TIPPING POINTS IN THE EARTH SYSTEM

Observable Early Warning Systems for AMOC collapse, suitable for use in a changing climate, and interactions with other Tipping Elements

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Summary for publication

The Atlantic Meridional Overturning Circulation, or AMOC, is a global system of ocean currents that plays a fundamental role in the world's climate. In the North Atlantic the AMOC brings warm, salty surface water northwards from low latitudes. The heat is lost to the atmosphere at higher latitudes in the North Atlantic, and this heat makes the climate of much of Europe warmer than it would be if the AMOC were not there. Once the ocean water has given up its heat it becomes colder, and hence denser, so it sinks to deep below the ocean surface, where it flows back to the south. The deep water rises back up to the surface in other parts of the world's ocean, completing the circuit (Figure). For this reason the AMOC is sometimes described as a 'conveyor belt' circulation. It acts rather like a central heating system: the water is heated in low latitudes (the 'boiler'), carried by the ocean currents ('pipes') to the North Atlantic (the 'radiator'), where the heat is given up to the overlying air. The water is pumped around the system by the different densities of water (affected by both the temperature and the salinity or saltiness), and by the effects of wind which sucks cold water up to the surface in some parts of the world ocean. Changes to temperature (e.g. due to global warming) or salinity (e.g. due to fresh water input from a shrinking Greenland ice sheet, or changes in rainfall) affect the density of sea water, and so affect the strength of the 'pump'.

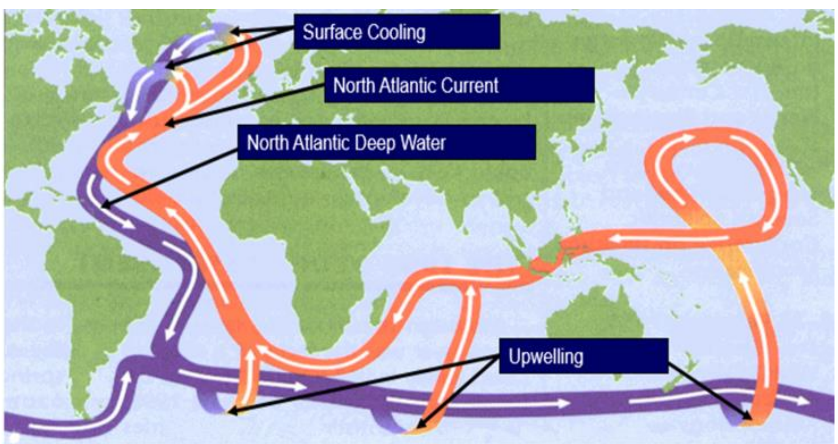

Figure: A schematic of the AMOC or 'conveyor belt' ocean circulation. Courtesy Met Office, UK

For many years, scientists have known that there is a theoretical possibility for the AMOC to cross a 'tipping point', and collapse from its current strong state, to a state with much weaker flow. If this were to happen there would be widespread impacts on climate: Europe and the rest of the Northern Hemisphere would become much cooler, and we would see large shifts in global patterns of rainfall. There is evidence that such changes in the AMOC have happened in the distant past, but could they happen over the coming decades or centuries?

Climate models are used to project changes in climate in the future due to emissions of greenhouse gases such as carbon dioxide. There is a strong agreement among different climate models that the AMOC will weaken over the 21st Century as climate warms, but the amount of weakening is uncertain. The effects of this AMOC weakening on climate are already included in climate projections, summarised by the Intergovernmental Panel on Climate Change (IPCC). The climate model projections do not generally show the AMOC crossing a tipping point in the 21st Century. However, there are still uncertainties in how climate models represent the AMOC. For this reason the IPCC recently concluded that there was only 'medium confidence' that the AMOC will not collapse. It is perhaps best to consider AMOC collapse as an unlikely event, but one that would have huge impacts if it were to happen. Such low likelihood but high impact events are an important part of the overall risks of climate change. An analogy from everyday life might be the risk of a house fire, which is unlikely but would have devastating impacts. We might manage this risk by installing a smoke alarm as an early warning device.

In this work we aim to improve understanding of whether a collapse of the AMOC could happen in future as a result of global warming, and to develop tools that could help society to become resilient to this risk. We especially focus on the possibility of developing an early warning system that would allow time to adapt or to accelerate efforts to slow down climate change, if it were discovered that an AMOC collapse was imminent. We have also worked to improve understanding of the impact of an AMOC collapse, if it occurred, on another area of the climate system that is vulnerable to tipping points, namely the Amazon rainforest. These are our key findings:

- Because direct, continuous observations of the AMOC only started in 2004, our knowledge of how the AMOC has been evolving in the recent past is limited. We have developed ways of using other observations with a longer past record (such as ocean surface temperature), to extend our knowledge of the AMOC back in time. We have discovered that a range of different indirect observations is needed to detect all possible types of AMOC change.

- We have explored various ways in which these indirect observations could be used to provide early warning of AMOC collapse. Some of the observations suggest that the AMOC has been coming closer to a tipping point over the past 120-150 years.

- Working with climate modelling colleagues internationally, we have run a set of standardised climate model experiments that we are analysing to understand the key factors that determine whether the AMOC will collapse, and whether it could recover if climate change were reversed. We expect this to lead to improvements in the way future climate models represent the AMOC.

- A lot of previous theoretical research on AMOC collapse has considered a rather idealised scenario in which fresh water (from the shrinking Greenland ice sheet) is the only factor influencing AMOC changes. We have extended the theory to a more realistic case where changes in heating and rainfall, due to global warming, are combined with Greenland ice sheet changes to produce AMOC changes. We have identified how a few key properties of the climate system affect AMOC tipping points. If we can better measure those key properties we will improve our knowledge of the risks of AMOC collapse. We find that the response of the Greenland ice sheet to warming is one of those key factors, and this confirms that the previous theory is still relevant.

- We have used new, higher resolution climate models to produce a more detailed assessment of the impacts of an AMOC collapse on the Amazon basin. The new models allow us to resolve rainfall changes in different parts of the basin and different seasons. Overall the results do not suggest that an AMOC collapse would destabilise the Amazon rainforest.

There is still a great deal of research and development needed before a practical early warning system for AMOC collapse can be put in place. However, our results have taken a number of important steps on that path.

Work carried out

Note: TiPES publications are referenced with a *, e.g. Boers 2021*

Starting point:
The possibility of tipping behaviour in the AMOC was first introduced by Stommel (1962). Since then the possibility of AMOC tipping and the existence of bistable AMOC states has been shown in a range of models, from the simple box model used by Stommel, right up to complex climate general circulation models (GCMs). This framework has been used to interpret abrupt changes in the palaeoclimate record. While there is consensus that AMOC tipping is a theoretical possibility, there is little agreement on how close to tipping the present AMOC may be, or even how to estimate this. Likewise, while there is broad agreement that global warming will result in a weakening of the AMOC over the 21st Century, there is a wide range of projections of how much weakening will occur (IPCC 2021). Furthermore, research on AMOC tipping points and on AMOC response to increasing greenhouse gases has to a large extent followed parallel paths, with much of the work on tipping points being driven by idealised scenarios of fresh water input to the North Atlantic, independent of any effects of warming. These factors led IPCC 2021 to conclude:

"The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all emissions scenarios. While there is high confidence in the 21st century decline, there is only low confidence in the magnitude of the trend. There is medium confidence that there will not be an abrupt collapse before 2100. If such a collapse were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons, and drying in Europe"

This suggests that AMOC tipping should be considered a high impact, but low likelihood outcome. As also recognised by IPCC 2021, such outcomes are a key component of climate risk.

Work carried out in Task 3.1:
The work to date in Task 3.1 aims to develop capabilities to manage the high impact, low likelihood risk of AMOC tipping, and to improve some of the deficiencies in current scientific understanding, through four strands of work:

1. Identify suitable AMOC proxies or 'fingerprints' to detect AMOC changes, and to provide early warning of tipping
2. Extend 'traditional' understanding of AMOC response to fresh water input, to include CMIP6-class GCMs and to seek unifying understanding of what determines the different tipping responses among different models
3. Build a theoretical understanding of possible AMOC tipping responses to the more realistic scenario of increasing greenhouse gases rather than fresh water input, and determine what parameters of the climate change response determine whether the AMOC will tip.
4. Improve understanding of connections between AMOC tipping and other tipping elements, specifically the Amazon

We discuss progress on each of these strands in turn.

Strand 1: Detection and early warning of AMOC tipping through AMOC 'fingerprints'

Detection of future long-term changes in the AMOC will require a suitably long observed timeseries. Similarly, timeseries analysis methods for identifying early warning signals through decreasing restoring rates, commonly measured in terms of increasing variance and autocorrelation (‘critical slowing down’), require a timeseries long enough for trends to emerge. First, the different indicators of critical slowing down have to be estimated on sliding windows and each of these windows needs to be sufficiently large to obtain reliable statistical estimates of the indicators; secondly, there needs to be sufficient time coverage so that meaningful trends can be inferred. Continuous observations of the AMOC through the RAPID-MOCHA array are only available since 2004, and other AMOC timeseries such as OSNAP and SAMOC/SAMBA are even shorter. This is insufficient time to detect clear trends over natural variability. Therefore, there is considerable interest in using observational AMOC proxies or ‘fingerprints’, i.e. observable variables that are highly correlated with the AMOC strength, but for which a longer timeseries is available, or natural variability is weak leading to a strong signal-to-noise ratio for the AMOC change. In this work we consider proxies based on the instrumental record, recognising that palaeoclimatic proxies offer the potential to extend further back in time.

In Boers 2021* we have used a range of sea-surface-temperature (SST) and subsurface (top 300m) salinity-based AMOC fingerprints from observation-based reconstructions over the past 120-150 years (Fig. 1a,b), to look for signs of critical slowing down that could be used to anticipate that the AMOC might be approaching a critical transition. For seven of the eight fingerprints there is a significant increase in variance and autocorrelation (not shown here) over the observation period, suggesting an approach towards a tipping point. A more robust ‘restoring rate’ indicator has been constructed that is independent of any temporal changes in the internal noise driving the system over the observing period (see paper for details). For this indicator, all of the eight fingerprints show a significant increase in the indicator towards the critical value of zero (Fig. 1c,d). Taken together these results indicate that the fingerprints (and hence by implication the AMOC) have been coming closer to tipping over the past 120-150 years.

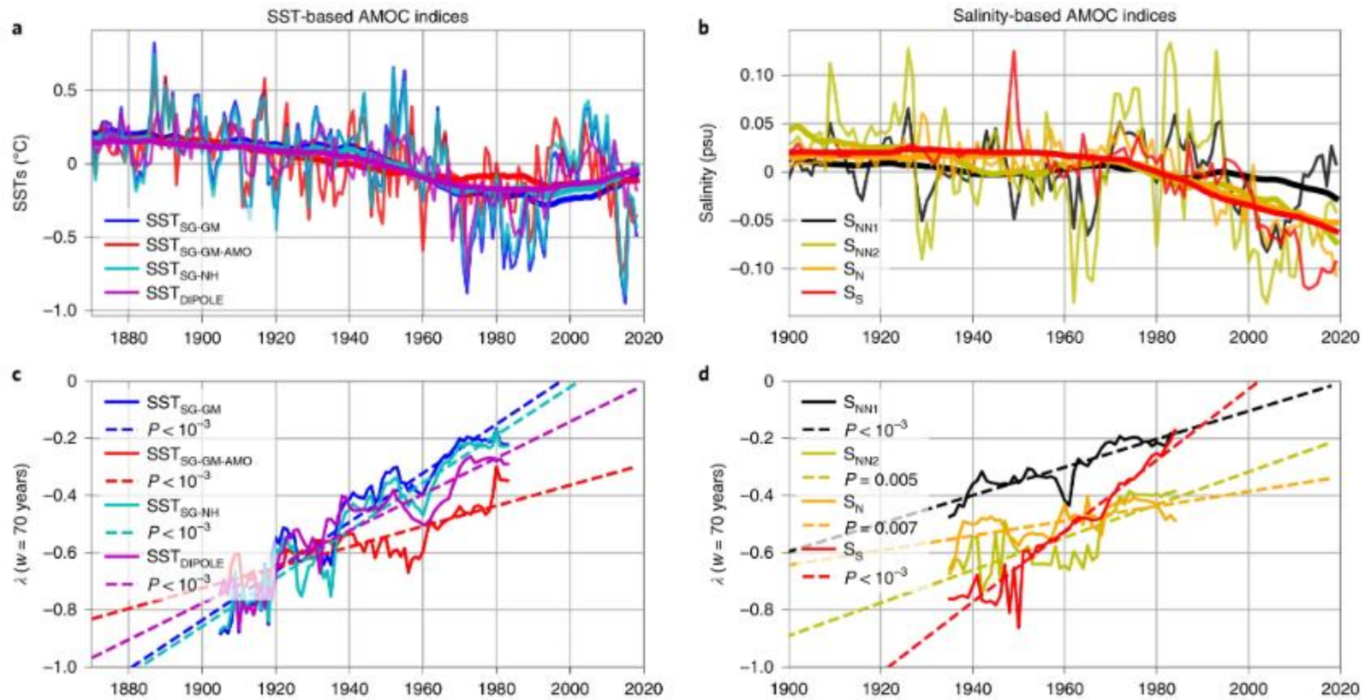

Figure 1. *Timeseries of (a) four SST-based AMOC fingerprints and (b) four salinity-based AMOC fingerprints over the past 120-150 years, derived from observationally-based products. Timeseries of the restoring rate index of critical slowing down λ, derived from the SST-based (c) and salinity-based (d) proxies, using a 70-year sliding time window and showing an increase in λ towards the critical value of zero. Derived from Boers 2021*.*

In using such approaches, and looking forward to detection and early warning of future changes, it is important to establish how closely the different fingerprints represent the AMOC change we are interested in. The eight fingerprints considered by Boers 2021* are all supported by analysis of links between AMOC strength and SST or salinity in models. In a complementary study (Jackson and Wood 2020*) we have undertaken a systematic analysis of AMOC fingerprints using a suite of 21 experiments with the climate model HadGEM3-GC2. This model is a forerunner of the UK's CMIP6 climate model HadGEM3-GC3.1, and is thus representative of the current generation of global climate models. It is run with eddy-permitting ocean resolution (0.25° in the horizontal). A range of candidate AMOC fingerprints is considered based on proposals in the literature. The experiments considered include internal AMOC variability in a pre-industrial control run, AMOC response to gradually increasing atmospheric CO_2 ('1PC', typically a weakening AMOC), AMOC weakening in response to fresh water input ('Hosing'), and AMOC recovery following cessation of fresh water input ('Recovery').

Table 1 shows the correlation of various fingerprints with the actual AMOC for the various experiments. Unsurprisingly the correlations are strong for metrics that are basically measuring the AMOC itself at some latitude (e.g. RAPID, OSNAP), but importantly some indirect metrics also show high correlations for some of the experiments. The fingerprint "m_dipole" (a North Atlantic – South Atlantic density dipole index) shows significant correlation with the AMOC over all types of change.

	Control	1PC	Hosing	Recovery	N:$p < 0.05$
RAPID	**0.99**	**1.00**	**0.99**	**0.98**	21
RAPID_FC	**0.52**	**0.97**	**0.96**	**0.87**	21
RAPID_UMO	0.25	−0.44	−0.21	0.32	11
OSNAP	**0.86**	**0.98**	**0.96**	**0.87**	19
SST_dipole	0.37	**−0.82**	**0.91**	0.52	15
SST_caesar	0.18	**0.87**	**0.90**	0.49	13
SST_spg	**0.53**	**0.96**	**0.87**	0.64	16
amv1	**0.65**	0.50	**0.98**	**0.77**	17
amv2	**0.56**	**0.95**	**0.94**	0.70	18
Tsub	0.32	**0.95**	0.22	0.57	11
uohc	0.09	**0.67**	−0.61	0.29	8
LS_mid	0.30	**0.96**	**0.87**	0.40	12
LS_dipole	0.37	**0.99**	**0.98**	0.66	16
m_dipole	**0.74**	**0.96**	**0.98**	**0.80**	18
z_dipole	−0.40	**0.96**	**0.94**	0.57	15
26N_dipole	0.22	**−0.91**	−0.16	−0.26	8
pintg	**0.56**	**0.98**	**0.94**	0.66	15
LS_mld	0.39	**0.97**	**0.87**	**0.83**	19
SPG_mld	0.44	**0.97**	**0.95**	**0.84**	19
sl0	−0.15	**0.66**	0.32	0.04	4
sl1	0.12	**0.92**	0.74	0.45	10

Table 1. *Correlations of decadal mean AMOC at 26.5°N with a range of potential AMOC metrics and fingerprints, across different types of experiment with the global climate model HadGEM3-GC2. Significant correlations (p<0.05) are shown in* ***bold****. The final column shows the number of model experiments (out of a total of 21) which show a significant correlation. From Jackson and Wood 2020*. See paper for details of the metrics/fingerprints.*

We have re-calculated these correlations for the recent NAHosMIP experiments (See Strand 2 below), which use the CMIP6 model HadGEM3-GC3.1, for three of the 'dipole' metrics in Table 1 which appeared to give good results. Results for these new runs are shown in Table 2. These metrics appear to continue to give strong correlations with the AMOC during the Hosing phase, but less so during the Recovery phase. This sounds a note of caution that multiple model studies will be needed to build confidence that proposed AMOC fingerprints are robust.

Fingerprint	**Hosing**	**Recovery**
m_dipole	**0.96**	0.15
LS_dipole	**0.73**	**0.71**
SST_dipole	**0.94**	0.84

Table 2: *As Table 1, for three of the metrics shown there, calculated for new runs using the NAHosMIP protocol (see Strand 2) with the CMIP6 models HadGEM3-GC3-1LL and HadGEM3-GC3-1MM.*

As important as correlation is the signal-to-noise ratio, as this determines how quickly a long-term change can be detected above internal noise in the fingerprint variable. It is possible that some fingerprints could detect certain types of change earlier than observations of the AMOC itself. Table 3 shows signal-to-noise ratios for a selection of the above fingerprints. Two of the fingerprints, m_dipole again and LS_dipole (a vertical density dipole index in the Labrador Sea) give faster detection times than the AMOC itself (M26) for 'Hosing' experiments, and LS_dipole also shows somewhat faster detection of response to gradually increasing CO_2.

	hos01	hos02	hos03	hos05	hos10	1PC	N	s2n
M26	30	7	5	7	7	34		3.0
M45	39	13	10	5	9	25	2	2.2
AOHT	30	10	8	13	7	38	0	2.2
RAPID	29	12	10	12	7	32	2	2.9
OSNAP	24	10	8	5	5	27	4	2.9
m_dipole	21	3	3	3	3	44	5	11.6
LS_dipole	18	7	3	2	2	29	5	9.6
SPG_MLD	28	7	7	5	3	32	4	3.2

Table 3: *Years to detect a change in various AMOC metrics and fingerprints, for a range of HadGEM3-GC2 experiments. Experiments 'hos01' etc are 'hosing' experiments with fresh water inputs of 0.1 Sv, 0.2 Sv etc up to 1.0Sv. Experiment '1PC' is gradually increasing CO_2 concentrations (1% per year). N shows the number of experiments (out of 6) in which the detection time is faster than the detection time from observing the AMOC at 26.5°N itself ('M26'). S2N shows the average signal-to-noise ratio across all the experiments. From Jackson and Wood 2020*.*

In some of the hosing experiments the AMOC experiences a temporary recovery when hosing is switched off, before reducing again to a weak state. A number of the metrics replicate (or exaggerate) this temporary recovery; however, the mixed layer depth ('SPG_MLD') is a useful metric in this scenario because it quickly distinguishes those experiments where the AMOC recovers from those where the AMOC stays in a weak state after a temporary recovery.

Overall Boers 2021* uses a number of AMOC fingerprints to show reasons for concern that the AMOC may be approaching a tipping point, while Jackson and Wood 2020* show that no one fingerprint is ideal for detecting all types of AMOC change, but that a suitable combination of fingerprints, based on density, SST and mixed layer depth may have the potential for early detection, and possibly understanding the cause, of changes. Development of a suitable multivariate fingerprint will be a topic of future research.

It should also be remembered that the patterns of change represented by the fingerprints may also be caused by other factors not directly related to the AMOC. For example, recent work has suggested that the so-called North Atlantic Warming Hole seen in SST observations and linked to AMOC changes, may also have arisen as an atmospheric response to cloud feedbacks (Keil et al. 2020) or warming in the Indian Ocean (Hu and Fedorov 2020). While fingerprints are the best way to extend our knowledge of the AMOC back before continuous direct AMOC observations, it will be important to support such studies with improved understanding of all the potential causes of observed change in the fingerprint variables.

Strand 2: Extend understanding of AMOC response to fresh water input

We have initiated and are leading the NAHosMIP (North Atlantic Hosing Model Intercomparison Project) to examine the sensitivity of the AMOC to the addition of freshwater in the North Atlantic (hosing) in CMIP6 climate models. The models participating are HadGEM3-GC3-1LL, HadGEM3-GC3-1MM, CanESM5, EC-Earth3, CESM2, IPSL-CM6A-LR, MPI-ESM-LR and MPI-ESM-HR, which all participated in CMIP6 and include partners both from within and beyond TiPES.

We applied 0.3 Sverdrups (10^6 m^3/s) of additional freshwater over the subpolar North Atlantic and Arctic (with compensation applied throughout the volume of the world's oceans to prevent the total freshwater content drifting). These are idealised experiments designed to test the sensitivity of the AMOC, rather than using potential future freshwater inputs. We conducted experiments where this hosing was applied for 20 and 50 years (plus in some models 70 or 100 years) and then stopped the hosing.

All of the models show an AMOC weakening during hosing (grey lines in Fig. 2). However, the amount of weakening varies between models and there is a variety of responses when hosing is stopped (coloured lines in Fig. 2). In some experiments/models the AMOC recovers quickly when hosing stops, while in others it does not recover (for at least 100 years), suggesting that the unperturbed AMOC is bi-stable, and a tipping point has been crossed.

We have made an initial investigation of whether there are observable indicators of whether the AMOC will recover. The experiments where the AMOC does not recover are those where it has weakened to the weakest states, and where March mixed layer depths have been reduced to the lowest values, before hosing stops (Figure 3).

Although weakening the AMOC to below around 6 Sv results in the AMOC not recovering in these experiments, this is not a robust threshold: in experiments forced by increasing greenhouse gases, rather than fresh water hosing, the AMOC recovers once greenhouse gas concentrations are returned to initial levels, even if it has fallen below 6 Sv. Hence the AMOC strength itself may not be a robust indicator of tipping in the more realistic case of an AMOC forced by both warming and fresh water. The March mixed layer depth may be a more robust threshold, but further work is needed to confirm this. Although mixed layer depth itself might be difficult to observe at appropriate scales, signatures of deep convection can be seen in changes in subsurface water properties.

A headline journal paper on NAHosMIP, describing the experimental protocol and initial results, is in preparation and will form the primary reference for future more detailed analyses of mechanisms of weakening, recovery and non-recovery. The goal is to achieve an understanding of the key processes and indicators of tipping, that is independent of any individual model.

Data from some of the NAHosMIP runs, and related runs of HadGEM3-GC2, have been made available to other TiPES partners for study of climatic impacts of AMOC weakening (Task 3.4) and interaction with other tipping elements (e.g. Task 3.2).

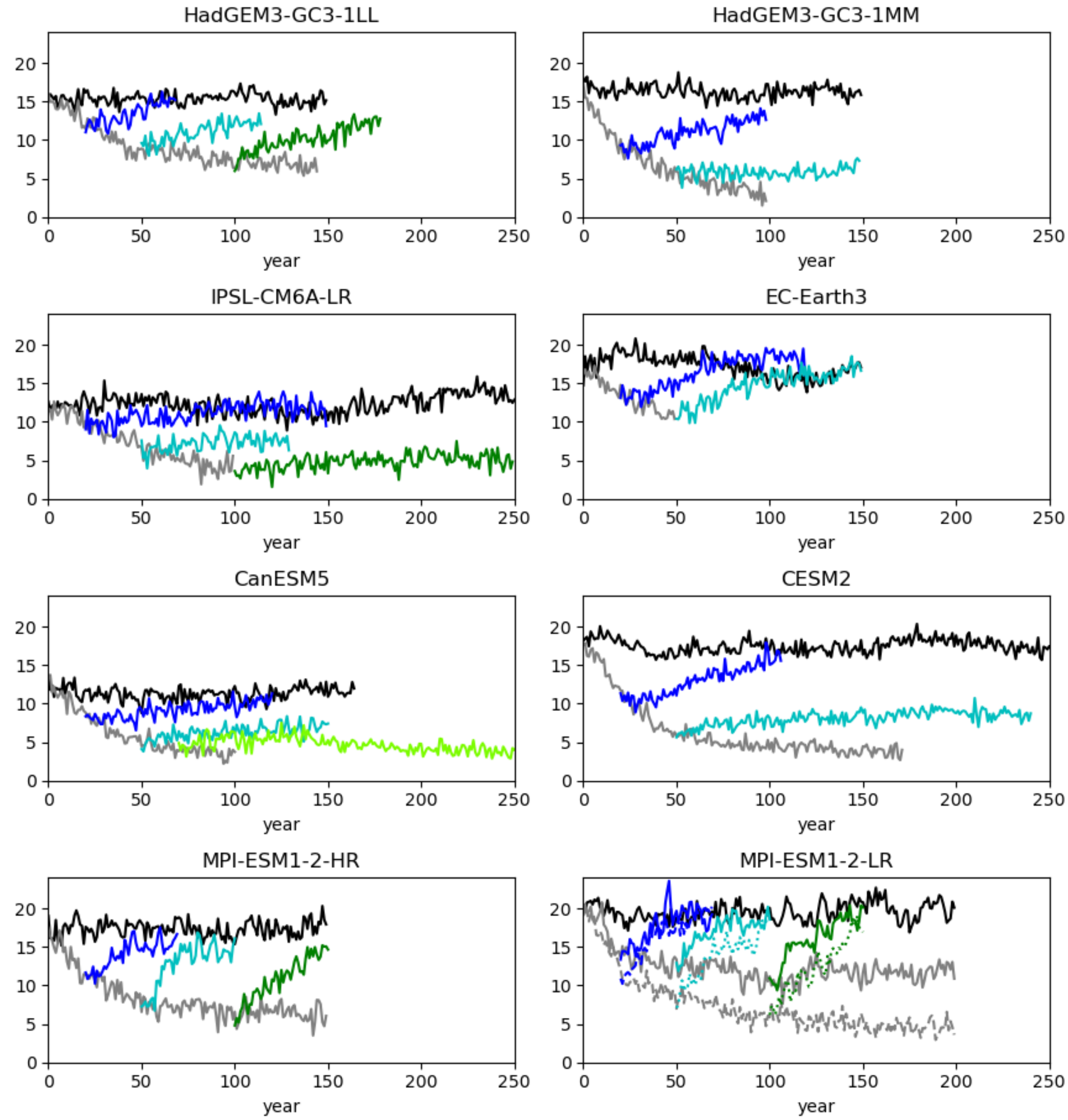

Figure 2. *AMOC strength (maximum in depth at 26.5N) for the NAHosMIP hosing experiments. Each panel shows experiments conducted with different models. Experiments are the control (black), u03-hos (grey: hosing of 0.3 Sv continued indefinitely), u03-r20 (blue: hosing stopped after 20 years), u03-r50 (cyan: hosing stopped after 50 years), u03-r70 (light green: hosing stopped after 70 years) and u03-r100 (green: hosing stopped after 100 years). MPI-ESM1-2-LR also shows the same experiments with a stronger hosing rate of 0.5 Sv (dashed lines).*

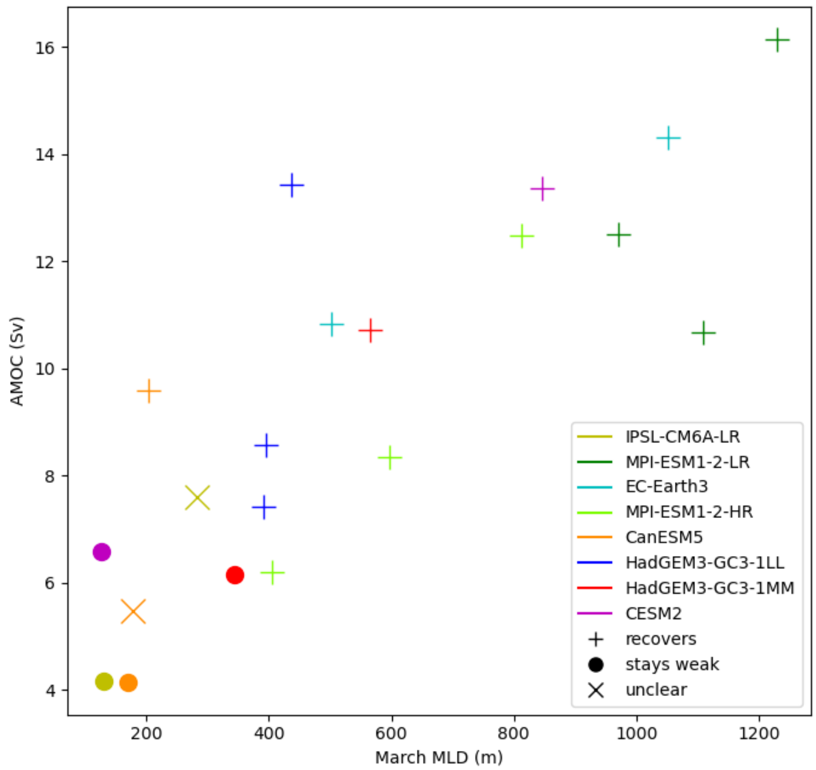

***Figure 3.** Two potential indicators of whether AMOC will recover when hosing is stopped: AMOC strength and March mixed layer depth before hosing stops (averaged over the previous decade). Those experiments where the AMOC recovers are indicated with a plus sign, those where the AMOC stays weak are indicated with a circle, and those where the experiment is not long enough to distinguish whether the AMOC is recovering are shown with crosses. Different colours indicate different models.*

As an alternative approach to timeseries analysis as an early warning indicator (EWI) for AMOC tipping (critical slowing down, see Strand 1), a more physically based EWI has been proposed by Alkhayuon et al 2019. Alkhayuon et al used a simple AMOC box model (Wood et al. 2019) to derive timeseries trajectories in (S_N, S_T) space, where S_N is the mean salinity of the subpolar North Atlantic and S_T is the mean salinity of the Atlantic thermocline. They showed that all trajectories that curve anticlockwise in (S_N, S_T) space eventually lead to a collapsed AMOC state. Physically this is related to the Stommel salinity advection feedback (Stommel 1962) which is the fundamental cause of AMOC tipping. Monitoring S_N and S_T (for example using the Argo float array) therefore has potential as an EWI: once the trajectory develops anticlockwise curvature the AMOC is destined to collapse, and the anticlockwise curvature can develop decades or even centuries before a major AMOC weakening occurs.

We have extended the analysis of this potential EWI by examining (S_N, S_T) trajectories in the HadGEM3-GC3-1LL and HadGEM3-GC31-MM runs in NAHosMIP. Fig. 4 shows sample trajectories from the

HadGEM3-GC31-MM runs (top right panel of Fig. 2). The run with continuous hosing shows a change to anticlockwise curvature, suggesting that the AMOC is moving to a stable off state. The trajectories for the runs where hosing is stopped after 20 or 50 years are ambiguous: in both cases there is a hint of clockwise curvature, suggesting that the AMOC may eventually recover if the runs are continued, but the internal variability of (S_N, S_T) (shown by the green box) is quite large. This makes detection of a robust change in curvature challenging. To be a practical EWI, the (S_N, S_T) curvature would need to be detectable above natural variability in a reasonable time. Future work will assess detectability in more detail.

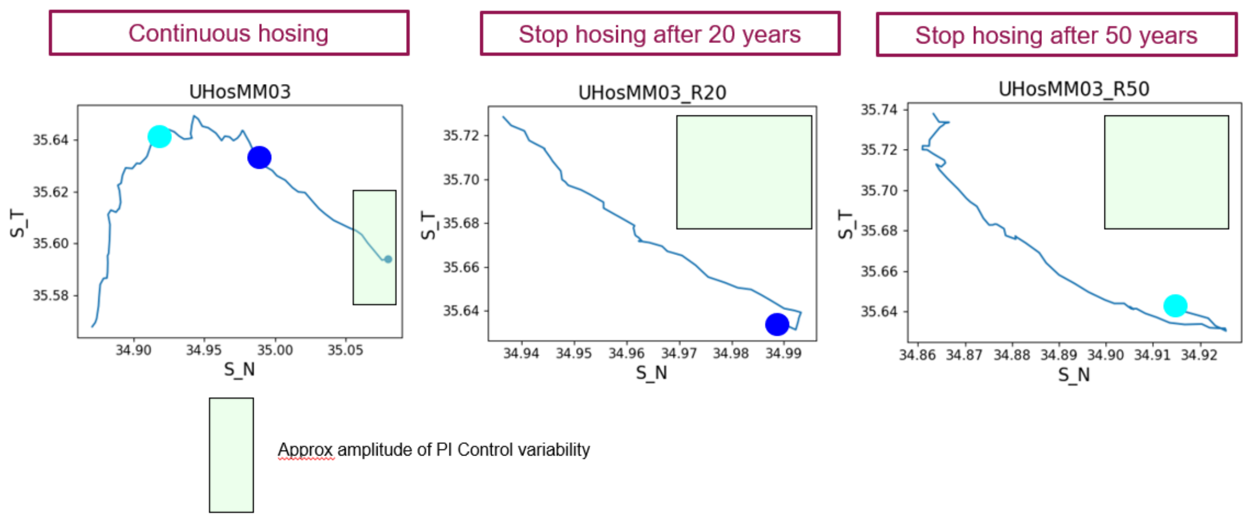

Figure 4. *Trajectories in (S_N, S_T) space as a possible early warning indicator for AMOC tipping, in the three NAHosMIP runs using the model HadGEM3-GC31-MM (see Fig 2, top right panel). Anticlockwise curvature is an early indicator of passing a tipping point to a weak AMOC state. The panels have different scales but the green box has the same size in (S_N, S_T) space in all panels and indicates the approximate amplitude of internal variability in a control run of the model. To be a practical EWI the curvature of the trajectory needs to be detectable above the internal variability.*

A key limitation of the (S_N, S_T) early warning indicator, and indeed in the vast literature using fresh water forcing to study AMOC tipping, is that it only considers hosing scenarios in which salinity forcing is the main driver, rather than the more realistic scenario forced by greenhouse gases, where both temperature and salinity changes play a role. Work to address this limitation is described in Strand 3 below.

Strand 3: Extend understanding of AMOC tipping to more realistic global warming scenarios

Since the pioneering work of Stommel (1962) first identified the possibility of tipping behaviour in the AMOC, the study has been dominated by investigations of the response of the AMOC to fresh water input to the North Atlantic (so-called 'hosing'). This makes sense because the fundamental mechanism of tipping depends on the fact that salinity anomalies accumulate of periods of decades in the ocean, while large scale temperature anomalies are damped by radiative feedbacks. Nonetheless studies of potential future AMOC response to global warming suggest that the initial response is dominated by a weakening due to warming, not freshening, with salinity only coming into play on a longer timescale (e.g. Gregory et al 2006, Thorpe et al 2001). So a more policy relevant assessment of the risks of AMOC tipping will need to consider the combined effects of temperature and salinity changes on the AMOC under plausible greenhouse gas forcing.

We have made a step towards developing this understanding by developing a simple AMOC box model that takes account of both thermal and haline effects, including the coupling between the energy and water cycles. We show that our model can reproduce many of the AMOC responses seen in previous climate model (GCM) experiments driven by increased CO_2 concentrations.

Our model is based on a previous model by Wood et al (2019), which divides the ocean into 5 boxes corresponding to major water masses. The temperatures of the boxes were largely fixed and the AMOC was controlled by density anomalies arising from salinity changes. The model physics consisted of salinity conservation in each box, with salinity transports due to an AMOC that was driven by density (and hence salinity) anomalies in the boxes. This coupling between the AMOC and salinity introduces the possibility of bifurcations and tipping in the dynamics, which were analysed by Alkhayuon et al (2019). The model was shown in Wood et al 2019 to reproduce well the AMOC tipping behaviour seen in several hosing experiments with the FAMOUS climate GCM.

We have extended the model to include active temperature variables in all the boxes, with temperature controlled by heat conservation. The model is now forced by specified CO_2 concentrations, rather than specified fresh water input, and water fluxes into the ocean are linked to temperature through the response of the atmospheric water cycle and the Greenland ice sheet. This leads to three key model parameters:

- Climate sensitivity (°C, the equilibrium warming of surface temperature for a doubling of atmospheric CO_2)
- Hydrological sensitivity ($°C^{-1}$, the proportional increase of atmospheric inter-basin water transports per °C of warming)
- Greenland sensitivity (the amount of additional fresh water input from the Greenland ice sheet per °C of warming)

We first show that the model reproduces key aspects of the AMOC response to CO_2 increase that are seen in GCMs, and go on to evaluate the role of the above three parameters in AMOC tipping. We focus on the AMOC response in a standard CMIP experiment ($4xCO_2$) in which CO_2 is instantaneously increased to four times pre-industrial values and maintained there over a multi-century run. This simple forcing scenario allows the different mechanisms and timescales of AMOC response to appear clearly. Fig. 5 shows a typical AMOC response, from the CMIP6 model HadGEM3-GC3-1LL. The AMOC weakens initially in response to warming (lightening) of the subpolar North Atlantic source water. On a longer timescale the AMOC partially recovers, as intensification of the atmospheric water cycle leads to a salting of the Atlantic basin, and that saltier water is gradually transported to the subpolar region. Such a response is commonly seen in GCMs, but the extent of the recovery varies between models, and in some cases the final AMOC is stronger than the initial state (e.g. Stouffer & Manabe 2003)

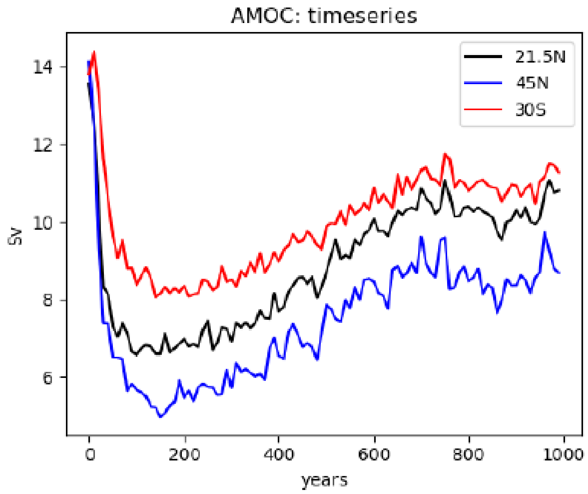

Figure 5. *Evolution of the AMOC strength at three latitudes as a function of time, in an instantaneous $4xCO_2$ experiment using the CMIP6 model HadGEM3-GC3-1LL. Run courtesy Tim Andrews, Met Office Hadley Centre.*

When forced with the same $4xCO_2$ scenario, our new box model produces a similar response of wekening followed by recovery, over much of the parameter space of the above three parameters (Figure 6a). By decomposing the AMOC into a component driven by density gradients related to salinity, and a component driven by density gradients related to temperature, we see that even if the initial and final AMOC strengths are similar, the relative contributions of temperature- and salinity-driven density gradients have changed, with salinity playing a stronger role in the final state than in the pre-industrial state.

Other responses are possible for different values of the three key parameters. Figure 6b shows a case in AMOC collapse occurs, while Figure 6c shows an unusual case in which the AMOC appears to have collapsed, but spontaneously recovers after around 1000 years. A single example of this spontaneous recovery has been seen in the GCM literature, with a now rather old version of the GFDL model (Stouffer & Manabe 2003).

An advantage of our box model is that we can explore parameter space much more fully than would be possible for GCMs, to understand under what circumstances AMOC tipping would be likely. In Figure 7 we show the final AMOC strength, as a function of the three parameters above. We see that AMOC collapse tends to occur at higher values of Greenland Sensitivity. The unusual behaviour of collapse followed by spontaneous recovery (Fig 6c) tends to occur near the middle right of the plots, i.e. high climate sensitivity and moderately high Greenland Sensitivity.

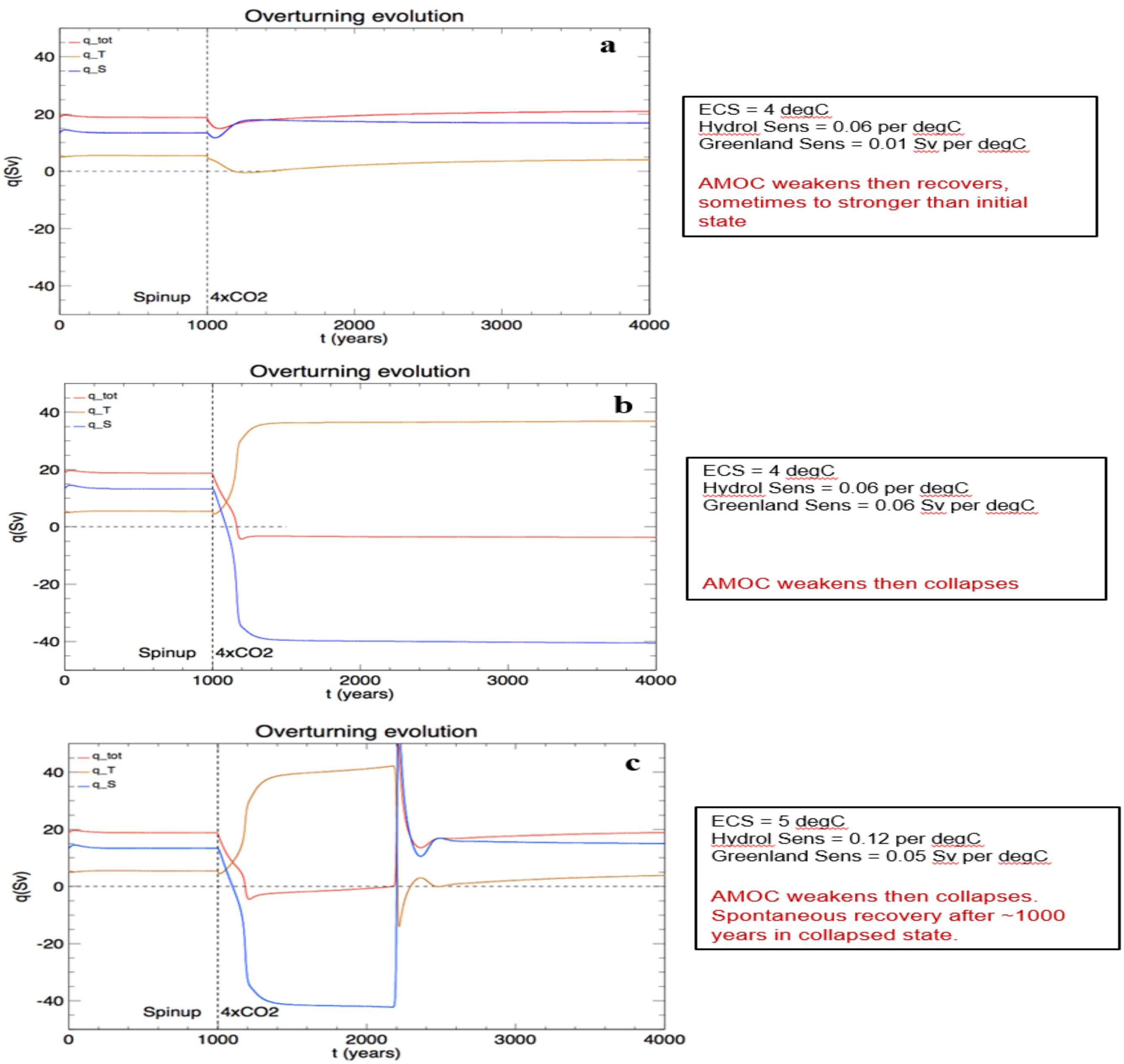

Figure 6. *Three typical AMOC responses to instantaneous CO_2 increase in the box model, with different parameter values. CO_2 concentration is increased to four times pre-industrial after a 1000-year spinup period, then held fixed for 3000 years. Red lines show the total AMOC, brown lines show the temperature-driven component, and blue lines show the salinity-driven component.*

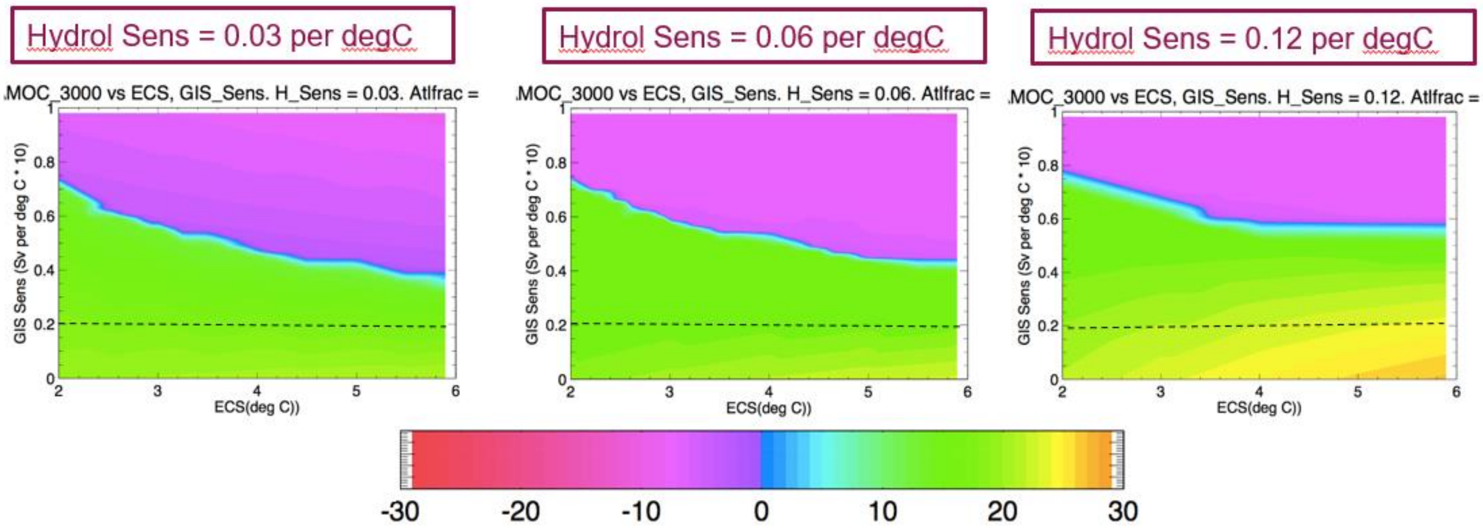

Figure 7. *Sensitivity of the final AMOC strength in Sv, to the three parameters Climate Sensitivity (ECS, horizontal axis), Greenland Sensitivity (GIS Sens, vertical axis) and Hydrological Sensitivity (plots show three values spanning a plausible range). Purple colours represent AMOC collapse. Other box model parameters are taken from Wood et al (2019) and are calibrated to the FAMOUS GCM. The dashed line shows an estimate of the 95th percentile value for GIS Sens, based on the expert elicitation study of Bamber et al (2019).*

Figure 7 allows us to develop a preliminary 'climate storyline' for AMOC collapse (IPCC 2021). In other words, it allows us to ask: "What would the parameters of the real climate system have to be for an AMOC collapse to be likely?". We can deduce the following:

- AMOC collapse is possible for values of climate sensitivity and hydrological sensitivity that are within plausible ranges. It is somewhat more likely when climate sensitivity is at the high end, and hydrological sensitivity at the low end of plausible ranges.
- In all cases, collapse only occurs at values of Greenland Sensitivity that are higher than the 95th percentile value derived from the assessment of Bamber et al (2019) (dashed lines in Fig. 7)
- In cases where the AMOC does not collapse, it recovers from its initial weakening over a period of centuries. At high values of hydrological sensitivity (right hand panel) the final AMOC state can be stronger than the initial state, which would likely lead to additional regional warming over Europe.

The necessity for a very high value of Greenland Sensitivity in all cases confirms the consensus view that AMOC collapse is a high-impact but low-likelihood event, at least in the 21st Century. However, because of the potential for high impact, such events are a critical part of climate change risk that needs to be managed (IPCC 2021). The development of early warning indicators is potentially a valuable element in such a risk management approach.

The results should be considered indicative only at this stage. In particular the background box model parameters are representative of the FAMOUS GCM (as in Wood et al 2019), and it will be important to explore parameters representative of more recent GCMs to see if AMOC tipping could be plausible at lower values of Greenland Sensitivity. The parametrisation of hydrological sensitivity used here (scaling all basin surface fresh water fluxes with temperature) may be too simple, and needs to be tested by detailed analysis of GCM results. The results emphasise the value of ongoing research to better quantify these three large scale parameters of the climate system, in order to better assess the risks of future AMOC tipping.

Strand 4: Interaction of AMOC with other tipping elements: Amazon basin

It is generally accepted that a collapse of the AMOC would lead to a pronounced southward shift of the Intertropical Convergence Zone (ITCZ), which can in turn affect the tropical monsoon systems. In particular, such a southward ITCZ shift would affect the Amazon rainforest, which has been suggested to be another major Earth system tipping element (Lovejoy and Nobre 2018). However, in particular for the case of tropical South America, the impacts of a southward ITCZ shift are complex and different generations of comprehensive models have suggested both increases and decreases in overall precipitations sums there (Stouffer et al. 2006; Jackson et al., 2015). Especially the relationships between tropical Atlantic SST anomalies and rainfall anomalies in the Amazon basin, as well as seasonal effects, merit more in-depth investigations.

In Ciemer et al. 2021*, the authors combined (i) observed relationships between tropical Atlantic SST anomalies and Amazon rainfall with (ii) a conceptual model of the AMOC, as well as (iii) comprehensive model simulations of SST fields corresponding to a hosing-induced AMOC collapse (from Jackson et al., 2015). The results suggest that – if the observation-inferred Atlantic-SST – Amazon-rainfall relationships remain similar after an AMOC collapse, the latter would in fact lead to a pronounced increase of Amazon mean annual precipitation. In this sense, a collapse of the AMOC would have a stabilizing effect also on the Amazon rainforest.

While Ciemer et al. 2021* focused on the effect on mean annual precipitation in tropical South America, Good et al. 2021* focused on the detailed effects of an AMOC collapse and associated southward shift of the ITCZ on the seasonal distribution of rainfall in tropical South America. For this purpose, Good et al. used the same comprehensive model simulations from (Jackson et al., 2015) but including the precipitation fields in addition to the SST fields, comparing the fields for a strong AMOC with the corresponding ones for a weak AMOC. The seasonal effects over the Amazon are complex because the seasonal cycle is almost exactly out of phase between the northern and southern parts of the basin, and investigating the effects of an AMOC collapse in this context is further complicated by the southward bias in ITCZ position that many models have, leading to a possible overestimation of drying in response to an AMOC collapse in March and July. Despite existing biases, a consistent picture of a drier wet season, but a wetter dry season following an AMOC collapse can be inferred from the model results (Fig 8). Given that dry-season rainfall sums are likely to be more critical than during the wet season (slight reductions of abundant wet-season precipitation are not expected to have a significant impact on the rainforest), these results suggest – in line with Ciemer et al. above – that an AMOC collapse would likely have a positive effect on the Amazon rainforest.

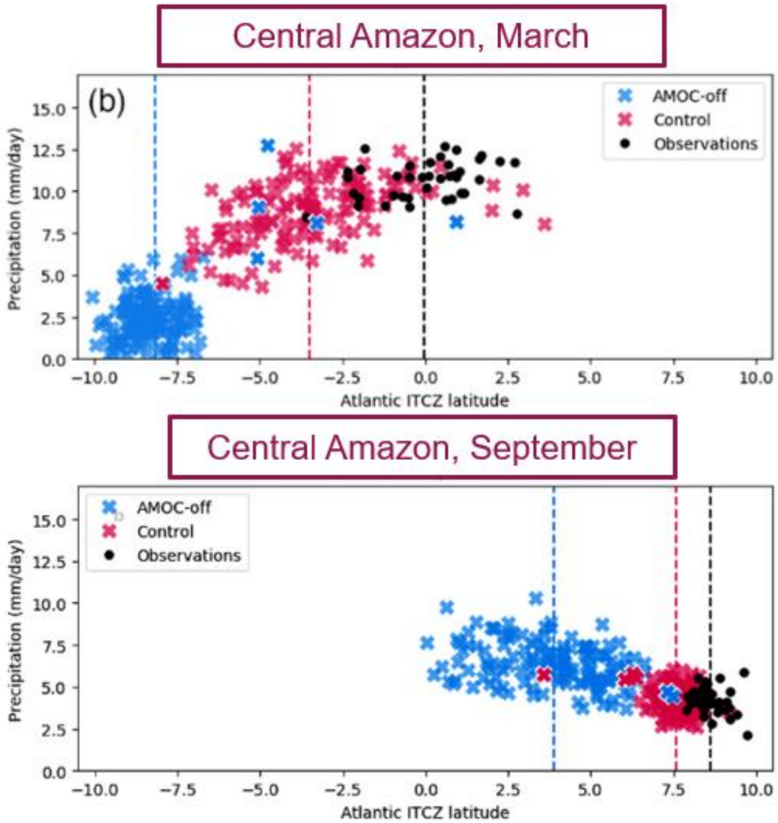

Figure 8. *Simulated changes in precipitation in the Central Amazon region (plotted against latitude of the Intertropical Convergence Zone), for model simulations with unperturbed AMOC (Control, red) and collapsed AMOC (blue). AMOC shutdown induces a drier wet season but a wetter dry season. Derived from Good et al 2021**

Main results achieved

- Analysis of historical observations of a number of AMOC proxies or 'fingerprints' suggests that critical slowing down may have been occurring, indicating that the AMOC is coming closer to a tipping point, over the past 120-150 years.
- Analysis of a range of such AMOC fingerprints in a climate model shows that different fingerprints are good for detecting different types of AMOC change. A suitable combination of several observable variables may provide a multivariate AMOC proxy suitable for detection and early warning of all likely AMOC changes.

- An alternative, physically based early warning indicator for AMOC collapse, based on Atlantic salinity observations, has been tested in two CMIP6 climate models. Results indicate that observations may be needed for several decades to detect the early warning signal above natural variability.
- The collapse or recovery of the AMOC after a period of fresh water input has been evaluated in eight CMIP6 models. The critical period of fresh water input, after which the AMOC is committed to collapse (‘resilience time’) varies among models, but there appear to be threshold values of the AMOC strength and subpolar mixed layer depth that indicate whether the critical time has been passed.
- A simple model has been developed to extend the traditional theory of AMOC response to fresh water input, to consider more realistic cases driven by global warming. Preliminary results in this framework suggest that AMOC tipping is only possible if the response of the Greenland ice sheet to warming is above the 95th percentile of published estimates, supporting the view that AMOC collapse is a high impact, low likelihood outcome.
- Analysis of the impacts of AMOC collapse on Amazon precipitation show a drying in the wet season but a wetting in the dry season, potentially resulting in a net beneficial effect on the Amazon rainforest.

Progress beyond the state of the art

- First evaluation of critical slowing down in the instrumental period, based on a range of AMOC fingerprints
- First systematic evaluation of the potential of a range of different AMOC fingerprints to detect different types of AMOC change
- NAHosMIP the first systematic attempt to understand AMOC tipping responses in state-of-the-art CMIP GCMs. Specific advances over a previous study by Stouffer et al 2006 are the concentration on the latest generation of CMIP climate models (as opposed to a combination of GCMs and EMICs), and examination of AMOC resilience and recovery after fresh water input ceases.
- Progress towards understanding detection times for AMOC tipping signals in the presence of natural climate ‘noise’ – a key factor in developing practical, deployable early warning indicators
- Extension of traditional studies of AMOC response to fresh water forcing, to the more realistic scenario of heat and fresh water forcing driven by increasing greenhouse gases.
- Detailed sub-regional evaluation of the impacts of AMOC collapse on the Amazon basin.
- A number of these advances exploit the ability to run multiple climate model simulations with eddy-permitting ocean resolution and increased atmospheric resolution. This has only become possible with recent advances in computer power.

Impact

How has this work contributed to the expected impacts of TiPES?

Expected impact	TiPES outcome/results	Contribution to expected impact
"Supporting major international scientific assessments such as the IPCC"	TiPES will put forward guidelines for improving the accuracy and reliability of climate models, model selection, and computation of TPs across the model hierarchy. Shortcomings in the present generation of earth system models will be investigated. New EMIC and ice sheet model parameterizations will be generated; the boundary conditions for TEs will be better defined for all models; and new ESM (isotope) code will be written to enable more appropriate model-data evaluations. (WP2-5/O1).	Identified key modelling factors for AMOC tipping (identified as an important area of uncertainty by AR6)
	TiPES will provide improved criteria on where and how to collect data for reliable EWSs, and how to quantify forecast lead times based on such indicators (WP1, WP3, WP5/O2). These 2 outcomes, in turn, will help identify cost-effective prediction methods with quantified reliability. The prediction methods so developed will be tested across the hierarchy of models and that information will then serve to refine these methods and make them suitable for routine application in IPCC-class models.	Improved understanding of the properties of different AMOC proxies for EWSs, including detection times in the presence of natural variability.
"increase confidence in climate change projections"	TiPES will assess and improve the parameterisations of comprehensive ESMs (in particular EC-Earth, HadGEM3/UKESM, and CESM) of the CMIP-6 class to improve the representation of TEs in a collaborative effort of WPs 1-3 (O1).	Improved understanding of what are the key model processes. Pull through to model development requires a multi-year timescale. TiPES partners are well connected into a number of major model development groups across Europe. Recommendations will be assembled towards the end of TiPES.
"providing added-value to decision and policy makers"	TiPES will use different data sources to design EWSs and will substantially advance the theory of EWSs in view of forthcoming transitions. These theoretical advances will help develop skilful forecast schemes. We will also quantify their reliability and associated uncertainties (WP1, WP3, WP5 / O2).	AMOC fingerprints relevant to TPs have been evaluated. Several fingerprints have been analysed showing evidence of critical slowing down over the past 120-150 years. Novel EWIs for AMOC collapse have been proposed.
"sustaining Europe's leadership in climate	TiPES is a collaborative effort across diverse disciplines, such as Earth system modelling, time series analysis, paleoclimatology, applied mathematics and statistics, theoretical physics, formal risk assessment and decision theory.	Several peer-reviewed papers have already been published, with more in preparation.

science"	The groups taking part in TiPES are leading in their respective fields and are spread across eleven European countries.	
	The TiPES research endeavours are ambitious and far reaching: we will aim at attracting the best international talents to join our team, and take advantage of our extensive international research networks to solicit and educate excellent candidates.	NAHosMIP is led from TiPES, and includes high profile partners from the climate modelling community beyond Europe.

Impact on the business sector
Impacts on the business sector are expected to be indirect and have not been a focus so far.

Lessons learned and Links built

Lessons:
Examination of detection times in AMOC observations and fingerprints has emphasised the importance of addressing practical observational questions (observation/sampling error, signal to noise ratios) as we build towards practical early warning systems.

Covid restrictions have made the building of cross-institutional and cross-WP links more challenging. Nonetheless the hard work of the project management and a number of the project scientists has enabled a good level of project collaboration to be developed (through e.g. regular webinars, Gathertown sessions and other virtual meetings). These mechanisms will likely be valuable in the post-Covid era and will facilitate the journey to effective project collaboration in a net zero environment. Face to face meeting is still important and the upcoming TiPES GA (September 2022) will provide an important opportunity to deepen collaborations within the project.

Links:
AMOC collpase simulations using a high resolution climate model have been made available to other areas of TiPES, and are being used in Tasks 3.2 and 3.4.

NAHosMIP has built a deeper scientific collaboration on AMOC tipping pionts among international climate modelling groups (in Europe and beyond)

TiPES scientists are engaging with ongoing discussions on the possible development of a TipMIP under the auspices of the WCRP Lighthouse Activity on Safe Landing Climates.

Relations to the TiPES crosscutting themes

Theme 1. Tipping Elements in data and models

By employing a hierarchy of models, with process-based traceability from the simpler models to the GCMs, we are able to explore possible climate behaviours that are outside the range of existing GCM behaviour. This allows us to push against the limitation that GCMs may be tuned excessively to stable representation of the present-day climate.

Exploration of AMOC fingerprints is allowing us to build beyond the very restricted time period of available direct AMOC observations.

Theme 2. Climate response and Early Warning Signals

The work in this deliverable is directly targeted at investigating practical Early Warning Indicators for AMOC tipping. Further discussion is needed to establish how the properties of EWIs investigated here are fitted into the Response Theory approach. These discussions will be initiated with consortium partners over the coming months.

Theme 3. Nonlinear and non-autonomous systems

The traceable model hierarchy used in this work allows concepts to be developed using simple models that are amenable to dynamical systems analysis, and these concepts then used to guide analysis and experimentation with the computationally expensive GCMs. For example, ideas developed under strand 3 of this deliverable will be used in the later stages of TiPES to guide GCM experiments into regions where tipping behaviour is likely to be seen. This approach will allow us to develop 'storylines' of what would be the key properties of the real climate system required for AMOC collapse to be imminent – an alternative and complementary approach to early warning.

Theme 4. Data and decisions

The increased understanding of potential Early Warning Indicators for AMOC tipping, developed by this work, provide important information to enable adaptive decision pathways. Essentially, effective EWIs allow commitment to expensive adaptation or resilience measures to be deferred until it is clear that they will be needed. Integration with decision making frameworks will be explored with WP5 and 6.

Contribution to the top level objectives of TiPES

Objective 1-Identify tipping elements (TEs) and their interactions in models and data

The AMOC is well-established as a potential climate tipping element, with a substantial literature discussing the nature of tipping from theoretical and palaeocilmate perspectives. The work described here takes this knowledge further by establishing the mechanisms and circumstances under which the AMOC may tip under plausible pathways of future climate change driven by anthropogenic greenhouse gases, rather than the traditional idealised fresh water forcing scenarios.

Objective 2-Provide approaches for the identification and validation of Early Warning Signals

The work described here extends and complements previous work on Early Warning Signals in three ways:

- Real application of observed AMOC fingerprints to detect 'critical slowing down' over the instrumental period.
- Developing EWS's based on physical AMOC mechanisms, to complement statistical timeseries analyses
- Extending the evaluation from idealised fresh water forcing scenarios to the more realistic case of AMOC changes driven by greenhouse gas forcing, and hence involving temperature, as well as salinity changes

Objective 3-Characterise climate response in the presence of Tipping Points (TPs)
The work described here does not contribute directly to this objective. However, the insights obtained may provide a practical case study for theoretical characterisations of climate response developed in WP4 and 5. This will be discussed with WP 4/5 colleagues at the upcoming TiPES Assembly.

Objective 4-Define and identify safe operating spaces
The work described here does not contribute directly to this objective. However, the insights obtained – in particular 'storylines' of how the characteristics of the real climate system would look if the AMOC was close to tipping - may provide a practical case study for theoretical characterisations of safe operating spaces developed in WP 4, 5 and 6. This will be discussed with WP4/5/6 colleagues at the upcoming TiPES Assembly.

Objective 5-Bridge the gap between climate science and policy advice
The progress described here towards practical early warning indicators for AMOC tipping provides an additional 'weapon' in the fight to adapt and build resilience to climate risk. The possibility of early warning opens up a more flexible approach through adaptive decision pathways that recognise tipping as a 'high impact, low likelihood' risk. Early warning enables expensive adaptation measures to be deferred until it becomes clear that they will be needed.

A pair of workshops was held in the UK in April 2022 to consider climate science needs to inform policy and adaptation action on high impact, low likelihood climate risks (including tipping points). The workshops were organised by one of the authors of this deliverable (Wood) and convened groups of UK government officials involved in climate mitigation and adaptation policy. A conclusion from the workshops was that the concepts of storylines and early warning are potentially valuable approaches, but that some specific case studies would be valuable to test the ability of the science to inform actual decision making. Discussions are in place to identify and fund such case studies. While this work has been funded outside TiPES, close contact will be maintained and insights shared. We will explore the possibility of building on this work at a European level as part of TiPES.

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Dissemination and exploitation of TiPES results

Dissemination activities

Type of dissemination activity	Name of the scientist (institution), title of the presentation, event	Place and date of the event	Estimated budget	Type of Audience	Estimated number of persons reached	Link to Zenodo upload
Organisation of a workshop	Richard Wood, Met Office.	Glasgow, UK 3rd November 2021	-	Policy makers, Scientific	200	-

	CoP26 Science Pavilion event on 'High Impact, Low Likelihood climate outcomes'. Thomas Stocker, University of Bern was a panellist.			Community		
Social media	Richard Wood, Met Office. Twitter spaces discussion from CoP26	Twitter, 2nd November 2021	-	General public	150	-
Social media	Richard Wood, Met Office. Twitter spaces discussion on HILL outcomes	Twitter, 25th January 2022.	-	General public	200	-

Peer reviewed articles

Title	Authors	Publication	DOI	Is TiPES correctly acknowledged?	How much did you pay for the publication?	Status?	Open Access granted	Comments on embargo time imposed by the publisher	If in Green OA, provide the link where this publication can be found

Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation	N. Boers	Nature Climate Change	10.1038/s41558-021-01097-4	YES		Published	Yes	-	-
Fingerprints for Early Detection of Changes in the AMOC	L.C. Jackson and R.A. Wood	Journal of Climate	10.1175/JCLI-D-20-0034.1	YES		Published	Yes	-	-
Impact of an AMOC weakening on the stability of the southern Amazon rainforest	C. Ciemer, R. Winkelmann, J. Kurths, N. Boers	Eureopean Physical Journal – Special Topics	10.1140/epjs/s11734-021-00186-x	YES		Published	Yes	-	-
How might a collapse in the Atlantic Meridional Overturning Circulation affect rainfall over tropical South America?	P. Good, N, Boers, C.A. Boulton, J.A. Lowe, I.Richter	Climate Resilience and Sustainability	10.1002/cli2.26	YES		Published	Yes	-	-

Uptake by the targeted audiences To be filled in by the project office
As indicated in the Description of the Action, the audience for this deliverable is *(mark with an X here below):*

x	The general public (PU) is and is made available to the world via CORDIS.
	The project partners, including the Commission services (PP)
	A group specified by the consortium, including the Commission services (RE)
	This reports is confidential, only for members of the consortium, including the Commission services (CO)

This is how we are going to ensure the uptake of the deliverables by the targeted audiences:

Intellectual property rights resulting from this deliverable
None