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Development of early warning approaches for the most impactful climate tipping points

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INTRODUCTION

There are multiple sub-systems of the Earth's climate system that could pass a tipping point this century under high-end climate change (Lenton et al. 2008; McNeall et al. 2011) (Figure 1). Passing such a tipping point implies a self-amplified transition into an alternative state. Examples include a collapse of the Atlantic ocean overturning circulation, an irreversible shrinkage of the Greenland ice sheet, or the year-round loss of Arctic sea-ice. Such transitions in turn imply large impacts on societies, which accumulate at a rate governed by the system in question – for example, Arctic sea-ice once tipped could be lost on a decadal timescale, whereas the sea-level rise from a shrinking Greenland ice sheet would take centuries to accumulate. Many such tipping points are irreversible "points of no return".

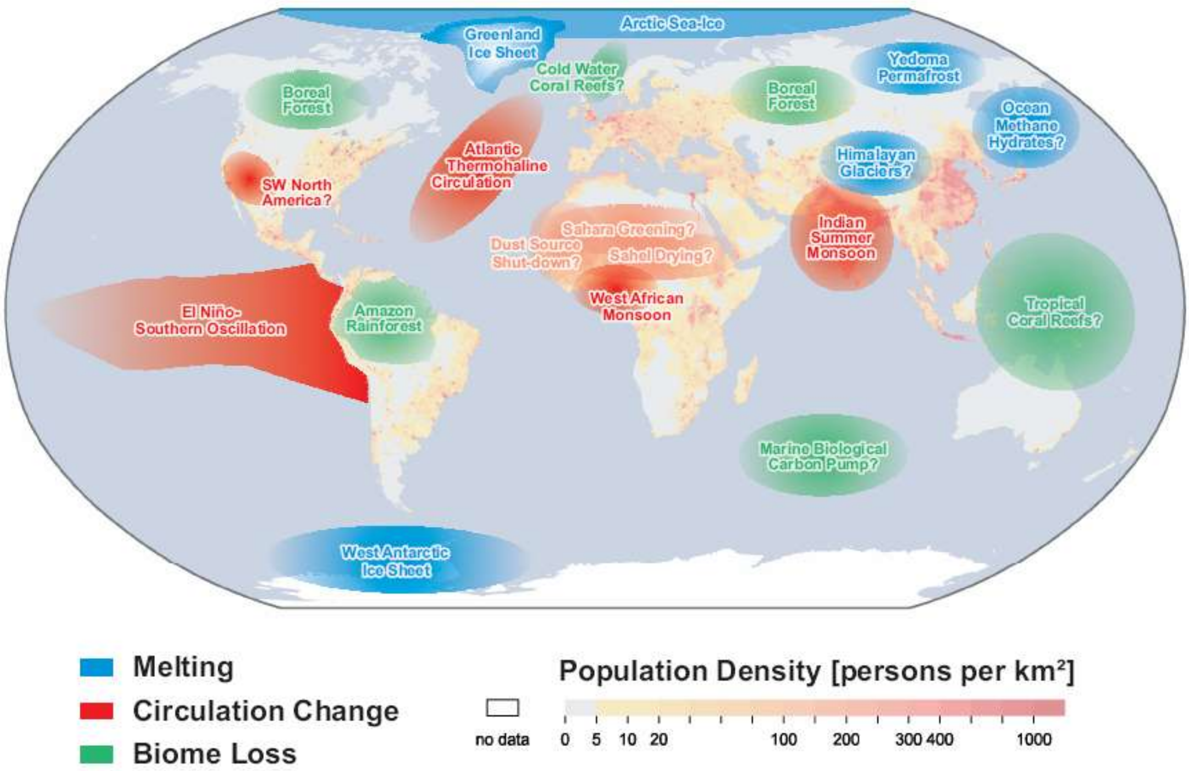

Figure 1. Potential tipping elements in the Earth's climate system, updated from Lenton et al. (2008).

This deliverable has examined the potential for early warning of climate tipping points. One can ask: Why do we need early warning of climate tipping points? The obvious answer is that passing any of the candidate climate tipping points poses a significant risk to societies, and if we have early warning of those risks they could be reduced. Taking risk to mean the product of the likelihood of a tipping event and its impacts (Figure 2), then there are two clear ways that early warning could reduce risk – one is to reduce the likelihood of a tipping event (e.g. by provoking more aggressive climate mitigation action), the other is to reduce the impacts of a tipping event (e.g. by triggering pre-emptive adaptation measures). Which of these strategies to pursue will depend somewhat on the tipping element in question and how early warning can be provided. However, even if warning is too late for mitigation action to avoid a tipping point, there will almost always be potential for adaptation action to reduce its impacts – meaning early warning has considerable societal value.

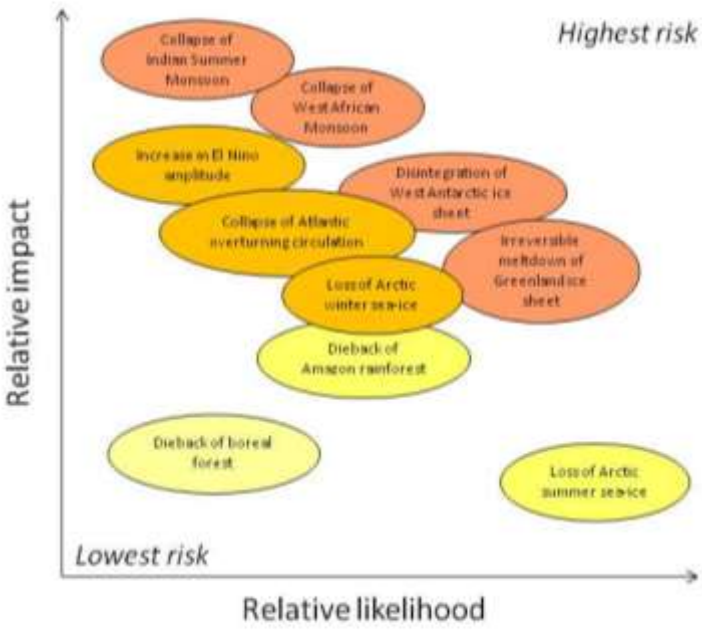

Figure 2. Risk matrix for potential climate tipping points updated from Lenton (2011).

Here we consider how to provide early warning of tipping points, concentrating on the development of early warning methods, and testing them against specific case studies of climate tipping points. Then we consider how to prioritise tipping point early warning effort. This depends on the intersection of two considerations; an assessment of which tipping elements have the greatest potential for early warning, and an assessment of which tipping points pose the biggest risks (Figure 2). By virtue of their sheer size, all the tipping elements mapped out in Figure 1 would have large impacts if they passed a tipping point. Amongst these candidate tipping elements we can begin to rank the relative risk they pose in terms of estimates of their likelihood and their impacts (Lenton 2011) (Figure 2). In future deliverables for this project we will update this risk assessment of climate tipping points – for now we use it as one foundation for prioritising early warning effort. We conclude with an overview of the specific observational needs for tipping points that we identify as priorities for early warning effort, discussing the implications for European climate observing strategies.

EARLY WARNING – THE BASIC PRINCIPLES

Recent work has suggested that there are generic early warning signals prior to a tipping point in a wide range of complex dynamical systems (Scheffer 2009; Lenton 2011). The basic idea is that a system whose current state is losing its stability will become less resilient to perturbations that it receives from its environment, and this will show up as slowing recovery rate from those perturbations (Held and Kleinen 2004; Scheffer et al. 2009). In terms of the feedbacks that govern the behaviour of a system, what is happening is that the negative feedbacks (damping processes) that maintain the stability of the current system state are getting weaker – giving the potential for positive feedbacks to take over and propel a transition to an alternative state. The strength of negative feedback in a system is described mathematically by a quantity called its leading eigenvalue, which is a negative (real) number describing the exponential decay rate of fluctuations. As a tipping point is approached, the leading eigenvalue becomes less negative – signifying weaker negative feedback and a slowing down of fluctuations. The overall phenomenon called 'critical slowing down' (or CSD for short) is illustrated in Figure 3.

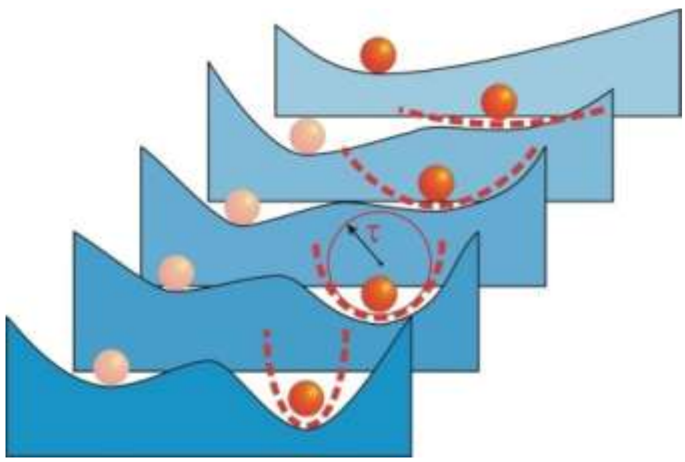

Figure 3. Schematic of critical slowing down on approaching a tipping point from Lenton et al. (2008; Lenton 2011).

In Figure 3, the system starts in a stable configuration (bottom left) – represented by the bold red ball in the right-hand valley ('potential well'). Imagine that the ball in the valley is continually being nudged by a fast process, which we can think of as weather variability in the climate system. Initially, the ball will roll back quickly to its lowest energy state (the bottom of the valley). However, on going from bottom left to top right we are slowly forcing the system in a way that makes its current state less stable until it passes a tipping point, losing all stability (the valley disappears) and the ball must roll into the other stable state. Before that happens there are tell-tale signs of the loss of stability – the ball will roll back slower from a given fluctuation as the valley gets shallower, and it will also move further sideways for a given nudge. The curvature of the valley (denoted by 'τ') represents the timescale of recovery of fluctuations, which gets longer as the tipping point is approached.

The question becomes; how can we detect such critical slowing down in a complex system like the climate system? In experimental systems, we can deliberately perturb them and directly measure the slowing down as a tipping point is approached (Carpenter et al. 2011; Veraart et al. 2012). But in the climate system such experimental intervention would amount to geoengineering, which is undesirable for many, whether or not it is technically feasible. Instead we need ways of detecting the signal of critical slowing down in existing climate data.

In general, as critical slowing down occurs, time-series data will become more correlated with itself. Such 'auto-correlation' from one point to the next is measured by the lag-1 autocorrelation function (AR(1)) (Held and

Kleinen 2004; Dakos et al. 2008). Alternatively, detrended fluctuation analysis (DFA) examines how correlations decay with distance in time from a given point following a power law (Livina and Lenton 2007). The signal of critical slowing down is increasing AR(1) and an increasing DFA-exponent, which amounts to increasing 'memory' in the time-series. Equivalently, slowing down can be detected as a shift in power from high to low frequencies – also called a spectral 'reddening' of time-series data – meaning slower fluctuations of increased amplitude (Kleinen, Held and Petschel-Held 2003).

Perturbations or noise tend to be amplified as a tipping point is approached and this should lead to increased variance in data (Carpenter and Brock 2006; Ditlevsen and Johnsen 2010). In terms of Figure 3, for a given nudge, the ball moves further in a shallower potential well. Also, for the type of tipping point sketched in Figure 3 (known technically as a 'saddle-node' or 'fold' bifurcation) the skewness of the distribution of data should increase as a tipping point is approached (Guttal and Jayaprakash 2008) – with greater amplitude deviations in the direction of the state the system is destined to shift to than in the opposite direction. Furthermore, one might expect to see a greater contribution of extreme deviations as a threshold is approached, which is described by increased kurtosis, or 'peakedness' of a probability distribution (Biggs, Carpenter and Brock 2009). If the noise level is relatively high the system may even 'flicker' – briefly transitioning into the alternative state, before it undergoes a more permanent shift. The spatial equivalents of increasing correlation, variance, and skewness have also been proposed as early warning indicators of tipping points in systems where spatial information is available (Litzow, Urban and Laurel 2008; Guttal and Jayaprakash 2009; Dakos et al. 2010). Although harder to visualise, the underlying principles are the same.

These various early warning indicators have been tested in a variety of model systems, and to a lesser extent in experimental systems and in real data. Existing work suggests that critical slowing down prior to a tipping point is the most robust early warning signal, followed by increasing variance, whilst increasing skewness and kurtosis are less generic. A cautionary note is that in trying to detect critical slowing down, parameter choices in the statistical analyses (such as filtering bandwidth and sliding window length) can affect the significance, and even the sign, of any trend in early warning indicators (Dakos et al. 2008; Lenton et al. 2012). The majority of existing studies nominally consider ecological tipping points (Lenton 2012), but are focused on a relatively small set of simple mathematical models with only a few tests on field data (Litzow, Urban and Laurel 2008; Carpenter et al. 2011). There are less studies on early warning of climate tipping points (Lenton 2012), but they have considered a wider range of model complexity (Held and Kleinen 2004; Livina and Lenton 2007; Lenton et al. 2009; Boulton, Good and Lenton 2013) and paleo-data records (Livina and Lenton 2007; Dakos et al. 2008; Lenton et al. 2012).

In this deliverable we have tried to advance the field by testing early warning methods on the output of state-of-the-art climate models exhibiting climate tipping points. Building on previous work that looked for early warning signals of Amazon rainforest dieback in versions of the Hadley Centre's HadCM3 model (Boulton, Good and Lenton 2013), we present two new case studies. First we look for early warning of a collapse of the Atlantic meridional overturning circulation in FAMOUS – a lower resolution version of HadCM3 (Boulton, Allison and Lenton 2014). Then we examine whether there is early warning of abrupt year-round Arctic sea-ice loss that occurs in several models in the CMIP5 database, under the high-end 'RCP8.5 extended' forcing scenario.

An important consideration to bear in mind is that the early warning theory just outlined is based on a separation of three timescales; the timescale of forcing (τ_{forcing}), the timescale of the system itself (τ_{system}), and the timescale at which it is observed ($\tau_{\text{observation}}$). It is assumed that the system in question is forced much slower than its own dynamical timescale, and is observed much more frequently than its own dynamics, i.e.

$$\tau_{\text{forcing}} \gg \tau_{\text{system}} \gg \tau_{\text{observation}}$$

TEST CASE – COLLAPSE OF THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION

The Atlantic meridional overturning circulation (AMOC) is essentially the Atlantic branch of the thermohaline circulation (that extends around the global ocean). It has long been recognised that the AMOC has the potential for rapid collapse (Stommel 1961), and while the likelihood of this occuring in the 21st Century is generally considered to be low (Zickfeld et al. 2007; Kriegler et al. 2009; Lenton 2011; Collins et al. 2013), the impacts could be substantial if it were to occur. Many previous model studies have examined the impacts of a collapse of the AMOC by forcing it to occur by adding an extra flux of freshwater to the North Atlantic region (and taking it away from the rest of the ocean). These suggest that while impacts on global mean temperature would be small, substantial cooling would be expected in Europe and eastern North America, along with reduced precipitation in Europe and an additional increase in sea level rise of 80cm along Atlantic coasts by 2150 (Vellinga and Wood 2008; Kuhlbrodt et al. 2009; Yin, Schlesinger and Stouffer 2009).

A few previous studies have analysed whether there is early warning of AMOC collapse if this excess freshwater flux is steadily increased. This requires a fast model in order to integrate it for long enough. The Earth system models of intermediate complexity, CLIMBER-2 (Held and Kleinen 2004) and GENIE-1 (Livina and Lenton 2007), show early warning signals of AMOC collapse but have very simplified atmospheres. A more complete model, GENIE-2 has a 3-D atmospheric GCM coupled to a 3-D ocean with somewhat simplified physics and also shows early warning of AMOC collapse (Lenton et al. 2009). Here we consider FAMOUS, which is a fully coupled ocean-atmosphere GCM and thus the most complex model yet tested. We make use of an existing experiment with FAMOUS where an AMOC collapse is forced over 800 years (Hawkins et al. 2011).

The results (Figure 4) (Boulton, Allison and Lenton 2014) show critical slowing down of fluctuations in the AMOC before it collapses. The strength and reliability of the early warning signal varies with latitude (Figure 5). The AMOC is currently monitored at 26°N where there are reliable early warning signals in this model world. However, the warning signals are even more statistically significant toward the southern boundary of the Atlantic and in the Northernmost Atlantic. Interestingly these are locations where investment is currently going into the development of AMOC monitoring arrays (discussed below).

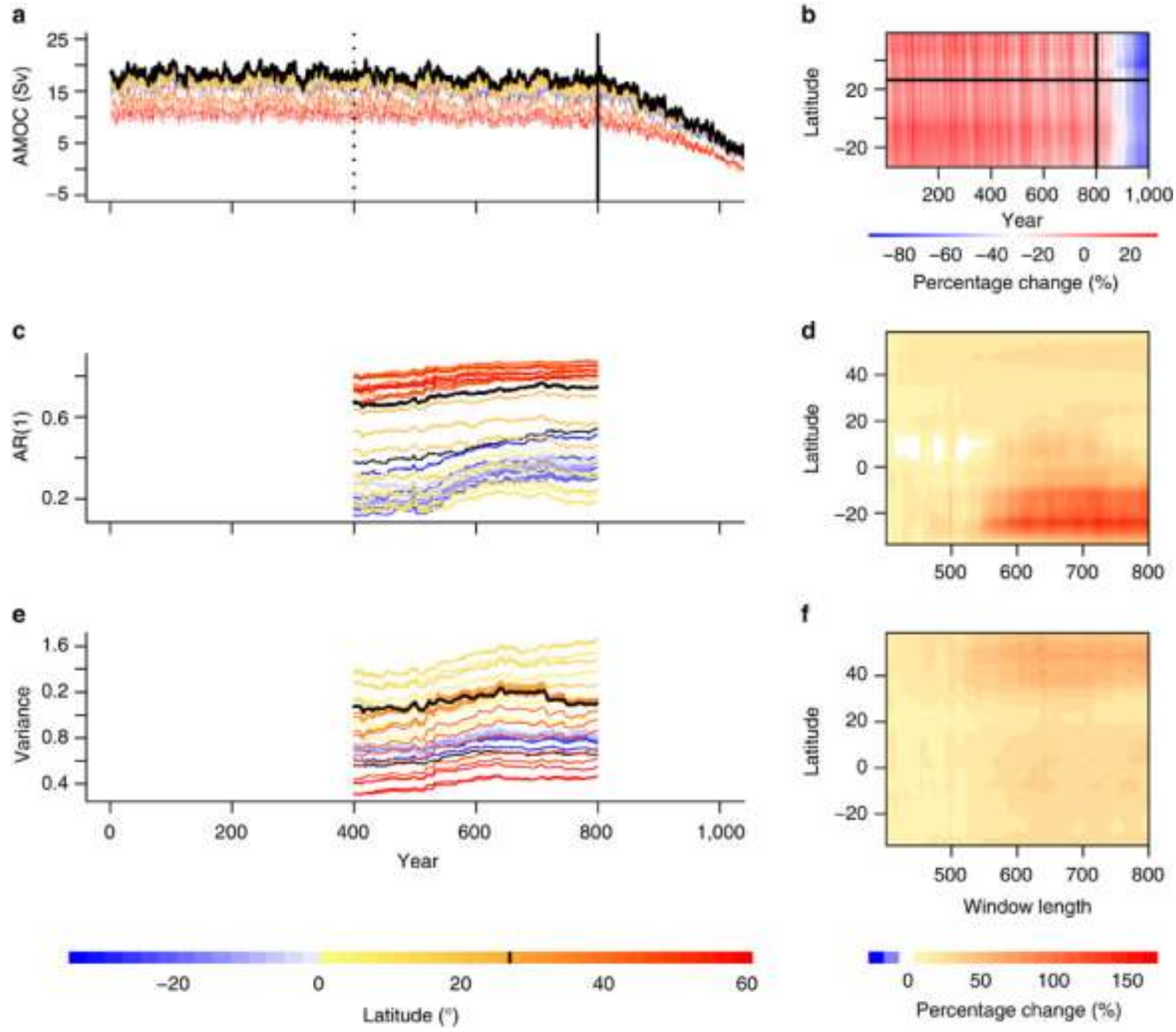

Figure 4. Early warning of AMOC collapse in the FAMOUS AOGCM (Boulton, Allison and Lenton 2014). (a) Annual time series of AMOC (Sv) at each latitude are cut before collapse begins at 800 years (solid vertical line). (b) Time series are also shown as a contour plot in the time-latitude plane. They are then detrended and the analysis carried out on the residuals. A sliding window length of 400 years is used (dotted vertical line in (a) marks the end of the first window) to estimate candidate early warning signals: (c,d) AR(1) coefficient, and (e,f) variance. Time series are coloured according to their latitude and 26.25°N (where the AMOC is currently monitored) is shown in black.

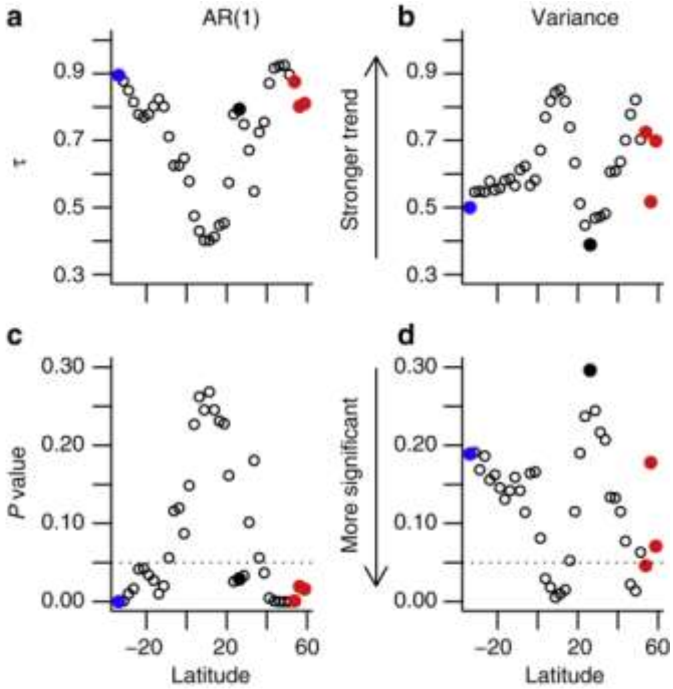

Figure 5. Tendency and significance of early warning indicators as a function of latitude (Boulton, Allison and Lenton 2014). Kendall's τ values are calculated to determine the tendency of estimated (a) **AR(1) coefficient and** (b) **variance indicators. Significance of results, using bootstrapped null model ensembles to determine *P* values, are plotted for** (c) **AR(1) and** (d) **variance. Any *P* values below the dotted horizontal line are significant at the 95% level (*P*<0.05). Black filled-in points correspond to 26.25°N. Approximate locations of the future OSNAP and SAMOC monitoring arrays are shown in red and blue, respectively.**

At these high latitude locations, the signal of critical slowing down can become statistically significant at the p<0.05 level 250 years before the AMOC collapse begins – a very early warning. However, in order to detect a statistically significant early warning signal in the model, it requires over 500 years of prior data of the AMOC strength. This is comparable to the timescale for water to circulate around the Atlantic basin. It means that in reality, early warning of AMOC collapse will require some paleo-data reconstruction of the AMOC strength during the last millennium.

One slightly puzzling aspect of the results is that the timescale of the forcing in this model experiment is comparable to the timescale of the system itself ($\tau_{forcing} \approx \tau_{system}$). Hence the AMOC is clearly lagging the freshwater forcing and collapses roughly 300 years after its equilibrium state has already lost its stability. We might expect this to interfere with the early warning signals but experiments with a simpler model suggest that the dynamics of the lagged AMOC system are well described by a linear model. In our early warning search we are fitting a linear model. Hence as long as we remove any non-stationary trends in the data (which is a standard part of the method) the early warning signal should remain (as it does).

The model experiment uses an idealised linear increase in freshwater forcing which is comparable in magnitude to observed increases in freshwater input to the North Atlantic region (Boulton, Allison and Lenton 2014). However, anthropogenic forcing may become faster and be more non-linear in character. Future work needs to examine whether early warning signals would still be expected under more realistic forcing.

There is an alternative, complementary approach to probing the stability of the AMOC, which has been examined in the same model simulations (Hawkins et al. 2011). It involves a flux measure (called 'F_{ov}') of whether the AMOC is a net importer of salt or freshwater at its southern boundary. This provides a diagnostic of whether it is in a regime where an alternative stable state is already available (cf Figure 3) – 'bi-stability' – or has only one stable state. If the AMOC imports salt this is a self-amplifying situation (helping keep the waters in the basin denser and more prone to sinking), diagnostic of bi-stability. This positive feedback also indicates a potential vulnerability to AMOC collapse, because a decrease in overturning strength will import less salt tending to further weaken the AMOC. In the FAMOUS simulation as freshwater forcing is increased, the model switches from importing freshwater (positive F_{ov}) to importing salt (positive F_{ov}), consistent with a loss of AMOC stability.

TEST CASE – YEAR-ROUND LOSS OF ARCTIC SEA-ICE

The areal coverage of Arctic sea-ice is already in an accelerating decline, with summer ice loss having abruptly increased from 2007 onwards (Livina and Lenton 2013). There is much debate about whether the loss of summer Arctic sea-ice cover involves passing a tipping point, with some studies suggesting it could (Abbot, Silber and Pierrehumbert 2011; Livina and Lenton 2013) and others that it does not (Eisenman and Wettlaufer 2009; Notz 2009; Tietsche et al. 2011). After the loss of summer ice becomes the norm, ice should still reform in the winter. However, if warming continues, in high-end climate change scenarios there is the possibility of winter (i.e. year-round) ice loss. The requisite warming is unlikely to be reached this century but could occur next century. The abrupt loss of winter sea-ice cover is a stronger candidate for tipping point behaviour (Lenton et al. 2008; Eisenman and Wettlaufer 2009). Indeed four models in the CMIP5 database (used in the latest IPCC assessment report) show abrupt loss of winter sea-ice in the 22nd century (Figure 6). Total loss of Arctic sea-ice could abruptly amplify Arctic warming (Screen and Simmonds 2010) thus impacting on ecosystems and human activities in the Arctic, and potentially altering weather extremes in Europe (Screen and Simmonds 2013).

We have examined whether there is an early warning signal before the abrupt loss of year-round Arctic sea-ice cover in the CSIRO model (shown in green in Figure 6). Initial results tantalisingly showed an increase in AR(1) in the time-series prior to the sea-ice collapse. However, further research revealed a problem of lack of timescale separation between the frequency of annual sampling of the model output and the inherent timescale of the sea-ice which is also close to 1 year (i.e. $\tau_{system} \approx \tau_{observation}$). This means that the apparent early warning signal is not reliable because we are not able to resolve the decay of fluctuations in the system. Getting more frequent model output ought to help with this, but it raises the separate problem that there is a very strong seasonal cycle of insolation forcing the sea-ice (along with the steady global warming signal). Previous work has sought to remove the seasonal cycle from sea-ice data and analyse the fluctuations around it (Livina and Lenton 2013). However, this is fraught with difficulties if the nature of the seasonal cycle itself is changing shape.

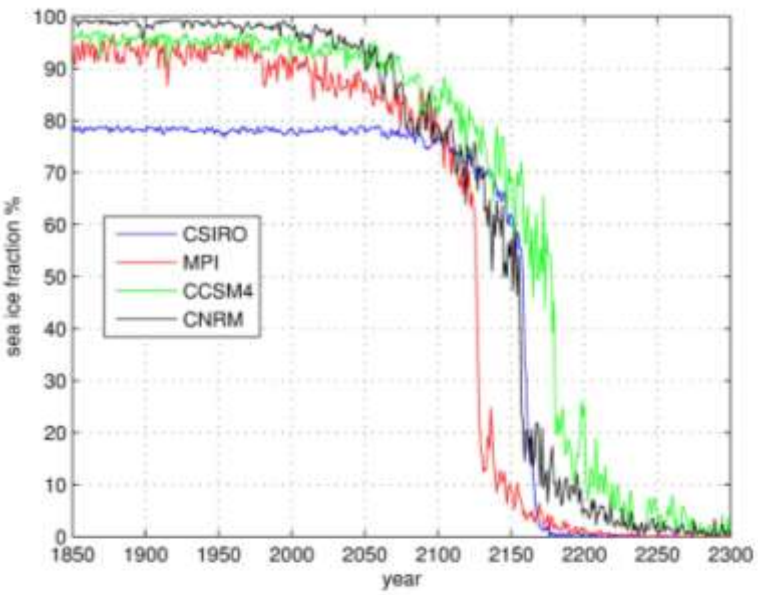

Figure 6. Abrupt loss of year-round Arctic sea-ice cover during the 22nd century in four CMIP5 models under the RCP8.5 extended forcing scenario.

Instead we have come up with a way of using the amount of time lag of the sea-ice cover behind the seasonal forcing as a diagnostic of critical slowing down. The basic idea is that if the sea-ice is exhibiting critical slowing down it should lag further behind the seasonal forcing.

In the usual early warning method one measures the statistics of the time taken for the system to recover from noisy, random perturbations. The Arctic sea ice however is constantly and predictably perturbed by the seasonal cycle which offers a more deterministic way to determine the change in the time scale of the system and therefore whether the system is experiencing critical slowing down. One can determine this time scale by how much the system's response lags the forcing and also by the change in the amplitude of the system's response.

Our results suggest, unfortunately, that it will be hard to observe critical slowing down for the Arctic sea ice, the reason being that the ice change in stability occurs in a very short period of time making robust diagnosis of early warning signals very difficult. This conclusion is reached for simple, more idealised models of sea ice and it is possible that in reality the sea ice has a more progressive decline in stability making observation possible. We are still investigating this question.

Although our work suggests an early warning of Arctic sea ice tipping is very difficult, the research has spawned a new set of techniques that will help with early warnings of tipping points in generic systems with periodic forcing and without a clear time scale separation. Examples of periodic forcing are seasonal, diurnal or even Milankovich (orbital) cycles.

Another offshoot from this particular case study has been the use of spectral methods of the system's response to periodic forcing. As the system's response becomes more nonlinear (as it does near a tipping point) one sees harmonics of the period of the forcing being generated in the system's response spectrum. This is potentially useful as knowledge of the nonlinearities in the system can tell one whether the system has the potential for a safe, explosive or catastrophic tipping point as well as the shift to an increasingly nonlinear response regime.

EXTENDING EARLY WARNING METHODS

Our two case studies add to the existing body of work showing some promise for early warning of climate tipping points. However, they have also highlighted some issues with the method of looking for critical slowing down in one-dimensional time-series. We have suggested above some ways of improving the method in one-dimensional cases. However, the real climate system is 'high-dimensional' and therefore has the potential to exhibit much more complex behaviour than is possible in one-dimension – for example any oscillatory dynamics are inherently (at least) two-dimensional (even if they are observed in a 1-D time-series). Atmosphere, ocean and ice-sheet dynamics can all exhibit internal modes of variability as well as coupled modes of variability between them. These include major modes of short-term climate variability such as the El Nino Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), as well as much longer-term modes of variability such as the Dansgaard-Oeschger cycles (series of abrupt climate changes in the last ice age) and the ice age cycles themselves.

This inspired us to extend the early warning method to multi-dimensional systems (Williamson and Lenton 2015). Dynamical systems frequently have behaviour that cannot be described by exponential decay to a fixed point (the basis of the existing early warning methods). Systems can oscillate or be chaotic as well as sit at fix points. These behaviours must be modelled by second or higher order autonomous differential equations (where time is not an explicit parameter in their dynamics). They can also be driven by periodic forcing (non-autonomous systems). Systems can transition between these different dynamical regimes when passing through bifurcation points. These bifurcations represent a larger range of the possible tipping points than the usual early warning method can deal with. Moreover, if one blindly applies the usual early warning method to systems that are not adequately described by the one dimensional dynamics the method assumes, one can get a completely fictitious answer hence a generalised method should prove useful.

It is still possible to see critical slowing down on the approach to higher-dimensional tipping points, and our generalised method picks this up, because it is a generalisation of the usual method. However, there are special cases where critical slowing down does not occur and some other characteristic behaviour signals an approaching tipping point. An example is a tipping point described mathematically by a homoclinic bifurcation – where a periodic orbit (oscillating state) loses its stability. Instead of critical slowing down, the system shows a characteristic reduction in its frequency of oscillation before the tipping point (Figure 7). In our extended method this is governed mathematically by a decrease in the imaginary part of the leading eigenvalue in the system (rather than its real part becoming less negative) (Figure 8).

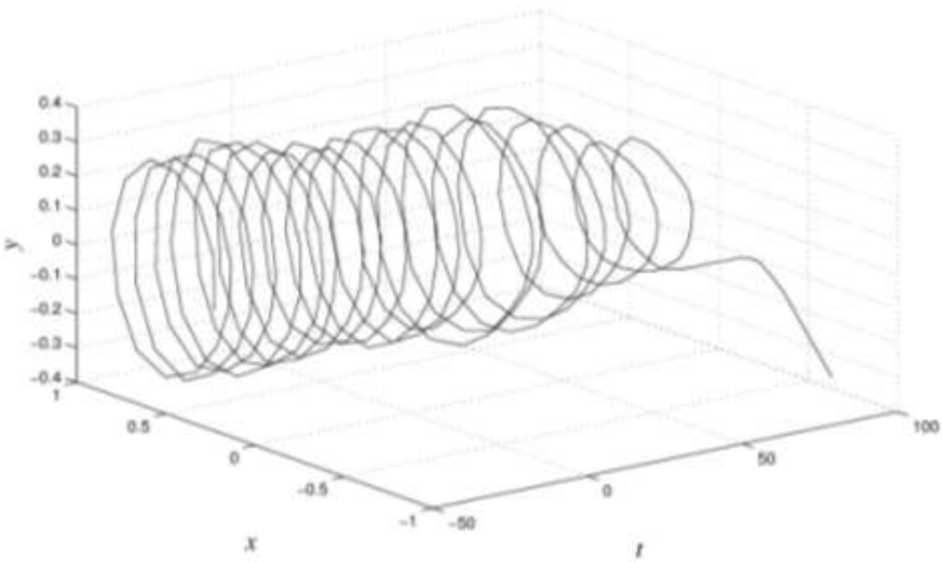

Figure 7. Time series of a system with a homoclinic bifurcation: Plotted are the two variables x and y, that fully describe the two dimensional system against time, t. The control parameter, alpha, is varied linearly and slowly towards the bifurcation, alpha=0, when t=100. One can see the system abruptly change around this time as the attractor disappears.

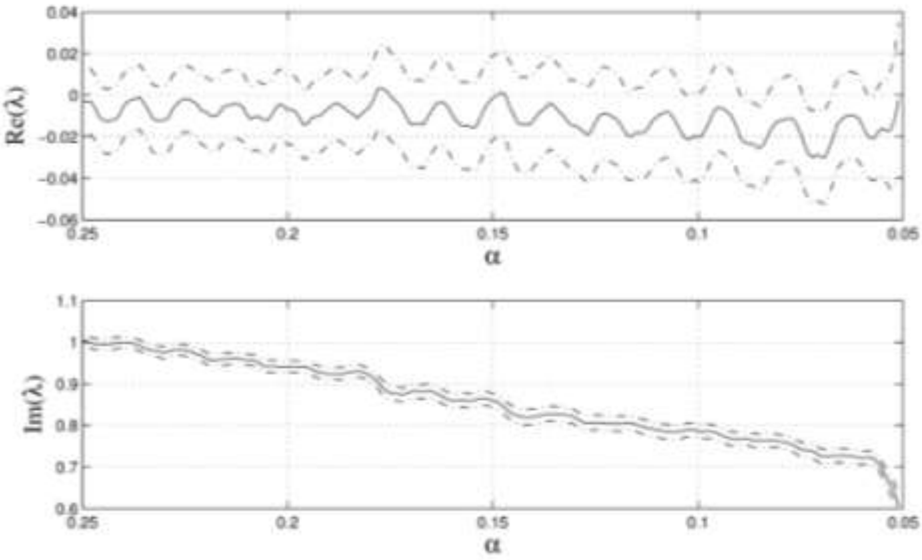

Figure 8. Early warning indicators for the homoclinic bifurcation using our extended method. The x axis is the control parameter alpha and the system reaches the homoclinic bifurcation at alpha=0. The top panel shows the real part of the governing eigenvalue of the system, which here is fairly constant showing a lack of critical slowing down in the system. The lower panel shows the imaginary part of the governing eigenvalue, which is related to the oscillation frequency of the system, and shows a marked decrease on the approach to the homoclinic bifurcation.

Our extended method thus suggests that different types of tipping point can give qualitatively different types of early warning signals, and this might conceivable be used to detect what type of tipping point is approaching. The extended method also opens the possibility of applying early warning techniques to spatial data, if each spatial location is treated as a single dimension of the multidimensional system. To give a concrete example, previous research has suggested that the ‘green Sahara’ state seen in early Holocene records (prior to around 5000 BP) and in some future projections (Figure 1) could represent an alternative stable state for the vegetation-climate system in West Africa, that appears or disappears through passing a tipping point. The green state is only stable as a collective of multiple spatial locations. To put it another way, the presence or absence of vegetation in one location may stabilise or destabilise other spatial locations by increasing or suppressing rainfall. Using the extended method, each spatial location can be modelled as a new variable, coupled to each other through rainfall. If the method is given the time series from each spatial location, it can reveal which combination of spatial locations forms an unstable collective (the critical modes) and whether they exhibit critical slowing down or not. This is just one example of many possible new applications of our method.

TARGETING EARLY WARNING EFFORT

Based on our method development, and a review of available data, we have assessed the potential for generic early warning signals across a range of candidate climate tipping points (Table 1).

Table 1. Early warning potential for different tipping elements

System	Approximate timescale of forcing ($\tau_{forcing}$)	Approximate timescale of system (τ_{system})	Timescale of observations/ *reconstructions* ($\tau_{observation}$)	Interval of observations/ *reconstructions* (AD)	Potential for generic early warning signals
Arctic sea-ice	100 yr	1-10 yr	1 day 1 yr *5 yr*	1979-present 1870-1995 *561-1995* [A]	Medium
GIS	100 yr	1000 yr	~1 month rare *1 yr*	2003-present 1930s onward *1840-2010* [B]	Low
WAIS	100 yr	>300 yr	rare (Antarctic total)	1993-present [C]	Low
AMOC	100 yr	100 yr	1 day *1 month* *1 yr*	2004-present *1850-present* *900-2000* [D]	Medium
ENSO	100 yr	50-100 yr	1 day *1 yr*	1950-present *900-2000* [E]	Medium
ISM	100 yr	1 yr	1 day 1 month *1 yr*	1948-present 1871-present *900-2000* [F]	High
WAM and Sahel/Sahara	100 yr	1-10 yr	1 month	1900-present [G]	High
Amazon	100 yr	50 yr	1 month	2000-present [H]	Low
Boreal forest	100 yr	50 yr	limited	1985-present [I]	Low

[A](Kinnard et al. 2011) [B](Box and Colgan 2013) [C](Hanna et al. 2013) [D](Rahmstorf et al. 2015) [E](Li et al. 2011) [F](Shi, Li and Wilson 2014) [G]doi:10.6069/H5MW2F2Q [H](Hilker et al. 2014) [I](Chen et al. 2014)

The best prospects for tipping point early warning should exist for 'fast' systems, such as the seasonal monsoon systems of West Africa (WAM) and the Indian sub-continent (ISM), because they show the cleanest separation of timescales, and require less of a reconstructed data record. The Arctic sea-ice should also have a good separation of timescales, but as discussed above, its potentially rapid loss of stability and the strong seasonal cycle make early warning more difficult to detect. For 'intermediate' timescale systems such as the AMOC or major forest biomes, where $\tau_{forcing} \approx \tau_{system}$, the potential for early warning appears to depend on the system, with AMOC showing more promise in model studies than the Amazon (Boulton, Good and Lenton 2013; Boulton, Allison and Lenton 2014). Early warning in these systems also needs a long record ($>\tau_{system}$) of the system's natural behaviour and that is missing in the case of the Amazon and boreal forests. The timescale of past shifts in ENSO regime (Li et al. 2011; Li et al. 2013) also suggests a lack of separation of timescales ($\tau_{forcing} \approx \tau_{system}$), but encouragingly there are several long reconstructions of its past behaviour. For really 'slow' systems such as major ice sheets where $\tau_{system} > \tau_{forcing}$ the problems of lack of timescale separation and lack of data are exacerbated, making anticipating a tipping point by the generic methods we have discussed extremely challenging. However, their slow dynamics mean these systems pose less of a threat of rapid change, so seeking an early warning signal is less urgent.

In general, where generic early warning methods fail, there is still the option of designing a system-specific early warning indicator. Such an indicator has been suggested for Amazon rainforest dieback (Boulton, Good and Lenton 2013), and for AMOC collapse (Hawkins et al. 2011), but not as far as we aware for other potential tipping points.

The actual prioritisation of early warning effort should be based not just on which systems have the greatest potential for early warning, but also on which tipping events pose the greatest risk to societies – especially those where early warning would allow policy intervention to reduce that risk (e.g. through pre-emptive adaptation even if the tipping point is unavoidable). The risk assessment of different tipping elements will be revisited in future deliverables from this work package. Here we use a preliminary update of the 'risk matrix' from Lenton (2011) (Figure 2, collapsing the results down on to a single 'risk' axis), combined with our assessment of early warning potential (Table 1). From this we plot a 'prioritisation matrix' of risk versus early warning potential for different tipping points (Figure 9).

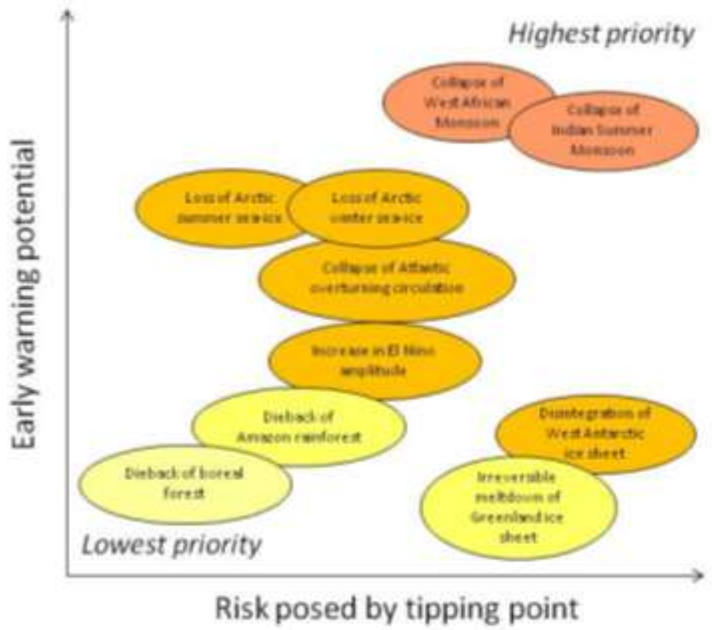

Figure 9. Prioritisation matrix for tipping point early warning effort based on preliminary assessment of risk and early warning potential.

This prioritisation exercise suggests that from a global perspective, research effort should be invested in examining the potential for early warning systems for monsoon disruption in India and West Africa. Furthermore, there are a cluster of potential tipping points which combine moderate to high risks with some reasonable early warning potential, including collapse of the AMOC, loss of Arctic sea-ice, and a change in the ENSO regime. Other systems suffer from a lack of early warning potential due to a lack of data, violating the theory, or both. However, the Amazon rainforest and boreal forest could still be targets for designing system-specific early warning indicators, especially if reconstruction of their past variability can be improved and extended. For the ice sheets a strategy (currently pursued) of direct monitoring and reconstruction of their past variability seems more realistic than seeking early warning of slow, irreversible changes that may already be underway (Joughin, Smith and Medley 2014; Rignot et al. 2014).

A subset of tipping points that can have a major impact on Europe have previously been identified (Levermann et al. 2012). These include the AMOC, Arctic sea-ice, Greenland and West Antarctic ice sheets, as well as Alpine glaciers and a Northern Hemisphere ozone hole (not considered here). Amongst these, the AMOC and Arctic sea-ice are priorities for early warning effort (Figure 9). The list could also be extended to include the Eurasian boreal forests and permafrost regions. However, the potential to detect climate-related regime shifts in Arctic terrestrial ecosystems is severely limited by the coverage and nature of current monitoring activities (Mård Karlsson et al. 2011).

Overall, this assessment is far from exhaustive or final, but it should be taken as an example of how to approach the prioritisation of tipping point early warning efforts.

FURTHER RESEARCH AND OBSERVATIONAL NEEDS

Given our tentative identification of some candidate targets for tipping point early warning effort, we now consider in more detail the observational needs for those systems. In general, climate and impacts models can be used to point towards quantities that could be monitored for early warning and where to monitor them, but this must be followed up with actual data gathering and attempts to reconstruct the past variability of specific systems, especially as currently available data are often insufficient (Table 1). Hence real time monitoring systems need to be improved, and better targeted at the variables that reveal most about the underlying dynamics of the system in question.

1.1 Atlantic Meridional Overturning Circulation (AMOC)

For the AMOC, the overturning stream function itself is the best target to monitor. However, direct measurements of the overturning are relatively recent; monitoring of the AMOC at 26.25°N by the 'RAPID' array has now been underway for just over a decade. Efforts are also underway to establish monitoring arrays in the Northernmost Atlantic, by the Overturning in the Sub-polar North Atlantic Program (OSNAP), and at the Southern boundary of the Atlantic by the South Atlantic Meridional Overturning Circulation (SAMOC) project. Interestingly, our study with the FAMOUS model (Boulton, Allison and Lenton 2014) suggests that there are reliable early warning signals of AMOC collapse at 26°N in that model (black in Figure 5) and that the early warning signals are even better in the locations of the OSNAP (red) and SAMOC (blue) proposed monitoring arrays. However, one should not rely on a single model for such an assessment – a range of models should be examined to see if they give consistent results for where it is best to monitor for early warning signals of AMOC collapse. SAMOC has the additional advantage that it can monitor a complementary, system-specific stability indicator for the AMOC ('F_{ov}') at the southern boundary of the basin.

As outlined above, successful early warning of AMOC collapse will also require some paleo-data reconstruction of the AMOC strength during the last millennium. This has to rely on some indirect proxies of the overturning strength. A currently favoured approach uses the observation that in models fluctuations in North Atlantic sea surface temperature (or the difference between North and South Atlantic sea surface temperatures) are strongly correlated with fluctuations in the underlying AMOC strength. Hence several groups have reconstructed North Atlantic temperatures using paelo-data proxies from around the basin (such as tree rings) and derived AMOC fluctuations from that. Recently a specific region of the northernmost Atlantic has been targeted to reconstruct AMOC strength over the past millennium (Rahmstorf et al. 2015). The interval of proxy data overlaps with the interval of direct observational data for sea surface temperature (1850 onwards), thus allowing a continuous reconstruction of AMOC strength. Currently these reconstructions are only used to make inferences about changing AMOC strength, but they can in principle be used to diagnose the stability of the AMOC and whether it is changing.

Even if early warning of AMOC collapse were ultimately to prove infeasible, better monitoring of the AMOC will improve our capability to forecast (multi-)decadal variability in circulation strength, known as the Atlantic Multi-decadal Oscillation (or 'AMO' for short). AMO variability in turn provides decadal climate forecasting skill around the North Atlantic region, including the ability to forecast intervals of Sahel drought (Sutton and Allen 1997; Sutton and Hodson 2005). Hence investment in an AMOC early warning system would have substantial side benefits across a range of timescales.

1.2 Arctic sea-ice

Satellite observations of Arctic sea-ice areal coverage exist at daily resolution since the end of the 1970s. There are also much rarer measurements of sea-ice thickness, mostly from military submarines. Efforts have been made to reconstruct the annual minimum sea-ice coverage for the past century from ship records. This has been extended back over the past 1450 years (at 5 year resolution) using a range of proxy records around the Arctic ocean basin (Kinnard et al. 2011). Hence there is a relatively good dataset for Arctic sea-ice areal cover, given that this is a 'fast' system which should not need a particularly long record of its past behaviour but does require high-temporal-resolution sampling, as supplied by satellite observations.

Our research suggests that collapse of the year-round Arctic sea-ice cover warrants further study with complex models. In this deliverable we deduced from an idealised model that there could be difficulties obtaining an early warning signal of sea-ice collapse because its stability properties change very quickly when approaching the collapse. However, this needs to be re-examined in more complex models.

1.3 Monsoons

The South Asian Monsoon (Indian) Summer Monsoon has recently been reconstructed from 15 tree ring chronologies over past millennium (Shi, Li and Wilson 2014). The dataset correlates reasonable well with the instrumental record, from reanalysis studies, which spans 1948-present. There is also an all-India monsoon rainfall index (AIMRI) based on 306 rain gauges in India, which extends back to 1871 at monthly resolution. Given that the monsoon itself is a 'fast' system, modulated by lower frequency modes of climate variability, this is good data coverage for examining the potential for early warning signals.

In West Africa there are fewer weather stations with long records. A Sahel rainfall index has been constructed from 1900 to present (doi:10.6069/H5MW2F2Q) showing inter-annual variability in rainfall based on 14 weather stations. Clearly better climate observatories are needed in Africa, and reanalyses could be used to try and better reconstruct past WAM variability. It is also more challenging to reconstruct the history of the monsoon from proxies, but some interesting efforts are underway (Azzoug, Carré and Schauer 2012).

1.4 Implications for European climate observing strategies

Our research highlights that tipping point early warning requires a joined-up approach that combines models and data, and that combines paleo-data reconstruction, the observational record, and real-time monitoring – both *in situ* and remotely sensed. This requires the bringing together of different communities of scientists toward a common goal, within a common theoretical framework.

Earth observation is one important component of this strategy, which is the focus of attention, particularly through the Global Earth Observation System of Systems (GEOSS) initiative. Efforts are ongoing to define 'essential variables' to monitor. For example a set of 50 'essential climate variables' were identified[1] by the Global Climate Observing System (GCOS) in 2010. Our reflection on this exercise is that it would be worthwhile to identify a set of 'early warning variables' for climate tipping points, and try to ensure that they at least overlap with (and preferably are entirely contained within) the set of 'essential climate variables'.

[1] http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

SUMMARY

This deliverable has shown that there is considerable potential for early warning of some (although not all) of the most impactful climate tipping points. These include a collapse of the Atlantic Meridional Overturning Circulation (AMOC), which would profoundly affect the climate of Europe. We have used a full-complexity climate model to indicate where the most reliable early warning signals of AMOC collapse are expected, and thus help guide the design of a prospective early warning system (Boulton, Allison and Lenton 2014). The method of early warning has been extended such that it can now be applied to a wider range of potential climate tipping points and dynamical behaviours that cannot be reduced down to 1-dimension (Williamson and Lenton 2015). We have assessed the potential for generic early warning signals across the set of climate tipping points previously identified (Lenton et al. 2008). Combining this with an assessment of the risk posed by these different tipping points, tentatively updated from previous work (Lenton 2011), we offer a preliminary prioritisation of tipping elements to target for early warning effort. Observational and further research needs are outlined for these tipping elements. The over-riding, general recommendation is that a substantive tipping point early warning effort will require a joined-up approach of modelling and data gathering that connects existing scientific communities.

REFERENCES

Abbot, D. S., M. Silber and R. T. Pierrehumbert (2011). "Bifurcations leading to summer Arctic sea ice loss." Journal of Geophysical Research **116**: D19120.

Azzoug, M., M. Carré and A. J. Schauer (2012). "Reconstructing the duration of the West African Monsoon season from growth patterns and isotopic signals of shells of Anadara senilis (Saloum Delta, Senegal)." Palaeogeography, Palaeoclimatology, Palaeoecology **346–347**(0): 145-152.

Biggs, R., S. R. Carpenter and W. A. Brock (2009). "Turning back from the brink: Detecting an impending regime shift in time to avert it." PNAS **106**(3): 826-831.

Boulton, C. A., L. C. Allison and T. M. Lenton (2014). "Early warning signals of Atlantic Meridional Overturning Circulation collapse in a fully coupled climate model." Nat Commun **5**.

Boulton, C. A., P. Good and T. M. Lenton (2013). "Early warning signals of simulated Amazon rainforest dieback." Theoretical Ecology **6**(3): 373-384.

Box, J. E. and W. Colgan (2013). "Greenland Ice Sheet Mass Balance Reconstruction. Part III: Marine Ice Loss and Total Mass Balance (1840–2010)." Journal of Climate **26**(18): 6990-7002.

Carpenter, S. R. and W. A. Brock (2006). "Rising variance: a leading indicator of ecological transition." Ecology Letters **9**(3): 311-318.

Carpenter, S. R., J. J. Cole, M. L. Pace, R. Batt, W. A. Brock, T. Cline, J. Coloso, J. R. Hodgson, J. F. Kitchell, D. A. Seekell, L. Smith and B. Weidel (2011). "Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment." Science **332**(6033): 1079-1082.

Chen, D., T. Loboda, S. Channan and A. Hoffman-Hall (2014). "Long-Term Record of Sampled Disturbances in Northern Eurasian Boreal Forest from Pre-2000 Landsat Data." Remote Sensing **6**(7): 6020-6038.

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

Dakos, V., M. Scheffer, E. H. van Nes, V. Brovkin, V. Petoukhov and H. Held (2008). "Slowing down as an early warning signal for abrupt climate change." PNAS **105**(38): 14308-14312.

Dakos, V., E. van Nes, R. Donangelo, H. Fort and M. Scheffer (2010). "Spatial correlation as leading indicator of catastrophic shifts." Theoretical Ecology **3**(3): 163-174.

Ditlevsen, P. D. and S. J. Johnsen (2010). "Tipping points: Early warning and wishful thinking." Geophysical Research Letters **37**: L19703.

Eisenman, I. and J. S. Wettlaufer (2009). "Nonlinear threshold behavior during the loss of Arctic sea ice." PNAS **106**(1): 28-32.

Guttal, V. and C. Jayaprakash (2008). "Changing skewness: an early warning signal of regime shifts in ecosystems." Ecology Letters **11**: 450-460.

Guttal, V. and C. Jayaprakash (2009). "Spatial variance and spatial skewness: leading indicators of regime shifts in spatial ecological systems." Theoretical Ecology **2**: 3-12.

Hanna, E., F. J. Navarro, F. Pattyn, C. M. Domingues, X. Fettweis, E. R. Ivins, R. J. Nicholls, C. Ritz, B. Smith, S. Tulaczyk, P. L. Whitehouse and H. J. Zwally (2013). "Ice-sheet mass balance and climate change." Nature **498**(7452): 51-59.

Hawkins, E., R. S. Smith, L. C. Allison, J. M. Gregory, T. J. Woollings, H. Pohlmann and B. de Cuevas (2011). "Bistability of the Atlantic overturning circulation in a global climate model and links to ocean freshwater transport." GRL **38**: L10605.

Held, H. and T. Kleinen (2004). "Detection of climate system bifurcations by degenerate fingerprinting." Geophysical Research Letters **31**: L23207.

Hilker, T., A. I. Lyapustin, C. J. Tucker, F. G. Hall, R. B. Myneni, Y. Wang, J. Bi, Y. Mendes de Moura and P. J. Sellers (2014). "Vegetation dynamics and rainfall sensitivity of the Amazon." Proceedings of the National Academy of Sciences **111**(45): 16041-16046.

Joughin, I., B. E. Smith and B. Medley (2014). "Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica." Science **344**(6185): 735-738.

Kinnard, C., C. M. Zdanowicz, D. A. Fisher, E. Isaksson, A. de Vernal and L. G. Thompson (2011). "Reconstructed changes in Arctic sea ice over the past 1,450 years." Nature **479**(7374): 509-512.

Kleinen, T., H. Held and G. Petschel-Held (2003). "The potential role of spectral properties in detecting thresholds in the Earth system: application to the thermohaline circulation." Ocean Dynamics **53**: 53-63.

Kriegler, E., J. W. Hall, H. Held, R. Dawson and H. J. Schellnhuber (2009). "Imprecise probability assessment of tipping points in the climate system." PNAS **106**(13): 5041-5046.

Kuhlbrodt, T., S. Rahmstorf, K. Zickfeld, F. Vikebø, S. Sundby, M. Hofmann, P. Link, A. Bondeau, W. Cramer and C. Jaeger (2009). "An Integrated Assessment of changes in the thermohaline circulation." Climatic Change **96**(4): 489-537.
Lenton, T. M. (2011). "Early warning of climate tipping points." Nature Climate Change **1**: 201-209.
Lenton, T. M. (2012). "What early warning systems are there for environmental shocks?" Environmental Science and Policy **27**: S60-S75.
Lenton, T. M., H. Held, E. Kriegler, J. Hall, W. Lucht, S. Rahmstorf and H. J. Schellnhuber (2008). "Tipping Elements in the Earth's Climate System." Proceedings of the National Academy of Sciences **105**(6): 1786-1793.
Lenton, T. M., V. N. Livina, V. Dakos, E. H. van Nes and M. Scheffer (2012). "Early warning of climate tipping points from critical slowing down: comparing methods to improve robustness." Phil Trans A **370**(1962): 1185-1204.
Lenton, T. M., R. J. Myerscough, R. Marsh, V. N. Livina, A. R. Price, S. J. Cox and GENIEteam (2009). "Using GENIE to study a tipping point in the climate system." Phil Trans A **367**(1890): 871-884.
Levermann, A., J. Bamber, S. Drijfhout, A. Ganopolski, W. Haeberli, N. R. P. Harris, M. Huss, K. Krüger, T. M. Lenton, R. W. Lindsay, D. Notz, P. Wadhams and S. Weber (2012). "Potential climatic transitions with profound impact on Europe: Review of the current state of six 'tipping elements of the climate system'." Climatic Change **110**: 845-878.
Li, J., S.-P. Xie, E. R. Cook, G. Huang, R. D'Arrigo, F. Liu, J. Ma and X.-T. Zheng (2011). "Interdecadal modulation of El Nino amplitude during the past millennium." Nature Clim. Change **1**(2): 114-118.
Li, J., S.-P. Xie, E. R. Cook, M. S. Morales, D. A. Christie, N. C. Johnson, F. Chen, R. D/'Arrigo, A. M. Fowler, X. Gou and K. Fang (2013). "El Nino modulations over the past seven centuries." Nature Clim. Change **3**(9): 822-826.
Litzow, M. A., J. D. Urban and B. J. Laurel (2008). "Increased spatial variance accompanies reorganization of two continental shelf ecosystems." Ecological Applications **18**(6): 1331-1337.
Livina, V. N. and T. M. Lenton (2007). "A modified method for detecting incipient bifurcations in a dynamical system." Geophysical Research Letters **34**: L03712.
Livina, V. N. and T. M. Lenton (2013). "A recent tipping point in the Arctic sea-ice cover: Abrupt and persistent increase in the seasonal cycle since 2007." The Cryosphere **7**: 275-286.
Mård Karlsson, J., A. Bring, G. D. Peterson, L. J. Gordon and G. Destouni (2011). "Opportunities and limitations to detect climate-related regime shifts in inland Arctic ecosystems through eco-hydrological monitoring." Environmental Research Letters **6**(1): 014015.
McNeall, D., P. R. Halloran, P. Good and R. A. Betts (2011). "Analyzing abrupt and nonlinear climate changes and their impacts." Wiley Interdisciplinary Reviews: Climate Change **2**(5): 663-686.
Notz, D. (2009). "The future of ice sheets and sea ice: Between reversible retreat and unstoppable loss." Proceedings of the National Academy of Sciences USA **106**: 20590-20595.
Rahmstorf, S., J. E. Box, G. Feulner, M. E. Mann, A. Robinson, S. Rutherford and E. J. Schaffernicht (2015). "Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation." Nature Clim. Change **advance online publication**.
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**(10): 3502-3509.
Scheffer, M. (2009). Critical Transitions in Nature and Society, Princeton University Press.
Scheffer, M., J. Bacompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk and G. Sugihara (2009). "Early warning signals for critical transitions." Nature **461**: 53-59.
Screen, J. A. and I. Simmonds (2010). "The central role of diminishing sea ice in recent Arctic temperature amplification." Nature **464**(7293): 1334-1337.
Screen, J. A. and I. Simmonds (2013). "Exploring links between Arctic amplification and mid-latitude weather." Geophysical Research Letters **40**(5): 959-964.
Shi, F., J. Li and R. J. S. Wilson (2014). "A tree-ring reconstruction of the South Asian summer monsoon index over the past millennium." Sci. Rep. **4**.
Stommel, H. (1961). "Thermohaline convection with two stable regimes of flow." Tellus **13**: 224-230.
Sutton, R. T. and M. R. Allen (1997). "Decadal predictability of North Atlantic sea surface temperature and climate." Nature **388**(6642): 563-567.
Sutton, R. T. and D. L. R. Hodson (2005). "Atlantic Ocean Forcing of North American and European Summer Climate." Science **309**(5731): 115-118.
Tietsche, S., D. Notz, J. H. Jungclaus and J. Marotzke (2011). "Recovery mechanisms of Arctic summer sea ice." Geophysical Research Letters **38**(2): L02707.
Vellinga, M. and R. A. Wood (2008). "Impacts of thermohaline circulation shutdown in the twenty-first century." Climatic Change **91**(1-2): 43-63.
Veraart, A. J., E. J. Faassen, V. Dakos, E. H. van Nes, M. Lurling and M. Scheffer (2012). "Recovery rates reflect distance to a tipping point in a living system." Nature **481**: 357-359.

Williamson, M. S. and T. M. Lenton (2015). "Detection of bifurcations in noisy coupled systems from multiple time series." Chaos: An Interdisciplinary Journal of Nonlinear Science **25**(3): 036407.
Yin, J., M. E. Schlesinger and R. J. Stouffer (2009). "Model projections of rapid sea-level rise on the northeast coast of the United States." Nature Geoscience **2**: 262-266.
Zickfeld, K., A. Levermann, M. Morgan, T. Kuhlbrodt, S. Rahmstorf and D. Keith (2007). "Expert judgements on the response of the Atlantic meridional overturning circulation to climate change." Climatic Change **82**(3): 235-265.