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CLIMATE-SYSTEM TIPPING POINTS AND EXTREME WEATHER EVENTS

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Introduction

The climate system is a most delicate fabric of interwoven planetary components (such as the atmosphere, the oceans, the cryosphere, the soils, and the ecosystems) that interact through intricate physical, chemical, geological and biological processes (such as advection, upwelling, sedimentation, oxidization, photosynthesis, and evapotranspiration). The fascination for that system as an integral part of the nature surrounding us is as old as mankind. However, the scientific understanding of the climate system's make-up and dynamics, as well as the cultural perception of its vulnerability to human interference, are quite young: We eventually become aware of the fact that even slightly pulling one single string might have the potential to tear apart the entire fabric. Anthropogenic global warming, resulting from the industrial burning of gigantic amounts of fossil carbon, is an evident candidate for such a disruptive pull.

Thoroughly understanding the potentially devastating consequences of that warming is the key precondition for effective mitigation and adaptation measures. Unfortunately, scientific progress in the pertinent fields has been slow until fairly recently due to the intellectual challenges posed by the manifold nonlinearities characterizing the climate system. It seems, however, that we are now entering an exciting new research phase that will dramatically deepen and multiply our insights about non-regular climate behavior. So we have an interesting story to tell.

Our article roughly divides the nonlinearities field into two main camps, one embracing *extreme weather* characteristics and the other identifying *critical transitions* of vital Earth System components ("tipping elements"). It is important though to recognize that those camps are not independent. In fact, a number of links exist, some of which will be discussed here. And many more links will be explored before long. What we know for sure already, however, is that Nature and *Homo sapiens* are now entangled in a fateful relationship: The most successful species on Earth has begun to shape that very Earth, although without a master plan or botcher plot so far. Thus we have finally entered the *Anthropocene*, the geological age of humankind, as Paul Crutzen once famously put it (Crutzen 2002). Through innumerable feedback mechanisms, the natural environment will react to human interference which will trigger massive counter-actions by our civilization (perhaps including so-called geoengineering measures), causing new and unforeseeable planetary side effects, and so forth. Whether this interactive dynamics tends to spin out of control or whether it can be directed to some stable equilibrium again, depends crucially on the nonlinearities involved and sketched in the following.

Human culture as we know it emerged through two great transformations, namely the Neolithic and the Industrial Revolution. The former was decisively favored by the exceptionally stable climatic conditions in the Holocene after the end of the last glacial period some 11,000 years ago (Figure 1). The development of agriculture, in turn, laid the foundation for rapid mechanization after 1750 that would not have happened, however, without the fortunate accessibility of fossil resources of exquisite energy density – mined in England first and on all continents later on. The overwhelming historic process of world-wide carbonization, which may be documented as the "c-story of humankind" (Figure 2), resulted not only in large-scale industrialization, but also helped to tap the immense human potential for creativity, discovery and progress for a better living. It appears like a sheer success story at a first glance, and yet it is not an untroubled narrative. For this carbonization of the world led to a multitude of negative externalities (as the economists would call them), not least the potential destabilization of the benign Holocene climate through the significant alteration of atmospheric greenhouse gas levels. As the latest IPCC Assessment Report demonstrates, the global mean surface temperature could rise above pre-industrial values by more than 4°C by 2100 under a business-as-usual scenario (RCP 8.5, Meinshausen *et al.*, 2011). As a consequence, our planet could be pushed into an uncomfortable realm, where many natural and cultural systems would be at risk of heavy stress, if not collapse.

Extreme Weather Events

Many of these risks were recently summarized in a flagship report by the World Bank (Schellnhuber *et al.*, 2012). One of the main findings of that report was that 5σ-weather phenomena – that is, extreme meteorological events (like heat waves) that on average happen only once in about a million years under stationary environmental conditions – will occur practically every year in the tropics or subtropics if the world warms by 4°C. This most challenging scenario is actually foreshadowed already by shifts in extreme-weather regimes as observed in recent decades, largely consistent with the still moderate anthropogenic climate modification enforced so far.

This is epitomized by the world-wide increase in record-breaking monthly-mean temperatures (see, for instance, Figure 3, adapted from Coumou, Robinson, & Rahmstorf, 2013).

Yet the frequency, character and severity of meteorological disasters that struck especially the Northern Hemisphere over the last 20 years cannot be fully explained by the statistical effects associated with unfolding global warming. Thus, the changes observed are not just the direct result of an upward shift of the otherwise unmodified temperature distribution, an effect that already significantly enlarges the extreme-events area under the typical temperature distribution curve. Latest scientific analyses rather indicate that high-impact events, such as the Russian heat wave and the Pakistan deluge in 2010, are related to an insidious transformation of the jet stream system (Figure 4). The most important branch of this Earth-scale westerly wind field meanders in 7-12 km height above the mid-latitudes of the Northern hemisphere and separates cold and temperate air masses (see, for instance, Archer & Caldeira, 2008; Branstator, 2002). Occasionally, huge northward and southward bulges of the jet stream emerge from the underlying non-linear fluid dynamics, the so-called Rossby waves. In general, these waves get straightened out again within a few days, yet they also may get stuck through subtle quasi-resonance mechanisms between traveling and stationary planetary waves (Petoukhov *et al.*, 2013). As a consequence, blocking weather conditions can arise, favoring long-lasting heat waves and droughts or floods resulting from persistent precipitation patterns.

Observational data indicate that the frequency of such weather situations has markedly increased over the last two decades (Coumou *et al.*, 2014; Screen & Simmonds 2014). Moreover, there is theoretical and empirical evidence that the increase is related to the disproportionally strong Arctic warming (especially after the year 2000, see Figure 5) in response to anthropogenic radiative forcing (Francis & Vavrus 2012). For the shrinking temperature difference between the mid latitudes and the high latitudes tends to weaken the Northern jet stream, causing it to split up in two branches confining persistent wind patterns. This is, however, just one of the mechanisms involved in a most intricate wave dynamics (Petoukhov *et al.*, 2013; Palmer 2013).

Tipping Elements in the Climate System

The jet stream system itself can be perceived as one of the above-mentioned tipping elements within the Earth's climate system (Lenton *et al.*, 2008). They form a collection of crucial circulation patterns, geophysical processes, cryospheric entities, and large-scale ecosystems that may be pushed into different modes of operation by massive human perturbation. The link between planetary waves and persistent extreme weather conditions, as sketched above, therefore illustrates how the anthropogenic switching of a defining component of the global environmental make-up trickles through the fabric of entangled climate processes down to the domain of our everyday experience. As indicated above as well, different tipping elements, like the Arctic sea ice and the Northern jet stream, seem to be intimately coupled via the anomalous decrease of wintertime sea-ice extension and the resulting shift in wind patterns (see, for instance, Petoukhov & Semenov, 2010, Francis & Vavrus, 2012). Identifying and quantifying those interactions belongs to the most exciting research challenges of this decade.

El Niño-Southern Oscillation (ENSO)

One of the most important tipping elements is the El Niño phenomenon, which is in turn the most conspicuous part of the so-called El Niño-Southern Oscillation (ENSO) pattern, a natural atmosphere-ocean seesaw dynamics in the tropical Pacific. The former can last for many months and sets in when trade winds that usually push higher-temperature upper-layer waters towards the west (into the "Pacific warm pool") break down. Once the heated water is allowed to slosh back to the east, it gives rise to an anomalous ocean warming off the West coast of South America. Since this tends to happen around Christmas, Peruvian fishermen named the event after the infant Jesus. Note that El Niño is so persistent because atmospheric and oceanic processes conspire, under certain conditions, to bring about a self-amplifying pattern of air pressure systems and sea temperature domains. As a rule, "La Niña", the cold sister of El Niño, starts to reign once that pattern collapses through stochastic mechanisms.

El Niño can trouble weather behavior around the globe and may wreak havoc in most distant regions. In the late 19th century, droughts and monsoon failures, floods and epidemic diseases like malaria, bubonic plague, dysentery, smallpox and cholera accompanied marked clusters of El Niño and opposing La Niña events, although an exclusive causal attribution is very hard to establish in this context. In the course of those tragic events, around 30-50 million premature deaths were counted in India, China and Brazil (Davis 2001, and Figure 6). The inhumane practices of late colonial exploitation aggravated the disaster, creating even more opportunities for grabbing territories from the "inferior peoples in the South" and for cementing the political rule of the North.

Due to its dominating role in natural climate variability, the ENSO pattern is subject of many topical studies. A recent paper has argued that extreme El Niño episodes will become more frequent with unabated global warming (Cai *et al.*, 2014). In order to avoid the worst negative impacts of such events, for instance on agriculture, fisheries, public health and tourism, early prediction through advanced scientific methods plays a key role. Until recently however, reliable forecasts became available only about 6 months before the onset of an El Niño which is often insufficient for effective preparedness and resilience measures. A novel prediction method (Ludescher *et al.*, 2013, 2014), relying on a network analysis of teleconnections (links) between site temperatures in the El Niño basin and the rest of the Pacific, allows to forecast those events at least one year ahead with a 3-in-4 probability (Figure 7). Thorough data evaluation with powerful complex-systems methods suggests that a cooperativity transition tends to happen as a precursor/trigger phenomenon of the East Pacific warming anomaly. This very approach has projected a 2014 El Niño appearance as early as 17 September 2013 (see again Figure 7).

Excursus: A Commitment to Global Change

The extremely long lifetime of anthropogenic CO_2 in the atmosphere – a significant fraction remains airborne for a thousand years or longer (see, for instance, Archer & Brovkin, 2008) – makes it important to assess slow climatic changes as well. These might not be easily discernible for laypeople (or even experts), yet they will strongly affect human civilization in the longer term. Due to their insidiousness such processes within the Earth system pose very specific risks. In the following, we sketch a few of those "slow threats".

Even if, in the year 2300, anthropogenic greenhouse gas emissions finally drop back to zero after a business-as-usual path with 4°C global warming by the end of this century (RCP 8.5), CO_2 will only very slowly disappear from the atmosphere. As a result, temperatures will fall only by 1 to 2°C during this millennium (Zickfeld *et al.*, 2013). In that scenario, thermal expansion of the ocean waters *alone* will cause a sea-level rise of 1.6 meters until the year 3000 and still continue. As an early response to anthropogenic radiative forcing, sea level has already been elevated by about 0.2 m since the beginning of the 20th century (mostly due to thermal expansion so far), and the rise is likely to accelerate (IPCC WG1 2013). In the longer term, over the course of 2000 years or so, the major contribution will stem from ice sheet melting on Greenland and Antarctica (see below). Using both computer simulations and sediment data, one can expect sea level rises by at least 2 meters per degree of warming (Levermann *et al.*, 2013). This illustrates that past and current human interference with the climate system represents a severe commitment to global change that can hardly been undone.

Delicate Giants at the Poles

Among the most precarious tipping elements are therefore the huge ice sheets on Greenland and Antarctica, which may start to disappear in an irreversible manner once certain critical thresholds ("tipping points") with respect to key environmental parameters are transgressed. Although this disappearance is expected to happen on timescales of hundreds to probably thousands of years, red lines may soon be reached or even have been crossed already.

For the Northern ice sheet on Greenland, the most determinant parameter is the surface temperature, which, in contrast to most of Antarctica, is high enough to instigate melting. In Greenland, the melt water can reach the base of the ice through huge moulins and lubricate the sediment upon which the ice sheet is moving. This effect enhances the speed of the ice streaming towards the ocean, where it can be affected by warmer water temperatures too. Surface melting also reduces the reflectivity of the ice, leading to further warming through increased absorption of solar radiation. Yet the quintessential mechanism which introduces a strongly nonlinear – and possibly irreversible – decay of the ice sheet is the surface-mass balance-height feedback: Even if, in the long term, global temperatures drop back below a threshold that initiated that nonlinear process, the reduced elevation of the ice surface is now exposed to milder temperatures and therefore still favors melting and possibly prohibits regrowth. A strong scientific underpinning of the political 2°C guardrail was associated with the idea to prevent the climate system to cross pertinent tipping points. Unfortunately, recent research suggests that the critical threshold for the subsistence of the Greenland ice sheet might be as low as 1.6°C global surface warming (Robinson *et al.*, 2012; Ridley *et al.*, 2010).

The Antarctic ice sheet, on the other hand, is especially susceptible to a particular environmental parameter: Since a large fraction of the ice is flowing into the ocean forming huge floating ice shelves, the sheet can be degraded from the lateral margins by rising water temperatures. As the ice shelves are weakened, either by melting from below or disintegration due to melt ponds at the surface and successive crack formation, they lose their ability to hold back the kilometer-thick ice further inland. For instance, the disintegration of the Larsen B ice shelf in 2002 over the course of only two months increased the speed of the glaciers feeding it by factors ranging from 2 to 8 (Rignot *et al.*, 2004; Scambos *et al.*, 2004; Rott *et al.*, 2011).

This tangle of processes can lead to a self-sustained ice loss if certain topographical conditions are fulfilled (Figure 8): If the ice rests on bedrock below sea-level and the bed is deeper towards the center of the ice sheet, the ice flow increases as the ice retreats, leading to even further retreat ("Marine Ice Sheet Instability", known as MISI; for a review regarding West Antarctica, see, e.g., Joughin & Alley 2011). These topographical conditions are typical for the West Antarctic ice sheet (Figure 9) which holds enough ice to raise global mean sea level by 3.3 meters (Bamber *et al.*, 2009). The most recent research (Joughin, Smith & Medley 2014; Mouginot, Rignot, & Scheuchl 2014) implies that a tipping threshold towards such an unhalted retreat might already have been crossed in West Antarctica. Even parts of the East Antarctic ice sheet – so far believed to be utterly stable – might "tip", once a critical ice plug near the coast melts away and thereby "uncorks" the basin upstream which would lead to additional 3-4 meters of global sea-level rise (Mengel & Levermann 2014).

Sea-level rise is especially critical in the tropics and sub-tropics (see Schellnhuber *et al.*, 2012) for several reasons. On the one hand, the ocean waters there will soar by up to 20% more than in the global mean. This is to a large extent due to a basic physics effect: Massive loss of ice near the poles reduces the regional gravitational pulling power on the surrounding ocean water, releasing lots of near-by waters for distribution at lower latitudes. On the other hand, because of high population densities and often inadequate urban planning, coastal cities in developing countries are particularly vulnerable to sea-level rise in concert with other impacts of climate change. This was demonstrated in a most woeful way by typhoon Haiyan when it struck the Philippines in November 2013 (Vidal & Carrington 2013).

Sustainability as a Joint Venture of Humanity and Nature

The central theme of the PAS-PASS workshop, "Sustainable Humanity, Sustainable Nature", ultimately raises the question whether there is such a thing as a "global tipping point" (Figure 10). There have been recent studies and speculations (Shakhova *et al.*, 2013; Rothman *et al.*, 2014; Whiteman *et al.*, 2013; van Huissteden *et al.*, 2011; Walter Anthony *et al.*, 2012) on thawing-emissions feedback processes involving the continental permafrost areas (especially in Siberia and boreal America) and the ocean shelves, where immense amounts of the strong greenhouse gas methane have been assembled and locked up for millions of years by physicochemical processes. Depending on the specifics of those processes, significant parts of the soil and sediment methane could be remobilized or converted, resulting in major releases of greenhouse gases in addition to the direct anthropogenic emissions (Schneider von Deimling *et al.*, 2012; Lenton 2012). In the very worst case, such a dynamics could conspire with other feedback mechanisms (like, e.g., tropical forest die-back) to bring about something that might qualify as an outright or partial "run-away greenhouse effect". The scientific evidence for that scenario is very shaky, yet this is a research frontier that urgently needs to be advanced over the next years. Even the persistence, after due scrutinization, of a, say, 2%-probability for a global tipping series of events triggered by human interference with nature should not be acceptable, since the losses risked would be beyond any measure.

From the natural science perspective, there are many *thinkable* (not necessarily *likely*) scenarios, where cascades of large-scale nonlinear events are triggered by the tipping of one crucial climate system element. This could eventually activate other tipping elements that are linked to the first one through causal relationships in space and time. The disintegration of an ice shelf followed by the collapse of the mother ice sheet, as explained above, is just one example in this context. That process might significantly affect the thermohaline circulation in the oceans (Rahmstorf 2002; Clark *et al.*, 1999; Marcott & Clark 2011; Clark *et al.*, 2002; Hu *et al.*, 2009) which could, in turn, change regional climate conditions and thus act back onto ice shelves elsewhere or heavily modify the subsistence conditions for marine ecosystems (Kuhlbrodt *et al.*, 2009).

From the social perspective, we would like to frame the argumentation with a "sustainable development cartoon" (Figure 11), recently introduced by the German Advisory Council on Global Change (WBGU 2014). This cartoon tries to visualize a complex narrative in a very simple way. Traditional development dynamics in line with a dull continuation of the "c-story of humanity" (see Figure 2) are contrasted with an alternative pathway guided by the overarching "Sustainable Development Goal" (SDG) of "safeguarding Earth system services". This goal is designed to protect the natural foundations of human progress while fostering poverty eradication and social cohesion across our planet. For the sake of illustration, our cartoon unfolds in mobility-emissions space, epitomizing the modern relationship between economic demands (such as moving people and goods in space) and environmental externalities (such as releasing heat-trapping exhaust gases). All data indicate that the relationship considered is strong indeed. However, we could as well tell our story in a space spanned by the two variables "meat consumption" and "soil erosion".

We depict the world population in this chart by a cloud of coins, each representing 100 million individuals. The coin material (gold, silver, copper) provides a (highly nonlinear) wealth metric. The current situation (A_0 and B_0, respectively, in Figure 11) is characterized by a grossly disparate distribution of wealth/income, where the richest people (in practically any country!) also cause the highest per-capita greenhouse gas emissions. The conventional paradigm, dominating the development economics discourse since the 1950s, aims at simply shifting this rather stretched cloud in a diagonal way by pumping even more fossil fuels into the global industrial metabolism: The rich will become disproportionally richer by this, but even the extreme poor will eventually benefit and get access to basic services such as mobility. So the theory goes, at least.

Even if this theory were intrinsically correct (in spite of mounting evidence against it; see the contribution of J. Stiglitz in this report), it would pathetically neglect the negative externalities accompanying climate change: When greenhouse gas emissions go through the roof in such a brute-force development scenario, dangerous global warming cannot be avoided anymore. In view of the 2°C guardrail and the associated finite carbon budget available for global civilization (WBGU 2009), the average per-capita & per-annum emissions allowance over the next fifty years is around 2-3 tons CO_2 eq. Our cartoon reflects the evident point that the diagonal upward stretching of the human cloud pushes the majority of the global population far into the non-sustainable realm (A_1). As a result, the entire situation becomes highly unstable and prone to "socioeconomic tipping events", as especially the poor have no means to cope with the dire impacts of climate change resulting from ever-rising greenhouse-gas emissions. Disparities grow further and further; eventually, the entire overstretched social fabric may come apart, as sketched in the cartoon (A_2).

There is an alternative to this gamble with nature and humanity though, as outlined in the right-hand part of Figure 11. In this scenario, the rich do not lead the global population into the non-sustainable domain beyond the 2-3 tons line, but are the first to *bend back* from greenhouse gas emissions (associated with mobility in our example)! In other words, the affluent become those change agents who ensure that the global population aims at respecting the climate guardrail on average (B_1). The reasons for such a "division of labor for sustainability" are compelling, since the rich (i) contribute by far the most to climate destabilization up to now, and (ii) have all the means to adopt lifestyles (e.g., working at home office) and technologies (e.g., electric cars) which are better for the environment. That avant-garde move should enable the less affluent to gain leeway in order to develop towards a better living standard in due course. This means that while leapfrogging unsustainable energy schemes is an option, in principle, for every society and every individual anywhere, *the responsibility for clean development is not with the poor, but with the wealthy*.

Note that humankind literally comes around in the final stage of our sustainability cartoon (B_2), where some of the more affluent people even pioneer negative-emissions mobility (using biofuels produced with carbon capture & sequestration techniques, for instance). In consequence, disparities get reduced rather than increased. Social stretching and potential rupture is not only avoided but reversed, and world society is closing ranks within a safe operating space (Rockström *et al.*, 2009).

Let us end by emphasizing that great transformational changes lie ahead of us in either case – whether we choose to pursue "business as usual" as long as possible or to adopt "sustainable development" as soon as necessary. "Don't think that nothing happens, if nothing happens!", as the German Chancellor Angela Merkel put it recently (paraphrased from the WBGU-Symposium 2012). Humankind is currently distorting the fabric of the climate system without fully understanding its making, thereby risking to sever critical links and to cause major discontinuities and disruptions. Research, science and education will play a decisive role in making the right choice, not least by providing robust evidence about the risks *and* the opportunities involved. In particular, the knowledge enterprise can outline powerful solutions and strategies for reconciling nature and humanity. This will require, however, to also transform our thinking about the world: "Problems cannot be solved with the same mindset that created them" (Albert Einstein).

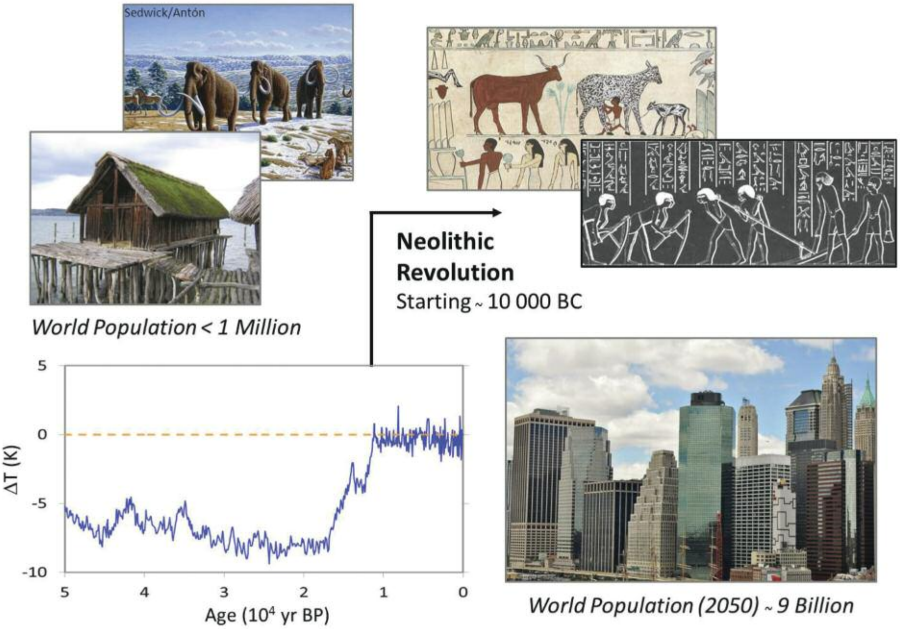


Figure 1: The Neolithic Revolution in the Holocene. With the onset of the stable climate of the Holocene some 12 000 years ago, small groups of human hunters and gatherers wandering the continents were given the opportunity to settle down. They practiced agriculture and domestication of plants and animals, but also transformed their societies into a more efficient system based on division of labor and trading. This change in life style allowed for the world population to eventually surpass the small number of less than a million individuals. The next major transformation was to ignite in the mid-18th century in Britain (Figure 2).

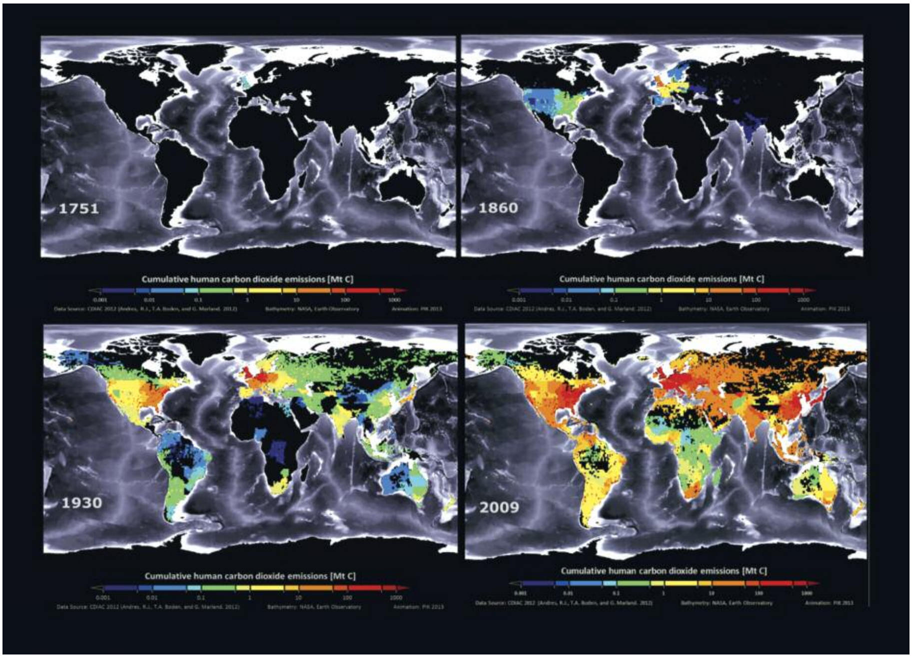


Figure 2: The "C-Story of Humankind": Cumulative Human Carbon Dioxide Emissions since the Industrial Revolution. Income, population density and cumulative emissions of carbon dioxide have undergone a remarkably parallel development since the industrial revolution, which originated in the textile industry of Lancashire, England, around 1760 and initiated the use of coal for manufacturing processes. The transformation of first the production and subsequently the transportation sector to a carbon-based economy initially spread to Western Europe and the United States. Later, around the beginning of the 20th century, the cumulative emissions of Co$_2$ become also significant for the overseas colonies and China. The current situation reflects the foundation of modern living on fossil carbon around the globe. For an animated version please refer to the web link in the bibliography (PIK 2013).

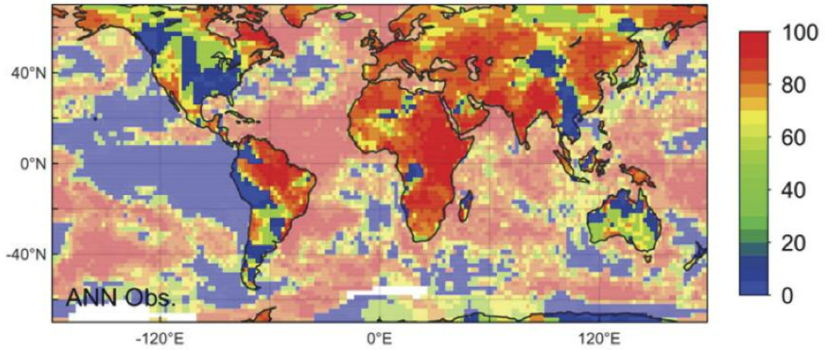


Figure 3: Heat Records due to Climate Change. Record-breaking monthly mean temperatures occur more often than could be expected from natural variability. The probability that such events in the last decade are due to climate change is about 80% in the global average (Coumou *et al*., 2013).

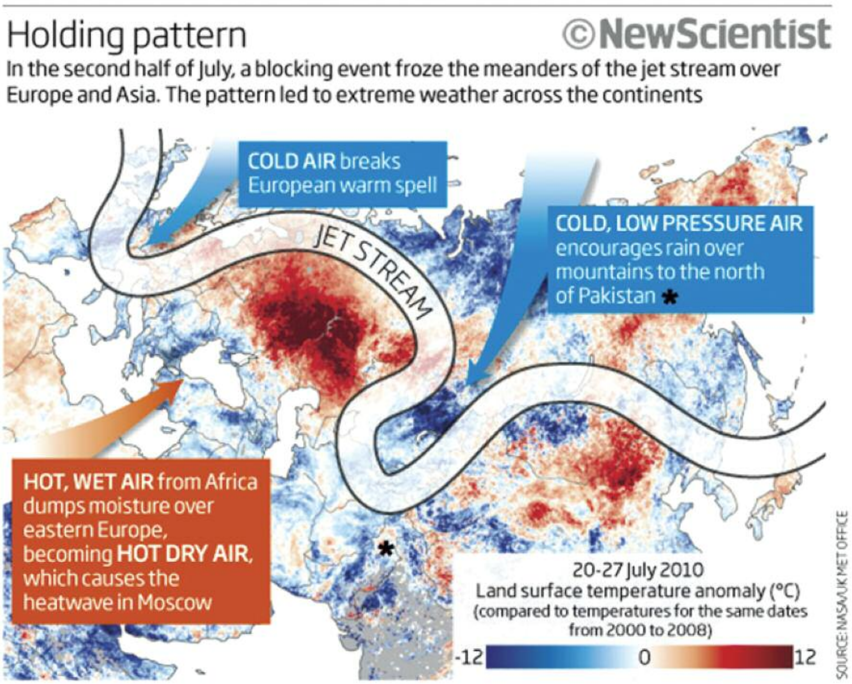


Figure 4: Synchronicity of Extreme Events. The Russian heat wave and the Pakistan flooding in 2010 are examples of synchronous extreme events that are tied to a blocking event in the atmosphere: the path of the jet stream freezes and high and low pressure systems stabilize resulting in constant local weather conditions for several weeks.

7-2011	Heat wave in the United States
7/8-2010	Russian heat wave and Pakistan flood
7-2006	European heat wave
8-2004	Winter like temperatures in Northern Europe
8-2003	European summer 2003 heat wave
8-2002	Elbe and Danube floods in Europe
7-2000	Floods in northern Italy and the Tisza basin, heat wave in the southern U.S.
7/8-1997	Great European Flood, floods in Pakistan and western U.S.
7-1994	Heat wave in southern Europe
7-1993	Unprecedented flood in the U.S.
7-1989	Widespread drought in U.S.
8-1987	Severe drought in the southeastern U.S.
8-1984	Severe heat and drought in the U.S.
7/8-1983	Severe heat and drought in U.S. mid-west

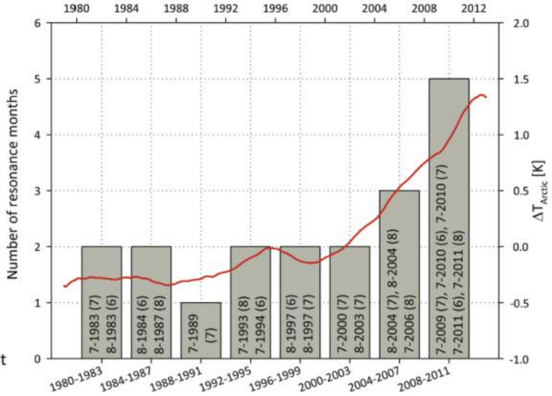
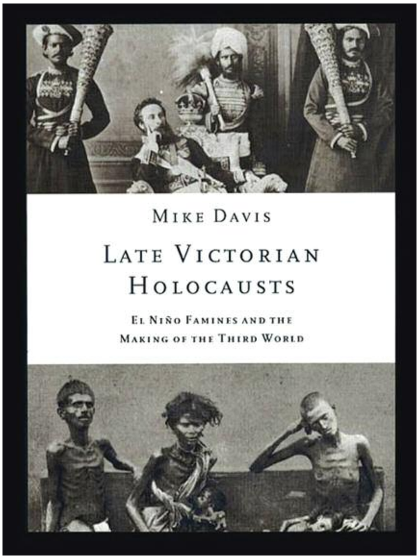


Figure 5: Increase in Quasi-Resonance Events. The increasing difference of surface warming between the Arctic and in the rest of the Northern Hemisphere (red line) as well as the number of July and August resonance months (grey bars, Petoukhov *et al*., 2013) are associated with extreme weather events (Coumou *et al.*, 2014).


MIKE DAVIS

LATE VICTORIAN HOLOCAUSTS

EL NIÑO FAMINES AND THE MAKING OF THE THIRD WORLD

Figure 6: Worldwide Historical Consequences of ENSO Events. In the late 19th century, around 30-50 million premature deaths in India, China and Brazil were related to droughts and monsoon failures, floods and epidemic diseases. Historian Mike Davis attributes the resulting "climates of hunger" to the El Niño-Southern Oscillation (Davis 2002).

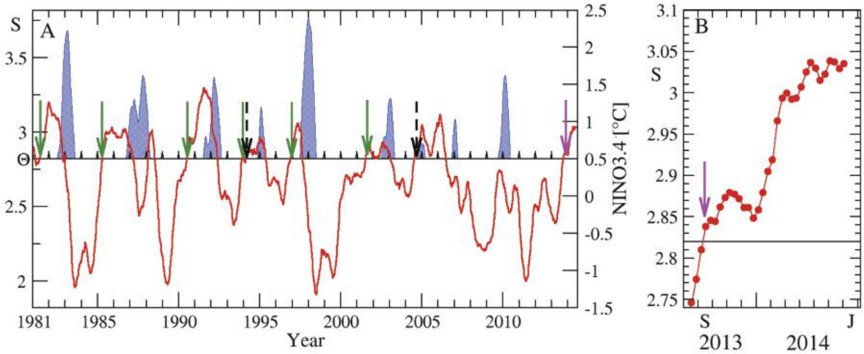


Figure 7: A Novel Method of Forecasting El Niño Events. The link strength *S* , describing teleconnections of temperatures between the El Niño basin and the rest of the Pacific (red curve), can be used as a very early warning bell for El Niño events (blue shaded areas) ringing at least one year ahead: If the link strength crosses a certain threshold from below (arrows) it is followed by an El Niño in three out of four cases (Ludescher *et al.*, 2013, 2014).

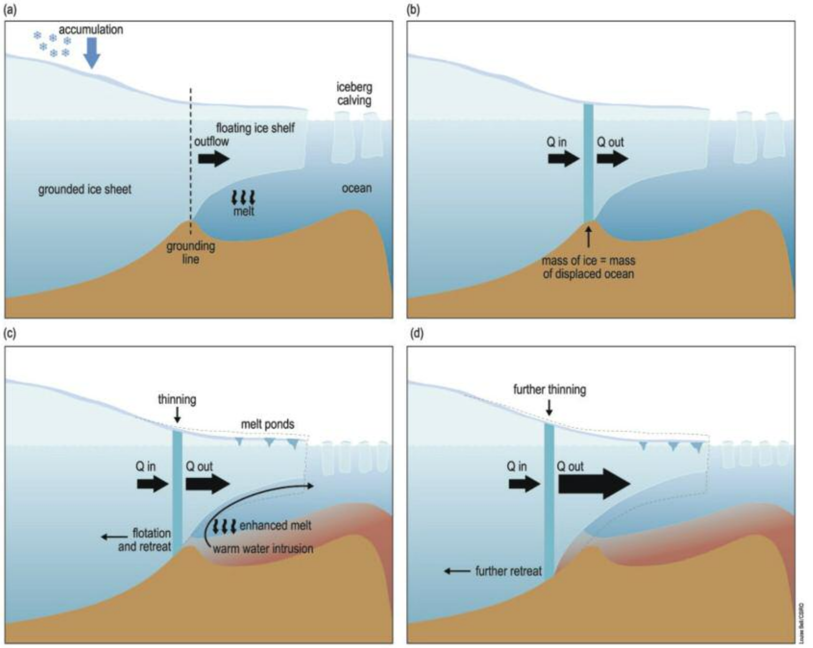


Figure 8: The Marine Ice Sheet Instability. The Marine Ice Sheet Instability (MISI) is the process leading to a potentially unstable retreat of a grounding line. (a) Profile of a marine ice sheet (b) Ice flux at the grounding line in steady state (c) Stronger outflow is triggered by ice-shelf melting and the grounding line starts to retreat. (d) Self-sustained retreat of the grounding line (IPCC WGI, box 13.2, Figure 1, 2013).

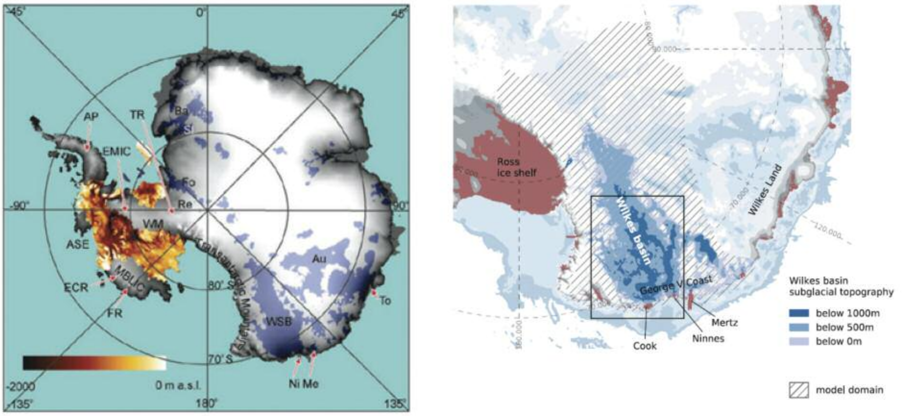


Figure 9: The Tipping Potential of the Antarctic Ice Sheet. Marine regions of the Antarctic ice sheet (i.e., areas where the ice sheet rests on a base below sea level, compare Figure 8) are potentially unstable. Left Panel: The marine West Antarctic ice sheet (red and orange colors) holds enough ice to raise sea level by 3.3 meters (Bamber *et al.*, 2009). The Wilkes Basin in East Antarctic could be subject to self-sustained ice loss as well if a critical ice plug near the cost is removed which would lead to additional 3-4 meters of global sea-level rise (Mengel & Levermann 2014).

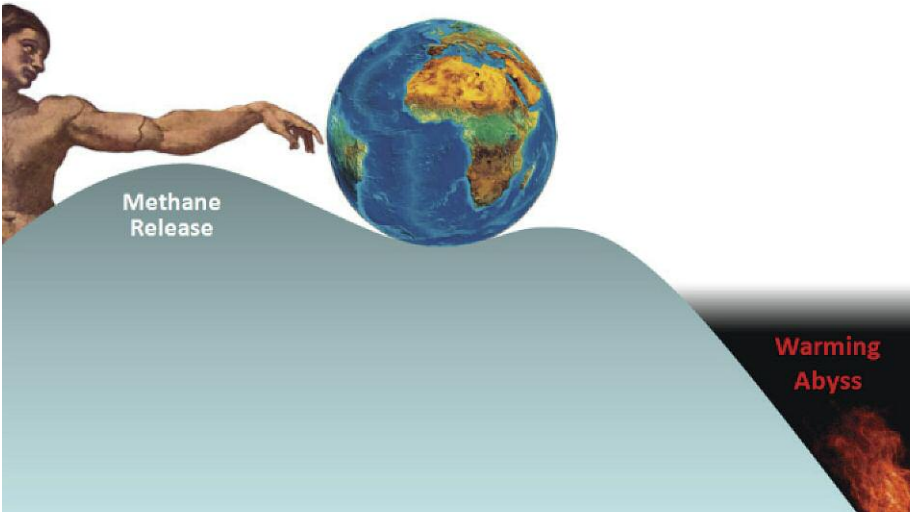


Figure 10: A Global Tipping Point? Methane release from ex-permafrost regions and oceanic shelves in the Arctic due to warming is a potential trigger for a runaway greenhouse effect: A self-enhancing process could set in because methane is a powerful greenhouse gas causing further warming and thus enhancing methane release even more.

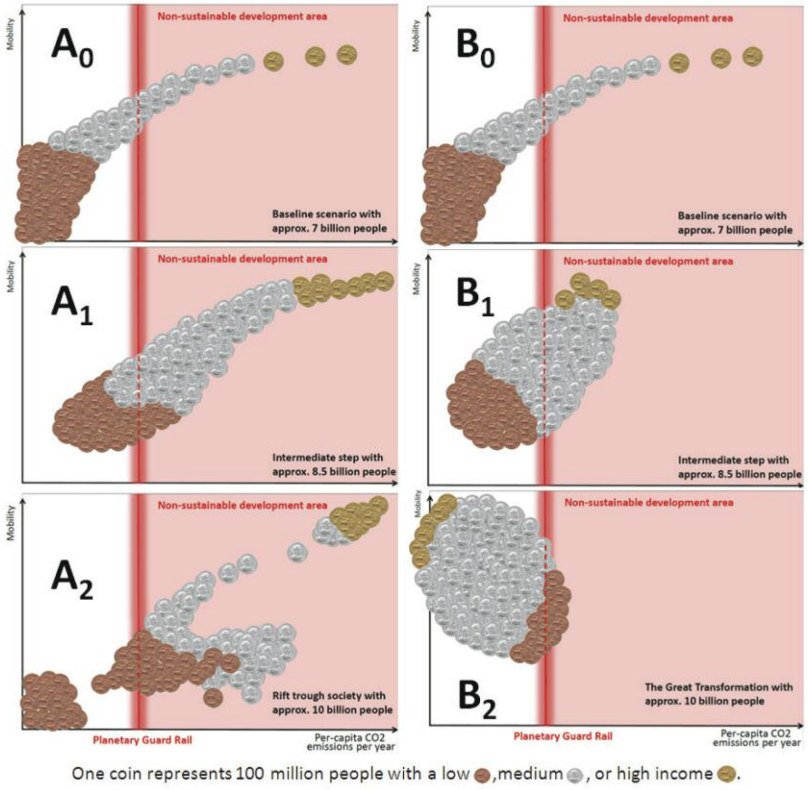


Figure 11: Alternative Development Paths. In this "development cartoon" prepared for WBGU (2014), income distribution, population development, per capita CO_2 emissions and wealth (represented here by the development indicator mobility) and their interrelations are all lined out for two alternative development strategies: While the traditional development paradigm (A_0-A_2) prescribes a shift towards a more carbon intensive lifestyle for everyone (A_1), a sustainable path (B_0-B_2) both reduces poverty and the carbon intensity of the lifestyle of the wealthy (B_1). Society therefore has the choice to either pursue traditional development strategies with the risk of tipping and breaking apart, not least because of the negative externalities of climate change (A_2), or to embrace the route to a Great Transformation, closing ranks and reaching global sustainability for both nature and humanity (B_2).

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