final energy use. Agriculture, Forestry and Other Land Use (AFOLU) includes land-based CO₂ emissions from forest fires, peat fires and peat decay. AR 5 WG 3 SPM.2.

10. Anthropogenic versus biogenic carbon

Carbon naturally circulates between the atmosphere, the ocean, and the terrestrial biosphere (living matter). Humans have altered the carbon cycle primarily through deforestation (which releases terrestrial carbon to the atmosphere), soil degradation (which releases carbon to aquatic environments and the atmosphere) and burning fossil fuels (which adds additional carbon to the cycle) (IPCC AR5 WG1 6.3.1). These disturbances are relatively small compared to the natural annual fluxes but still sufficient to trigger large changes in atmospheric and oceanic chemistry and the climate.

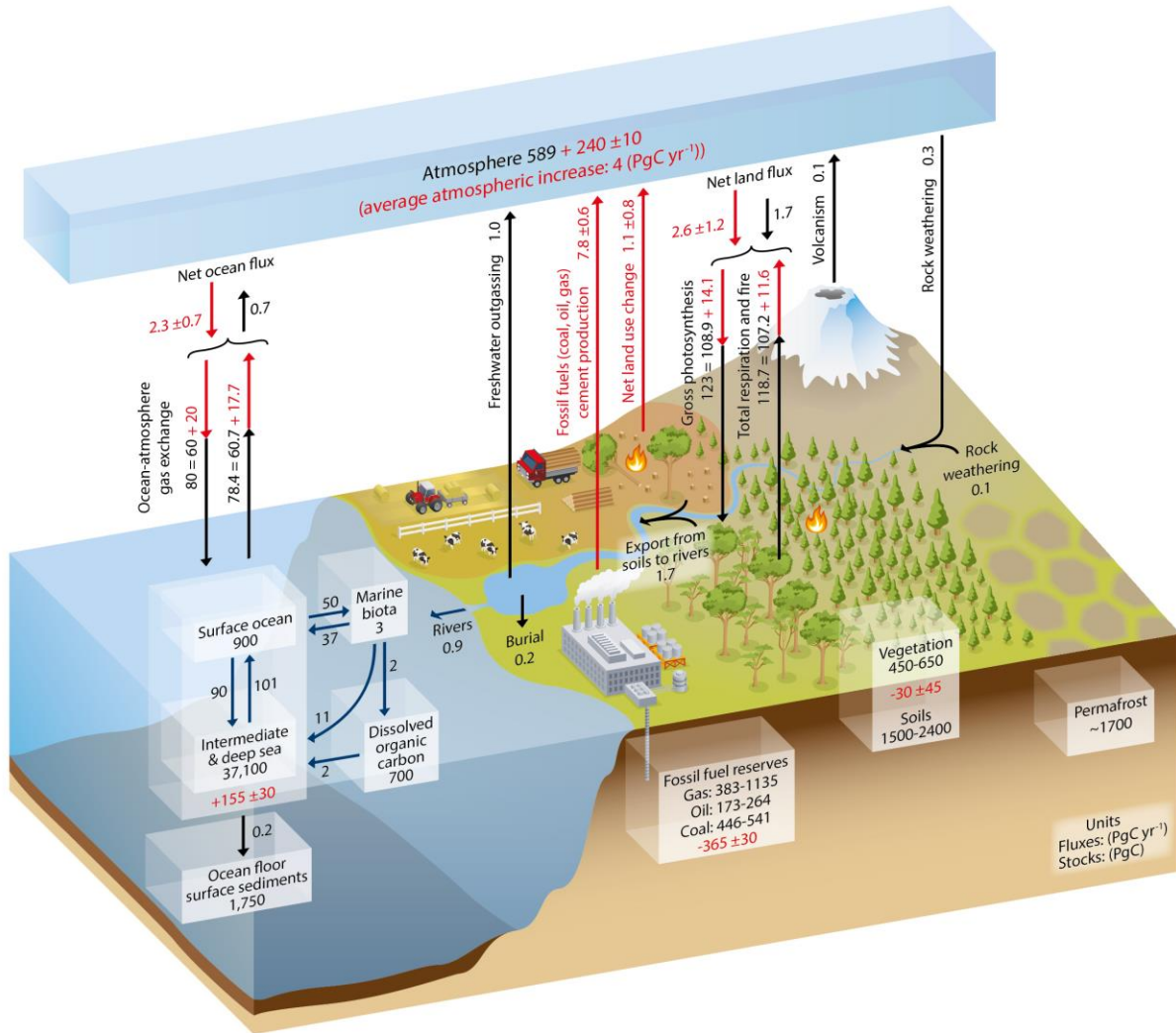


Figure 11: Simplified schematic of the global carbon cycle. Numbers represent reservoir mass, also called ‘carbon stocks’ in PgC and annual carbon exchange fluxes (in PgC/yr). Black numbers and arrows indicate reservoir mass and exchange fluxes estimated for the time prior to the Industrial Era, about 1750. Red arrows and numbers indicate annual ‘anthropogenic’ fluxes averaged over the 2000–2009 time period. These fluxes are a perturbation of the carbon cycle during Industrial Era post 1750. Red numbers in the reservoirs denote cumulative changes of anthropogenic carbon over the Industrial Period 1750–2011. By convention, a positive cumulative change means that a reservoir has gained carbon since 1750. IPCC AR5 WG1 6.1.

Some argue that the release of carbon from biomass, such as wood and crops, is climate neutral because the natural carbon cycle will absorb this carbon (American Forest & Paper Association). However, the biotic uptake of CO₂ from the atmosphere does not necessarily increase to compensate for these human-induced emissions. Also, these human activities can induce other changes in the landscape that trigger a net release of CO₂ to the atmosphere. Whether burning biomass instead of fossil fuels increases or decreases atmospheric CO₂ depends on a host of factors, including the type of biomass, the impact of harvesting, the alternative source of energy,

and the alternative fate of the biomass. Nevertheless, the notion that biomass emissions are inherently carbon neutral still forms the basis of some policy decisions (Searchinger et al., 2009; Aneja et al., 2015).

Be careful with the terms “anthropogenic” (human-origin) and “biogenic” (from living matter); they are not synonyms for “fossil” and “natural” carbon, and are often used inconsistently.

11. 2°C warming does not ensure safety.

Much of the discussion around climate change emphasizes future consequences; however, costly impacts have already begun to accumulate with an average global average temperature rise of only ~0.85 C above the preindustrial temperature baseline. In the U.S. for example, climate change contributed to the devastating floods caused by Superstorm Sandy through sea-level rise (Woodruff et al., 2013), and it has intensified the impacts of California’s ongoing drought (Williams et al., 2015). At a global scale anthropogenic climate change has negatively impacted water resources, food production, glaciers, sea ice, human health, as well as freshwater, terrestrial, and marine species (most notably coral reefs). Continued global temperature increases will further exacerbate the severity of such impacts, even if society succeeds in limiting warming to the 2°C threshold established in the [Cancun Agreements](#) and [Copenhagen Accord](#).⁵

The designation of 2°C of warming as a threshold – beyond which anthropogenic interference should be considered dangerous – originates from policy prescriptions rather than scientific ones (Randalls, 2010). Increasing evidence of risk from 2°C warming has spurred calls to lower the target. For example, the Alliance of Small Island States (AOSIS), noting the destructive impacts suffered by small island states already taking place with less than 1°C of warming, recognize a temperature increase beyond 1.5°C as an existential threat (Tschakert, 2015). The UNFCCC’s expert body has identified the 1.5°C target as a guardrail needed to shield against the uncertain impacts of 2°C warming on food production and threatened systems such as coral reefs and glaciers (UNFCCC 2015).

⁵ For a cogent and accessible – although nonscientific – discussion of the impacts of 2°C of warming on human well-being, see *Overheated: The Human Cost of Climate Change* by Andrew Guzman. For the most comprehensive summary of climate change impacts and related vulnerability, see the [IPCC AR5 WG2 Summary for Policymakers](#).

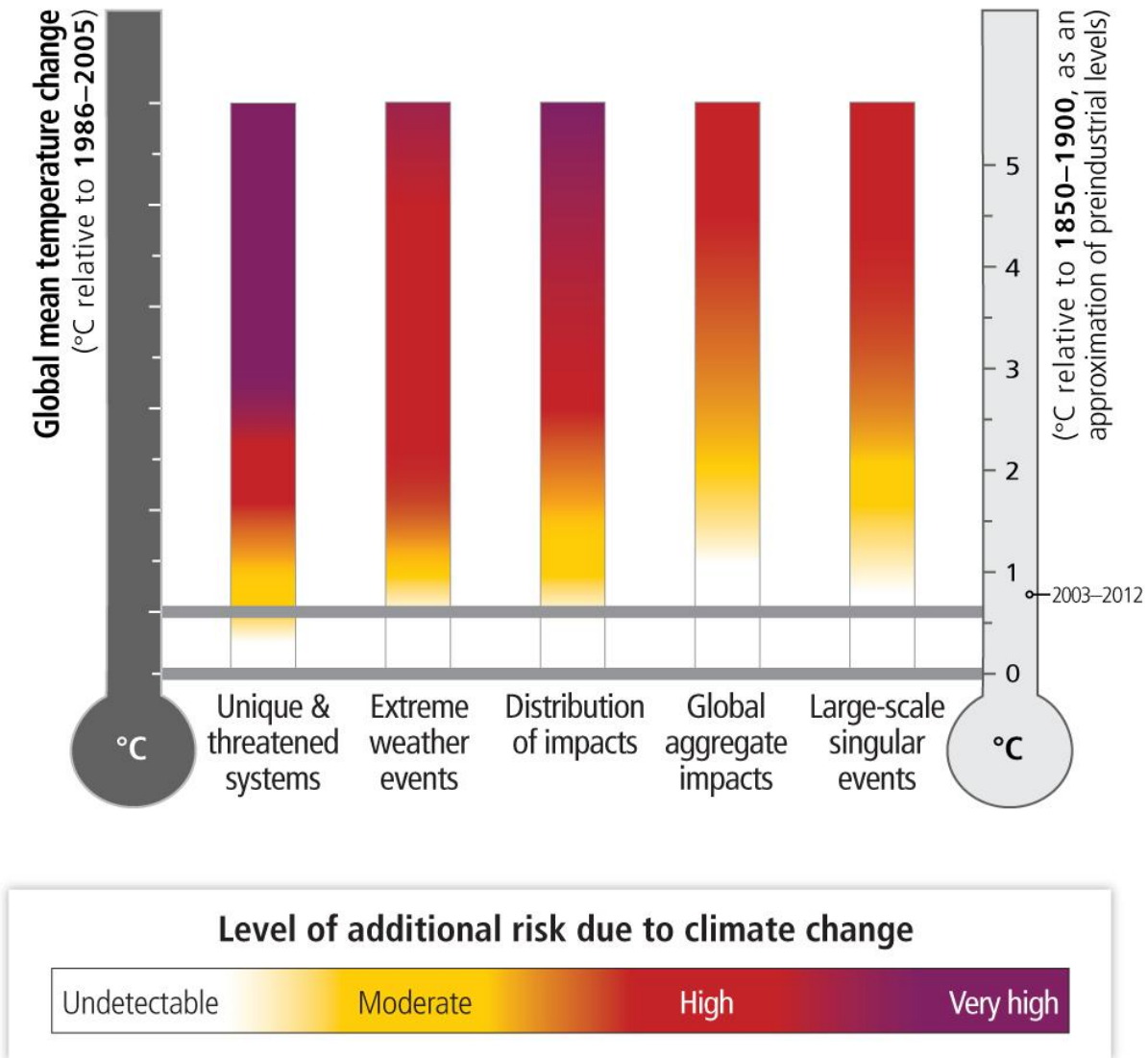


Figure 12: A global perspective on climate-related risks. Risks associated with reasons for concern for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. IPCC AR5 WG2 TS Box 5.

The current, business-as-usual GHG emissions trajectory (RCP 8.5) places society on a path toward 4°C of warming within this century. With a global temperature increase of 4°C, the effects of heat waves, drought, floods, and sea level rise on human systems (e.g. food production) and ecosystems (e.g. coral reefs, forest ecosystems) would be catastrophic and in some cases effectively irreversible.⁶ Although knowledge of a 4°C world remains imprecise, to quote British climatologist Kevin Anderson, “It is fair to say, based on many (and ongoing) discussions with climate change colleagues, that there is a widespread view that a 4°C future is

⁶ For a thorough discuss of the consequences of a 4°C world, see the World Bank’s 2013 report entitled [Turn down the heat: climate extremes, regional impacts, and the case for resilience](#).

incompatible with any reasonable characterisation of an organised, equitable and civilised global community (Anderson, 2012).”

The impact of climate change on human populations is heavily mediated by pre-existing social and economic problems, including poverty, racism, sexism, overpopulation, resource scarcity, and conflict, among others. Inequitable social, economic, and political systems result in particularly severe and disproportionate impacts on those with the least capacity for mobility, resilience and adaptation. Recent reports by the World Bank and the IPCC, cited above, as well as recent religious declarations on climate change, ([Laudato Si'](#), [Islamic Declaration on Global Climate Change](#)), emphasize the particular vulnerability of the poor and marginalized to the impacts of climate change.

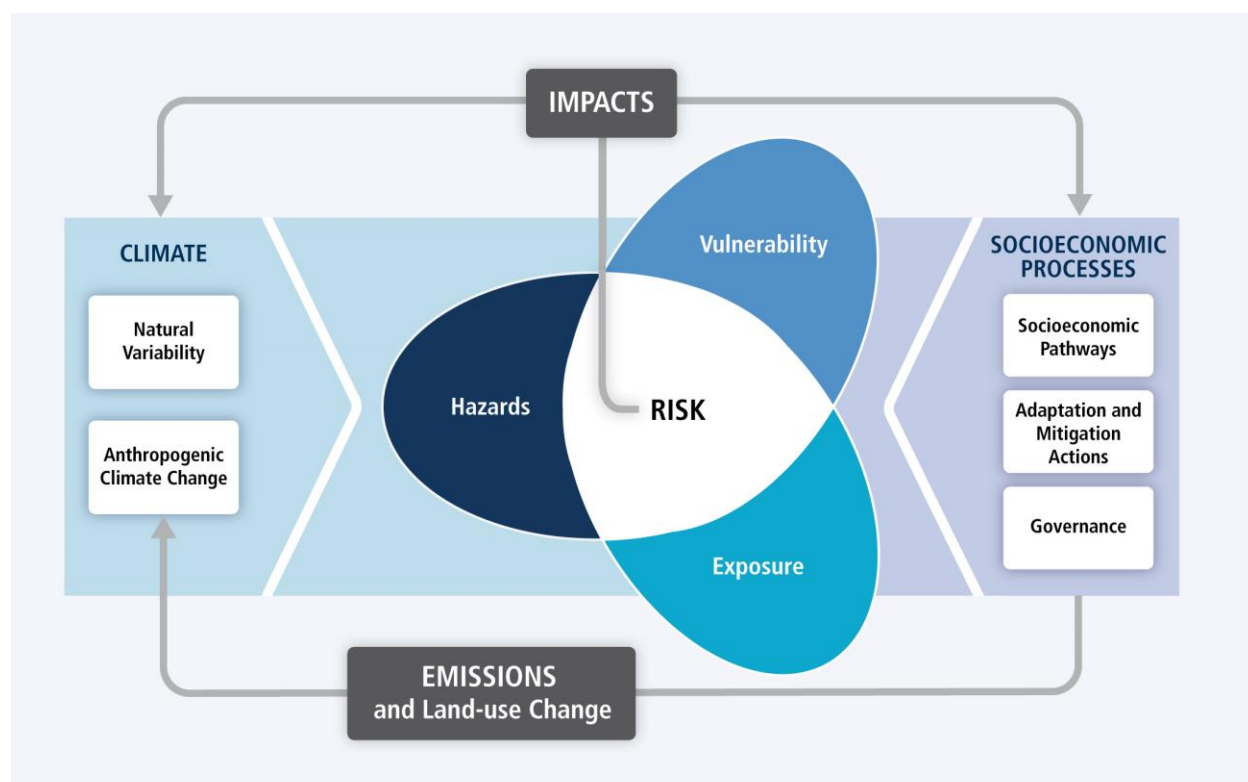


Figure 13: Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability.

12. Event Attribution

Policy-makers, the media, and the general public frequently want to know if a single event, such as a hurricane, flood, wildfire, or drought, is caused by climate change. The scientific community has several types of answers to such questions. One is that, because a change in climate is a change in averages over time, a more appropriate question is whether the frequency

or intensity of such events in the given region is changing over time, rather than whether a single event is due to climate change.

A second tack is to use statistical analyses to detect the signal of anthropogenic climate change in a given event. In other words, the goal is to determine the extent to which a specific event is consistent with anticipated climate change and anomalous in a world without climate change. Here is what the IPCC has to say about attribution:

Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence. As noted in the SAR (IPCC, 1996) and the TAR (IPCC, 2001), unequivocal attribution would require controlled experimentation with the climate system. Since that is not possible, in practice attribution of anthropogenic climate change is understood to mean demonstration that a detected change is ‘consistent with the estimated responses to the given combination of anthropogenic and natural forcing’ and ‘not consistent with alternative, physically plausible explanations of recent climate change that exclude important elements of the given combination of forcings. (IPCC, 2007).

For example, the extreme heat-wave in Europe in 2003 was extremely unusual (5 standard deviations from average) – in other words, very unlikely in a world without warming (Schär et al., 2004). However, such an event is consistent with the anticipated impacts of combined anthropogenic and natural climate forcings. Increasingly, many events are analyzed with such approaches to “attribute” the event to anthropogenic climate change.

A third approach is to ask how climate change impacted the magnitude of an event rather than its occurrence (Trenberth et al., 2015). A warmer atmosphere holds more moisture, exacerbating extreme rainfall events; higher land temperatures intensify drought by drying out the soil; and sea level rise means storm surges are higher than they would have been absent anthropogenic warming.

It may eventually be possible to trace extreme events back to conditions which are unequivocally due to climate change, but so far this is rare (Trenberth et al., 2015).

References

- _____, Islamic Declaration on Global Climate Change, available at:
<http://islamicclimatedeclaration.org/islamic-declaration-on-global-climate-change/>
- Adams, S., et al. 2013. *Turn down the heat: climate extremes, regional impacts, and the case for resilience* Washington DC; World Bank.
- American Forest and Paper Association, n.d. Carbon Neutrality of Biomass, accessed 15 September 2015 at <http://www.afandpa.org/issues/carbon-neutrality-of-biomass>
- Anderson, K. (2012) Climate Change Going Beyond Dangerous—Brutal Numbers and Tenuous Hope, *Development Dialogue*, 61: 16-40.
- Aneja, V., et al. (2015) Letter to Gina McCarthy, Administrator, US Environmental Protection Agency. Available at:
caryinstitute.org/sites/default/files/public/downloads/2015_itr_carbon_biomass.pdf
- Barnola, J.-M., D. Raynaud, C. Lorius, and N.I. Barkov. 2003. Historical CO₂ record from the Vostok ice core. In *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.
- Blasing, 2014. Recent Greenhouse Gas Concentrations, Carbon Dioxide Information Analysis Center <cdiac.ornl.gov/pns/current_ghg.html> DOI: 10.3334/CDIAC/atg.032
- Butler, J., and Montzka, S. (2015) The NOAA Annual Greenhouse Gas Index (AGGI).
<http://www.esrl.noaa.gov/gmd/aggi/aggi.html>
- Carbon Dioxide Information Analysis Center: <http://cdiac.ornl.gov/pns/convert.html#3>
- Chapin et al., (2014). Letter to John Holdren, Gina McCarthy, Michael Boots, Ernest Moniz and Dan Utech, Re: Recommendation to accurately account for warming effects of methane. Accessed 1 September 2015 at:
http://www.biologicaldiversity.org/programs/climate_law_institute/global_warming_what_how_why/methane/pdfs/Scientist_letter_re_methane_GWP_7-29-14.pdf
- Diffenbaugh, N. S., & Scherer, M. (2011). Observational and model evidence of global emergence of permanent, unprecedented heat in the 20(th) and 21(st) centuries. *Climatic Change*, 107(3-4), 615–624. doi:10.1007/s10584-011-0112-y
- Eco-cycle. (n.d.). Beyond Kyoto: Why Climate Policy Needs to Adopt the 20-year Impact of Methane <https://www.ecocycle.org/files/pdfs/methane20yearimpactecocycle.pdf>
- Dansgaard, Willi et al. (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364, no. 6434 218-220.
- England, M. H., McGregor, S., Spence, P., Meehl, G. A., Timmermann, A., Cai, W., Santoso, A. (2014). Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, 4(3), 222–227. doi:10.1038/nclimate2106
- Francis. *Laudato Si'*. [Encyclical Letter on Care for our Common Home].
http://w2.vatican.va/content/francesco/en/encyclicals/documents/papa-francesco_20150524_enciclica-laudato-si.html
- Guzman, A. T. (2013). *Overheated: the human cost of climate change*. Oxford University Press.
- Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR)
http://ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1
- Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR)
http://ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1
- Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4)
http://ipcc.ch/publications_and_data/publications_and_data_reports.shtml#1

- Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) <ipcc.ch>
- Le Quéré, C., Takahashi, T., Buitenhuis, E. T., Rödenbeck, C., & Sutherland, S. C. (2010). Impact of climate change and variability on the global oceanic sink of CO₂. *Global Biogeochemical Cycles*, 24(4), 1–10. doi:10.1029/2009GB003599
- Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., ... Zeng, N. (2015). Global carbon budget 2014. *Earth System Science Data*, 7(1), 47–85. doi:10.5194/essd-7-47-2015
- Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schnellhuber, H. J. (2008). Tipping elements in the Earth System. *Proceedings of the National Academy of Sciences*, 105(6), 1786–1793. doi:10.1073/pnas.0911106106
- Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Meir, P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), 20610–20615. doi:10.1073/pnas.0804619106
- Mann, M. E., Zhang, Z., Hughes, M. K., Bradley, R. S., Miller, S. K., Rutherford, S., & Ni, F. (2008). Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences of the United States of America*, 105(36), 13252–13257. doi:10.1073/pnas.0805721105
- Mantua, N. J., & Hare, S. R. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*, 58, 35–44.
- Marshall, J., and Plumb, R. A. (2008). *Atmosphere, Ocean, and Climate Dynamics: An Introductory Text*. Elsevier.
- Mora, C., Frazier, A. G., Longman, R. J., Dacks, R. S., Walton, M. M., Tong, E. J., ... Giambelluca, T. W. (2013). The projected timing of climate departure from recent variability. *Nature*, 502(7470), 183–187. doi:10.1038/nature12540
- Pearce, F. “What Is the Carbon Limit? That Depends Who You Ask.” Environment 360 <http://e360.yale.edu/feature/what-is-the-carbon-limit-that-depends-who-you-ask/2825> November 2014.
- Petit, J.R., D. Raynaud, C. Lorius, J. Jouzel, G. Delaygue, N.I. Barkov, and V.M. Kotlyakov. 2000. Historical isotopic temperature record from the Vostok ice core. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi: 10.3334/CDIAC/cli.006
- Randalls, S. (2010). History of the 2°C climate target. *Wiley Interdisciplinary Reviews: Climate Change*, 1(4), 598–605. doi:10.1002/wcc.62
- Ricke, K. L., & Caldeira, K. (n.d.). Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters*, 9(12), 124002. doi:10.1088/1748-9326/9/12/124002
- Rogelj, J., Meinshausen, M., & Knutti, R. (2012). Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change*, 2(4), 248–253. doi:10.1038/nclimate1385
- Ruddiman, W. F. (2003). The Anthropogenic Greenhouse Era Began Thousands of Years Ago. *Climatic Change*, 61, 261–293. doi:10.1007/s10584-005-7278-0
- Ruddiman, W. F. (2007). The Early Anthropogenic Hypothesis: Challenges and Responses. *Reviews of Geophysics*, 45(4), RG4001. doi:10.1029/2006RG000207

- Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M. A., & Appenzeller, C. (2004). The role of increasing temperature variability in European summer heatwaves. *Nature*, 427(6972), 332–336. doi:10.1038/nature02300
- Scheffer, M. (2010). Foreseeing tipping points. *Nature*, 467, 6–7. doi:10.1038/467411a
- Schuur, E. a. G., McGuire, a. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., ... Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. *Nature*, 520(7546), 171–179. doi:10.1038/nature14338
- Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., ... Tilman, G. D. (2009). Climate change. Fixing a critical climate accounting error. *Science (New York, N.Y.)*, 326(5952), 527–528. doi:10.1126/science.1178797
- Shaw, M. R. (2002). Grassland Responses to Global Environmental Changes Suppressed by Elevated CO₂. *Science*, 298(5600), 1987–1990. doi:10.1126/science.1075312
- Tans, Pieter, and Keeling, Ralph. NOAA/ESRL www.esrl.noaa.gov/gmd/ccgg/trends and Dr. Ralph Keeling, Scripps Institution of Oceanography scrippsco2.ucsd.edu. Accessed August 28, 2015.
- Trenberth, K. E., Fasullo, J. T., & Shepherd, T. G. (2015). Attribution of climate extreme events. *Nature Climate Change*, (June), 6–11. doi:10.1038/nclimate2657
- Tschakert, P. (2015). 1.5° C or 2° C: A conduit's view from the science-policy interface at COP20 in Lima, Peru. *Climate Change Responses*, 2(1), 3.
- UNFCCC Subsidiary Body for Scientific and Technical Advice (2015). Report on the structured expert dialogue on the 2013–2015 review. FCCC/SB/2015/INF.1
- Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, 109(1), 5–31. doi:10.1007/s10584-011-0148-z
- Wayne, G.P. (2013) *The Beginner's Guide to Representative Concentration Pathways*. Skeptical Science.
- Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon, and E. R. Cook (2015), Contribution of anthropogenic warming to California drought during 2012–2014, *Geophys. Res. Lett.*, doi:10.1002/2015GL064924
- Woodruff, Jonathan D., Jennifer L. Irish, and Suzana J. Camargo (2013), Coastal flooding by tropical cyclones and sea-level rise, *Nature* 504.7478: 44-52.