Tipping Points meeting, London, 14 March 2011

Note prepared on behalf of the Government Office for Science by the Met Office: Peter Good, Jason Lowe, Richard Wood.

Executive summary

The Government Office for Science convened a scientific meeting on 14 March 2011, under the chairmanship of Sir John Beddington (Government Chief Scientific Adviser), bringing together leading UK experts to review the current evidence and views on potential thresholds, or "tipping points", in the climate system.

The discussion covered broadly: the current scientific evidence on potential tipping points; paleo-climate events and their relevance to current climate issues and projections; gaps in current understanding and predictive capability; and policy implications and communications issues.

There is wide acceptance in the scientific community that there are likely to be "tipping points" in the climate system, where a significant, qualitative change in state occurs in response to a small perturbation. Crossing such tipping points could lead to accelerated, committed or irreversible change. However there is substantial scientific uncertainty in quantifying the position and likelihood of passing key thresholds, and in terms of associated impacts. Current estimates of the likelihood of triggering large-scale and/or irreversible climate events are largely based on expert judgement, informed by paleo-climatic evidence, computer models and current understanding of the underlying physical processes. The high level of uncertainty, combined with the potential for very significant impacts if one or more "tipping points" were to be triggered, means that the policy response is likely to require a risk management approach.

Paleo-climate reconstructions provide evidence of past rapid change events, for example the Paleocene-Eocene Thermal Maximum (PETM), which took place around 50 million years ago and involved a major climatic warming which took place over around 1000 years, possibly driven by rapid methane release. Current cumulative anthropogenic carbon release is around one third of the way towards the level that triggered such events in the past.

Climate models are used to provide short term forecasts and longer term projections, to interpret recent climatic variations and paleo-climatic changes, and to understand the physical processes that may drive threshold behaviour. However several examples are

known where the models used in the IPCC Fourth Assessment may not represent physical mechanisms of tipping elements correctly, due to limitations in resolution and in the processes that can currently be included in models.

'Early warnings' for tipping points through Earth system monitoring may be possible and may help manage the risks, although the uncertainty in modelling such events remains large. Three types of 'health check' approach were mentioned: (i) general statistical methods, (ii) process-based identification of key variables to monitor, and (iii) initial value prediction. Each was seen to have different advantages and disadvantages. The critical need for long-term monitoring was emphasised, while many existing observations are tied to short-term research programs. A clear set of long term monitoring priorities for tipping points has not yet been developed.

It is important to be able to interpret 'surprises' in new observations (e.g. the 2007 dip in Arctic sea-ice), so that such observations can be put into context. These interpretations must be developed through careful application of quantitative, process-based knowledge of the climate system.

After a high level review of the scientific evidence, the meeting considered how the risk of "tipping points" and system thresholds could be better included in policy development and wider public debate. There was consensus that the science in this area is particularly hard to communicate clearly. In part this is due to the danger of communicating an overly negative message; positive messages that make the public feel part of the solution are more likely to effect behaviour change. There was broad agreement on the requirement for a set of different (but self-consistent) narratives to meet the needs of individual audiences, using metaphors to aid clarity and understanding, and applying a risk-management framework.

Narratives can provide audiences with a means of thinking about both linear and non-linear climate changes in ways that makes sense to them. These might, for example, highlight increased vulnerability drawing on recent events (e.g. earthquakes). Experience in developing narratives for other science-into-policy areas could be made use of here. There was strong agreement that improved policy engagement will require better quantification of the potential societal impacts and risks, including in relation to food, water, energy and physical security.

This wider scoping of the field, where more research is needed, includes consideration of thresholds in the socio-economic systems that would be impacted by climatic change. This may involve identifying new scientific questions of interest by working backwards from projected socio-economic thresholds and effects.

Future scientific advance will require stronger multi-disciplinary working, better ways of combining all forms of information (e.g observations, paleo-climate reconstructions and models), and drawing on understanding of the underlying physical and biogeochemical processes. For computer models, the way forward is likely to include higher resolution modelling of atmospheric and ocean dynamics, improved representation of the underlying processes, and more insightful evaluation against observations and paleo-data. High performance computing resource is a fundamental limiting factor on the rate of progress in these areas. An urgent requirement is to assess the capabilities and limitations of the new 'AR5-type' generation of models, and there are some initiatives that are beginning to do this.

On the policy front, most progress is likely to be made if international engagement on the potential socio-economic impacts of tipping points can be informed by a growing understanding of the thresholds at which they may occur.

A further (smaller) meeting later this year will focus in more depth on next steps, in particular in relation to policy implications and the development of appropriate narratives.

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1. Introduction

The meeting was organised by the Government Office for Science and chaired by Sir John Beddington (Government Chief Scientific Adviser), to review on evidence and scientific perspectives on potential climate "tipping points" and to consider policy implications and research priorities.

A list of those who attended is attached, together with the programme.

This note aims to reflect the main themes of the meeting, rather than to present a detailed record. Presentations given at the meeting are available separately.

Much of the discussion summarised relates to general principles about how to improve the science and its communication. This is presented in the following broad areas: tipping points in the past; the view of current risks; policy perspective and communication; the "health check" concept; and a summary of ways forward.

The evidence on individual elements of the Earth's system believed to be at risk of non-linear change was reviewed at a high level. The science base for these elements is reported in other papers. The following example systems were considered: Atlantic Meridional Overturning Circulation (AMOC); Arctic sea ice; ice sheets and sea level; accelerated carbon release from permafrost and methane hydrates; die back of tropical and boreal forests; El Nino Southern Oscillation (ENSO); monsoons (Asian and West-African). Discussion of specific elements and systems is included below where this helps to illustrate general themes. The potential interactions between tipping elements was also highlighted.

Definitions and issues

'Tipping elements' are components of the climate system which could undergo a significant, qualitative change in state in response to a small perturbation. The 'tipping point' is the point in the forcing or in a feature of the system at which this occurs. This point would be plausibly reached during the current century (the 'policy time horizon'), have an effect within the next 1000 years (the 'ethical time horizon') over a spatial scale of at least 1000km. Both bifurcation-type behaviours (e.g. the classical AMOC picture of hysteresis in response to freshwater forcing) and reversible non-linear behaviours are possible.

This definition includes a wide range of potential types and rates of change which may need quite different treatments (in both science and policy spheres). The terms 'abrupt', 'committed' and 'irreversible' were introduced to describe some of the main possible behaviours.

The meeting focussed on tipping points within the physical climate system, however it was pointed out that the definition could reasonably be extended also to socio-economic impacts from climate change (e.g. a small perturbation to storm tracks so that they no longer intersected the Australian Coast could have major impacts on farmers there).

Issues specific to tipping elements

Some specific properties of tipping elements were mentioned which would make them more difficult to address and prepare for compared to more linear change.

In particular, a fundamental change in system state is likely to be involved that has generally not occurred in recent observable history (outside the paleo-climate record), and may never have occurred. The mechanisms involved in the state change may be rather different than those dominating observable variability. This limits the relevance of recent observations, and of associated model validation and improvements.

Model biases may be especially important in researching tipping elements, dramatically changing the simulated likelihood of a transition occurring. For example, most 'AR4-type' models fail to simulate the change in the West African monsoon 5500 years ago because they have biases in the mid-Holocene climate. There is also evidence that the AMOC is too stable in 'AR4-type' models, as compared to AMOC behaviour deduced from paleo data on past changes.

The role of natural climate variability in relation to potential tipping elements was discussed. It is possible that the mean state of a system may be below the tipping threshold, but a system may unpredictably transition due to random internal variability. This may be particularly important when considering the long-term effects of mitigation. It was also noted that long-term variability can be large in some of these systems (e.g. long ENSO simulations, or in the paleo-climate record), which affects how we interpret recent observations, or assess future predictability. Further, the rate of change of elements of the system (e.g. rate of warming) may be important in determining whether a tipping element is triggered.

It was proposed that indices/drivers other than global mean temperature also need to be considered. Examples include direct effects of aerosols, ozone and CO_2 on vegetation, the strength of the AMOC for NW European climate, and brown haze for monsoons.

Finally, there was some discussion on the diverse range of behaviours (including ‘abrupt’, ‘committed’ or ‘irreversible’ change), and how these affected possible responses in both the science and policy spheres. For example, ‘abrupt’ changes might imply insufficient time for adaptation without advance warning, whereas ‘committed’ changes may mean that there is in principle time for some element of mitigation of the change and adaptation to it. But actions would need to be started long before any major impacts of committed change were visible, which could provide a ‘credibility barrier’ in building support for these.

2. Tipping points in the past: paleo-climate evidence

Paleo-climate reconstructions are valuable: to identify past rapid change events; to highlight processes and mechanisms that could be important; to investigate different states of the Earth system; and to provide data to test and evaluate models. Evidence of rich variability in the past was presented to the meeting, including several different mechanisms of tipping-like behaviour.

Issues

Two main issues were raised in relation to the use of paleo-climate reconstructions to improve understanding of future change.

Firstly, paleo-climate reconstructions give *indirect* measurements of climate through proxies. Thus, as with models, it is necessary to retain a degree of scepticism about physical inferences from these proxies. An example is the abrupt change associated with the West-

African monsoon around 5500 years ago, as evidenced largely by the dust core record. The character of that record could arise potentially from abrupt change in the vegetation or in the monsoon. Another example is the behaviour of ENSO during the Pliocene: mean-state reconstructions had been interpreted by some as implying a 'permanent-ENSO', whereas physical understanding and models suggested that ENSO variability could have still been operational. Recent coral data has now given evidence for ENSO-like variability during the Pliocene.

Secondly, the past contains no perfect analogue of the next century. For example, some periods had much greater land-ice coverage than at present, or change may be dominated by different types of forcing with different seasonal components. This makes it hard to draw conclusions about future change without evidence from other sources, including the use of models. Models may be used to transfer understanding from past events whilst also taking account of constraints on future change and current conditions.

However several examples were shown where 'AR4-type'models struggle to represent rates of abrupt change, or even past climate states. For example, 'AR4-class' models cannot reproduce the mid-Holocene state of the West-African monsoon, so they cannot reliably be used to investigate the subsequent abrupt change. A long-standing problem is that models cannot reproduce temperatures at the PETM event, with errors of up to 20°C. Also, there is evidence from variability over the past 60,000 years that AMOC simulations may be overly stable to freshwater forcing, and respond too slowly in 'AR4-class' models (although caution was given that AMOC change is not the only explanation for Dansgaard-Oeschger Cycles[1]).

The geological evidence (independent of models) from the Paleocene-Eocene Therman Maximum (PETM) 55 million years ago and other episodes involving large methane release weres highlighted, taking place over timescales of 1,000-10,000 years. It was suggested that more should be made of the fact that current anthropogenic carbon release is already around one third of that of the perturbation that triggered the PETM. That geologically abrupt event is known to have caused such extensive ocean acidification that $CaCO_3$-rich bottom sediments from the deep ocean were dissolved and a substantial number of benthic foraminiferal species became extinct. Recovery of the ocean to the point that $CaCO_3$-rich sediments could again accumulate took roughly 100,000 years, providing independent support for models suggesting that atmospheric concentrations of anthropogenic carbon will decay very slowly.

[1] Abrupt warming events observed during the last glacial period , which brought temperatures to near near-interglacial conditions before cooling again took place

Ways forward

It was agreed that more effort is needed to assess state-of-the-art models against paleo-climate data. This must take account of the strengths and weaknesses of paleo-climate reconstructions and be informed by physical understanding, so a good cross-community dialogue will be important. There is a need to bridge the gap between geological and modelling activities. At the same time, the risk of over-optimism in what paleo-climate reconstructions can tell us must be managed. Model ‘hierarchies’ or ’spectra’ and clever experimental design will be needed to overcome the challenges of modelling the very long timescales involved.

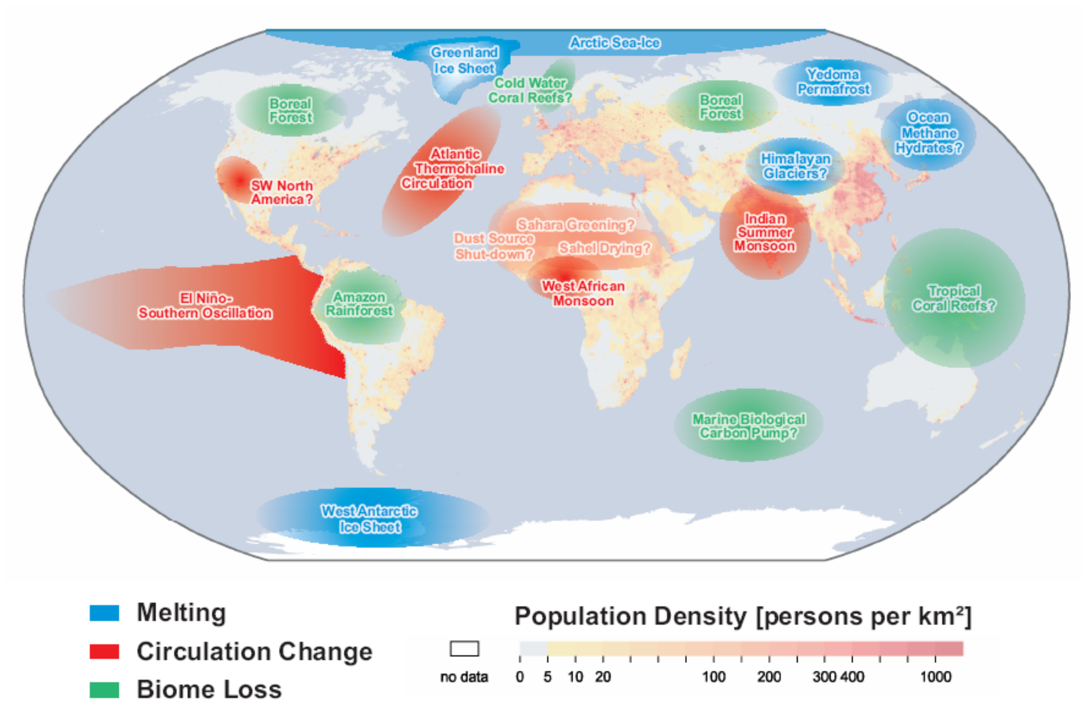
3. View of current risks

Current estimates of the likelihood of triggering large-scale and/or irreversible events in the climate system are largely based on expert judgement and computer models. Expert judgement is informed by paleo evidence, computer models and also current understanding of physical constraints. However there is widespread agreement that the climate conditions that trigger these events has, in most cases, sizeable uncertainty.

Earth system elements that may be subject to non-linear change, as presented to the meeting, are shown in the diagram below.

Tipping elements in the climate system

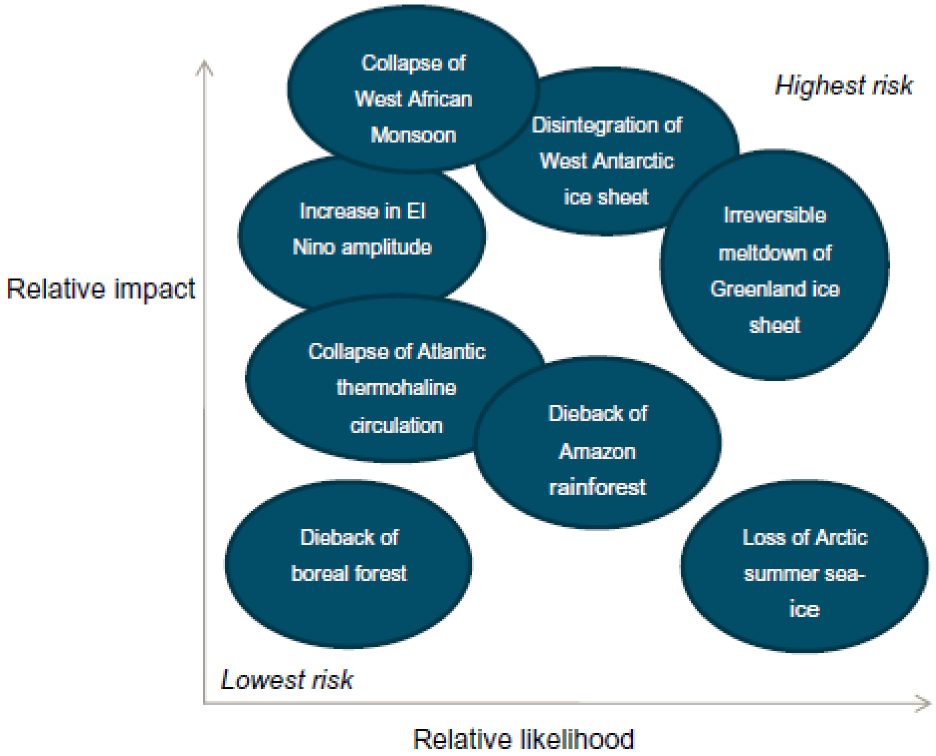
Presented by Prof Tim Lenton



Current expert opinion holds that, overall, the likelihood of at least one form of dangerous non-linear change in the climate system occurring below 4°C global warming is significant. Identifying the risk of specific forms of change is much harder.

An attempt to characterise and compare risks was presented in the form of a simple diagram, with tipping elements as currently identified marked on axes of "likelihood" and "impacts" - the risk associated with an individual tipping point being triggered being the product of the assessed likelihood and impact. This was suggested to be a good method of communicating policy advice, but it was recognised too that the uncertainties associated with both axes are large and so any presentation to policy makers needs carefully to reflect this.

Risk matrix for tipping events
Presented by Prof Tim Lenton



Ice sheet melt was highlighted as having relatively high overall risk, although more work is needed on the potential impacts for all tipping elements so far proposed.

The potential importance of interactions between tipping elements was discussed, with the linkages between the different Earth systems thought to be at risk of non-linear change highlighted. It was agreed that caution is needed in drawing conclusions from these inter-relationships, e.g. that a cascade effect would necessarily take place ('domino dynamics'). In practice, interactions will take place as part of the complex dynamics of the climate system as a whole, with a further factor being the progressive evolution of more incremental climate changes also impacting the system in multiple ways.

Models

Issues

There was much discussion about the suitability of numerical models for simulating tipping points. Several examples were given where 'AR4-type' state-of-the-art models may be labelled as not fit for purpose in this context.

A fundamental constraint relates to supercomputing capability. Simulation of tipping element systems is especially computationally expensive as it involves: high spatial resolution (to plausibly capture key processes like freshwater transport or tropical convection); detailed representation of earth-system components (e.g. ice sheets or forests); and long model simulations (e.g. investigating reversibility of the AMOC or to compare with paleo-climate data).

It was noted that showing the imperfection of models is relatively easy. Deriving useful information from imperfect models, and improving the models, is much harder – but in many cases possible. Given the relatively small size of the climate modelling community, it was suggested that a balance must be struck between having sufficient breath of expertise behind each individual model, given their increasing complexity, and allowing diverse scientific approaches behind a range of different models.

It was noted that model biases tend to favour stability, compared to observed changes in the paleo-record

Uncertainties in linear change can also cause large uncertainties in tipping element simulations. A common factor in studying a number of vulnerable climate elements is the relatively large uncertainties in projections of linear precipitation change, which plays a part in many of the non-linear tipping elements being considered.

An allied problem concerns the inadequacy of current glaciological models to forecast ice sheet behaviour under a range of forcings. It has become clear that mechanical degradation, bed lubrication and under-ice melting beneath floating ice shelves - all neglected in current models - may play key roles in shrinking ice sheets and raising sea level.

Ways forward

Proposals for moving forward included: increased model resolution and improved process representation, intelligent use of model 'hierarchies'/'spectra', intelligent experimental design and evaluation against a wider range of observations, including paleo-climate data.

Additionally, the capabilities of the new 'AR5-type' generation of models will need to be assessed. Ice sheet models must be significantly improved.

Appropriate use of model hierarchies was seen as important. An alternative term - 'spectrum' - was suggested to avoid implicit ranking of the models. It was noted that it is important to understand the physical relationship between different models in a spectrum. Indeed, understanding this relationship is part of the process of improving physical understanding overall. A general principle is that in simple models it is easier for single processes to dominate the response, leading to sharp transitions in state. In more complex models, compensating processes can smooth out the response.

A possible reason for some model biases is that they simply may not have the appropriate combination of parameters. This can be investigated using parameter perturbation experiments. In the context of the AMOC, some intermediate complexity models may do a better job of simulating freshwater transport than the state-of-the-art GCMs due to fortuitous combination of parameters. Models should also be adapted to better represent the true state of the Antarctic climate (with its stable boundary layer) and the behaviour of sea ice (which exerts a significant control on albedo) at both poles.

Given the need highlighted to draw on the paleo-climate record to improve models, paleo-climate experiments are planned as part of the current Coupled Model Intercomparison Project (CMIP5). Long standing model biases with respect to paleo-climate reconstructions suggest potential for model improvement. The long timescales involved in paleo-climate imply long run times, but some potential was identified to mitigate this through intelligent model experimental design.

4. Policy perspective and communication

Issues

Two main issues were considered: communication of the complex science messages and the policy response.

It was argued that even linear climate change can be hard for non-scientists to understand, not least because the current rates of global warming and sea level rise are so slow and small as to be hardly visible to lay audiences – and the public tends to associate climate directly with weather. Non-linear change, including inherent uncertainties and risks, is even harder to communicate, with the ensuing messages likely to be even more unwelcome. It was noted that the potential for such changes had not really sunk in with the policy community, certainly at an international level where assimilating linear change issues is for many challenging enough. Additionally, audiences will have differing backgrounds and may be affected in different ways, so presentational approaches and messages will often need to be bespoke. For example, in an international context where individual countries will each have their own particular concerns over specific vulnerabilities.

Communications may also need to overcome existing scepticism, whilst avoiding the danger of apparent scare-mongering if issues are presented too negatively. Indeed, it was noted also that 'tipping elements' need not always be negative - a message seen to be of relevance for both science and policy.

It was highlighted that socio-economic vulnerability has increased linked to the evolution of modern societies (e.g. mega cities, communication networks, real-time banking). There may be a need to think in radically new ways about future developments to increase resilience.

In terms of policy implications, it was suggested that the balance of uncertainties and risks attaching to tipping elements favoured a strong response to both mitigate and adapt - the "precautionary principle". There is a need to consider potential "tipping points" in the development of adaptation strategies.

Given the uncertainty about thresholds, limited mitigation or adaptation options may be possible once GHG emissions and/or global or regional temperature increases have passed a given point. Moreover, it was noted that the point of commitment to non-linear change in a system may be passed well before significant effects are observed.

Ways forward

The Committee for Climate Change approach of having two target thresholds - including a 'small chance of exceeding 4°C warming' - was mentioned as a way of including tipping point risks within a policy response framework. There is a key need to strengthen the information base to inform policy actions, including in relation to prediction capability, impacts assessments and the development of health check/early warning systems.

The risks associated with tipping points can be reduced to some extent by reducing socio-economic vulnerability, and adaptation planning should take account of this. In some cases reducing vulnerabilities may require a fundamental change of direction.

Strong caution was expressed about geo-engineering as a future response, given that many approaches advocated would themselves introduce new climate forcings, with uncertain systemic effects and the potential for unintended side-effects.

Some ideas were mentioned to facilitate communication to both the policy community and the public. For example, by considering the range of suggested tipping elements together in a global perspective it is possible to make more reliable statements of probability. For example, that the risk of at least one event being triggered below 4°C warming is not small. It can also be stated that the risk grows continuously with increasing forcing, partly because uncertainties on thresholds are large.

It was highlighted that some non-CO_2 forcings might be easier to control (e.g. aerosol effects on monsoons), as long as physical understanding of their effect was sufficiently strong.

Socio-economic and policy implications need to be recognised in setting research and observational priorities. For example, a 50% decrease in AMOC may be very important, even if not considered a 'collapse' or state change. Another example came from a model simulation of the West African monsoon, where warming in the Gulf of Guinea weakened the monsoon but increased precipitation over West Africa. In relation to sea level rise, the design of the Thames barrier has distinct thresholds in surge height – above particular thresholds, there is a step change in the cost of barrier enhancement to achieve the required level of protection. Vulnerabilities in social systems can significantly affect thinking on which thresholds may be most important to focus on. Some work is underway in this area but the field remains embryonic[2].

There is merit in prioritising tipping elements for attention by working backwards from their expected impacts. Some changes may be apparently smooth from a climate system perspective but non-linear in terms of societal impacts. For example, a small change in the position of the Atlantic storm track could have a major impact on the climate of southern England. Other possibilities mentioned included potential shifts or changes in the character of: high pressure blocking events; the rainfall dipole between the Yellow and Yangtze rivers; the storm track location with respect to Australia. Small changes in the Arctic Oscillation have already caused significant winter cooling in Europe and North America that has reversed global warming in some people's minds.

Presentation will be key in engaging the policy community and society as a whole on tipping point risks. A strong positive message could make the public feel part of the solution, e.g.

[2] A joint British Academy/Royal Society meeting at the Kalvi Centre on 13/14 April reviewed more broadly tipping points and coupled socio-economic systems.

highlighting the societal benefits of a low-carbon economy. However it was felt that this would need to be backed up by clear messages on the risks faced.

There was agreement on the need for a self-consistent set of narratives for different audiences, using metaphor and a risk-based framework (including implications for food, energy, water and physical security). At the same time, it was noted that given the state of current knowledge quantifying risk (e.g. via 'high','medium','low' labels) and relating it to risks arising from linear change will be challenging.

Narratives should provide audiences a way of thinking about both linear and non-linear changes that makes sense to them. This might include highlighting increased vulnerability using the metaphor of recent events (e.g. earthquakes). It was suggested that the probabilistic message used to present bird-flu risk could be effective: presenting the chance of an event occurring within X years, or perhaps the chance of an event occurring below 4°C temperature rise. This is similar to the gambling metaphor; people understand this better than pure probability.

Various communications tools exist that might help, and a UN review of early warning systems may contain valuable lessons. Experience gained in developing relevant narratives in the context of food and farming challenges could also be drawn on. The approach taken in a previous study which attempted to characterise 'millions of people at risk' was highlighted. Finally, social networking was mentioned as a way of engaging younger audiences, who will affect future policy.

5. Health check concept

The concept of an 'Earth system health check' was discussed, as a way of combining observational and modelling evidence to estimate risk of approaching thresholds. Three types of 'health check' were mentioned: general statistical methods, process-based observations and initial value modelling.

There is ongoing work on general statistical methods of detecting imminent transitions. These are based on fundamental behaviour near tipping points. They may be used as early warning to detect tipping point behaviour including where understanding of the system is limited. Some success has been demonstrated using paleo-climate reconstructions. Work is ongoing to make these methods as robust as possible. As well as temporal structure, spatial structure may give information about approaching tipping points (e.g. Amazon dieback).

An alternative approach involves process-based observing methods. Physical understanding and models are used to identify key variables to observe. Various examples were summarised where there is, in principle, ability to implement 'health checks'. A number of relevant observations are in place, at least over the short term. The example of freshwater transport as an indicator of AMOC stability was cited.

Issues

It was suggested that the terminology of 'early warning systems' may be inappropriate, for two reasons. First, these methods may not give precise information on when (or if) a transition is to be expected. Secondly, some changes (e.g. Amazon dieback) may have long timescales, even if triggered in the relatively near term.

The individual 'health check' or 'early warning' approaches have differing strengths and weaknesses. The general statistical methods are significantly more useful for 'fast-responding' systems (e.g. monsoons) than for others. This is because they rely on extracting the longest internal timescale from observations. There is also some sensitivity to data filtering choices. Process-based observing systems are reliant on physical understanding. Both this approach and initial value methods are sensitive to model error.

Current observing programs are generally tied to limited life-span research programs, whereas long-term monitoring is critical. One consideration is the need to handle 'surprises' in new observations, such as the 2007 dip in Arctic sea ice. More attention needs to be given to educating the potential audience about the likely range of variability about the mean of current trends. In that sense, neither the extreme warmth of 1998, a major El Niño year, nor the extreme dip in Arctic sea ice in 2007, were "unexpected". These events, like the European heat wave of 2003, belong in the tails of normal distribution curves. A narrative is needed that can differentiate between tipping points and curve tails.

Ways forward

The term 'health check' was suggested to be more appropriate than 'early warning'. Others preferred simply "Earth system monitoring".

Linked to discussions on narratives, it was suggested that uncertainty in evidence from 'early warning systems' could be communicated by discussing how the 'gambling odds' of a transition are evolving.

Each of the forms of 'health check' identified can usefully contribute. Ongoing work in all areas will help make these more robust. As scientific understanding advances, the potential for new health check related observations will also emerge.

Sustained, long-term monitoring needs to be extended through international initiatives such as the Global Climate Observing System. This requires long-term commitment to observing system elements, such as Argo floats and moorings to provide information about the state of the AMOC.

Process-based understanding, and further advances in this regard, will be important in attempting to distinguish between upcoming abrupt change and internal variability.

6. Summary of ways forward / conclusions

Policy engagement and communication

- A conventional risk management approach, taking account of the likelihood and severity of potential tipping points being triggered, is a good way of communicating policy advice. However uncertainties regarding both axes mean that more work is needed on the potential impacts and vulnerability of the main tipping elements.

- There is a key need to help policy makers understand better the likely wider impacts of tipping element changes, for example in the context of food, water, energy and physical security, with an associated requirement for further research in these areas.

- A reasoned policy response includes: a strengthened case for mitigation; strengthening the scientific evidence base; development of appropriate adaptation strategies; and, related to the last, a reduction in socio-economic vulnerability.

- Strong positive messages need to be incorporated in the development of a self-consistent set of narratives for varying audiences – policy and public, drawing on metaphors where these aid understanding and presenting risks in understandable ways.

Strengthening scientific information

- There is a need to extend cross-disciplinary working and to more effectively bring together different sources and forms of information, taking account of the strengths

- There is a need for sustained (long-term) observations of key climate tipping point elements, both from a "health check" and an "early warning" perspective, as well as for obtaining data to test models.

- There is a need for further research to estimate the wider impacts on human and ecosystem welfare that might arise from crossing different tipping points.

- Expert elicitation can be useful as a means of combining uncertain information, but careful interpretation is needed where questions may have no clear answer. It was suggested that while biases are possible, uncertainty in scientific knowledge is the fundamental limit. As well as quantitative output, there is also useful qualitative information in the reasoning expressed behind different expert answers. Recognition needs to be given to the limits on predictability due to the inherent chaos of parts of the climate system.

- Process understanding, and the further improvement of this, is critical. For example, to assess the capability (or otherwise) of models to reproduce the basic physical processes required to simulate a given 'tipping element'. Also, to understand physically the relationships between different models, and the processes behind apparent model improvements. Such understanding is important too in checking the plausibility of inferences from observations or paleo-reconstructions. It can be used also as a constraint, e.g. in how multiple observations or paleo-climate reconstructions may be combined, or to impose physical limits on the upper or lower bounds of future changes.

- More effort is needed to assess state-of-the-art models against paleo-climate data, taking account of the strengths and weaknesses of paleo-climate reconstructions and drawing on physical understanding. There is a need to bridge the gap between geological, glaciological and modelling activities.

- Higher spatial resolution and more detailed treatment of atmospheric and ocean processes will be important to improve model capability. Intelligent use of model 'hierarchies'/'spectra', intelligent experimental design and more detailed validation against paleo-climate data may also be important. The cabilities of the new 'AR5-type' generation of models will need to be assessed. High performance computing resource is a fundamental limiting factor on the rate of progress in these areas.

- For an 'Earth system health check', there is a need to combine the different approaches, possibly making use of the Global Climate Observing System to ensure long-term monitoring. To be ready for 'surprises', process-based understanding will be key to distinguish between upcoming abrupt change and internal variability.

23 May 2011

Climate Tipping Points Event – Attendee List

Name	**Affiliation**
SPEAKERS	
Prof Tim Lenton	University of East Anglia
Dr Jason Lowe	Met Office
Prof Paul Valdes	Bristol University
David Warrilow	DECC
Dr Richard Wood	Met Office
ATTENDEES	
Prof Jonathan Bamber	Bristol University
Dr Helene Banks	Met Office
Sir John Beddington	GO Science
Dr Olivier Boucher	Met Office
Dr Peter Challenor	National Oceanography Centre
Amanda Charles	GO Science
Prof Peter Cox	Exeter University
Dr David Galbraith	Oxford University
Dr Peter Good	Met Office
Georgie Gould	GO Science
Prof Jonathan Gregory	NCAS, Univ of Reading and Met Office Hadley Centre, Exeter
Nick Grout	GO Science
Prof Sir Brian Hoskins	Reading University
Dr Chris Huntingford	CEH
Dr Chris Jones	Met Office
Dr Heike Langenberg	Nature Geoscience
Dr Bryan Lovell	Geological Society
Prof Yadvinder Malhi	Oxford University
Nafees Meah	DECC
Prof Tim O'Riordan	University of East Anglia
Prof Tony Payne	Bristol University
Dr Jeff Ridley	Met Office
Quirin Schiermeier	Nature
Prof Julia Slingo	Met Office
Steve Smith	Climate Change Committee
Prof Meric Srokosz	National Oceanographic Centre

Climate Tipping Points Event – Attendee List

Name	**Affiliation**
Dr Colin Summerhayes	Cambridge University
Prof Rowan Sutton	NCAS
Sandy Thomas	GO Science
Prof David Vaughan	British Antarctic Survey
Prof Bob Watson	Defra

Climate "Tipping Points" / Thresholds Meeting

14th March 2011, 11.00-17.00

One Great George Street, Westminster, SW1P 3AA

11.00	**1. Introduction** Sir John Beddington
11.10	**2. Overview of tipping elements and current understanding of thresholds** Prof Tim Lenton, Professor of Earth System Science, UEA - Thermohaline circulation - Arctic sea ice - Greenland and Antarctic ice sheets - Methane and permafrost - Biosystems: Forest/Amazon dieback - Monsoon systems (India, West Africa) - ENSO - Interactions / feedbacks - Signals **Group Discussion**
12.40	**3. LUNCH**
13.20	**4. What can the past tell us (palaeo records)?** Prof Paul Valdes, University of Bristol, Professor of Physical Geography **Group Discussion**
14.30	**5. Future projections, early warning signals and indicators** Dr Jason Lowe, Dr Richard Wood, Met Office **Group Discussion**
15.50	**6.** Coffee Break
16.00	**7. Implications for policy and society** Group discussion introduced by David Warrilow - Expected state of knowledge in IPCC AR5 - Research / monitoring priorities and gaps

	- How long might the world have to react? - What policy responses are possible and appropriate?
16.50	Closing comments and consideration of next steps

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