

High-end climate change and adaptation

About the WASP and the Policy Briefs

- The Science for Adaptation Policy Brief Series is an initiative of the World Adaptation Science Programme (WASP). The briefs target researchers, policymakers and practitioners to help them bridge the science-policy-action interface.
- The WASP is led by the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) and the Green Climate Fund (GCF). Its Secretariat is hosted at UNEP, Nairobi. The current Chair of the WASP is Mr. Youssef Nassef at the UNFCCC, Bonn.
- WASP's mission is to ensure researchers, policymakers and practitioners have the knowledge and capacity necessary to underpin effective adaptation to climate change.

Introduction - multiple pathways to high-end climate change

If the future consequences of human-caused climate change can be categorised as high-end, medium and low-end, we can consider the medium category to represent the outcomes of current expectations of human influence on climate and central estimates of climate system responses based on current scientific understanding. Low-end represents a smaller level of change, and high-end represents a higher level of change. If current energy policies continue, the central estimate for the resulting global warming is 3°C above pre-industrial by 2100 (Hausfather and Ritchie 2019). This paper therefore defines high-end climate change as warming above this rate.

If CO₂ concentrations reach approximately 940 parts per million (ppm) by 2100, global warming is projected to reach between 3°C and 6°C by 2100 (Figure 1). This widely-used scenario is useful for illustrating the risks associated with high-end climate change.

Key messages

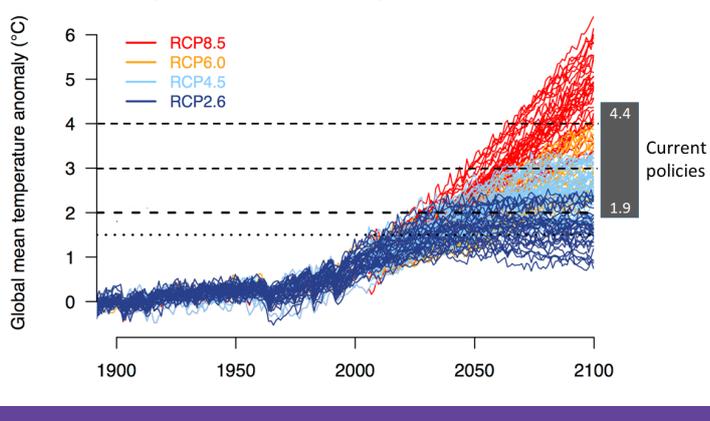
- Global warming of 4°C relative to pre-industrial would lead to severe impacts worldwide, with frequent extreme human heat stress conditions in the Tropics, hundreds of millions more people affected by coastal and river flooding, more time under extreme drought conditions in many regions, more high fire risk weather, widespread threats to food security and increased extinction risks for large numbers of species.
- 4°C global warming by 2100 is within the range of outcomes projected by extrapolating emissions from current worldwide energy policies. Faster warming is possible with higher emissions or with stronger feedbacks than typically assumed.
- Sea level rise is projected to continue for at least several centuries even with low levels of global warming. In high-end scenarios, up to 7m sea level rise is projected by 2500.
- Although adaptation to high-end climate change could be possible in some sectors and regions to some extent, there can be significant barriers related to, for example, governance, economic constraints and the speed of planning and implementation.
- In many cases there are limits to adaptation, and high-end climate change could instead require transformational changes such as large-scale human migration, and/or bring increased risks to human security.
- To provide more robust advice to inform adaptation, further research is required to reduce the uncertainties in projected future climate change and to quantify and understand current and potential adaptation and its limits.

Although this level of CO₂ build-up is often associated with a scenario of global emissions higher than expected from current policies (Hausfather and Peters 2020), it could also arise from much lower emissions if carbon cycle feedbacks are strong (Booth *et al.* 2017; Betts and Hausfather 2020).

Even without considering the possibility of strong carbon cycle feedbacks, 4°C by 2100 is well within the range of possible global warming projected by extrapolating the International Energy Agency scenarios based on current policies (Figure 1) (Hausfather and Ritchie 2019), and becomes even more likely next century if the current trajectory continues.

This paper draws on a range of sources that consider either the high CO₂ concentrations scenario (940 ppm by 2100) or analysis of impacts specifically at 4°C global warming. Impacts of high-end climate change are considered both for this century and beyond, and the scope and limits of adaptation discussed.

Figure 1: Projections of climate change to 2100. Coloured lines show global average temperature change relative to 1850-1900 from multiple climate model simulations from the 5th Coupled Model Intercomparison Project (CMIP5), driven by four different representative concentration pathways (RCPs) of CO₂, other greenhouse gases and aerosol pollution. See Collins *et al.* 2013 for further information on CMIP5. Grey bar shows the range of warming by 2100 expected from emissions consistent with an extrapolation of current energy policies, as proposed by Hausfather and Ritchie 2019.



Impacts of high-end climate change in the 21st Century

High-end climate change would impact people, societies and ecosystems in very many ways, involving many components of the climate system. The following discussion highlights some key examples.

Human heat stress

At 4°C global warming, more than 10% of the global land surface is projected to see temperature and humidity reaching levels that pose extreme heat stress risks for a quarter of days in summer (Figure 2a). Wide areas including large parts of the Indian subcontinent, north Africa, south-east Asia and northern Australia would be at risk of extreme heat stress for around 2 months in summer. Currently, approximately 30% of the world's population is exposed to heatwave conditions strong enough to increase death rates for at least 20 days per year, and this is projected to increase to up to 74% of the global population in projections with high-end change (Mora *et al.* 2017). While not everybody exposed to “deadly” conditions would die, they would experience conditions which are known to have caused some deaths when they occurred previously.

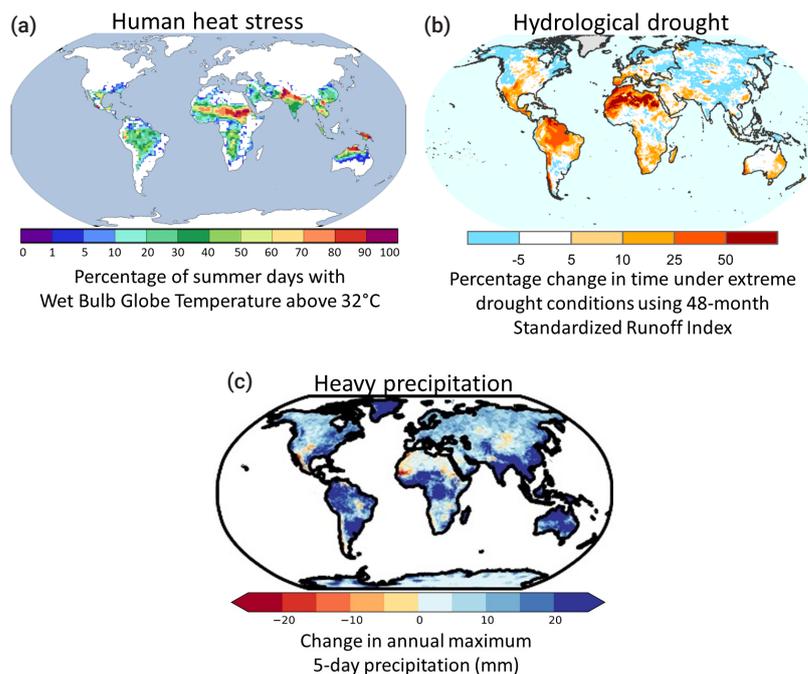
Drought and river flows

Many regions will experience more drought due to declining rainfall and increased evaporation (Figure 2b), partly offset by reduced water use by plants under higher CO₂. In contrast, some regions will experience reduced drought. In many regions, the precise changes cannot be predicted and could be in either direction. For example, at 4°C global warming, the Indian subcontinent and south-east Asia are projected to experience a wide range of annual rainfall changes from a 40% decrease to over a 50%

increase. Most other tropical and sub-tropical regions could see similar ranges of outcomes. The annual flows of many of the world's major rivers including the Amazon, Mississippi and Nile could decrease by 20% to 40%, but also could increase by similar amounts (Figure 3a). This uncertainty poses a huge challenge for adaptation planning.

Figure 2: Average projected climate changes and impacts at 4°C global warming.

Notes: (a) Wet Bulb Globe Temperature (WBGT) is a measure of human heat stress risk, and includes temperature, humidity and solar radiation. 32°C WBGT is recognised as “extreme risk” of heat stress. Mean of several simulations with the CMIP5 climate models. (b) Source: Koutroulis *et al.* 2019. (c) After: Betts *et al.* 2018, using data for 4°C global warming from version 3.1 of the EC_Earth climate model (Wyser *et al.* 2016).



Heavy rainfall and flooding

A hotter land surface drives stronger thunderstorms and heavy downpours, and a warmer atmosphere holds more water as a supply for rain, and so heavy precipitation is also projected to generally increase (Figure 2c) (Arnell *et al.* 2019; Betts *et al.* 2018). The risk of river flooding is therefore expected to increase (Arnell *et al.* 2019; Dottori *et al.* 2018) unless improved flood management measures are put in place. At 4°C global warming, an additional 69 to 269 million people per year worldwide are projected to be affected by river flooding compared to the present day (Alfieri *et al.* 2017), with current population levels. The largest projected increases are in east and south Asian countries, with around 50 million people affected in China, and around 10 million or more in each of India, Bangladesh, Vietnam, Myanmar, Thailand and Pakistan (Figure 3b). Many countries are projected to experience over a 400% increase in the number of people affected by river flooding (Alfieri *et al.* 2017).

Food insecurity

Yields of major crops are projected to decline in the tropics but increase in temperate regions, in response to high-end scenarios of climate change and CO₂ concentrations (Rosenzweig *et al.* 2014), although increased heat stress could also cause temperate crop yields to decrease (Schauberger *et al.* 2017). However, food security is affected by more than just crop yields – it also includes access to food, which depends on societal factors such as transportation and economic conditions, which themselves can also be affected by climate change. Changes in both drought and flooding could increase

vulnerability to food insecurity through all these factors, and while adaptation investment could offset this at low levels of climate change, the effectiveness of this could be limited for high-end scenarios (Richardson *et al.* 2018).

Ecosystems and biodiversity

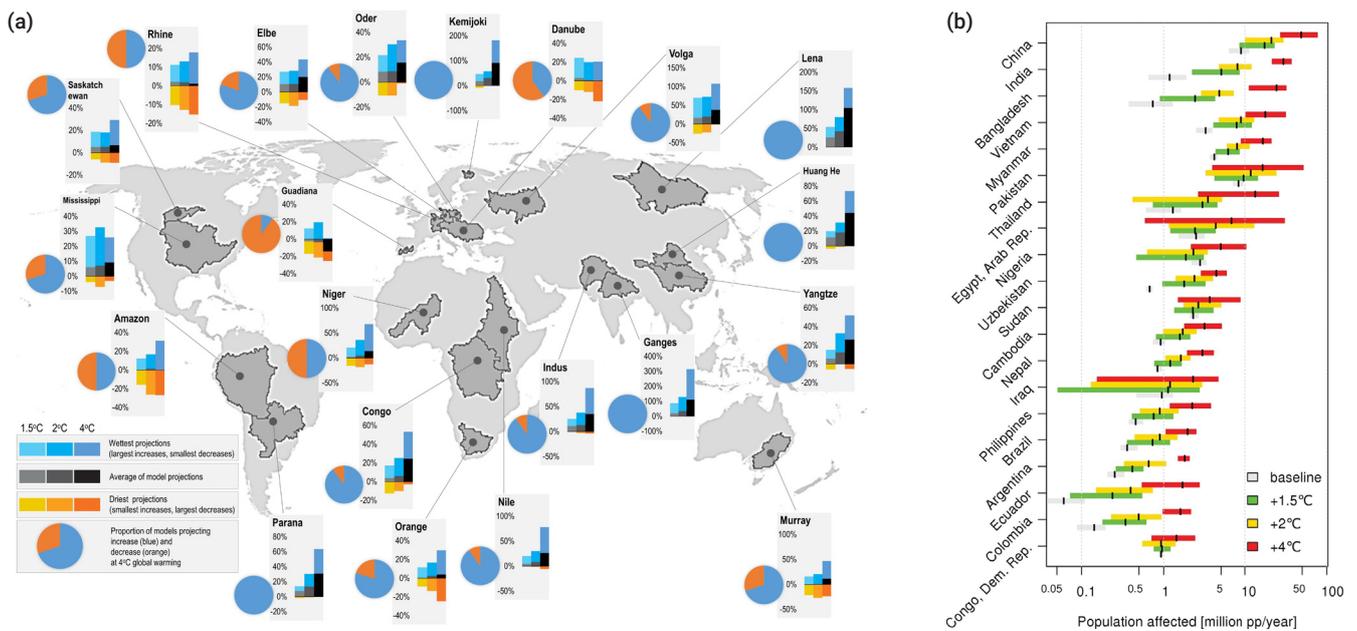
Many local climates would change to outside the ranges to which many species are adapted, increasing the risk of extinctions of many species. In high-end scenarios, approximately 57 ± 6% of plants and 34 ± 7% of animals are projected to lose at least 50% of their present climatic range by the 2080s (Warren *et al.* 2013). Approximately 10% - 30% of the global land area is projected to undergo changes in the ecosystem type, and hotter, drier weather would substantially increase the risk of wildfire worldwide (Betts *et al.* 2015).

Coastal flooding

Flooding risk will increase along coastlines due to rising sea levels. Under high-end scenarios, sea levels are projected to rise by approximately 0.5m to 1.3m by 2100 (Mengel *et al.* 2016). Some authors argue that a 2m sea level rise by 2100 cannot be ruled out (Bamber *et al.* 2019) but this remains controversial.

A sea level rise of 0.5m by 2100 would cause approximately 72 million people worldwide to be affected by coastal flooding at least once a year (Nicholls *et al.* 2011) (Figure 4a), assuming a global population of 7 billion but with a different geographical distribution to today (IPCC 2000). A 2m sea level rise by 2100 would affect 187 million people.

Figure 3: Quantifying uncertainties in projected river flows and flooding. (a) Projected changes in flows in selected major river basins at 1.5°C, 2°C and 4°C global warming for multiple model runs. Length of bars shows range of outcomes across the full set of simulations. Blue: increased flows; orange: decreased flows; black: median projection. After: Betts *et al.* 2018, using additional model simulations and additional data for 4°C global warming (Koutroulis *et al.* 2019). (b) Projected numbers of people affected by river flooding from multiple climate model runs for present day, 1.5°C, 2°C and 4°C global warming. Length of bars show full range of outcomes, black lines show the median. Source: Alfieri *et al.* 2017.



High-end climate change in the next century and beyond

It is crucial to look beyond the end of the 21st Century. Even if climate sensitivity and biogeochemical feedbacks are insufficient to lead to 4°C global warming by 2100, if greenhouse gas (GHG) concentrations continue to rise, 4°C warming will occur sooner or later. Whenever 4°C is reached, several of the major consequences will not fully emerge until later.

In particular, sea level rise is projected to continue to increase beyond 2100, since the melting of glaciers and ice sheets is not instant and there would be a lag of decades, centuries or even millennia before the full responses to warming are completed. Warming of ocean waters also requires centuries to take full effect. Under high-end scenarios in which CO₂ concentrations exceed 700 ppm, sea level rise over the next 500 years would be between 1m and 7m (Church *et al.* 2013) (Figure 4b).

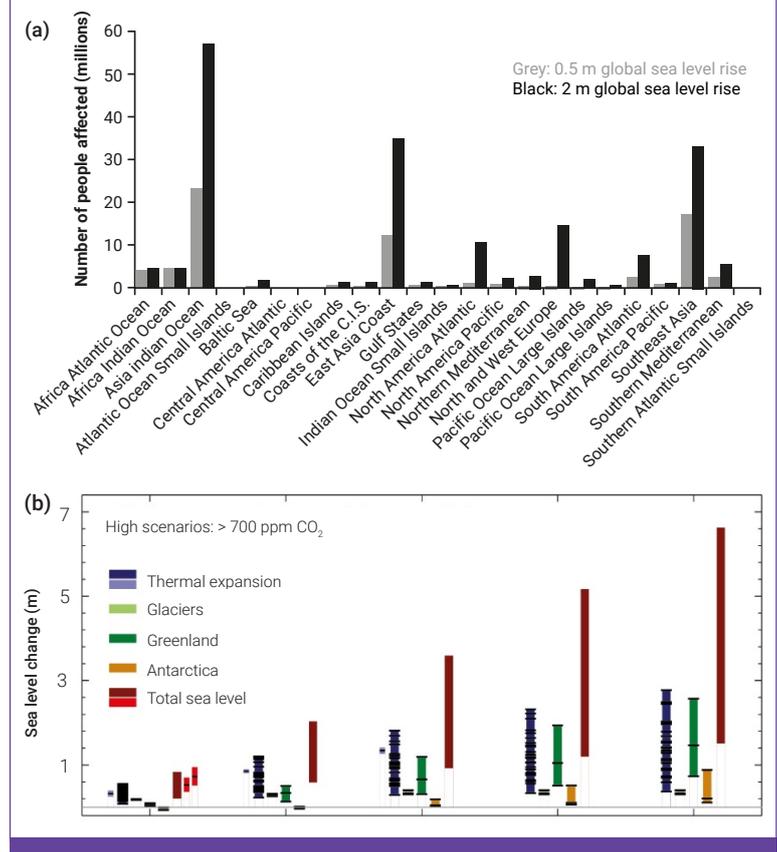
It is possible that an ongoing melting of the Greenland ice sheet could be triggered, which could become self-reinforcing by reducing the altitude of the ice sheet surface and bringing it to warmer lower layers of the atmosphere. Over thousands of years this alone would raise the sea level by 6m.

Other self-reinforcing changes are also possible (McNeall *et al.* 2011), including the thawing of Arctic permafrost and large-scale die-back of forests. Both these mechanisms could release further quantities of GHGs to the atmosphere, increasing the rate of global warming.

Sudden climate shifts may also occur, such as a shutdown of the northward flow of water in the North Atlantic, which keeps western Europe relatively warm for its latitude (Jackson *et al.* 2015). Such a shutdown would lead to severely cold winters in that region. However, while this shutdown is theoretically possible, and has occurred in the distant past, the IPCC assessed this as “very unlikely” (a 10% chance or less) to occur during the 21st Century (Collins *et al.* 2013).

If CO₂ emissions from fossil fuel burning continued in the long term, there are sufficient resources to allow continued global warming and an eventual total melting of the Antarctic ice sheet, raising sea levels by 3m per century in the first millennium and ultimately raising sea levels by 58m (Winkelmann *et al.* 2015).

Figure 4: Impacts of coastal flooding and projected long-term sea level rise. (a) People affected by coastal flooding more than once per year with global mean sea level rise (SLR) of 0.5m and 2m. SLR of 0.5m is within the range of all current projections this century. SLR of 2m is outside the range projected for 2100 by the IPCC, but remains possible in the 22nd Century. The number of people affected by flooding depends on the population assumed. This study uses a population projection for the SRES A1B scenario for 2100. Modified from: Nicholls *et al.* 2011. (b) Projected ranges of global mean SLR and contributions of thermal expansion, ice sheets and glaciers for the next 500 years, under scenarios of high CO₂ concentrations (above 700 ppm). Source: Church *et al.* 2013.



If global warming were to continue unchecked to very high levels, heat stress conditions could exceed the limits of human survival in the hotter regions of the world. At 7°C global warming, such conditions would start to be seen in parts of the tropics, and at 11°C to 12°C global warming would cover the regions currently inhabited by the majority of the human population (Sherwood and Huber 2010).

Adaptation and its limits under high-end climate change

For some impacts within this century, human adaptation to high-end climate change may be possible, for example:

- by increased indoor cooling to reduce heat stress risks;
- through building flood defences or floodplain management in areas at increased risk of river or coastal flooding;
- by improved water management and storage practices, and increased extraction of deep groundwater, in areas under increased drought risk.

Some of these adaptations would have large energy requirements (Parkes *et al.* 2019) which, without a shift to low-carbon technologies, could increase the burden of atmospheric GHGs (a maladaptation).

However, there are barriers and limits to adaptation. Socioeconomic conditions can strongly affect the ability to adapt, for example through population size and characteristics, wealth (or its absence), modes of governance and the quality and quantity of existing infrastructure (Richardson *et al.* 2018; Koutroulis *et al.* 2019). Well-educated and wealthy societies should have high capacity to adapt. Low adaptive capacity may exist where there is high unemployment, poverty or civil unrest.

The effectiveness of adaptation depends on whether it can take place on the appropriate timescale. To minimise impacts, adaptation actions either need to be effective immediately, or be planned and implemented in advance before the increased climate hazard has taken effect. For major infrastructure, such as flood barriers, reservoirs, transport networks and energy system assets, such planning requires investment years or decades in advance, which requires decisions to be made on the basis of deeply uncertain estimates of long-term benefits. The limits to predictability and the complexity and risks involved in decision-making may provide practical barriers to effective adaptation. If 4°C global warming occurred earlier than expected, for example due to strong feedbacks in the climate system, there would be less time to plan and implement adaptation. Abrupt climate changes would pose particular difficulties for adaptation ahead of time.

High-end climate change often implies increases in hazards which are potentially large but hard to quantify with confidence, which means that a risk assessment approach is often required. For example, rising sea levels inevitably imply that improvements to London's current flood protection will be required at some point. Whereas the costs of this will be very large, the costs of a catastrophic flood would be even larger. Decisions on long-term flexible planning should be informed by a high-end scenario which is regarded as unlikely but plausible.

For risks of drought and river flooding under high-end climate change, the very large uncertainty in rainfall changes poses an even greater challenge since even the sign of change is uncertain (Figure 3). If it cannot be confidently predicted whether rainfall will increase or decrease, as is the case for much of the world, adaptation plans need to account for both possibilities, and remain flexible for further evolution (Greve *et al.* 2018). Non-linear climate changes which change the direction of change, such as cooling in western Europe due to

ocean circulation disruption, could render some adaptation actions obsolete and require entirely new approaches.

A key issue for adaptation of other species and ecosystems includes the rate of climate change, as this affects whether species have time to track shifts in their optimal climate conditions through migration or dispersal (Settele *et al.* 2014). Interactions with human land use can also be important – adaptation to changing climates by migration and dispersal may be more difficult in a fragmented landscape. Even if individual species can adapt in these ways, differential changes between species can lead to changes in the ecosystem character.

Adaptation needs will grow if the climate continues to warm further, to the point where it might eventually exceed practical or physical limits (e.g. height of flood barriers, finite size of groundwater resources). This may be more likely if self-reinforcing feedbacks occur.

Other changes would be harder to adapt to in the first place and would require transformational change as opposed to adaptation. Increased periods of extreme heat stress would make it simply impossible to work or enjoy leisure pursuits outdoors, unless innovations of clothing and behaviour became available and acceptable. At very high levels of warming, heat stress beyond human survival could effectively render some regions uninhabitable (Sherwood and Huber 2010). Some coastal regions may not be considered economically worthwhile to protect from increased flooding, so again would become uninhabitable due to inundation. With many cities and regions currently home to very large numbers of people being exposed to potentially major threats from coastal flooding and heat stress risks, this could imply large numbers of people migrating due to loss of habitable areas.

Even without such extreme situations affecting large-scale habitability, environmental migration already takes place. The relationships between environment change and migration are highly complex and it is impossible to make reliable predictions of the numbers of people who would be displaced by certain impacts, since different societies and individuals have very different levels of tolerance and resilience (Adger *et al.* 2014). There is evidence that environmental shocks can play a role in major societal upheavals, and it is expected that human security will be progressively threatened as the climate changes (Adger *et al.* 2014).

Nevertheless, the larger stresses arising from high-end climate change would be expected to increase the likelihood of major, transformational societal changes and/or increased risks of shocks. Avoiding high-end climate change would reduce the risks of exceeding limits to adaptation and entering unknown and unpredictable territory for human society. However, it is not yet clear that such changes will be avoided, and there may at least be a period of "overshoot" with global warming exceeding the Paris Agreement targets of 1.5°C or 2°C for a period before being reduced. Transformational adaptation may well be needed to either bring society through a temporary overshoot period, or to deal with the ongoing increases in challenge if anthropogenic GHG emissions do not reach net zero.

Further research needs

Several critical research areas could improve the scientific advice informing adaptation to potential high-end climate change. Narrowing the range of uncertainty in projected future climate change would facilitate more robust adaptation planning. This includes translation of policies into emissions projections, the strength of carbon cycle feedbacks, and the magnitude of climate sensitivity.

Information on current adaptation and its effectiveness is also crucial. Since much adaptation is local and often reactive or spontaneous rather than planned (“autonomous adaptation”), it can be difficult to obtain reliable data at large scales. Information on the limits to adaptation can be even more challenging to obtain. It is also important to research how the limits may be determined by human perceptions, e.g. the extent to which impacts and risks can be tolerated. Truly interdisciplinary studies of adaptation involving close, effective collaboration between natural and social sciences remain rare and hence are a key research need.

References:

- Adger, W.N., Pulhin, J.M., Barnett, J., Dabelko, G.D., Hovelsrud, G.K., Levy, M., et al. (2014). Human security. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.). Cambridge: Cambridge University Press. Chapter 12. 755-791.
- Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., et al. (2017). Global projections of river flood risk in a warmer world. *Earth's Future* 5(2), 171-182. <https://doi.org/10.1002/2016EF000485>.
- Arnell, N.W., Lowe, J.A., Challinor, A.J., and Osborn T. J. (2019). Global and regional impacts of climate change at different levels of global temperature increase. *Climatic Change* 155, 377–391. <https://doi.org/10.1007/s10584-019-02464-z>.
- Bamber, J., Oppenheimer, M., Kopp, R.E., Aspinall, W.P., and Cooke, R.M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences of the United States of America* 116 (23), 11195–11200. <https://doi.org/10.1073/pnas.1817205116>.
- Betts, R.A., Golding, N., Gonzalez, P., Gornall, J., Kahana, R., Kay, G., et al. (2015). Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences* 12, 1317–1338. <https://doi.org/10.5194/bg-12-1317-2015>.
- Betts, R.A., Alfieri, L., Bradshaw, C., Caesar, J., Feyen, L., Friedlingstein, P., et al. (2018). Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376(2119), 1-27. <https://doi.org/10.1098/rsta.2016.0452>.
- Betts, R.A. and Hausfather, Z. (2020). How ‘carbon cycle feedbacks’ could make global warming worse. <https://www.carbonbrief.org/analysis-how-carbon-cycle-feedbacks-could-make-global-warming-worse>. Accessed 10 November 2020.
- Booth, B.B., Harris G.R., Murphy J.M. House, J.I., Jones C.D., Sexton D. et al. (2017). Narrowing the Range of Future Climate Projections Using Historical Observations of Atmospheric CO₂. *Journal of Climate* 30, 3039-3053. <https://doi.org/10.1175/JCLI-D-16-0178.1>.
- Church, J.A., Clark P.U., Cazenave A., Gregory J.M., Jevrejeva S., Levermann A., et al. (2013). Sea Level Change. In: *Climate Change 2013: The Physical Science Basis*. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge: Cambridge University Press. Chapter 13. 1137-1216.
- Collins, M., Knutti, R., Arblaster, J., Dufresne J., Fichet, T., Friedlingstein, P., et al. (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis*. Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M.M.B., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.). Cambridge: Cambridge University Press. Chapter 12. 1029-1136.
- Dottori, F., Szewczyk, W., Ciscar, J., Zhao, F., Alfieri, L., Hirabayashi, Y., et al. (2018). Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change* 8, 781-789. <https://doi.org/10.1038/s41558-018-0257-z>.
- Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., et al. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability* 1, 486–494. <https://doi.org/10.1038/s41893-018-0134-9>.
- Hausfather, Z. and Ritchie, J. (2019). A 3C world is now “business as usual”. <https://thebreakthrough.org/issues/energy/3c-world>. Accessed 10 November 2020.
- Hausfather, Z. and Peters, G. (2020). Emissions – the ‘business as usual story’ is misleading. *Nature* 577, 618-620. <https://doi.org/10.1038/d41586-020-00177-3>.
- Intergovernmental Panel on Climate Change (2000). *Special Report on Emissions Scenarios*. Calvo, E., Chadwick, M., Ishiumi, Y., Parikh, J., Nakicenovic, N. and Swart, R. (eds.). Cambridge: Cambridge University Press. <https://www.ipcc.ch/report/emissions-scenarios/>.
- Jackson, L.C., Kahana, R., Graham, T., Ringer, M.A., Woollings, T., Mecking, J.V., et al. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics* 45, 3299–3316. <https://doi.org/10.1007/s00382-015-2540-2>.
- Koutroulis, A., Papadimitriou, L., Grillakis, M., Tsanis, I.K., Warren, R. and Betts, R.A. (2019). Global water availability under high-end climate change: A vulnerability based assessment. *Global and Planetary Change* 175, 52-63. <https://doi.org/10.1016/j.gloplacha.2019.01.013>.

- McNeill, D., Halloran, P.R., Good, P., and Betts, R.A. (2011). Analyzing abrupt and nonlinear climate changes and their impacts. *Wiley Interdisciplinary Reviews: Climate Change* 2(5), 663-686. <https://doi.org/10.1002/wcc.130>.
- Mengel, M., Levermann, A., Frieler, K., Robinson, A., Marzeion, B., and Winkelmann, R. (2016). Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences of the United States of America* 113(10), 2597-2602. <https://doi.org/10.1073/pnas.1500515113>.
- Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R. et al. (2017). Global Risk of Deadly Heat. *Nature Climate Change* 7, 501–506. <https://doi.org/10.1038/nclimate3322>.
- Nicholls, R.J., Marinova, N., Lowe, J.A., Brown, S., Vellinga, P., de Gusmao, D., et al. (2011). Sea-level rise and its possible impacts given a 'beyond 4°C world' in the twenty-first century. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369, 161-181. <http://doi.org/10.1098/rsta.2010.0291>.
- Parkes, B., Cronin, J., Dessens, O. and Sultan, B. (2019). Climate change in Africa: costs of mitigating heat stress. *Climatic Change* 154, 461–476. <https://doi.org/10.1007/s10584-019-02405-w>.
- Richardson, K.J., Lewis, K.H., Krishnamurthy, P.K., Kent, C. and Hanlon, H.M. (2018). Food security outcomes under a changing climate: impacts of mitigation and adaptation on vulnerability to food insecurity. *Climatic Change* 147, 327–341. <https://doi.org/10.1007/s10584-018-2137-y>.
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., et al. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences* 111(9), 3268-3273. <https://doi.org/10.1073/pnas.1222463110>.
- Schauberger, B., Archontoulis, S., Arneth, A., Balkovic, J., Ciais, P., Deryng, D., et al. Consistent negative response of US crops to high temperatures in observations and crop models. *Nature Communications* 8, 13931 (2017). <https://doi.org/10.1038/ncomms13931>.
- Settele, J., Scholes, R., Betts, R., Bunn, S., Leadley, P., Nepstad, D., et al. (2014). Terrestrial and inland water systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.). Cambridge: Cambridge University Press. Chapter 4. 271-359.
- Sherwood, S.C. and Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences* 107(21), 9552–9555. <https://doi.org/10.1073/pnas.0913352107>.
- Warren, R., VanDerWal, J., Price, J., Welbergen, J.A., Atkinson, I., Ramirez-Villegas, J., et al. (2013). Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change* 3(7), 678-682. <https://doi.org/10.1038/nclimate1887>.
- Winkelmann, R., Levermann, A., Ridgwell, A. and Caldeira, K. (2015). Combustion of available fossil-fuel resources sufficient to eliminate the Antarctic Ice Sheet. *Science Advances* 1(8), 1-5. <https://doi.org/10.1126/sciadv.1500589>.
- Wyser, K., Strandberg, G., Caesar, J. and Gohar, L. (2017). Documentation of changes in climate variability and extremes simulated by the HELIX AGCMs at the 3 SWLs and comparison to changes in equivalent SST/SIC low-resolution CMIP5 projections. <https://helixclimate.eu/wp-content/uploads/2018/04/HELIX-603864-D3.1-Documentation-of-changes-in-climate-variability-and-extremes-simulated-by-the-HELIX-AGCMs-copy.pdf>. Accessed 10 November 2020.

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