Effect of Potential Climate Tipping Points on UK Impacts

Dr Helen Hanlon, Dr Matthew Palmer and Prof Richard Betts

Acknowledgements: We wish to express our appreciation for scientific advice provided by Dr Laura Jackson, Dr Eleanor Burke, Rosie Eade, Dr Paul Ritchie and Prof Julia Slingo.

Met Office Hadley Centre

Contents

Executive Summary

The purpose of this report is to review current knowledge of climate tipping points and related processes and their potential impact on the UK were they to be passed, as input to the Technical Report of the UK's 3rd Climate Change Risk Assessment (CCRA3). This will inform judgements of the urgency of adaptation for managing the risks and opportunities considered in the CCRA3 Technical Report.

The CCRA3 is concerned mainly with outlining government action required in the next 5 years to protect the UK against potential impacts of climate change that could occur in the future. So included in this report is consideration of the timescale of adaptation plans required within the next 5 years.

The physical mechanisms by which the UK could be affected, should certain tipping point thresholds be passed, is discussed. For example:

- **AMOC weakening leading to widespread cooling and drying in Europe, or a stronger North Atlantic storm track which would cause an increase in winter storms in the UK. AMOC weakening could be exacerbated by Greenland ice melt.**
- **Accelerating Antarctic melting would lead to faster sea level rise around the UK, sea levels predicted for 2100 and beyond could be realised earlier with up to 2m by 2100.**
- **Accelerated Antarctic melting could also be further exacerbated by AMOC weakening leading to enhanced warming in the Southern Ocean and changes in ENSO leading to enhanced warming in Ross and Amundsen seas.**
- **The North Atlantic jet stream is closely linked to the UK weather patterns, tipping points, such as AMOC weakening or Artic sea ice loss could possibly change its strength or position. For example, a southward shift in the jet stream would lead to weaker mid-latitude westerlies leading to colder winters in Europe.**
- **Permafrost thaw, Amazon and Boreal forest dieback involve carbon-cycle or biogeochemical feedbacks that result in additional global warming thereby amplifying UK impacts.**

There is however huge uncertainty in the probability of abrupt changes such as these tipping points which presents a considerable challenge to adaptation planning.

1 Introduction

A tipping point is generally defined as the critical threshold beyond which a qualitative change occurs in a system. In terms of the climate tipping points these are processes that are critical to the climate system on a subcontinental scale which if reached would have long-term consequences. Specific examples of climate tipping points are given in Table 1 and Figure 1 and are mainly related to processes such as:

- Carbon cycle and biogeochemical feedbacks
- Changes in the cryosphere, some of which have implications for sea level
- Large-scale shifts in climate patterns causing regional climate changes.

The tipping points we discuss here fit into those 3 main broad categorisations, although not all fit into a single category, eg: Amazon dieback is considered as a biogeochemical feedback that has an effect globally but it also has effects on local rainfall and its regional climate. Where a tipping point falls into multiple categories, we have categorised it by the dominant effect.

There are many potential climate tipping points spread across the Globe which could link together (Lenton et al 2019). Something that is currently not well understood is what different tipping points in combination might result in or whether we should expect different outcomes if one precedes another. Kriegler et al. 2009 and Lenton et al. 2008 both note that the probability of some tipping points can vary depending on whether another has already occurred. These are described as a “cascading effects” where the occurrence of one tipping point triggers a change in the climate system which accelerates another. For example, East Antarctic ice loss is not expected to reach a tipping threshold until there is > 5°C global warming but melting elsewhere and changes to the Atlantic meridional overturning circulation (AMOC) could lead to sea level rise and Southern Ocean warming, which would in turn accelerate East Antarctic melting (Steffen et al. 2018).

This report discusses the potential impacts that passing a tipping point, or cascade of tipping points, could have on the UK specifically. Included is some discussion on how tipping points could link together if that link ultimately impacts the UK. Here we focus on direct meteorological impacts but there could also be indirect impacts such as supply chain issues due to a tipping point affecting a critical location on the supply chain.

The discussion of tipping points in this report is ordered by the scale of the subsequent impact. Firstly, Carbon cycle and biogeochemical feedbacks which could accelerate global warming through climate feedbacks that have implications globally. Then changes in the cryosphere, which have implications for sea level. Followed by those which cause large-scale shifts in climate patterns causing regional climate changes.

Figure 1: Map of tipping points that could be important for UK impacts. Those represented by red circles are large-scale shifts in climate patterns causing regional climate changes. Blue circles are cryosphere changes that increase global sea level rise and subsequently UK sea levels. Green circles are tipping points that involve carbon-cycle or biogeochemical feedbacks that result in additional global warming thereby amplifying UK impacts due to global warming.

Table 1: Summary of each tipping point's impact and implications for the UK

Tipping Point	Unprecedented or magnification of existing impact	Global impacts	Mechanisms to UK impact	Implications for time scale of UK impacts?	Implications for UK adaptation decisions
Permafrost Thaw Section 2.1	Arctic Permafrost extent is already in decline and there is high confidence in total disappearance by 2100 under high emission scenario RCP8.5 which projects a reduction in extent of 30-99% by 2100 (IPCC SROCC, 2019) Which could amplify global mean temperatures by 0.13–0.27 °C (Schuur et al. 2015) or by up to an additional 12% of global temperature increase (Burke et al. 2017) by 2100. Abrupt permafrost thaw would be unprecedented	Abrupt thaw would and amplify global mean temperatures further though additional carbon dioxide emission into the atmosphere leading to further significant increase of global temperatures. Release of methane leading to additional greenhouse gas warming (only short-term ~10years) Global mean sea level rise through destabilisation of mountain glaciers which is significant up to (0.32 ± 0.08m, IPCC SROCC, 2019) but small compared to other contributions. Contribution to global sea level from ground ice alone (~0.027 to 0.088m sea level rise, Zhang et al. (2000))	Additional increases in global mean temperatures would in turn enhance further the impacts UK is already experiencing or expecting due to global warming. Increase in global mean sea level also translates into an increase for UK regional sea levels.	Impacts of global warming could occur earlier if abrupt permafrost thaw provides additional atmospheric greenhouse gas concentrations.	Current projections of Global atmospheric carbon dioxide concentrations and therefore global temperature rise could be exceeded, or higher warming levels reached sooner. Therefore, UK impacts associated with higher warming levels would also occur earlier than expected.

Dieback of the Amazon rainforest Section 2.2	Unprecedented loss	Reduced Carbon capture enhances global warming by an estimated additional 0.3°C (Cox et al 2000, Betts et al 2004, Betts et al. 2008) Increasing CO_2 drives Plant stomata conductance feedback which can lead to changes in tropical precipitation pattern	Amplified global warming Possible effect of tropical rainfall pattern changes through teleconnection but it is not clear how and no evidence for it.	Impacts of global warming could occur earlier if loss of Amazon forest, a large carbon sink, leads to significant increase of ~0.3°C atmospheric greenhouse gas concentrations. So, adaptation would need to factor that additional warming by looking at what the impacts would be at a warming level 0.3°C higher than currently projected.	Current projections of Global atmospheric carbon dioxide concentrations and therefore global temperature rise projections could be exceeded, or higher warming levels reached sooner with the addition of 0.3°C. Therefore, UK impacts associated with higher warming levels would occur earlier than expected.

Boreal forests dieback Section 2.3	Unprecedented loss	Reduced Carbon capture increasing global atmospheric carbon dioxide concentrations could contribute to global warming Global cooling due to albedo increase in higher latitudes. Net effect is currently unknown due to complexity of the multiple processes involved (IPCC AR5d)	The mechanism to UK could be through amplified global warming but as the net-effect is currently unknown it is not possible to draw any conclusions on this.	Impacts of global warming could occur earlier if loss of Boreal forest, a large carbon sink, leads to significant increase in atmospheric greenhouse gas concentrations.	Impacts of boreal forest loss, a large carbon sink but also low albedo area is hard to predict due to complex combination of multiple uncertain processes

Tipping Point	Unprecedented or magnification of existing impact	Global impacts	Mechanisms to UK impact	Implications for time scale of UK impacts?	Implications for UK adaptation decisions
Dynamic instability of the West Antarctic ice sheet Sections 3.2.3 and 3.2.4	Antarctica is already melting and having an effect on sea level. So, it would be magnification of the melt rate to unprecedented rates, causing ice loss due to marine ice sheet and ice cliff instability exacerbated by higher ocean temperatures.	Accelerated global mean sea-level rise	Accelerated global sea-level rise leads to regional sea-level rise in the UK.	Current climate projections estimate of UK sea level rise of ~ up to 1m by 2100. Acceleration of Antarctic melting could add up to another 1m by 2100 so the high end-scenario for UK sea level rise is 2m by 2100. (IPCC SROCC, 2019, UKCP09 H++ Lowe et al. 2009 and combined estimates detailed below)	Coastal defences may require increased adaptation beyond current predicted limits. For example, the Thames Estuary 2100 project (Ranger et al. 2013) Especially if upper limit of RCP8.5 is considered as a worst-case scenario.

Retreat of the Greenland ice sheet Sections 3.2.1 and 3.2.2	Magnification of current ice mass loss and increase risk of AMOC shutdown described in section 4.1.	Freshwater influx to subpolar North Atlantic could further weaken AMOC Greenland ice melt contribution to Global mean sea-level rise of 10s centimetres by 2100 (IPCC SROC 2019) Accelerated ice mass loss is possible through Surface mass balance-elevation feedbacks that could increase Greenland contribution to global sea level rise by an additional 15% above current projections (Church et al 2013) Even with additional mass loss through self-reinforcing feedbacks Greenland ice melt does not pose the same imminent threat as Antarctica in terms of sea-level change which is of the order metres, see sections 3.2.3 and 3.2.4.	Enhanced AMOC weakening -> increase in severe cold weather impacts Greenland ice melt does add ~10s cm to global mean sea level rise and therefore to UK sea level rise. However, this effect is offset by our proximity to Greenland and gravitational effects of Greenland ice loss means the UK sea levels do not increase as they do on average globally, up until a certain level the Greenland contribution is actually a reduction to UK sea levels slightly offsetting contributions from other sources (eg: Antarctica, glaciers, etc…)	It would take 1000s of years for Greenland ice melt alone to lead to significant increase in UK sea levels an effect which is minimised by our proximity to Greenland.	Greenland ice melt will contribute small changes to UK sea levels which vary regionally around UK but these will be small relative to other sources such as thermal expansion and Antarctic mass loss see sections 3.2.2, 3.2.3 and 3.2.4 Increased risk of AMOC shutdown which would lead to an increase in very cold severe winters. This is very unlikely but remains plausible this century and would call for an alternative decision as most projections of UK temperatures are showing increases and a reduction in cold winter impacts.

Tipping Point	Unprecedented or magnification of existing impact	Global impacts	Mechanisms to UK impact	Implications for time scale of UK impacts?	Implications for UK adaptation decisions
Atlantic thermohaline circulation shutdown (AMOC) Section 4.1	Shutdown is very unlikely but still a plausible scenario over the next century.	Widespread cooling in the northern hemisphere, less precipitation in the northern hemisphere midlatitudes and a stronger North Atlantic storm track and southwards shift in the ITCZ (Jackson et al. 2015)	Weakening would bring less warm water/ air into Northern Europe so increased severe cold-weather impacts. Reduction in precipitation could exacerbate droughts, particularly in Summer, which would be somewhat offset by reduced temperatures but impact on agriculture would be expected. Increased snowfall, especially over high ground Increased winter storms bring more precipitation to westerly coasts Additional local sea-level change of tens of cm (see Figure 13, Vellinga & Wood (2008))	Further weakening is likely by 2050 and very likely by 2100. Latest projections from analysis of multiple climate models estimate a 34-45% reduction in strength by 2100 (Weijer et al 2020). Collapse is very unlikely by 2100	Widespread drying could mean up to 50% reduction in net primary production (Jackson et al. 2015) and 10% reduction in total income from arable land. Impacts on agriculture an order of magnitude greater with AMOC shutdown compared to steadier climate change (Ritchie et al 2020) Increase in severe cold weather and drought impacts More winter storms Sea level rise of tens of cms (see Figure 13, Vellinga & Wood (2008))

Arctic sea ice reduction Section 4.2	Arctic sea ice thaw is already being observed. Arctic sea ice extent has been declining during all months of the year, with the strongest reductions seen in September at a rate of -12.8 ±2.3% per decade (1979-2018) (IPCC SROCC, 2019).	Reduction in Albedo leading to increase in arctic ocean temps and accelerates global temperature rise. Changes in primary production of marine ecosystems impacting polar fisheries Change in position of jet streams and storm tracks eg: polar jet stream, ITCZ, tropical storms	Southward shift of polar jet stream Acceleration of global warming due to reduction in Polar albedo Weaker mid-latitude westerlies leading to increase in frequency of extreme weather events in Europe (eg: severe cold winters, flooding, drought and heatwaves)	The physical mechanisms responsible for the modelling impacts are also not fully understood. So currently it is not possible to hypothesise the effect a tipping point leading to rapid Arctic sea-ice loss may have globally or on the UK. This is being investigated in the PAMIP experiments (Smith et al. 2019)	Arctic sea-ice loss could lead to colder winters, increase in frequency of extreme weather including severe winters and increased summer rainfall in Europe. Which for the UK, could mean more frequent or severe cold -weather impacts in winter and increased summer flooding. However, due to disparity in the results of the different modelling studies this is a highly speculative hypothesis. Acceleration of global temperature rise leading to reaching warming levels earlier and hence impacts associated with higher warming levels.

Change in North Atlantic Jet streams Section 4.3	Unprecedented change in the position or strength of Jet stream.	Weakening or changes in position due to reduction of Arctic Sea ice in warmer climates	A weaker jet stream across the North Atlantic could change position more and as it does would influence the weather patterns seen in UK. Specifically, a weakening would lead to more frequent occurrence of blocking patterns which are linked to high impact weather in UK and increased probability of extremes such as drought, flooding, cold spells, and heat waves. (Francis and Vavrus 2012) A Southward shift of the jet stream could lead to increased northern European precipitation in Summer (Screen 2013)	The uncertainty in how the jet stream may change means it is currently not possible to say what effect the UK would face. The main mechanism by which the UK could be affected would be if Artic sea ice loss resulted in, for example, a change in the position of the jet stream. However, the likelihood of this occurring and its subsequent impacts are subject to the same caveats as stated above for arctic sea ice loss. There is also a lack of consensus across studies on how the jet stream may change.	Current projections and analysis of future UK weather patterns suggest a tendency to more mild/unsettled weather in future winters and more drier and settled weather in future summers (McSweeny & Thornton 2020). Changes to the jet stream would affect the frequency of those weather patterns potentially having the opposite effect and requiring a different policy response to that based on current projections.

2 Carbon cycle and biogeochemical feedbacks

2.1 Permafrost Thaw

There is high confidence that a large area of Arctic near-surface permafrost will disappear this century as a result of the warming climate. Projections show an estimated reduction of 2-66% under RCP2.6 and 30-99% under RCP8.5 by 2100 (IPCC SROCC, 2019). CMIP6 projections of loss of permafrost extent due to sensitivity to increasing global mean surface temperature between 1.8 and 3.0 10^6 km^2/°C (25-75% range) (Burke et al. 2020, Table 5).

Permafrost is a mixture of soil, rocks and ice which remains permanently frozen throughout the year. In the warm season the top of the permafrost thaws to a depth denoted the 'maximum summer thaw depth' and then re-freezes in autumn. Carbon stored in the permafrost is relatively inert as temperatures are too cold for much microbial activity to occur. In permafrost regions global warming is causing rising temperatures, between 2007-2016 ground temperature in the continuous permafrost zone increased by 0.39 ± 0.15°C and discontinuous by 0.20 ± 0.10°C (Biskaborn et al. 2019). Arctic permafrost is affected more due to polar amplification (Smith et al. 2018), which is when external radiative forcing leads to greater change in surface temperatures at high latitude (ie: polar regions) than the change in the global average surface temperature.

Permafrost thaw which could lead to a large amount of carbon/methane being released into the atmosphere as warmer temperatures allow for more microbial activity. This addition of greenhouse gases to the atmosphere would increase global warming and lead to further thaw, this is a feedback term referred to as the "permafrost carbon feedback". Currently, there is some evidence for northern permafrost regions releasing additional methane and carbon dioxide due to thaw but there is low agreement on this (IPCC, SROCC, 2019).

Methane is a greenhouse gas which is more effective at trapping heat than carbon dioxide, so this could have an additive effect on global warming. However, this effect would be short lived as methane breaks down in the atmosphere much quicker (~10 years) than carbon dioxide (~hundreds of years) (IPCC AR5c, 2013).

"Arctic and boreal permafrost regions contain 1460–1600 Gt organic carbon, almost twice the carbon in the atmosphere (medium confidence)" IPCC SROCC, 2019

Should all the permafrost thaw, this carbon would not necessarily all end up released into the atmosphere immediately. The timescales of soil carbon decomposition are much slower than the projected rate of permafrost thaw. In addition, there is likely to be enhanced vegetation growth caused by warmer temperatures and increased atmospheric CO2 concentrations. Permafrost thaw can occur gradually – by a year on year deepening of the maximum summer thaw depth or abruptly with the landscape suddenly collapsing.

Current models typically assume a gradual deepening of the maximum summer thaw depth. Schuur et al. 2015 collate estimates of potential carbon release from the permafrost zone from multiple modelling experiments based on this assumption. Under high emission RCP8.5 or SRES A2 scenarios, projections estimate carbon release from permafrost to be in the range 37–174 Pg carbon by 2100, with an average across models of 92 ± 17 Pg carbon. This gives a possible range of additional global warming of 0.13–0.27 °C by 2100 and up to 0.42 °C by 2300(Schuur et al. 2015). More recently Burke et al (2017) used an intermediate complexity climate model with more complex land surface models and showed the additional warming from the permafrost carbon feedback is between 0.2% and 12% of the change in the global mean temperature by the year 2100 and 0.5% and 17 % of global mean temperature by 2300, where these ranges reflect differences in land surface models, climate models and emissions pathways.

Abrupt thaw is associated with landscape changes and happens when increasing temperatures melt ground ice, causing land surface to collapse into the space previously occupied by ice and alters the hydrology of the surface. This process is called "thermokarst" (see Olefeldt et al. 2016 and Turetsky et al. 2019 more detailed description) and only occurs at point locations not widespread areas. It is thought that around 20% of the northern permafrost region is susceptible to future thermokarst development, (Olefeldt et al. 2016). This process of rapid thawing is typically not included in large scale models (eg: CMIP6) which only include limited detail on permafrost dynamics. So, there is a possibility that abrupt thaw would provide an additional carbon source to the atmosphere that is not currently accounted for in latest projections (Walter Anthony et al. 2018). This poses a threat as a possible tipping point if there were many thermokarst landscape collapses potentially releasing more carbon dioxide and methane into the atmosphere. Simulations of carbon release through abrupt permafrost thaw by Turetsky et al. (2020) show a change from net carbon uptake to net release with cumulative emissions up to 80 ± 19 PgC by 2300, which would be a significant contribution to overall global warming.

IPCC SROCC 2019 also states, with high confidence, that permafrost thaw along with glacial retreat has reduced the stability of high mountain slopes which would lead to faster melting and increased contribution to global sea level and consequently regional sea level. It has already been noted in the Cryosphere section above though that the total contribution to sea level possible from glaciers alone is relatively small (32 ± 8cm) compared to other contributing factors (ie: thermal expansion and large ice sheet melting). Permafrost thaw contribution to sea level rise alone is even smaller, Zhang et al. (2000) estimate the global volume of ground ice to be equivalent to ~2.7–8.8 cm sea level rise.

2.1.1 Possible Impacts

Permafrost thaw is considered a possible carbon source to the atmosphere (Schuur et al. 2015), that would be larger if thaw is abrupt (Turetsky et al. 2020). The impact to the UK would be an indirect one with permafrost thaw affecting overall global temperatures through release of additional greenhouse gases resulting in reaching global warming levels earlier. As such this also means it could indirectly affect other tipping points which are sensitive to global temperature rise. Global temperature rise caused by the release of permafrost carbon is between 0.2 and 12% (by 2100) and 0.5 and 17 % (by 2300) of the global mean temperature change (Burke et al. 2017). Where the permafrost feedback has a greater impact on the low-emissions scenario (RCP2.6) than on the higher-emissions scenarios (Burke et al. 2017).

Also, if permafrost thaw contributes significant additional greenhouse gases to the atmosphere this will reduce the budget of anthropogenic CO2 emissions to keep below a certain level of global warming (Burke et al. 2018). Gasser et al. (2018) compare the carbon budgets and targets of the Paris Climate Change agreement with carbon emissions from permafrost model and conclude permafrost could use up 10-100% of emissions budget to reach 1.5° C and up to 25% of budget to reach 2° C. Once emitted these additional carbon emissions would be irreversible for centuries.

2.2 Dieback of the Amazon rainforest

The Amazon is a tropical forest which has high rates of evapotranspiration, stable high humidity climates and store larger mass of Carbon than temperate or boreal forests (Bonan, 2008). Increasing greenhouse gas concentrations are causing the changes to each of those facets of Amazon climate. Changes in precipitation and increasing temperatures could limit growth in the Amazon leading to reduction in forest cover reducing its effectiveness as a carbon sink. This is an example of a self-reinforcing “carbon cycle feedback” because as global warming induces a reduction of carbon uptake by the forest, that further enhances the atmospheric growth rate of CO_2. Carbon-cycle feedbacks such as these are expected to significantly accelerate climate change over the 21st century (Cox et al 2000). Cox et al 2000 performed experiments comparing simulations of a fully coupled carbon-climate model (where the Amazon experiences significant dieback) to that with fixed vegetation and found a 1.5°C difference in Global mean temperature response. The Amazon contributes ~20% to this total land carbon cycle feedback on atmospheric CO_2 (Betts et al 2004). So, by assuming a linear relationship between global mean temperature and atmospheric CO_2 concentration, Betts et al 2008 find the effect of Amazon dieback on global mean temperature to be an increase of 0.3°C. Although it must be noted, the effects of anthropogenic deforestation on landcover have not been included in these models.

Specifically, when dieback starts to occur due to warmer temperatures there is also a reduction in evaporative cooling, which in turn amplifies the local temperature leading to further dieback. This is another self-reinforcing feedback that could lead to a tipping point beyond which the Amazon may not recover.

Climate change and changes in rainfall patterns from loss of the Amazon rainforest would primarily impact the global carbon and water cycles through biogeophysical and carbon cycle feedbacks. Under higher atmospheric CO_2 concentrations plant stomata could open less reducing the amount of evaporation of water into the atmosphere (Cao et al. 2010, Swann et al. 2016, Leipprand and Gerten, 2006). This disrupts the water cycle as there is less water vapour in the atmosphere available to form into precipitation thereby reducing the region's precipitation further. This is called the "plant stomatal conductance feedback". Using Earth system model experiments, Kooperman et al. 2018 show that reductions in plant stomatal conductance and transpiration are the primary cause of the changes to tropical precipitation in South American forests. However, these changes are complex and depend on the scale and pattern of the deforestation (Lawrence and Vandecar, 2015).

There are also suggestions that Amazon precipitation would be sensitive to AMOC shutdown (Good et al. 2018) but studies looking at this do not agree on whether that change would lead to an increase or decrease of vegetation (Bozbivik et al. 2011 and Parsons et al. 2014).

Reduced precipitation due to global warming could lead to Amazon forest dieback and increase in the frequency and intensity of drought is already increase in Amazonia, especially so in the Southern Amazon which was already drought prone (IPCC SRCCL, *In press*). Increased drought conditions would also present an even higher risk of wildfires which are already considered a significant risk to the region due to climate change and methods of deforestation (Golding and Betts, 2008). There are other possible regional effects such as changes in hydrological extremes in the region, eg. river streamflows (Fowler et al. 2019).

In the event of forest dieback, additional carbon would be released into the atmosphere as it is no longer being captured by the vegetation which would accelerate global warming and in turn magnify the associated pattern of precipitation change. Betts RA, et al. (2004) estimate the additional precipitation reduction due to the biogeophysical and carbon cycle feedbacks along with soil respiration change to be 25%.

There have been studies looking at how precipitation would change elsewhere in the world if large tropical forests were completely removed. IPCC SRCCL shows a map produced by Lawrence and Vandecar (2015) collating results from these in Figure 2. Although, none of these found a teleconnection between any of the tropical forests and UK precipitation.

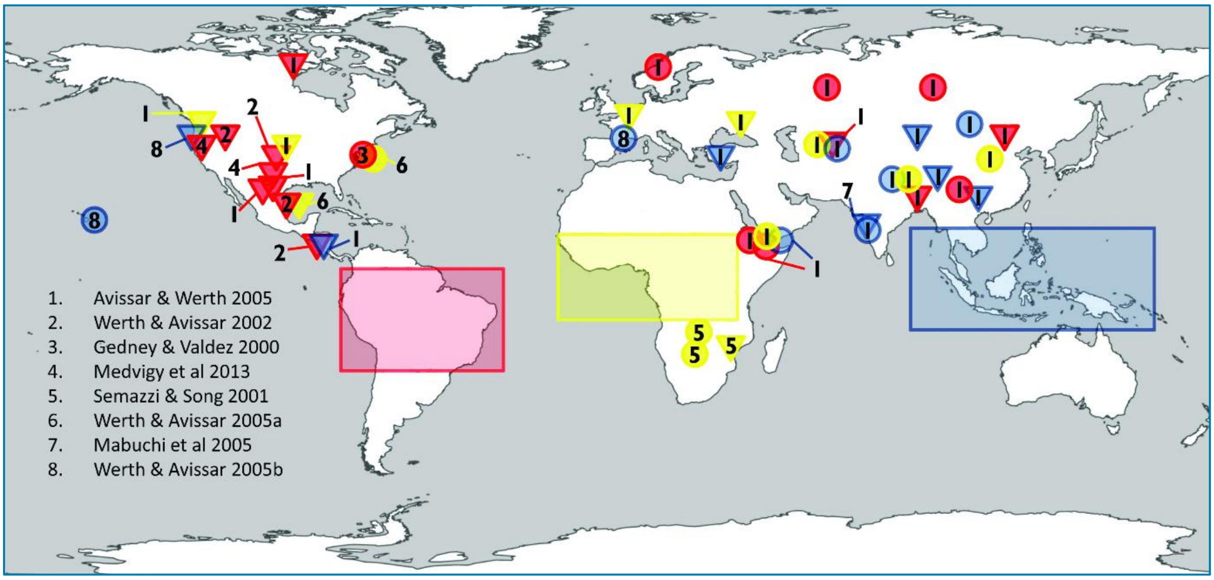

Figure 2: "Extra-tropical effects on precipitation due to deforestation in each of the three major tropical regions. Increasing (circles) and decreasing (triangles) precipitation result from complete deforestation of either Amazonia (red), Africa (yellow) or Southeast Asia (blue) as reviewed by Lawrence and Vandecar (2015). Boxes indicate the area where tropical forest was removed in each region" Taken from IPCC SRCCL (in press) and Lawrence and Vandecar (2015).

It is possible the Amazon could prove to be a climate tipping point as there are fire-vegetation and climate-vegetation feedbacks (Hirota et al (2011), Staver et al (2011) and Hoffmann et al (2012)) which could lead to an abrupt reduction in forest cover in the Amazon. Good et al (2018) consider that these could be realised with a relatively small change in external forcing and be irreversible but the processes behind this are poorly characterised.

2.2.1 Possible impacts

Through self-reinforcing feedbacks between the climate and vegetation there are proposed ways in which abrupt tipping point could be reached leading to unprecedented loss of the Amazon rainforest and disruption to the carbon and water cycles of the region. There are already changes in tropical precipitation being seen, reductions in the Amazon, that are expected to worsen with climate change.

There is little evidence to support the idea that there is a teleconnection that would lead to impact in UK. Amazon dieback could impact the UK if the suggestion presented in the Kriegler et al (2009) and Cai et al (2016) expert elicitations, and also Steffen et al (2018) that hypothesises amazon dieback could cause changes in tropical moisture supply led to an ENSO Shift to a more persistent El Nino phase Cai et al (2016). A change in ENSO could affect UK as El Nino conditions are linked to colder than average winters in the UK (Ineson and Scaife (2009), Toniazzo and Scaife (2006)). This could also influence AMOC by enhanced water vapour export from the Atlantic to the pacific and link back to UK via AMOC weakening (See AMOC section).

So, with regards to UK impacts, as with other tipping points discussed, it could be the UK is impacted indirectly through dieback leading to reduced carbon capture that amplifies global warming. If loss of Amazon forest, a large carbon sink, leads to significant increase in atmospheric greenhouse gas concentrations this could prompt exceedance of global temperature rise projections or higher warming levels reached sooner. Therefore, UK impacts associated with higher warming levels would also occur earlier than expected.

2.3 Boreal forests dieback

High latitude warming is projected to increase dieback and disturbance in boreal forests by drought, fire, pests and disease which could alter its structure, composition and functioning as it will experience greater temperature and rainfall extremes than they are currently adapted to (IPCC SRCCL, in press).

All types of forests have a cooling effect on global climate as they capture carbon from the atmosphere. Dieback would reduce this effect and more CO_2 would remain in atmosphere increasing the overall net amount present. This is true of both the Boreal forests at high latitudes (45°-70°N) and tropical forests but the uptake of CO_2 by boreal forests is moderate when compared with tropical forests (Bonan et al. 2008). However, there are other impacts which are not the same for boreal forests to tropical Amazon rainforests. Boreal forests have a very different climate and effect on surrounding climates. For example, the rate of evapotranspiration in Boreal forests is much lower than tropical forests, like the Amazon, so it is not so humid and so changes are not expected to impact large scale precipitation patterns.

The main method for Boreal forests to impact the surrounding climates is through snow-ice-albedo feedbacks. Land covered in forests have a low albedo and therefore absorb more incoming solar radiation which then warms surrounding areas as heat is transported as *sensible heat flux*. As global climate warms snow and ice-covered regions in high northern latitudes are thawing so the existence of the boreal forests adds to this warming and supports additional snow/ice loss though a self-reinforcing cycle (Meissner et al. 2003, Snyder et al. 2004). In this case, Boreal forest dieback could mitigate the effect of snow melt/ permafrost thaw/ice loss in surrounding areas. Also, models suggest that lower surface albedo of boreal forests contributes to climate warming relative to unforested land (Thomas and Rowntree (1992), Bonan et al.(1992), Bonan et al. (1995), Douville and Royer (1997)) which may be greater than warming that could be offset through the carbon the vegetation could capture (Betts, 2000). So Boreal forest dieback would, at least to some extent have a cooling effect.

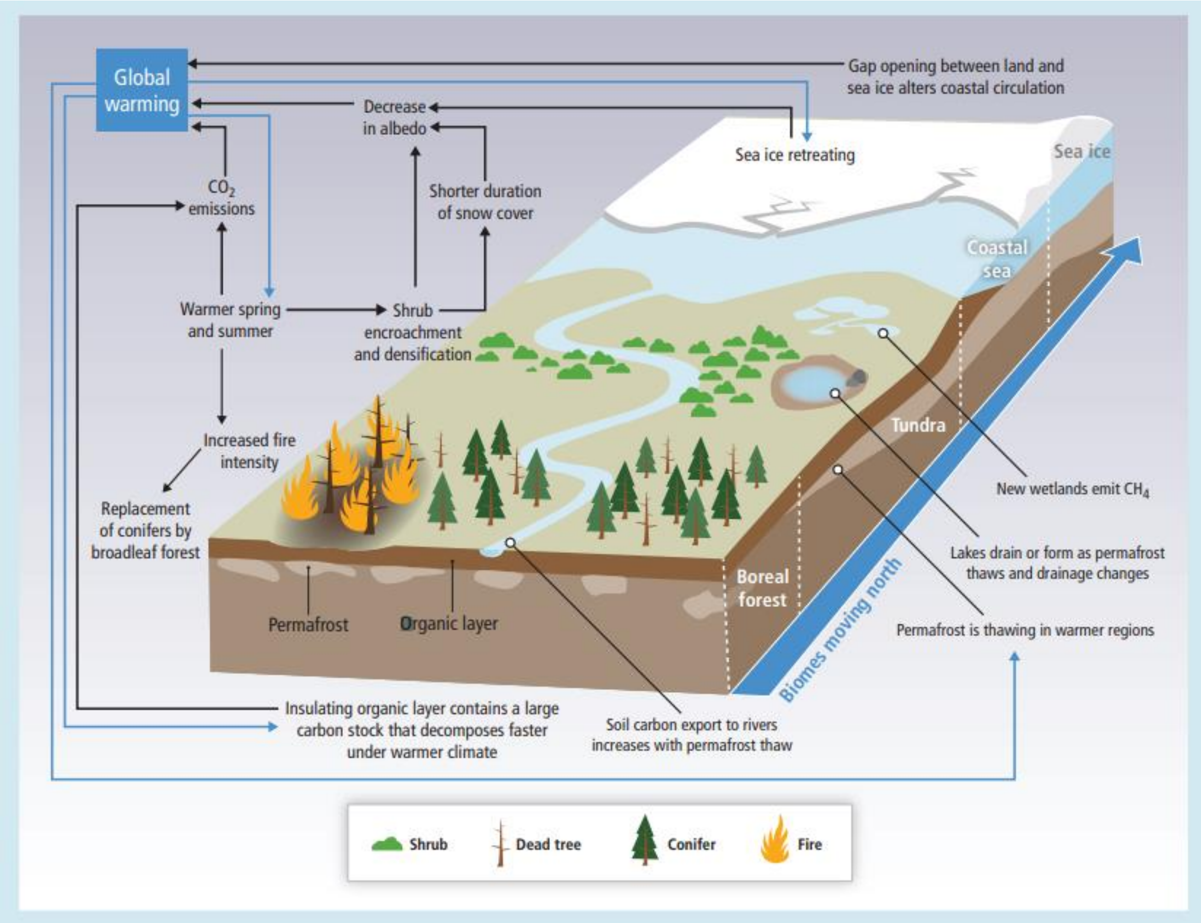

Figure 3: Diagram of processes influencing a Tundra-boreal biome shift (taken from IPCC AR5d). As the climate warms, Earth system models predict a northward shift of Arctic vegetation as the boreal biome migrates into the current tundra region, facilitated by intensification of the fire regime. Resulting in modifications to the surface energy budget, net ecosystem carbon balance, permafrost thawing and methane emissions. Along with net feedbacks to additional climate change.

2.3.1 Possible impacts

Net effect changes to boreal forest extent/composition and shift in the Tundra-boreal biome could have on global climate is complex and comprises many different aspects (see Figure 3). Modelling studies have estimated the net feedback, but these are poorly constrained by observations (IPCC AR5d). This means it is not possible to make confident estimates of how a boreal tipping point might impact the UK or globally.

3 Implications for sea level

Globally, there is enough land-based ice that if it were all to melt would lead to approximately 70 metres of global sea level rise (Church et al. 2001). Although this figure is based on all the land ice melting which would take thousands of years (Clark et al, 2016). The major ice sheets of Greenland and Antarctica have both exhibited an acceleration in mass loss over the last few decades (IPCC SROCC, 2019). The West Antarctic ice sheet may cross a tipping point whereby self-sustaining feedbacks could lead to a rapid acceleration in sea-level rise over the coming centuries (e.g., DeConto & Pollard, 2016). Although Greenland doesn't seem to pose the same imminent threat, research suggests that the trend in mass loss may become irreversible even with modest levels of sustained surface warming (Ridley et al. (2010), Solgaard et al. (2012), Pattyn et al. (2018) and IPCC SROCC (2019)).

Land-ice is overwhelmingly contained within Antarctica (~61 m, Church et al. 2001) and Greenland (~7 m, Church et al. 2001), mountain glaciers only equate to an equivalent global sea-level rise of about 0.32 ± 0.08m (IPCC SROCC, 2019). In this section we consider Greenland and Antarctica which hold the largest amount of land-ice that when melted would contribute significantly to future global sea-level rise. We also detail the mechanisms and plausible timescale for reaching tipping point level melting from these regions and what effect that might have on the UK.

3.1 Ice Mass Loss and Global mean sea level rise

Global mean sea level rise has been accelerating in recent years, 1902–2015 has seen an increase of 16 cm (likely range 12cm to 21cm, IPCC SROCC 2019). However, given the continuing acceleration of all the contributing components to unprecedented levels, global sea level rise over the 21st century will be significantly larger. To put this in context of latest global projections, the global model simulations with the different relative concentration pathway scenarios (RCP) project global mean sea level rise by 2100 (relative to 1986-2005) to be:

Table 2: Global Mean Sea Level Rise (GMSLR) at 2100. Range provided in brackets.

	CMIP5 GMSLR (*relative to 1986-2005,* *from IPCC SCROCC 2019 Table 4.4)*	**UKCP18 GMSLR (relative to 1981-2000)**
RCP2.6	43cm (29cm to 59 cm)	29cm to 66cm
RCP4.5	55cm (39cm to 72cm)	38cm to 79cm
RCP8.5	84cm (61cm to 1.1m)	56cm to 1.12m

[Note: addition of these different estimates would require scaling as they are not relative to the same time periods]

The largest contribution to the projections in Table 2 is from thermal expansion as the ocean water temperatures increase. There are also substantial contributions from ice melt of Greenland and Antarctic ice sheets and small contributions from glaciers which do not contain much ice and landwater changes, see Figure 4.

" The sum of ice sheet and glacier contributions over the period 2006–2015 is the dominant source of sea level rise (1.8 mm yr-1, very likely range 1.7–1.9 mm yr-1), exceeding the effect of thermal expansion of ocean water (1.4 mm yr-1, very likely range 1.1–1.7 mm yr-1) 22 (very high confidence)" IPCC SROCC, 2019

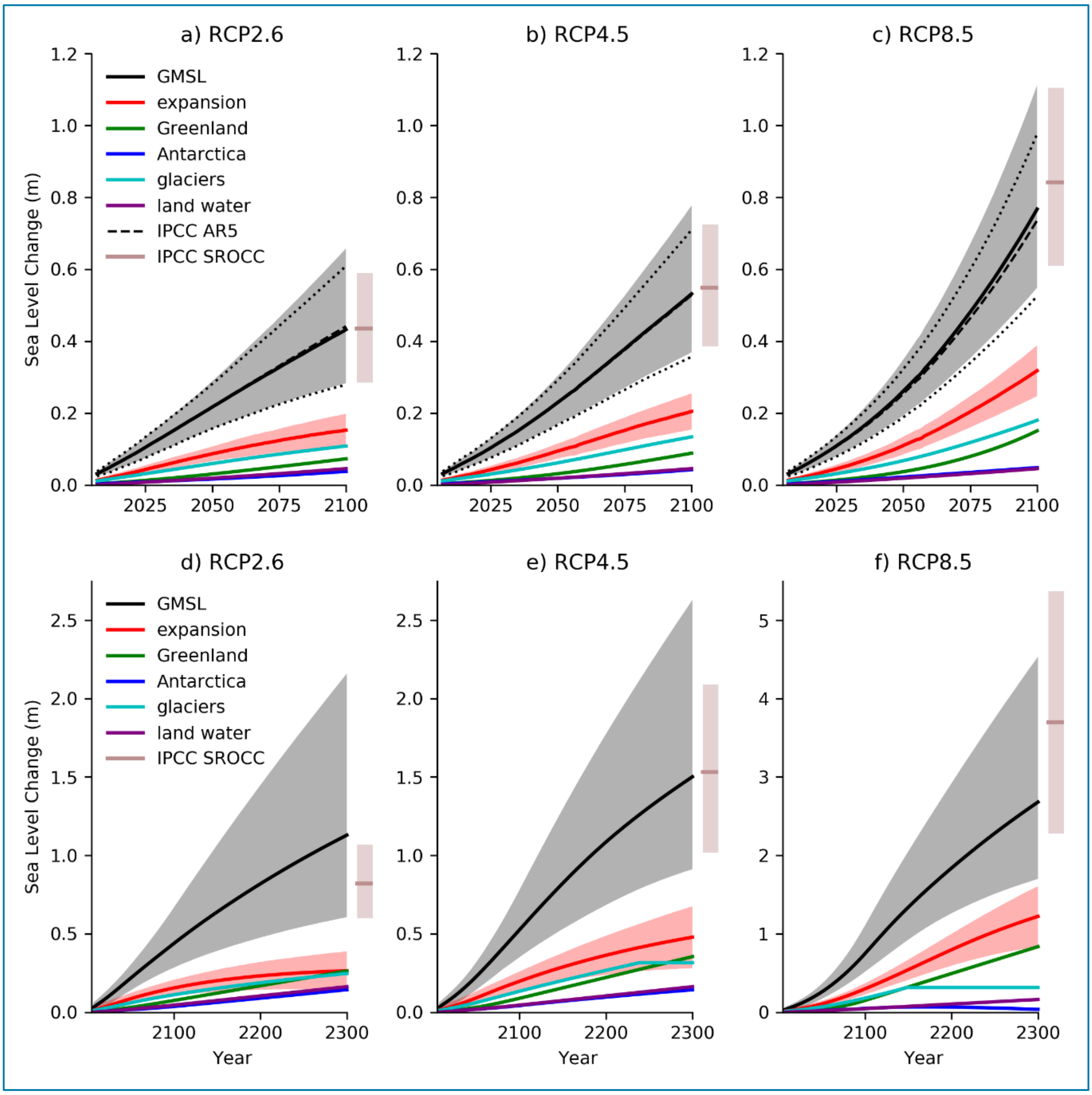

Figure 4: Individual contributions to global sea level rise up to 2100 (upper row) and 2300(lower row), taken from (Palmer et al. (2020)). Also shown for comparison is the total sea level projections presented in IPCC AR5 (Church et al, 2013) as black dotted line and IPCC SROCC 2100 (upper row) and 2300 (lower row) projection as a pink line (IPCC SROCC, 2019). All projections are shown relative to the 1986-2005 baseline.

The threat of accelerated global sea-level rise comes from the ice sheets, thermal expansion does not have the same potential for acceleration. The Antarctic ice sheet, which dominates the overall GMSL uncertainty, the impact of this is seen in the spread of GMSL projections. It is also important to note that projections (shown in Figure 4) show the central part of the distribution, in the case of a tipping we would want to look to the tails of the distribution which are not represented in Figure 4.

The question we are posing is how possible it is these contributions could be much larger were land-ice in Greenland and Antarctica to melt faster. To answer this, we need to consider the mechanisms for how land-ice in these regions can melt.

3.2 Estimating regional sea level change from global sea level rise.

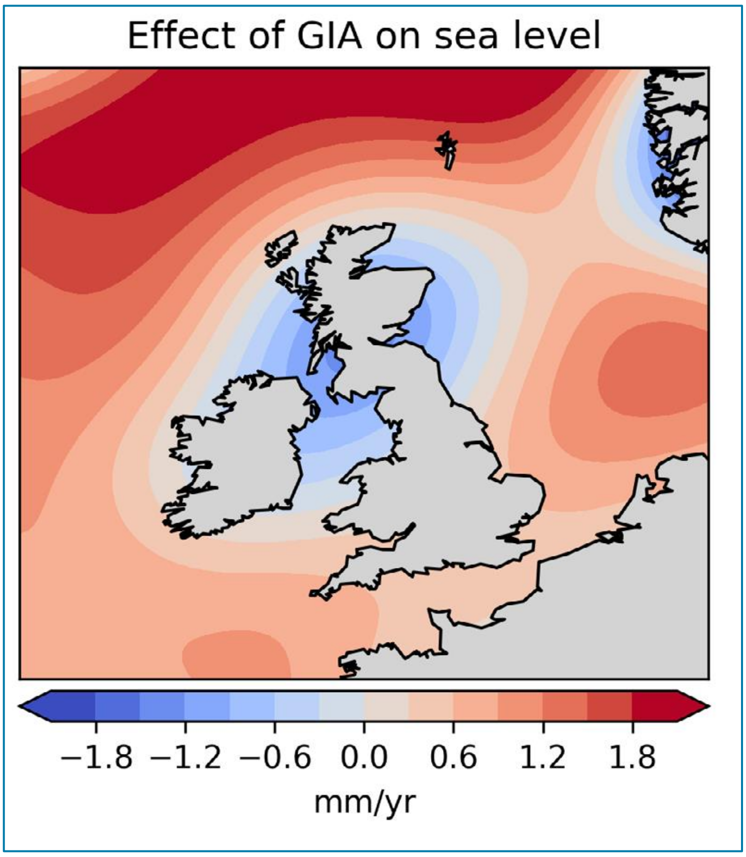

Figure 5 Effect of glacial isostatic adjustment (GIA) on sea level rise estimates around the UK taken from Figure A.1.1.5 from UKCP18 Marine report (Palmer et al 2018)

Whilst global and regional sea level changes are directly correlated, it is not as simple as global sea level increase equals regional sea level increase. Global sea level refers to the mean average sea level across the entire Earth. To estimate regional sea level changes the projected changes in land-based ice must be combined with spatial patterns, or “fingerprints”, that account for the response of Earth’s gravity, rotation and solid Earth deformation (e.g. Palmer et al, 2018). This means that the local sea-level contribution from ice mass changes can be amplified, diminished, or even reversed in sign for regions close to the ice mass loss. Estimates of Sea level rise for the UK are given in Palmer et al. (2018) based on two sets of fingerprints (to account for uncertainty in the fingerprint patterns) by Slangen et al, (2014) and Spada and Stocchi (2007).

The other effect that is incorporated into regional sea level rise estimates is glacial isostatic adjustment (GIA) (Church et al 2013). This effect is a result of the Earth’s mantle still responding to the loss of land ice following the termination of the last glacial period, about 10 thousand years ago. The largest effect on the UK from ongoing vertical land motion but also from associated changes to Earth’s gravity field and rotational effects (Shennan et al 2012). This component of the regional UK sea level rise estimates is negative over eastern Scotland where the sea level falls relative to the land and positive for the Southern UK indicating sea level rise (See Figure 5 for spatial pattern of GIA effect around the UK).

To calculate regional sea level estimates for the UK, Global sea level rise is first scaled by the region’s gravitational fingerprint and the region’s GIA adjustment is then added on top. As so,

$$\begin{aligned} &Regional\ sea\ level\ change \\ &\qquad = Global\ sea\ level\ change\ x\ regional\ gravitational\ fingerprint \\ &\qquad + regional\ GIA\ adjustment \end{aligned}$$

So, in some areas the resulting sea level change could be a reduction.

3.2.1 Greenland ice sheet

The main mechanism for Greenland ice melt is changes in surface mass balance, where ice melts faster than snow can accumulate, rather than instability of ice shelves. The current rate of ice sheet loss from Greenland is 278 ± 11 Gt yr^{-1} which is equivalent to 0.77 ± 0.03 mm yr^{-1} of global sea level rise (2006-2015) which is mostly due to surface melting (high confidence) and would be irreversible for millennia (IPCC SROCC, 2019). Complete loss of Greenland ice would be contributing around 7 m to global sea level rise, but this would take many thousands of years, as the surface mass balance process occurs at a steady rate that would not suddenly accelerate quickly unlike the marine ice shelf/cliff instability processes.

IPCC SROCC estimates sea level rise due to Greenland ice melt during the 21st century would be closer to 10s of centimetres (IPCC SROCCC, 2019). Which is an update on previous projections of 20-85mm by 2100 under RCP8.5 (by Church et al 2013).

Some self-reinforced melting may occur due to the surface mass balance–elevation feedback (Pattyn et al. 2018). Timing of this was initially to be thought of in the range of 3.1 (1.9–5.1)°C global warming by Gregory and Huybrechts (2006), but this was more recently revised to 1.6 (0.8–3.2) °C by Robinson et al. (2012). Leading to irreversible mass loss, should that level of global warming persist, and a further 0-15% surface mass balance which is equivalent to an additional 0 -14mm sea level rise by 2100 (based on RCP8.5, Church et al. 2013).

It is not considered possible that this could led to an abrupt change (IPCC SROCCC) unlike ice shelves in Antarctica which are subject to other melting processes which can be more rapid (see below). So, Greenland does not pose the same imminent threat as Antarctica in terms of sea-level change (except, potentially, through associated change in local dynamic sea-level change, as per Vellinga and Wood, 2008).

3.2.2 What does Greenland ice melt mean for the UK?

When translating global mean sea level rise projections into estimates for regions there are regional gravitational effects that must be considered. To account for these, the global contribution to sea level rise from Greenland is scaled with ‘fingerprints’ accordingly for the UK as in Figure 6, for its effect on UK sea level rise could be estimated. Greenland ice melt does not have such a large effect on the UK sea level as it does elsewhere or on average globally. This is because of the UK’s proximity to Greenland is such that it is close enough to be subject to the gravitational effects of ice mass loss redistribution.

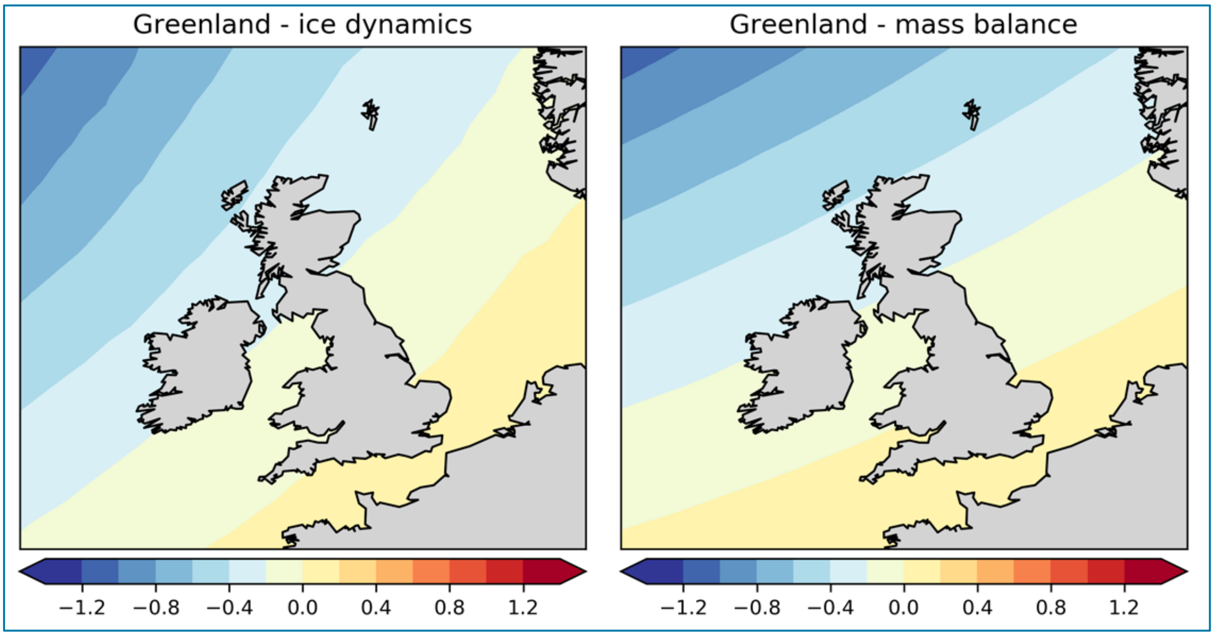

Figure 6: Fingerprint patterns of sea level rise adjustments necessary due to regional gravitational effects for Greenland.

The effect to UK due to ice loss purely from Greenland (not elsewhere) would be through changes to sea level (scaled as explained above) and weakening of AMOC. Weakening of AMOC due to increased freshwater input from Greenland melt leading to substantial regional sea-level changes through ocean dynamic sea-level change (see AMOC section above).

To summarise, for Greenland to form a tipping point that has significant effect on the UK the process would more likely be through AMOC weakening/shutdown due to ice melt injecting more freshwater in the Atlantic. This is because the main process for mass loss is surface melting - a process that occurs at a steady rate that would not suddenly accelerate unlike the marine ice shelf/cliff instability processes that could act elsewhere – and our proximity to Greenland reducing the sea level increase due to gravitational effects of Greenland ice loss.

3.2.3 West Antarctic ice sheet

IPCC SROCC estimates for 2006-2015 for ice mass loss from Antarctica are 155 ± 19 Gt yr_{-1} (equivalent to 0.43 ± 0.05 mm yr_{-1}), mostly due to rapid thinning and retreat of major outlet glaciers draining the West Antarctic Ice Sheet (very high confidence).

Changes in Antarctic Ice sheet extent are deemed possible (IPCC SROCCC, 2019) and there are several mechanisms by which this could occur:

- Change in surface mass balance – where ice melts faster than snow can accumulate - this is the dominant process for ice loss in East Antarctica.
- Ice flow processes – dynamical flow of ice and melting.
- Marine Ice Sheet Instability –this occurs when a critical threshold ("grounding line") is reached, where an ice sheet is no longer attached to the land bed beneath, so it floats atop ocean making it unstable, vulnerable to changes in circumpolar circulation and more likely to melt at a faster rate. (Rignot et al, 2014; Favier et al, 2014; Joughin et al, 2014)
- Marine Ice Cliff Instability (Pollard et al. 2015) - disintegration of floating ice shelves which leave behind structurally unstable coastal ice cliffs taller than around 100m in height that could collapse leaving further unstable ice cliffs that could in turn collapse leading to a self-reinforcing accelerating ice loss cycle.

The main risk of abrupt change comes from West Antarctica, which is losing ice mass primarily due to ice flow processes but could start rapidly losing more ice from accelerating instability processes. Self-sustaining feedback processes have been identified that could lead to a substantial acceleration in mass loss from Antarctica over the 21st century and beyond: Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) see Figure 7. Marine ice cliff instability self-sustaining feedback could lead to a contribution to global sea level rise from

Antarctica alone of around 1m by 2100 if it developed rapidly (DeConto and Pollard, 2016, Palmer et al. 2018 and Edwards et al. 2019). Then beyond 2100, if established, the impacts from MISI/MICI will be of much greater magnitude in the coming centuries.

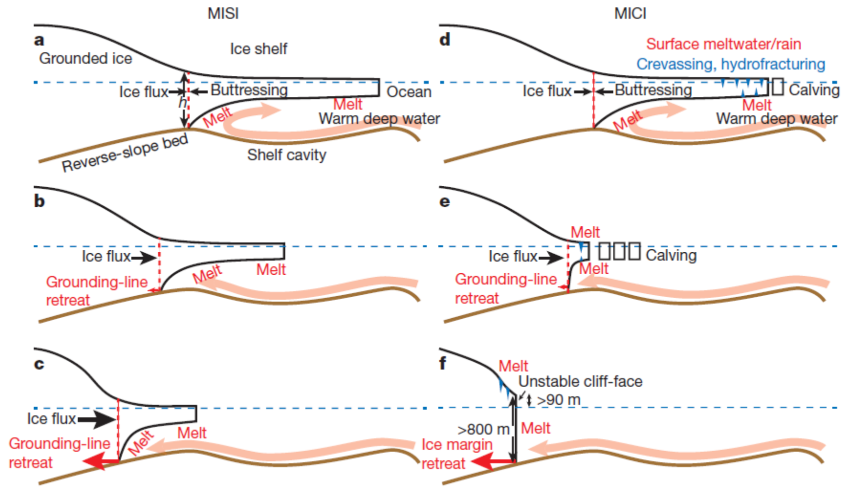

Figure 2 | Schematic representation of MISI and MICI and processes included in the ice model. Top-to-bottom sequences (**a–c** and **d–f**) show progressive ice retreat into a subglacial basin, triggered by oceanic and atmospheric warming. The pink arrow represents the advection of warm circumpolar deep water (CDW) into the shelf cavity. **a**, Stable, marine-terminating ice-sheet margin, with a buttressing ice shelf. Seaward ice flux is strongly dependent on grounding-line thickness *h*. Sub-ice melt rates increase with open-ocean warming and warm-water incursions into the ice-shelf cavity. **b**, Thinning shelves and reduced buttressing increase seaward ice flux, backing the grounding line onto reverse-sloping bedrock. **c**, Increasing *h* with landward grounding-line retreat leads to an ongoing increase in ice flow across the grounding line in a positive runaway feedback until the bed slope changes. **d**, In addition to MISI (**a–c**), the model physics used here account for surface-meltwater-enhanced calving via hydrofracturing of floating ice (**e**), providing an additional mechanism for ice-shelf loss and initial grounding-line retreat into deep basins. **f**, Where oceanic melt and enhanced calving eliminate shelves completely, subaerial cliff faces at the ice margin become structurally unstable where *h* exceeds 800 m, triggering rapid, unabated MICI retreat into deep basins.

Figure 7: Schematic Diagram displaying MISI and MICI ice -melt process. Taken from Deconto and Pollard 2016.

For RCP2.6, Deconto & Pollard (2016) estimates of Antarctic contribution to Global mean sea level rise are similar to that of UKCP18 but for higher emissions scenarios are considerably higher (Table 3 and Figure 8). This is because Deconto and Pollard (2016) have accounted for additional marine ice sheet/cliff instability processes described above.

Table 3: Global Mean Sea Level Rise (GMSLR) and Antarctic Contribution at 2100. Range provided in brackets.

	CMIP5 GMSLR *(relative to 1986-2005, from IPCC SCROCC 2019 Table 4.4)*	**CMIP5 Antarctic contribution to GMSLR *(relative to 1986-2005, from IPCC SCROCC 2019 Table 4.4)***	**Deconto and Pollard upper estimate of Antarctic contribution (relative to 2000, from Deconto & Pollard (2016))**	**Deconto and Pollard lower estimate of Antarctic contribution (relative to 2000, from Deconto & Pollard (2016))**
RCP2.6	43cm (29cm to 59 cm)	4cm (1cm to 11cm)	11cm (0 to 22cm)	2cm (-11cm to 15cm)
RCP4.5	55cm (39cm to 72cm)	6cm (1cm to 15cm)	49 cm (29 to 69cm)	26cm (-2cm to 54cm)
RCP8.5	84cm (61cm to 1.1m)	12cm (3cm to 28cm)	1.05m (75cm to 1.35m)	64cm (15cm to 1.15m)

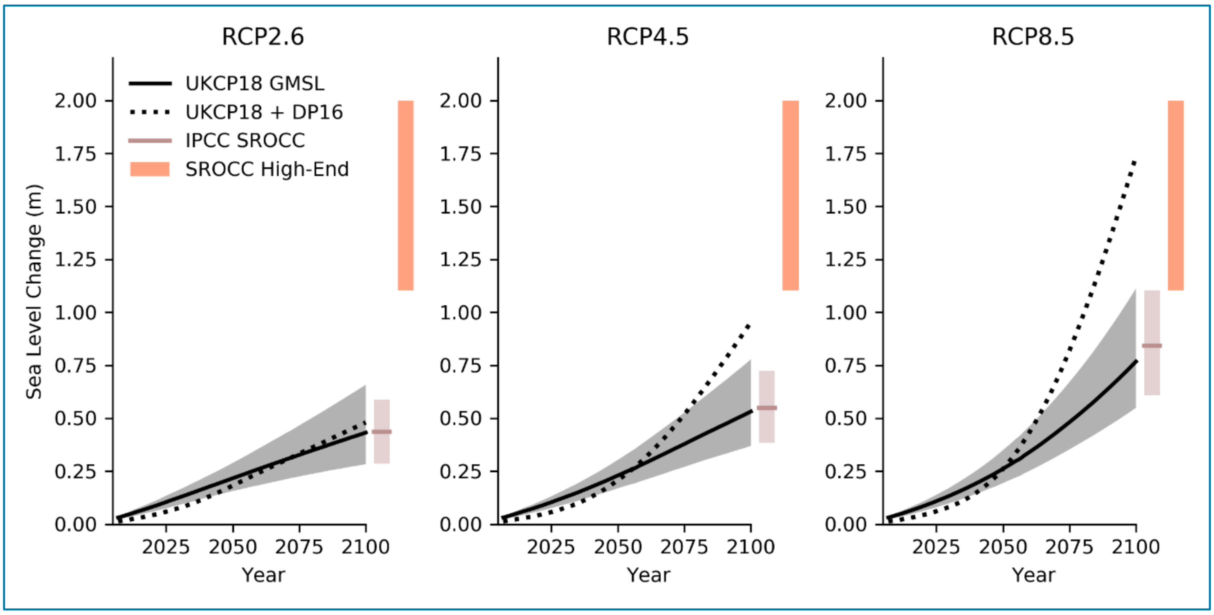

Figure 8: An illustration of the impact of DeConto and Pollard (2016) simulations of Antarctic ice mass loss on the UKCP18 21st century sea-level projections. Also shown are the *likely range* projections and High-End range from IPCC SROCC (2019).

However, they are not necessarily more likely as the surface melt rates used, which drive these instability processes, were considerably higher than that estimated by CMIP5 multi model projections which are estimating up to 1m by 2100 (See Figure 8). IPCC SROCC projects significant on-going committed sea level rise out to 2300 of several meters (IPCC

SROCC, 2019). A study by Clark et al. (2016) looking at long-term commitment to sea level rise estimated that with the 470Pg C released up to 2000, even if we were to reach net-zero emissions tomorrow, without further action we would be committed to approximately 1.7m (range of 1.2 to 2.2m) of global mean sea level rise. Further release of another 470Pg C resulting in approximately another 9m, most of which is due to Antarctic melting (Clark et al. 2016).

Figure 8 also shows these estimates of global mean sea level rise up to 2100 alongside those of H++ high-end scenario developed with UKCP09 projections and the Deconto and Pollard estimates that include accelerating instability processes MISI and MICI. Should either of these scenarios be realised in the event of Antarctica reaching a tipping point that accelerates melting, global mean sea level rise would be considerably higher than current projections of UKCP18 and IPCC. Importantly, there is huge uncertainty in the magnitude of this acceleration. IPCC does state low confidence in statements about this as there is uncertainty and lack of process understanding, with model experiments relying on parameterised processes.

3.2.4 What Antarctic melting means for the UK?

In contrast to the scaling for Greenland (Figure 6) the scaling for UK sea level estimates due to gravitation effects of Antarctic mass loss is very close to 1 for all UK regions (see Figure 9). So, the contribution to all areas of the UK from Antarctica alone does not vary much regionally and is similar to what it contributes globally.

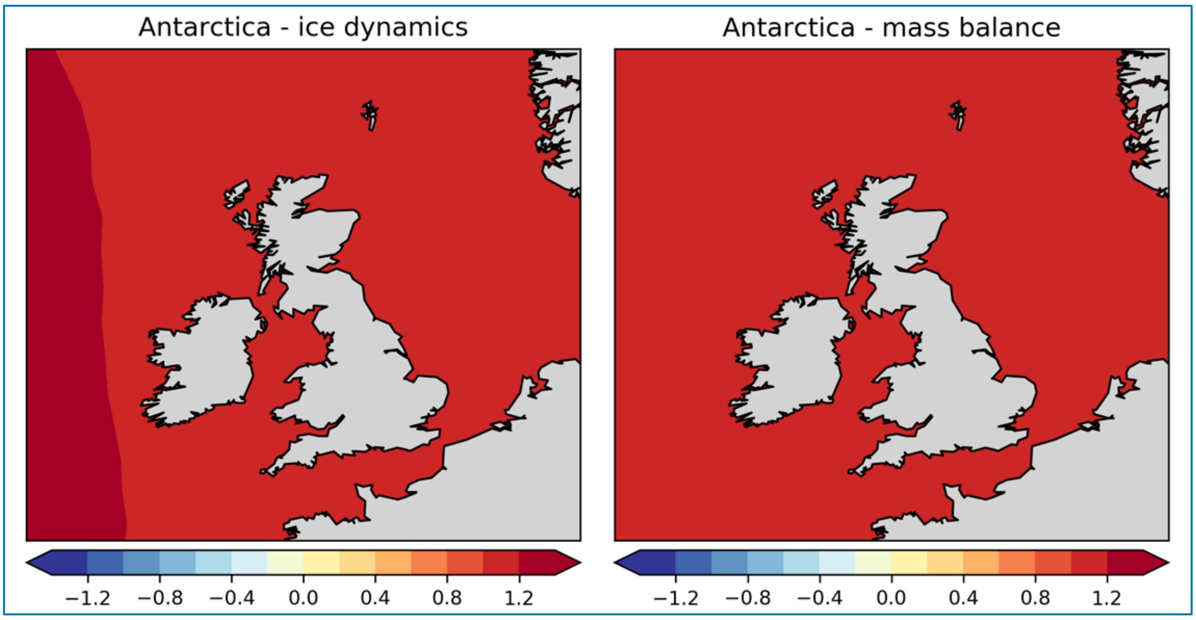

Figure 9 Fingerprint patterns of sea level rise adjustments necessary due to regional gravitational effects for Antarctic (lower). See for fingerprints for Greenland.

Table 4: Comparison of CMIP5 and Deconto and Pollard (2016) Antarctic contributions.

Scenario	CMIP5 Antarctic contribution in cm to GMSLR (*relative to 1986-2005, from IPCC SCROCC 2019 Table 4.4)*		Deconto and Pollard upper estimate of Antarctic contribution in cm (relative to 2000, from Deconto & Pollard (2016))		Deconto and Pollard lower estimate of Antarctic contribution (relative to 2000, from Deconto & Pollard (2016))	
RCP2.6	4	(1 to 11)	11	(0 to 22)	2	(-11 to 15)
RCP4.5	6	(1 to 15)	49	(29 to 69)	26	(-2 to 54)
RCP8.5	12	(3 to 28)	105	(75 to 135)	64	(15 to 115)

Table 4 it may seem that the Antarctic contributions to GMSLR in RCP8.5 of only a few cm by 2100 are trivial compared to the total GMSLR but in RCP8.5 which these values are based on does not include the same extent of marine instability or the self-enhancing feedback of ice shelf/ice cliff collapse that is included in the Deconto and Pollard (2016) experiment.

The UKCP18 RCP2.6 and RCP8.5 Antarctic contributions are replaced by the central estimate of Deconto and Pollard (2016) given in Table 4 and displayed alongside the original UKCP18 projections in Figure 10 for 4 UK Capital cities. It is clear from Figure 10 that when including Deconto and Pollard estimates of Antarctic melting (via MISI and MICI) that sea levels could rise far quicker than CMIP5-based projections from UKCP18 and IPCC suggest. So considerably accelerated Antarctic melting in the event of a tipping point could result in significantly higher levels of sea level rise of up to 2m by 2100 around the UK.

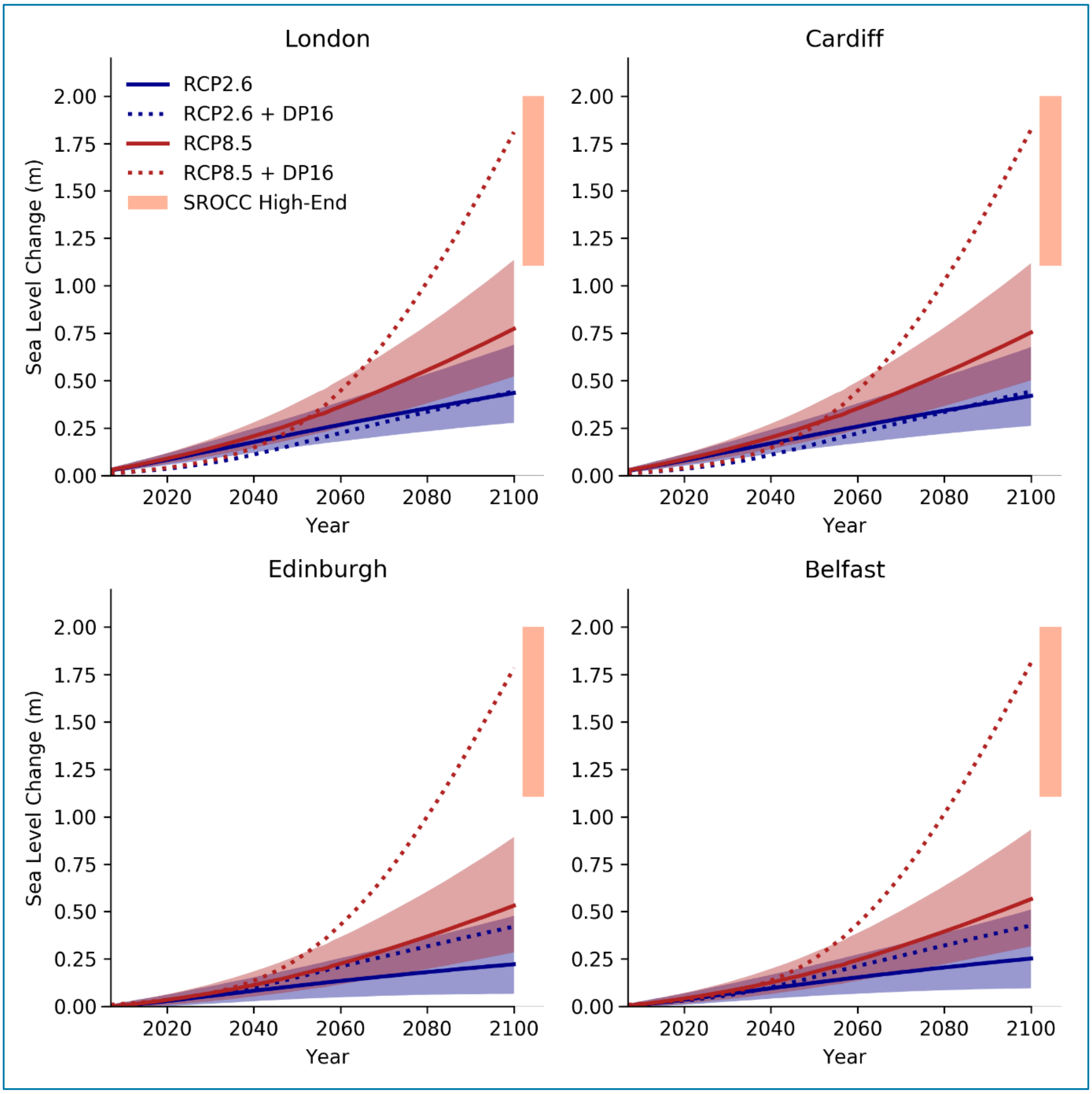

Figure 10: UKCP18 projections of sea level change up to 2100 at 4 locations around the UK close to major UK cities. The choice of these locations spans the range of sea level projections around the UK coastline. RCP2.6 projection is shown by a blue solid line, RCP8.5 is a red solid line with shading showing the uncertainty. These have been scaled with Deconto and Pollard estimates that include increased MISI and MICI shown by the dashed red line (RCP8.5) and dashed blue line (RCP2.6). Alongside in orange, is a high-end scenario range constructed based on the IPCC SROCC, which yields a very similar upper bound to the UKCP09 H++ scenario for the UK (Lowe et al, 2009).

3.3 Possible Impacts

There is no clear tipping point in this situation as Antarctica is already melting and having an effect on sea level, it is the highly uncertain melt rate, which could accelerate considerably, that we are considering here. The primary high-end scenario for UK sea level rises this century is based on IPCC SROCC, 2019. The lower bound is set as top of RCP8.5 likely range and upper bound is set at 2m. 2m is based primarily on expert elicitation studies and is a rise that cannot be ruled out (IPCC, SROCC 2019). Similarly, the H++ scenario for the UK presented in UKCP09 (Lowe et al, 2009), suggests an upper bound for the UK of 1.9m and this was based on paleo-evidence and kinematic constraints. Our adjustment to UKCP18 RCP8.5 projections with Deconto and Pollard Antarctic contribution estimates also gives evidence for up to 2m of sea level rise by 2100 around the UK (Figure 10). But only if additional Antarctic melting occurs, RCP8.5 does not reach 2m until at least the middle of the next (22nd) century (Figure 4f (global) and UKCP18, 2019 Figure 4.2.3 for UK capital cities). Suggesting, 2m of UK sea level rise could be realised if acceleration of Antarctic ice mass loss is accelerated beyond that accounted for by RCP8.5.

Regional sea level rise estimates are of major importance for coastal flooding risk and therefore coastal flood defence initiatives. An example of such is the Thames Estuary project (TE2100, Ranger et al. 2013) which is a plan to maintain resilience of Thames Estuary to future extreme water levels. The current estimates and plan align with the H++ scenario with sea level rise up to 2m and increase in surge of 0.95m combined to give a possible 2.95m increase in extreme sea level by 2100 (Howard et al. 2008) and this is expected to continue to increase even more beyond 2100. The TE2100 plan is also a good example of using 'Adaptation Pathways' considering the timing and sequence of adaptation measures required up to 2100 where there is large uncertainty in the projections of extreme sea level.

Essentially, sea level rise estimates currently considered, even with the highest emission scenarios, are far less than could be realised should a self-enhancing marine instability feedback increase Antarctic melting and accelerate the contribution Antarctic melting is making to Global and UK sea level rise. This is because "process-model based studies cannot yet provide this information, but expert elicitation studies show that a GMSL of 2 m in 2100 cannot be ruled out" (Chapter 4, IPCC, SROCC 2019)

Local variability of sea level could also increase, particularly if we start to see changes in tidal amplitude. Specifically, this could be through changes in extreme wave characteristics and storm surges linked to any changes in the jet stream or AMOC.

In the event of a tipping point of accelerating Antarctic melting, higher sea levels can be expected and sooner, so the levels predicted for 2100 and beyond could be realised earlier with up to 2m by 2100 at locations around the UK.

4 Regional climate changes

4.1 Atlantic thermohaline circulation (THC)/AMOC

The Atlantic Meridional overturning circulation (AMOC) transports heat northwards through the Atlantic Ocean resulting in a mild climate in the UK. It works by warm water from equatorial Atlantic travelling northwards where evaporation causes it to cool and become denser. The denser waters sink to a much lower depth of the ocean and are transported south where the circulation is completed through upwelling of waters to the surface caused by winds and mixing. In a warmer climate, projections suggest this circulation will weaken (IPCC AR5a) due to surface water retaining more heat and rainfall/ice melt injecting more freshwater into the ocean reducing its salt content. The weakening means the AMOC circulation would transport less heat northwards in the Atlantic which would cool the UK. Impacts of a gradually weakening AMOC are included in assessments based on model projections (IPCC AR5a) and show the cooling from AMOC weakening partially offsetting the warming from anthropogenic climate change in the UK. However, if the AMOC was to collapse, the impacts would be more severe, and the cooling could dominate.

AMOC shutdown is highly unlikely (IPCC SROCC), however were the AMOC to shut down, many more severe cold winters could be experienced in the UK, an impact that is not currently being considered in adaptation planning as the latest UK climate projections are indicating the opposite, (milder winters with fewer cold-weather related impacts on average), are most likely in a warmer climate (Hanlon et al 2021).

There are observations of AMOC strength and heat transport being taken in the North Atlantic (subtropics by RAPID[1] since 2004) and (subpolar by OSNAP[2] since 2014). Using RAPID measurements, the AMOC at 26.5°N was determined to be 17.2±0.9 Sv 2004-12 by McCarthy et al 2015 and it reduced to ~16Sv on average between 2008-2017 (Smeed et al. 2018), however longer observational records are required to determine whether this is an ongoing trend. Indirect evidence from 2017 observations based on Sea surface temperature reconstructions, show AMOC has weakened relative to 1850-1900 average (medium confidence) (IPCC SROCC). AMOC will very likely weaken further over the 21st century (high confidence) in response to increased greenhouse gases, as shown by coupled climate models (IPCC AR5a). Huge uncertainty remains as to the magnitude of the weakening but overall, it is likely there will be some decline by 2050 (IPCC AR5a). The latest results, using CMIP6 models project a possible AMOC decline between 6-8Sv which is a 34-45% reduction in strength by 2100 (Weijer et al. 2020).

AMOC total shutdown is very unlikely but substantial weakening remains physically plausible

[1] https://www.rapid.ac.uk/rapidmoc/
[2] https://www.o-snap.org/ and Lozier et al (2019)

(medium confidence). (IPCC SROCC, McCarthy et al 2020). Further ahead (although likely out of scope for this CCRA), by 2300 AMOC shutdown is "*as likely as not*" for high emission pathways so this longer-term risk could be mitigated by global CO_2 emission reduction (Medium confidence) (IPCC SROCC). For further confidence estimates of AMOC weakening, reasons for the weakening and possibility of shutdown before 2100 see McCarthy et al. 2020.

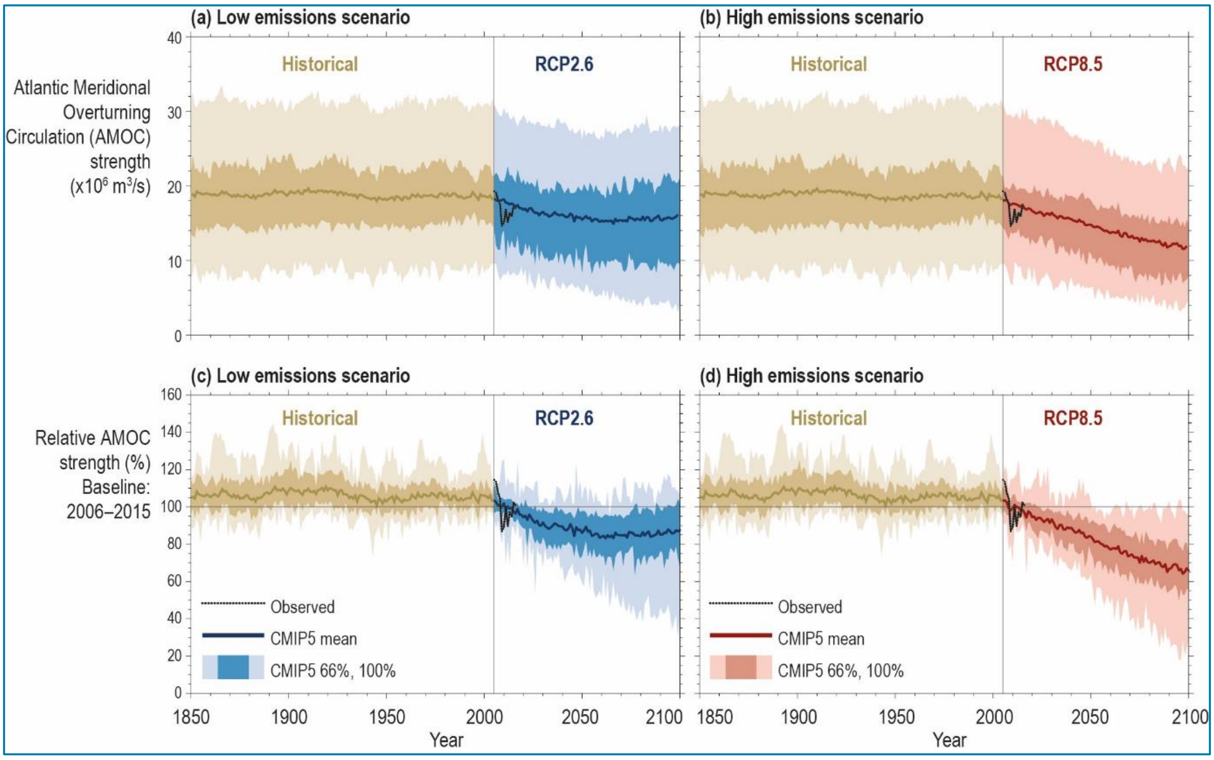

Figure 11: AMOC changes at 26°N as simulated by 27 models and observations from McCarthy et al. 2015. *Taken from IPCC SROCCC (Chapter 6, Figure 6.8, IPCC SROCCC).*

So even the highest RCP (RCP8.5) projects a substantial decrease this century but a shutdown is outside of the uncertainty range on these projections (Figure 11).

Most freshwater influx into the North Atlantic comes through mainly precipitation and affects the strength of AMOC. There are sources of additional freshwater input to the North Atlantic from Greenland land ice melt, Arctic sea-ice melt and through the Bering Strait to moderate the Precipitation/evaporation imbalance between the pacific and Atlantic oceans (Melling 2000). Various hosing experiments have been performed and show how additional freshwater influx into the North Atlantic could weaken the AMOC (Stouffer et al (2006), Hu et al (2011), Swingedouw et al (2013), Jackson & Wood (2018)) but these require large amounts of freshwater to shut down the AMOC compared to estimates of future additional freshwater input. However, the magnitude of the response to freshening is hugely variable across different models so there is large uncertainty in how AMOC could respond to rapid melting of Greenland for example. Also, as the real world AMOC response could be even more sensitive to freshening, shutdown this century is still considered a plausible, though very unlikely, scenario (IPCC SROCC).

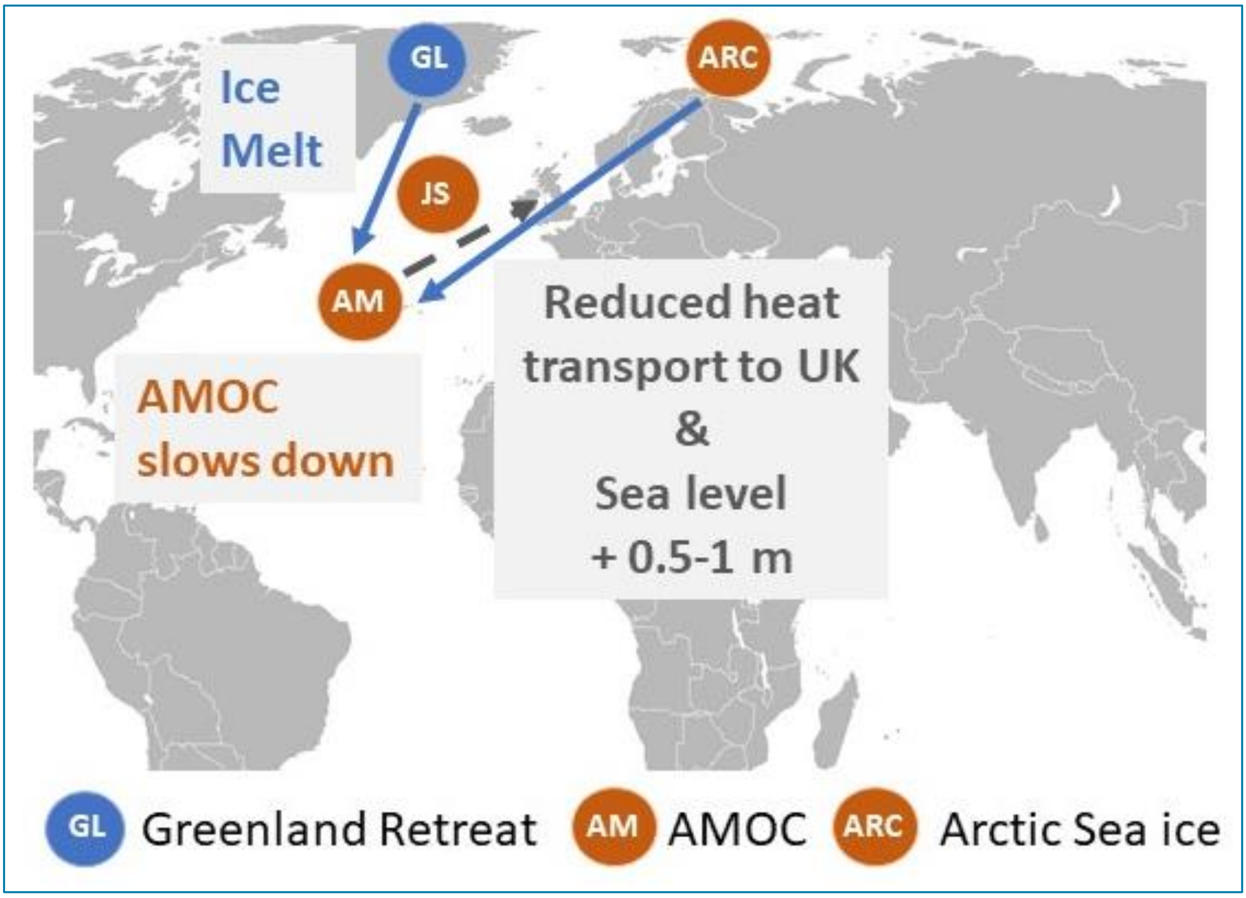

Figure 12: Diagram of process for UK Impact of AMOC shutdown.

4.1.1 Possible impacts

Modelling studies have shown that a shutdown of AMOC would lead to widespread cooling in the northern hemisphere, less precipitation in the northern hemisphere midlatitudes and a stronger North Atlantic storm track and southwards shift in the ITCZ (Jackson et al. 2015), along with a possible additional increase in local UK sea level of several tens of cm (Levermann et al 2005 (Figure 4), Vellinga & Wood 2008 (Figure 13), Katsman et al 2008 (Figure 5), Chen et al 2019(Figure S3)). Jackson et al (2015) consider European impacts especially and show that, given changes in circulation predicted by models, Europe (including the UK) could, should the process detailed in Figure 12 happen, experience these types of impacts:

- Cooling of several degrees
- Reduced rainfall (especially in Summer in conjunction with negative NAO)

- Increased winter storms which penetrate further inland due to strengthened storm track and localised increases to winter rainfall
- Increase in magnitude and duration of snowfall
- Stronger westerly winds in winter and weaker westerly winds in Summer
- Reduced river flow and surface water runoff which could moderate future flooding impacts
- Reduced vegetation and crop productivity due to cooling and decrease in water availability

Weaker AMOC would bring cooler conditions to the UK. Climate model simulations of AMOC collapse with HadGEM3 by Jackson et al. (2015) indicate a 3-7°C reduction in UK average surface temperatures, however the impact on UK temperatures of an AMOC reduction is model dependent and also dependent on the scenario. A large weakening of the AMOC with little global warming would result in colder UK temperatures, but a more gradual weakening would offset some of the warming from anthropogenic climate change. Using a climate model experiment where an abrupt AMOC collapse is forced Drijfhout (2015) shows AMOC collapse leading to a delay in global surface temperatures for up to 40-50 years. Which would delay the projected reduction in cold-weather related impacts expected in the UK due to climate change (Hanlon et al 2021).

Weaker AMOC would also lead to drier conditions to the UK as circulation pattern changes preventing the usual flow of Maritime air into Europe being cooler and reducing evaporation. This is particularly in summer (Jackson et al. 2015) which could increase drought impacts. However, in winter, only the eastern part of the UK sees drying as the western coast of UK is subject to increased storms due to extension eastwards of North Atlantic storm track.

Crop growth would also be impacted in the event of AMOC shutdown, Jackson et al. (2015) show large (up to 50%) reductions in net primary production across the UK with larger reductions seen in the North. Ritchie et al (2020) has shown that due to drying expected in a scenario where AMOC shutdown occurs by 2080 there would be at least 10% reduction in total income from Arable land farming without increased irrigation that reduction would be significantly larger if technological advances are invested in to meet the industry’s water demands the cost of which would be larger than the income it would generate. Overall Ritchie et al (2020) conclude climate change with an AMOC collapse would have an order of magnitude larger impact than it would without.

Despite reduced precipitation snowfall would increase in cold temperatures, particularly over higher ground, and snow event duration would also be longer (Vellinga& Wood 2002, Jacob et al 2005, Jackson et al. 2015)

Weakening of the AMOC would increase the meridional gradient in sea surface temperature in the North Atlantic that in turn would increase baroclinic instability which drive the storm track. Hence weakening AMOC strengthens the North Atlantic Storm track that also extends eastward towards Europe and would result in an increase in storms for the UK (Woollings et al. 2012, Jackson et al. 2015)

For further details see the Met Office AMOC factsheet at:
https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/climate/ocean-and-cryosphere-report/srocc_amoc.pdf

4.2 Arctic sea ice and snow cover reduction

Along with permafrost the Arctic also has large amounts of sea ice and snow cover which are also currently reducing in extent. Ice in the Arctic is sea ice which, unlike ice in Antarctica and Greenland, is floating on the sea so melting does not contribute to Sea level rise but does affect the global energy budget. As does spring snow cover in the Arctic region.

Arctic sea ice extent has been declining during all months of the year, with the strongest reductions seen in September at a rate of -12.8 ±2.3% per decade (1979-2018) (IPCC SROCC, 2019). The possible effect reduction in snow and sea ice cover would have is to reduce the polar albedo. Open ocean albedo is ~0.06 whereas sea ice albedo is ~0.5-0.7. So, as arctic sea ice and snow cover extent reduces, less incoming solar radiation is reflected, instead more being absorbed by the Arctic surface increasing net solar radiation absorption and therefore Arctic ocean temperature. This affects the global energy budget and could initiate a self-reinforcing feedback that accelerates global temperature rise and leads to further Arctic thaw (Flanner et al. (2011), Qu and Hall (2014) and Thackeray et al. (2016)).

The PAMIP modelling experiments (Smith et al. 2019), part of CMIP6, seek to further understand the causes and consequences of Polar amplification. Modelling studies have investigated how Polar amplification and resulting Arctic sea ice reduction could cause a dynamic response and changes to atmosphere and ocean circulation through changes to the positions of jet streams, storm tracks or planetary wave energy propagation. Such as:

- Weakening of the Atlantic meridional overturning circulation (AMOC) - see previous section on AMOC for the impacts that has on the UK- Sévellec et al. (2017) and Suo et al. (2017).
- A shift in the Intertropical Convergence Zone (ITCZ) (Chiang and Bitz, 2005) which could affect Sahel rainfall and tropical storm activity (Smith et al. 2017)
- Weakening of mid-latitude westerly winds because polar amplification reduces the Equator-to-pole surface temperature gradient, which could lead to cold winters in Europe (Smith et al. 2019).
- Increase in frequency of extreme weather events across the Northern Hemisphere mid-latitudes, including severe winters (Cohen et al. 2014)
- Increase in the probability of extreme events, including drought, flooding, cold spells, and heat waves due to slower eastward progression of Rossby waves that make the Northern hemisphere mid latitudes more susceptible to amplified and persistent weather patterns linked to those extremes (Francis and Vavrus, 2012)

- Simulations by (Screen, 2013) show Arctic sea ice loss causing a southward shift of the polar jet stream over Europe and increased northern European precipitation in Summer.

However, there remains a lack of consensus between climate modelling studies that look at the impact of reductions in Arctic sea ice. The physical mechanisms responsible for the modelling impacts are also not fully understood. These are the two main reasons motivating the PAMIP experiments (Smith et al. 2019) but currently it is not possible to hypothesise the effect a tipping point leading to rapid Arctic sea-ice loss may have globally or on the UK.

4.2.1 Possible Impacts

Changes in primary production of marine ecosystems in the region having an impact on polar fisheries. This would be further exacerbated by increased shipping activity in the region, especially likely in Arctic Summer as reduced ice extent improves accessibility to the region.

The main impact outside of the Arctic region, ie: the UK, would be though the acceleration of global temperatures leading to reaching warming levels earlier and hence impacts associated with higher warming levels.

Other impacts as suggested by the studies mentioned above, Arctic sea-ice loss could lead to colder winters, increase in frequency of extreme weather leading to severe cold winters, increased summer flooding, drought and heatwaves in Europe. However, due to disparity in the results of the different modelling studies this is a highly speculative hypothesis.

4.3 Change in North Atlantic Jet Stream

The North Atlantic Jet Stream is a core of strong winds around 5 to 7 miles above the Earth's surface, blowing across the North Atlantic from west to east. The position of the jet stream dictates the path weather systems and storms take across the North Atlantic towards the UK. Consequently, the position and strength of the Jet stream has a big impact on UK weather, influencing the frequency/magnitude of extremes, especially in Winter.

There is large variability in both the position and strength of the jet stream. The jet stream has 3 'preferred' positions – at around 35-38°N, 45-47°N and 58-60°N Woollings et al. (2010). The Jet stream often meanders from these positions. Depending on the strength of the Jet, these meanders can be small if the jet is strong or meanders tend to be larger if the jet is weak. The position can influence the type of weather the UK gets and meanders from its usual positions can cause extreme weather in the UK. Especially if the jet stalls in an unusual position, which is more likely when the jet is weaker, leading to more blocking events and high impact weather in the UK.

Francis and Vavrus 2012 propose that Arctic amplification due to Arctic sea ice decline may be weakening the jet stream. The result of this could be slower eastward progression of Rossby waves that make the Northern hemisphere mid-latitudes more susceptible to amplified or persistent weather patterns and an increase in the probability of extreme events, such as drought, flooding, cold spells, and heat waves.

Another suggestion, by Screen (2013), links Arctic sea ice loss to a southward shift of the jet stream that increases Northern Europe rainfall in Summer.

As discussed in section 4.2, the effects of Arctic amplification and Artic sea ice loss are still largely uncertain and lack consensus across studies so new experiments (PAMIP) to investigate this further are underway (Smith et al. 2019).

Some recent work on weather patterns, by McSweeney& Bett (2020) group defined types of weather pattern depending on associate jet stream position and link those to the differences in rainfall patterns associated with a strong jet in each of the three positions.

- When a strong jet is in the 'North' position (50-60°N) it brings wetter-than-average conditions to the northern Europe (Scotland and Scandinavia);
- Conversely in the 'South' position (30-40°N) it is Southern Europe (Spain and Mediterranean Europe) that receive greater than average rainfall.
- The UK experiences greater-than-average rainfall when a strong jet is in its 'Mid' position (40-50°N).

Analysis of future weather patterns with current projections show future increases in cyclonic and westerly wind conditions leading to mild/unsettled weather in UK in winter and reduction in Summer westerlies leading to more drier and settled weather in future summers (McSweeny & Thornton 2020). So, a southward shift of the jet stream and tendency towards less westerly weather patterns could act to magnify the impacts already projected for Summer. As such, the projected trend would be towards more mild/unsettled weather patterns in winter. As such, this influence is the opposite to the effect suggested in the event of a weaker Jetstream leading to cold spells, meaning the occurrence of a tipping point that leads to change in jet stream could have a different outcome than that currently expected from projections.

5 Discussion

How individual tipping points may affect the UK is summarised in Table 1. However, timing and order in which tipping points occur is also clearly important as they could influence each other, as one tipping point may precipitate another as per connections proposed by (Steffen et al. 2018, Lenton et al. 2019, Kriegler et al. 2009 and Cai et al. 2016).

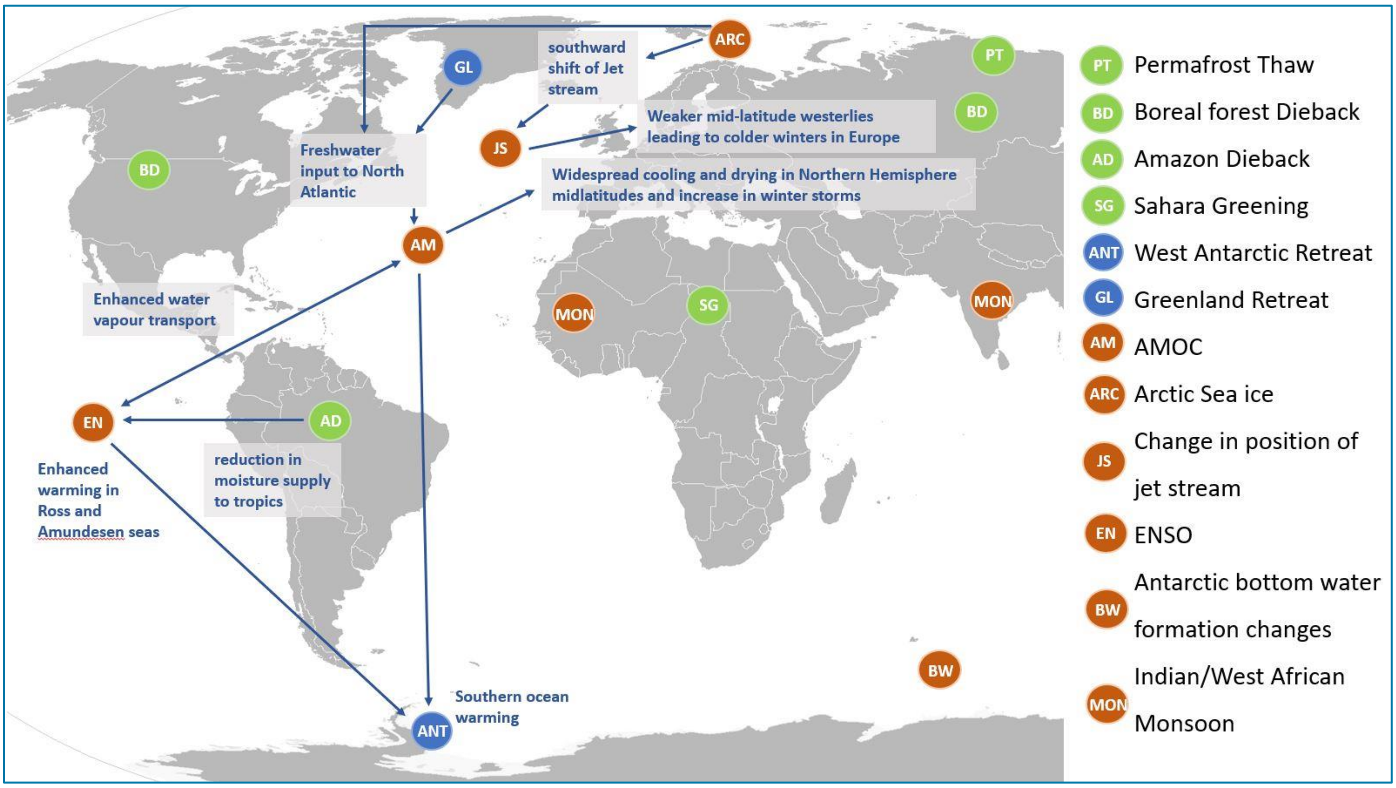

Figure 13 Tipping point interactions that could be important for UK impacts. Those represented by red circles are large-scale shifts in climate patterns causing regional climate changes. Blue circles are cryosphere changes that increase global sea level rise and subsequently UK sea levels. Green circles are tipping points that involve carbon-cycle or biogeochemical feedbacks that result in additional global warming thereby amplifying UK impacts due to global warming.

Considering how these tipping points could affect the UK (as discussed in Table 1), including tipping point interactions and mechanism by which they impact the UK (Figure 13), the following tipping points are important to consider as they could exaberate future UK impacts:

- Permafrost thaw, Amazon forest dieback and Boreal forest dieback involve carbon-cycle or biogeochemical feedbacks that result in additional global warming thereby amplifying UK impacts due to global warming.
- Greenland ice melt leading to AMOC weakening
- AMOC weakening leading to widespread cooling and drying in North hemisphere mid latitudes and stronger north Atlantic storm track and subsequent increase in winter storms.

- AMOC weakening leading to increase in ENSO variability (Timmermann et al. 2007)
- AMOC weakening leading to accelerated Antarctic Ice shelf melting due to enhanced warming in the Southern Ocean
- Arctic sea ice melting leading to change in position of the jet stream (southward)
- Southward shift in Jet stream would lead to weaker mid-latitude westerlies leading to colder winters in Europe.
- Accelerating Antarctic melting leading to faster sea level rise around the UK, sea levels predicted for 2100 and beyond could be realised earlier with up to 2m by 2100.
- Amazon dieback leading to an ENSO shift to a more persistent El Nino phase due to reduction in moisture supply to tropics
- ENSO leading to accelerated West Antarctic ice melt due to enhanced warming in Ross and Amundsen seas.

Uncertainty in the probability of abrupt changes such as these tipping points discussed above present considerable challenges to adaptation plans and decision making. This report has focussed purely on the physical impacts the UK may face should a tipping point be reached, however, there would likely be indirect effects such as supply chain breakdown and economic losses that could also result. Kopp et al. (2016) discusses economic implications of passing climate tipping points in more detail and suggests traditional cost-benefit analyses may not be so effective as the probability of these occurring is so hugely uncertain.

Ones not covered in this report but are considered in other literatures as potential tipping points are:

- Shift in location of West African monsoon
- Changes in Atlantic Deep-water formation
- Changes in Antarctic bottom water
- Change in strength of Indian summer monsoon causing disruption to agriculture and greater rainfall extremes in that region (Zickfeld et al. 2005)
- Sahara greening due to a shift in rainfall regime caused by a monsoon circulation switching on and acting to turn the normally very dry region into a wet one within just a few years (Schewe and Levermann 2017).
- Coral Reef Disappearing

These tipping point would have more localised effects, so it is less clear how the UK would be affected by these. Further investigation is required to assess if these could have an indirect impact on the UK or UK interests abroad.

References

Betts R.A. (2000). Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature*, *408*(6809), 187–190.

Betts R.A., P.M.Cox, M. Collins, P. P. Harris, C. Huntingford, and C. D. J. (2004). The role of ecosystem-atmosphere interactions in simulated Amazonian precipitation decrease and forest dieback under global climate warming. *Theoretical and Applied Climatology*, *78*, 157–175. https://doi.org/10.1007/s00704-004-0050-y

Betts, R., Sanderson, M., & Woodward, S. (2008). Effects of large-scale Amazon forest degradation on climate and air quality through fluxes of carbon dioxide, water, energy, mineral dust and isoprene. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1498), 1873–1880. https://doi.org/10.1098/rstb.2007.0027

Biskaborn, B. K., Smith, S. L., Noetzli, J., Matthes, H., Vieira, G., Streletskiy, D. A., Schoeneich, P., Romanovsky, V. E., Lewkowicz, A. G., Abramov, A., Allard, M., Boike, J., Cable, W. L., Christiansen, H. H., Delaloye, R., Diekmann, B., Drozdov, D., Etzelmüller, B., Grosse, G., … Lantuit, H. (2019). Permafrost is warming at a global scale. *Nature Communications*, *10*(1), 1–11. https://doi.org/10.1038/s41467-018-08240-4

Bonan, G. B., Pollard, D., & Thompson, S. L. (1992). Effects of boreal forest vegetation on global climate. *Nature*, *359*(6397), 716–718. https://doi.org/10.1038/359716a0

Bonan, G. B., Chapin, F. S., & Thompson, S. L. (1995). Boreal forest and tundra ecosystems as components of the climate system. *Climatic Change*, *29*(2), 145–167. https://doi.org/10.1007/BF01094014

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Bozbiyik, A., Steinacher, M., Joos, F., Stocker, T. F., & Menviel, L. (2011). Fingerprints of changes in the terrestrial carbon cycle in response to large reorganizations in ocean circulation. *Climate of the Past*, *7*(1), 319–338. https://doi.org/10.5194/cp-7-319-2011

Burke, E. J., Ekici, A., Huang, Y., Chadburn, S. E., Huntingford, C., Ciais, P., Friedlingstein, P., Peng, S., & Krinner, G. (2017). Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*, *14*(12), 3051–3066. https://doi.org/10.5194/bg-14-3051-2017

Burke, E. J., Chadburn, S. E., Huntingford, C., & Jones, C. D. (2018). CO_2 loss by permafrost thawing implies additional emissions reductions to limit warming to 1.5 or 2 C. *Environmental Research Letters*, *13*(2). https://doi.org/10.1088/1748-9326/aaa138

Burke, E., Zhang, Y., & Krinner, G. (2020). Evaluating permafrost physics in the CMIP6 models and their sensitivity to climate change. *The Cryosphere Discussions*, *February*, 1–33. https://doi.org/10.5194/tc-2019-309

Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016). Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nature Climate Change*, *6*(5), 520–525. https://doi.org/10.1038/nclimate2964

Cao, L., Bala, G., Caldeira, K., Nemani, R., & Ban-Weiss, G. (2010). Importance of carbon dioxide physiological forcing to future climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(21), 9513–9518. https://doi.org/10.1073/pnas.0913000107

Chen, C., Liu, W., & Wang, G. (2019). Understanding the Uncertainty in the 21st Century Dynamic Sea Level Projections: The Role of the AMOC. *Geophysical Research Letters*, *46*(1), 210–217. https://doi.org/10.1029/2018GL080676

Chiang, J. C. H., & Bitz, C. M. (2005). Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Climate Dynamics*, *25*(5), 477–496. https://doi.org/10.1007/s00382-005-0040-5

Church, J.A., J.M. Gregory, P. Huybrechts,M. Kuhn, K. Lambeck, M. T. Nhuan, D.Qin, and P. L.Woodworth, (2001). Changes in sea level. Climate Change 2001: The Scientific Basis, J. T. Houghton, Eds., Cambridge University Press, 639–693.

Church, J. A., Clark, P. U., Cazenave, A., Gregory, J. M., Jevrejeva, S., Levermann, A., Merrifield, M. A., Milne, G. A., Nerem, R. S., Nunn, P. D., Payne, A. J., Pfeffer, W. T., Stammer, D., and Unnikrishnan, A. S., (2013). Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark, P. U., Shakun, J. D., Marcott, S. A., Mix, A. C., Eby, M., Kulp, S., Levermann, A., Milne, G. A., Pfister, P. L., Santer, B. D., Schrag, D. P., Solomon, S., Stocker, T. F., Strauss, B. H., Weaver, A. J., Winkelmann, R., Archer, D., Bard, E., Goldner, A., … Plattner, G. K. (2016). Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change*, *6*(4), 360–369. https://doi.org/10.1038/nclimate2923

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., & Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*(9), 627–637. https://doi.org/10.1038/ngeo2234

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, *408*(6809), 184–187. https://doi.org/10.1038/35041539

DeConto, R. M., & Pollard, D. (2016). Contribution of Antarctica to past and future sea-level rise. *Nature*, *531*(7596), 591–597. https://doi.org/10.1038/nature17145

Douville, H., & Royer, J. F. (1996). Influence of the temperate and boreal forests on the Northern Hemisphere climate in the Météo-France climate model. *Climate Dynamics*, *13*(1), 57–74. https://doi.org/10.1007/s003820050153

Drijfhout, S. (2015). Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance. *Scientific Reports*, *5*(May), 1–12. https://doi.org/10.1038/srep14877

Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., … Wernecke, A. (2019). Revisiting Antarctic ice loss due to marine ice-cliff instability. *Nature*, *566*(7742), 58–64. https://doi.org/10.1038/s41586-019-0901-4

Favier, L., Durand, G., Cornford, S. L., Gudmundsson, G. H., Gagliardini, O., Gillet-Chaulet, F., … Le Brocq, A. M. (2014). Retreat of Pine Island Glacier controlled by marine ice-sheet instability. *Nature Climate Change*, *4*(2), 117–121. https://doi.org/10.1038/nclimate2094

Fowler, M. D., Kooperman, G. J., Randerson, J. T., & Pritchard, M. S. (2019). The effect of plant physiological responses to rising CO2 on global streamflow. *Nature Climate Change*, *9*(11), 873–879. https://doi.org/10.1038/s41558-019-0602-x

Flanner, M. G., Shell, K. M., Barlage, M., Perovich, D. K., & Tschudi, M. A. (2011). Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. *Nature Geoscience*, *4*(3), 151–155. https://doi.org/10.1038/ngeo1062

Francis, J. A., & Vavrus, S. J. (2012). Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, *39*(6), 1–6. https://doi.org/10.1029/2012GL051000

Gasser, T., Kechiar, M., Ciais, P., Burke, E. J., Kleinen, T., Zhu, D., Huang, Y., Ekici, A., & Obersteiner, M. (2018). Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release. *Nature Geoscience*, *11*(11), 830–835. https://doi.org/10.1038/s41561-018-0227-0

Golding, N., & Betts, R. (2008). Fire risk in Amazonia due to climate change in the HadCM3 climate model: Potential interactions with deforestation. *Global Biogeochemical Cycles*, *22*(4), 1–10. https://doi.org/10.1029/2007GB003166

Good, P., Bamber, J., Halladay, K., Harper, A. B., Jackson, L. C., Kay, G., … Williamson, P. (2018). Recent progress in understanding climate thresholds: Ice sheets, the Atlantic meridional overturning circulation, tropical forests and responses to ocean acidification. *Progress in Physical Geography*, *42*(1), 24–60. https://doi.org/10.1177/0309133317751843

Gregory, J. M. & Huybrechts, P. (2006) Ice-sheet contributions to future sea-level change. *Phil. Tran. R. Soc. A* **364**, 1709–1732 https://royalsocietypublishing.org/doi/10.1098/rsta.2006.1796

Hanlon, H.M., Bernie, D., Carigi, G. and Lowe, J.A. (2021) Future changes to high impact weather in the UK. *Climatic Change* DOI 10.1007/s10584-021-03100-5

Hirota, M., Holmgren, M., van Nes, E. H., & Scheffer, M. (2011). Global Resilience of Tropical Forest. *Science*, *334* (October), 232–235. https://doi.org/10.1126/science.1210657

Hoffmann, W. A., Geiger, E. L., Gotsch, S. G., Rossatto, D. R., Silva, L. C. R., Lau, O. L., Haridasan, M., & Franco, A. C. (2012). Ecological thresholds at the savanna-forest boundary: How plant traits, resources and fire govern the distribution of tropical biomes. *Ecology Letters*, *15*(7), 759–768. https://doi.org/10.1111/j.1461-0248.2012.01789.x

Howard, T., Lowe, J. A., Pardaens, A., Ridley, J., & Horsburgh, K. (2008). *Met Office Hadley Centre Projections of 21st Century Extreme Sea Levels for TE2100.* 54.

Hu, A., Meehl, G. A., Han, W., & Yin, J. (2011). Effect of the potential melting of the Greenland Ice Sheet on the Meridional Overturning Circulation and global climate in the future. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *58*(17–18), 1914–1926. https://doi.org/10.1016/j.dsr2.2010.10.069

Ineson, S., & Scaife, A. A. (2009). The role of the stratosphere in the European climate response to El Nĩo. *Nature Geoscience*, *2*(1), 32–36. https://doi.org/10.1038/ngeo381

[IPCC SROCC], Collins M., M. Sutherland, L. Bouwer, S.-M. Cheong, T. Frölicher, H. Jacot Des Combes, M. Koll Roxy, I. Losada, K. McInnes, B. Ratter, E. Rivera-Arriaga, R.D. Susanto, D. Swingedouw, and L. Tibig, 2019: Extremes, Abrupt Changes and Managing Risk. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

[IPCC AR5a] Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi and H.J. Wang, 2013: Near-term Climate Change: Projections and Predictability. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[IPCC AR5b] Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang, 2013: Observations: Cryosphere. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[IPCC AR5c] Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In:

Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[IPCC AR5d] Settele, J., R. Scholes, R. Betts, S. Bunn, P. Leadley, D. Nepstad, J.T. Overpeck, and M.A. Taboada, 2014: Terrestrial and inland water systems. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.

[IPCC SRCCL] Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press. https://www.ipcc.ch/srccl/chapter/chapter-2/

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woollings, T., Mecking, J. V., & Wood, R. A. (2015). Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate Dynamics*, *45*(11–12), 3299–3316. https://doi.org/10.1007/s00382-015-2540-2

Jackson, L. C., & Wood, R. A. (2018). Timescales of AMOC decline in response to fresh water forcing. *Climate Dynamics*, *51*(4), 1333–1350. https://doi.org/10.1007/s00382-017-3957-6

Jacob, D., Goettel, H., Jungclaus, J., Muskulus, M., Podzun, R., & Marotzke, J. (2005). Slowdown of the thermohaline circulation causes enhanced maritime climate influence and snow cover over Europe. *Geophysical Research Letters*, *32*(21), 1–5. https://doi.org/10.1029/2005GL023286

Joughin, I., Smith, B. E., & Medley, B. (2014). Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science*, 344, 735–739.

Katsman, C. A., Hazeleger, W., Drijfhout, S. S., Van Oldenborgh, G. J., & Burgers, G. (2008). Climate scenarios of sea level rise for the northeast Atlantic Ocean: A study including the effects of ocean dynamics and gravity changes induced by ice melt. *Climatic Change*, *91*(3–4), 351–374. https://doi.org/10.1007/s10584-008-9442-9

Kooperman, G. J., Fowler, M. D., Hoffman, F. M., Koven, C. D., Lindsay, K., Pritchard, M. S., Swann, A. L. S., & Randerson, J. T. (2018). Plant Physiological Responses to Rising CO2 Modify Simulated Daily Runoff Intensity With Implications for Global-Scale Flood Risk Assessment. *Geophysical Research Letters*, *45*(22), 12,457-12,466. https://doi.org/10.1029/2018GL079901

Kopp, R. E., Shwom, R. L., Wagner, G., & Yuan, J. (2016). Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, *4*(8), 346–372. https://doi.org/10.1002/2016EF000362

Kriegler, E., Hall, J. W., Held, H., Dawson, R., & Joachim, H. (2009). Imprecise probability assessment of tipping points. *Pnas*, *106*(13), 5041–5046. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2657590&tool=pmcentrez&rendertype=abstract

Lawrence, D., & Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, *5*(1), 27–36. https://doi.org/10.1038/nclimate2430

Leipprand, A., & Gerten, D. (2006). Global effects of doubled atmospheric CO_2 content on evapotranspiration, soil moisture and runoff under potential natural vegetation. *Hydrological Sciences Journal*, *51*(1), 171–185. https://doi.org/10.1623/hysj.51.1.171

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., & Schellnhuber, H. J. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(6), 1786–1793. https://doi.org/10.1073/pnas.0705414105

Lenton, T. M., & Ciscar, J. C. (2013). Integrating tipping points into climate impact assessments. *Climatic Change*, *117*(3), 585–597. https://doi.org/10.1007/s10584-012-0572-8

Lenton, T., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Shellnhuber, H. J. (2019). Climate tipping points - too risky to bet against. *Nature*, *575*, 592–595.

Levermann, A., Griesel, A., Hofmann, M., Montoya, M., & Rahmstorf, S. (2005). Dynamic sea level changes following changes in the thermohaline circulation. *Climate Dynamics*, *24*(4), 347–354. https://doi.org/10.1007/s00382-004-0505-y

Lozier, M.S., F. Li, S. Bacon, F. Bahr, A.S. Bower, S.A. Cunningham, M.F. de Jong, L. de Steur, B. DeYoung, J. Fischer, S.F. Gary, N.J.W. Greenan, N.P. Holliday, A. Houk, L. Houpert, M.E. Inall, W.E. Johns, H.L. Johnson, C. Johnson, J. Karstensen, G. Koman, I.A. LeBras, X. Lin, N. Mackay, D.P. Marshall, H. Mercier, M. Oltmanns, R.S. Pickart, A.L. Ramsey, D. Rayner, F. Straneo, V. Thierry, D.J. Torres, R.G. Williams, C. Wilson, J. Yang, I. Yashayaev, and J. Zhao, 2019. A Sea Change in Our View of Overturning in the Subpolar North Atlantic. *Science*, doi: 10.1126/science.aau6592

Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S., Bradley, S. (2009), UK Climate Projections science report: Marine and coastal projections. Met Office Hadley

Centre, Exeter, UK.

McCarthy, G. D., Smeed, D. A., Johns, W. E., Frajka-Williams, E., Moat, B. I., Rayner, D., … Bryden, H. L. (2015). Measuring the Atlantic Meridional Overturning Circulation at 26°N. *Progress in Oceanography*, *130*, 91–111. https://doi.org/10.1016/j.pocean.2014.10.006

McCarthy, G. D., Jackson, L. C., Cunningham, S. A., & Holliday, N. P. (2020). *Effects of climate change on the Atlantic Heat Conveyor relevant to the UK*. MCCIP Science Review 2020, 190–207. https://doi.org/10.14465/2020.arc09.ahc

McSweeney, C. & Bett, P. (2020) UKCP European Circulation Indices: Jet Stream Position and Strength. UKCP Factsheet. Met Office. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_factsheet_jet_stream.pdf

McSweeney, C. & Thornton, H. (2020) UKCP European Circulation Indices: Weather Patterns. UKCP Factsheet. Met Office. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18_factsheet_weather_patterns.pdf

Meissner, K. J., Weaver, A. J., Matthews, H. D., & Cox, P. M. (2003). The role of land surface dynamics in glacial inception: A study with the UVic Earth System Model. *Climate Dynamics*, *21*(7–8), 515–537. https://doi.org/10.1007/s00382-003-0352-2

Melling H. (2000) Exchanges of Freshwater through the Shallow Straits of the North American Arctic. In: Lewis E.L., Jones E.P., Lemke P., Prowse T.D., Wadhams P. (eds) *The Freshwater Budget of the Arctic Ocean*. NATO Science Series (Series 2. Environment Security), vol 70. 479–502. https://doi.org/10.1007/978-94-011-4132-1_20 Springer, Dordrecht

Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P., Mcguire, A. D., Romanovsky, V. E., Sannel, A. B. K., Schuur, E. A. G., & Turetsky, M. R. (2016). Circumpolar distribution and carbon storage of thermokarst landscapes. *Nature Communications*, *7*, 1–11. https://doi.org/10.1038/ncomms13043

Palmer, M. D., Howard, T. P., Tinker, J., Lowe, J., Bricheno, L., Calvert, D., … Wolf, J. (2018). *UKCP18 Marine Report*. Met Office (November), 133.

Palmer, M. D., Gregory, J. M., Bagge, M., Calvert, D., Hagedoorn, J. M., Howard, T., Klemann, V., Lowe, J. A., Roberts, C. D., Slangen, A. B. A., & Spada, G. (2020). *Exploring the Drivers of Global and Regional Sea-Level Change over the 21st Century and Beyond*. https://doi.org/10.1029/2019EF001413

Parsons LA, Yin JJ, Overpeck JT, et al. (2014) Influence ofthe Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics. Geophysical Research Letters 41: 146–151.

Pattyn, F., Ritz, C., Hanna, E., Asay-Davis, X., DeConto, R., Durand, G., Favier, L., Fettweis, X., Goelzer, H., Golledge, N. R., Kuipers Munneke, P., Lenaerts, J. T. M., Nowicki, S., Payne, A. J., Robinson, A., Seroussi, H., Trusel, L. D., & van den Broeke, M. (2018). The Greenland and Antarctic ice sheets under 1.5 °C global warming. *Nature Climate Change*, *8*(12), 1053–1061. https://doi.org/10.1038/s41558-018-0305-8

Pollard, D., Deconto, R. M., & Alley, R. B. (2015). Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure. *Earth and Planetary Science Letters*, *412*, 112–121. https://doi.org/10.1016/j.epsl.2014.12.035

Qu, X., & Hall, A. (2014). On the persistent spread in snow-albedo feedback. *Climate Dynamics*, *42*(1–2), 69–81. https://doi.org/10.1007/s00382-013-1774-0

Ranger, N., Reeder, T., & Lowe, J. (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes*, *1*(3–4), 233–262. https://doi.org/10.1007/s40070-013-0014-5

Ridley, J., Gregory, J. M., Huybrechts, P., & Lowe, J. (2010). Thresholds for irreversible decline of the Greenland ice sheet. *Climate Dynamics*, *35*(6), 1065–1073. https://doi.org/10.1007/s00382-009-0646-0

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl (2014), Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, *Geophysical Research Letters,* 41, 3502–3509, doi:10.1002/2014GL060140.

Ritchie, P. D. L., Smith, G. S., Davis, K. J., Fezzi, C., Halleck-Vega, S., Harper, A. B., … Bateman, I. J. (2020). Shifts in national land use and food production in Great Britain after a climate tipping point. *Nature Food*, *1*(1), 76–83. https://doi.org/10.1038/s43016-019-0011-3

Robinson, A., Calov, R., & Ganopolski, A. (2012). Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change*, *2*(6), 429–432. https://doi.org/10.1038/nclimate1449

Schewe, J., & Levermann, A. (2017). Non-linear intensification of Sahel rainfall as a possible dynamic response to future warming. *Earth System Dynamics*, *8*(3), 495–505. https://doi.org/10.5194/esd-8-495-2017

Screen, J. A. (2013). Influence of Arctic sea ice on European summer precipitation. *Environmental Research Letters*, *8*(4). https://doi.org/10.1088/1748-9326/8/4/044015

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., & Vonk, J. E. (2015). Climate change and the permafrost carbon feedback. *Nature*, *520*(7546), 171–179. https://doi.org/10.1038/nature14338

Sévellec, F., Fedorov, A. V., & Liu, W. (2017). Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation. *Nature Climate Change*, *7*(8), 604–610.

https://doi.org/10.1038/NCLIMATE3353

Shennan, I., Milne, G., and Bradley, S., (2012). Late Holocene vertical land motion and relative sea level changes: lessons from the British Isles, Journal of Quaternary Science, 27, 64-70. https://doi.org/10.1002/jqs.1532

Slangen, A. B. A., Carson, M., Katsman, C. A., van de Wal, R. S. W., Köhl, A., Vermeersen, L. L. A., & Stammer, D. (2014). Projecting twenty-first century regional sea-level changes. *Climatic Change*, *124*(1–2), 317–332. https://doi.org/10.1007/s10584-014-1080-9

Smeed, D. A., Josey, S. A., Beaulieu, C., Johns, W. E., Moat, B. I., Frajka-Williams, E., … McCarthy, G. D. (2018). The North Atlantic Ocean Is in a State of Reduced Overturning. *Geophysical Research Letters*, *45*(3), 1527–1533. https://doi.org/10.1002/2017GL076350

Smith, D. M., Dunstone, N. J., Scaife, A. A., Fiedler, E. K., Copsey, D., & Hardiman, S. C. (2017). Atmospheric response to Arctic and Antarctic sea ice: The importance of ocean-atmosphere coupling and the background state. *Journal of Climate*, *30*(12), 4547–4565. https://doi.org/10.1175/JCLI-D-16-0564.1

Smith, D. M., Screen, J. A., Deser, C., Cohen, J., Fyfe, J. C., García-Serrano, J., Jung, T., Kattsov, V., Matei, D., Msadek, R., Peings, Y., Sigmond, M., Ukita, J., Yoon, J.-H., & Zhang, X. (2019). The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification. *Geoscientific Model Development Discussions*, 12, 1139-1164 https://doi.org/10.5194/gmd-2018-82

Snyder, P. K., Delire, C., & Foley, J. A. (2004). Evaluating the influence of different vegetation biomes on the global climate. *Climate Dynamics*, *23*(3–4), 279–302. https://doi.org/10.1007/s00382-004-0430-0

Solgaard, A. M., & Langen, P. L. (2012). Multistability of the Greenland ice sheet and the effects of an adaptive mass balance formulation. *Climate Dynamics*, *39*(7–8), 1599–1612. https://doi.org/10.1007/s00382-012-1305-4

Spada, G., & Stocchi, P. (2007). SELEN: A Fortran 90 program for solving the "sea-level equation." *Computers & Geosciences*, *33*(4), 538–562. https://doi.org/https://doi.org/10.1016/j.cageo.2006.08.006

Staver, A. C., Archibald, S., & Levin, S. A. (2011). The global extent and determinants of savanna and forest as alternative biome states. *Science*, *334*(6053), 230–232. https://doi.org/10.1126/science.1210465

Steffen, W., Rockström, J., Richardson, K., Lenton, T. M., Folke, C., Liverman, D., Summerhayes, C. P., Barnosky, A. D., Cornell, S. E., Crucifix, M., Donges, J. F., Fetzer, I., Lade, S. J., Scheffer, M., Winkelmann, R., & Schellnhuber, H. J. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(33), 8252–8259. https://doi.org/10.1073/pnas.1810141115

Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A.

J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., Robitaille, D. Y., Sokolov, A., Vettoretti, G. & Weber, S. L. (2006). Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes. *J. Climate*, 19. doi: 10.1175/JCLI3689.1

Swann, A. L. S., Hoffman, F. M., Koven, C. D., & Randerson, J. T. (2016). Plant responses to increasing CO_2 reduce estimates of climate impacts on drought severity. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(36), 10019–10024. https://doi.org/10.1073/pnas.1604581113

Swingedouw, D., Rodehacke, C., Behrens, E., Menary, M., Olsen, S., Gao, Y., Mikolajewicz, U., Mignot, J. & Biastoch, A. (2013). Decadal fingerprints of freshwater discharge around Greenland in a multi-model ensemble. *Climate Dynamics*, 41, 695--720. doi: 10.1007/s00382-012-1479-9

Suo, L., Gao, Y., Guo, D., & Bethke, I. (2017). Sea-ice free Arctic contributes to the projected warming minimum in the North Atlantic. *Environmental Research Letters*, *12*(7). https://doi.org/10.1088/1748-9326/aa6a5e

Thackeray, C. W. and C. G. Fletcher, 2016: Snow albedo feedback: Current knowledge, importance, outstanding issues and future directions. Progress in Physical Geography, 40 (3), 392-408, https://doi.org/10.1177/0309133315620999

Timmermann, A., Okumura, Y., An, S. I., Clement, A., Dong, B., Guilyardi, E., Hu, A., Jungclaus, J. H., Renold, M., Stocker, T. F., Stouffer, R. J., Sutton, R., Xie, S. P., & Yin, J. (2007). The influence of a weakening of the Atlantic meridional overturning circulation on ENSO. *Journal of Climate*, *20*(19), 4899–4919. https://doi.org/10.1175/JCLI4283.1

Thomas, G., & Rowntree, P. R. (1992). The Boreal Forests and Climate. *Quarterly Journal of the Royal Meteorological Society*, *118*(505), 469–497. https://doi.org/10.1002/qj.49711850505

Toniazzo, T., & Scaife, A. A. (2006). The influence of ENSO on winter North Atlantic climate. *Geophysical Research Letters*, *33*(24), 1–5. https://doi.org/10.1029/2006GL027881

Turetsky, M. R., Jones, M. C., Walter Anthony, K., Olefeldt, D., Schuur, E. A. G., Koven, C., Mcguire, A. D., & Grosse, G. (2019). Permafrost collapse is accelerating carbon release. *Nature*, *569*, 32–24. https://www.nature.com/articles/d41586-019-01313-4

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., & McGuire, A. D. (2020). Carbon release through abrupt permafrost thaw. *Nature Geoscience*, *13*(2), 138–143. https://doi.org/10.1038/s41561-019-0526-0

Vellinga, M., & Wood, R. A. (2002). Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change*, *54*(3), 251–267. https://doi.org/10.1023/A:1016168827653

Vellinga, M., & Wood, R. A. (2008). Impacts of thermohaline circulation shutdown in the twenty-first century. *Climatic Change*, *91*(1–2), 43–63. https://doi.org/10.1007/s10584-006-9146-y

Walter Anthony, K., Schneider von Deimling, T., Nitze, I., Frolking, S., Emond, A., Daanen, R., Anthony, P., Lindgren, P., Jones, B., & Grosse, G. (2018). 21St-Century Modeled Permafrost Carbon Emissions Accelerated By Abrupt Thaw Beneath Lakes. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-05738-9

Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 Models Predict Significant 21st Century Decline of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters*, *47*(12). https://doi.org/10.1029/2019GL086075

Woollings, T., Hannachi, A., & Hoskins, B. (2010). Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society*, *136*(649), 856–868. https://doi.org/10.1002/qj.625

Woollings, T., Gregory, J. M., Pinto, J. G., Reyers, M., & Brayshaw, D. J. (2012). Response of the North Atlantic storm track to climate change shaped by ocean-atmosphere coupling. *Nature Geoscience*, *5*(5), 313–317. https://doi.org/10.1038/ngeo1438

Zhang, T., Heginbottom, J. A., Barry, R. G., and Brown, J. (2000): Further statistics on the distribution of permafrost and ground ice in the Northern Hemisphere, Polar Geography, 24, 126–131, https://doi.org/10.1080/10889370009377692

Zickfeld, K., Knopf, B., Petoukhov, V., & Schellnhuber, H. J. (2005). Is the Indian summer monsoon stable against global change? *Geophysical Research Letters*, *32*(15), 1–5. https://doi.org/10.1029/2005GL022771