Arctic Tipping Points in an Earth System Perspective

Paul Wassmann, Timothy M. Lenton

Abstract We provide an introduction to the volume *The Arctic in the Earth System perspective: the role of tipping points*. The terms tipping point and tipping element are described and their role in current science, general debates, and the Arctic are elucidated. From a wider perspective, the volume focuses upon the role of humans in the Arctic component of the Earth system and in particular the envelope for human existence, the Arctic ecosystems. The Arctic climate tipping elements, the tipping elements in Arctic ecosystems and societies, and the challenges of governance and anticipation are illuminated through short summaries of eight publications that derive from the Arctic Frontiers conference in 2011 and the EU FP7 project Arctic Tipping Points. Then some ideas based upon resilience thinking are developed to show how wise system management could ease pressures on Arctic systems in order to keep them away from tipping points.

Keywords Earth system · Tipping points · Climate tipping elements · Points of no return · Resilience

Sleeps a song in things abounding
that keep dreaming to be heard:
Earth's tunes will start resounding
if you find the magic word.

(Joseph v. Eichendorff's "Magic Wand",¹ translated
by Walter A. Aue)

INTRODUCTION

Life in the Arctic (Fig. 1) takes place amongst a dramatic, enigmatic and emotional tapestry of abrupt climatic, ecological, political and economic changes. The region is warming faster than anywhere else on the planet and this is

triggering rapid and unexpected changes in climate and associated ecosystems, which its societies depend upon (ACIA 2004; Screen and Simmonds 2010; Wassmann 2011). A systemic understanding of such a complex, coupled system needs a language that can assimilate new evidence, promote multidisciplinary comprehension and inspire research. We chose the magic words *tipping point* to inspire this special issue, because they offer a unifying metaphor for the abrupt changes that are already happening in the Arctic and for those that lie ahead. The Arctic in turn provides a forewarning of the kind of complex, non-linear changes that are expected to unfold elsewhere on the planet later this century. As such, the Arctic can provide valuable lessons for societies far away.

Unforeseen and rapid changes are all around us. The banking crisis, the Arab Spring, escalating riots in English cities—these are just a few recent examples of what might be called social 'tipping points'. But such events are rarely anticipated. This is astonishing, as experience tells us clearly that tipping points exist and some have detrimental consequences. Our clinging to simple, linear predictive models is bewildering because we all know that these models often fail to grasp reality correctly. Non-linearity and the potential for tipping points must thus become part of our thinking and management strategies.

This special issue grew out of the 2011 Arctic Frontiers conference (www.arctic-frontiers.com) which had *The Arctic in the Earth System perspective: the role of tipping points* as the focus for its science section. The conference began with a joint multidisciplinary session covering a wide range of scientific fields, representatives of which

¹ Wünschelrute. Schläft ein Lied in allen Dingen, die da träumen fort und fort, und die Welt hebt an zu singen, triffst du nur das Zauberwort.

Fig. 1 A Nenets watching a herd on the seemingly endless expanse of the tundra in northeastern Russia. Photograph: Svein Disch Mathiesen

were invited to elaborate what *Arctic tipping point* signified to them. Some of those presentations form the basis of contributions that are assembled in this volume. Others are drawn from the Arctic tipping points (ATP) project (www.eu-atp.org/), funded by the European Union's Framework Programme 7, which organised the conference. We have selected *AMBIO: A journal of the human environment*, because it addresses a multitude of readers and scientific fields that traditionally publish separately. Our aim is to raise awareness of tipping points in the Arctic region, and to encourage new inter-disciplinary thinking about how to tackle them.

AN EARTH SYSTEM PERSPECTIVE

The Arctic and its tipping points are key elements of the Earth system that sustains us, first highlighted in *AMBIO* in 1994 with a special issue on 'Integrating Earth System Science'. The magic word here is *system*. A system is a collection of interdependent parts (here the lithosphere, hydrosphere, atmosphere, biosphere and anthroposphere),

enclosed within a defined boundary. The Earth system is the conglomerate formed by human civilization and its planetary matrix, i.e. all parts of the Earth that interact with humans and their activities. Hence this volume addresses life in our times, including the members and manifestations of humans within the Arctic, and the nearby parts of the Northern Hemisphere that are significantly influenced by it.

Today's ATP take place in the *Anthropocene*, the latest interval of geologic time marked by a global impact of human activities on the Earth. The term was coined by the ecologist Eugene Stoermer, but has been widely popularized by the atmospheric chemist Paul Crutzen, who regards the recent influence of human behaviour on the Earth as so significant as to constitute a new geological era (Crutzen and Stoermer 2000). Although humans have influenced the Earth for millennia (e.g. reducing biodiversity), it was the industrial revolution that marked the start of truly global changes to the Earth's biogeochemical cycling, as reflected by changes in greenhouse gas concentrations, acidification of the ocean, eutrophication of freshwaters and coastal seas, etc. This volume focuses upon the role of humans in the Arctic component of the Earth system and in particular the envelope for human existence, the Arctic ecosystems.

WHAT IS A TIPPING POINT?

The famous statement of Linnaeus (1751) *natura non facit saltus* (nature makes no leaps) has been proven wrong. Thresholds, points of no return and phase changes are widespread in nature and changes are often not linear. Yet rapid and non-linear changes at large scales are often inadequately captured in current models of the Earth system. Nor do they seem to be properly understood when it comes to past changes of ecosystem dynamics, of natural resources such as fish, of political systems, or of economic prospects, to mention but a few relevant topics.

The recent surge in usage of the term *tipping point* can be seen as something of a counter to this past neglect. *Tipping point* encapsulates the non-linear notion that little things can sometimes make a big difference to the state of a system. The term was first applied in the late 1950s in the sociological literature (Nuttall 2012 [this issue]). However, its use only became commonplace in the last decade through the bestseller of Gladwell (2000). *Tipping point* is now a colloquialism, with a plethora of bewildering headlines from the press and scientific media reflecting this (Table 1). The upside of this popularity is that it gives everyone some intuitive grasp of an important concept (whereas terms such as ‘non-linearity’, ‘critical threshold’ and ‘bifurcation’ are largely restricted to scientific usage). The downside of such liberal usage is that it can strip a term of all useful meaning. As we have chosen to use *tipping point* in a scientific context, a need for definition and precision arises. What then is a tipping point?

For us, a tipping point is a point at which a relatively small perturbation can cause a large, qualitative change in

the future state of a system. This encapsulates the concept of a strongly non-linear response. In a linear system, a small input will cause a small, proportionate output. Only in a strongly non-linear system can a small input cause a large change in output. Such a change cannot happen all the time; only under particular conditions is a system so sensitive to perturbations. Those particular conditions, described in terms of some feature of a system, or some variable that is forcing it, are the tipping point.

In different academic fields, ‘tipping point’ can have different meanings. In its original use in sociology, it describes a previously rare phenomenon becoming rapidly and dramatically more common. This usage could also readily be applied to, e.g. the spread of infectious diseases, or of invasive species. Several other phenomena are also sometimes described as, or confused with, ‘tipping points’. The loss of unique species or ecosystem is certainly a ‘point of no return’ but it can occur incrementally without involving a tipping point. Confusion arises here because extinction is sometimes caused by a tipping point triggering the catastrophic collapse of an ecosystem.

Too many different meanings for ‘tipping point’ clearly do not aid scientific understanding. But at the same time too narrow a scientific definition of a ‘tipping point’ may exclude some impactful non-linear phenomena. In particular, many scientists seem to take ‘tipping point’ as synonymous with a ‘bifurcation point’ in the equilibrium solutions of a system, which necessarily implies some irreversibility, in which case all tipping points would be points of no return (even if not all points of no return are tipping points). However, the definition of ‘tipping point’ we adopt is broader, and it includes abrupt but reversible transitions.

Table 1 Examples of the term tipping point applied to the Arctic in media headlines

Ancient fossils show Arctic now near climate tipping point
Climate change: the tipping point of the iceberg
Arctic tipping points affect World climate
Arctic thaw may be at “tipping point”
Tipping point not likely for Arctic sea ice
Modelling the Polar bear tipping point
Tipping points: How Arctic warming could chill Western Europe?
Arctic tipping points: Can the Arctic recover?
Glaciers disappearing—Arctic at tipping point
Climate change tipping points for populations, not just species
Greenland ice sheet faces ‘tipping point in 10 years’
Arctic “tipping point” may not be reached
Yet another global warming keystone crumbles: Arctic ice ‘tipping point’ disproven
Arctic ice still melting, but we may never see an actual tipping point

What is really meant by the term in each case appears unclear

ARCTIC CLIMATE TIPPING ELEMENTS

The term ‘tipping element’ has been introduced to describe systems that can exhibit a tipping point, specifically those large-scale subsystems of the Earth system that can be switched—under certain circumstances—into a qualitatively different state by a small perturbation (Lenton et al. 2008). Among the candidate tipping elements previously identified, are Arctic sea ice, the Greenland ice sheet, Atlantic thermohaline circulation and boreal forests. In this special issue, Lenton (2012 [this issue]) revisits and expands this list of physical climate tipping elements in the Arctic, using past abrupt changes, current observations and model projections to identify which parts of the Arctic climate system might pass a future tipping point. The likelihood of future tipping points is assessed in terms of how much warming will be required to trigger them, and the available responses are considered, especially the

prospects for avoiding them. Other factors, such as, e.g. light, precipitation and stratification can also induce tipping points, but in the current phase of global change, warming is the most prominent, and in most cases ultimate, driver.

Wadhams (2012 [this issue]) provides much more detail on the most immediate Arctic climate tipping point; the rapid changes that are occurring to Arctic sea ice (Fig. 2). He discusses the reasons for them, and the methods being used to monitor the changing ice thickness. Wadhams (2012 [this issue]) argues that the trend towards smaller areas in summer, which reached temporary peaks in 2007 and 2011, will lead to an ice-free summer Arctic in less than 30 years. Within a decade, summer ice may be largely confined to a redoubt north of the north coasts of Greenland and Ellesmere Island, the only location where substantial multi-year ice will be found. This may be a tipping point for the ice cover, in that it will not return to a year-round cover but will change to a purely seasonal cover of first-year ice, as currently found in the Antarctic. Others have argued that because the loss of summer Arctic sea ice is readily reversible in models, it does not involve a tipping point. But this confuses a point of no return with a tipping point. The loss of Arctic summer sea ice may be an example of a reversible tipping point.

As the Arctic sea ice example neatly illustrates, identifying when a tipping point has occurred, and if possible

forecasting it in advance, is a key scientific challenge. Carstens and Weydmann (2012 [this issue]) address this challenge with a suite of simple statistical analyses, emphasising that changes in the standard error should be considered in addition to changes in mean properties. They confirm that the loss of Arctic sea ice accelerated by factor of ~ 5 in 1996. Importantly, they also discover that increases in random fluctuations were already observed in 1990, thus providing an early warning signal. This is consistent with theory for regime shifts, where declining resilience allows perturbations to be amplified before critical thresholds are exceeded and a system enters a new regime.

TIPPING ELEMENTS IN ARCTIC ECOSYSTEMS AND SOCIETIES

To qualify as a tipping element of the Earth system (Lenton et al. 2008), parts of the physical climate system must be above a certain size (length dimension of order 1000 km). However, one can also define a class of smaller scale, ecosystem ‘tipping elements’ and Duarte et al. (2012 [this issue]) do this for Arctic ocean ecosystems. They describe how Arctic environments and ecosystems contain multiple elements that contain alternative states, which are also subject to multiple forcing agents including ocean warming,

Fig. 2 The tipping element sea ice supports great vistas. Photograph: Rudi Caeyers

Fig. 3 The ice-enforced research vessel Helmer Hansen of the University of Tromsø hides behind glacial ice in Magdalenafjorden, Svalbard. Photograph: Ola Magnus Rapp

freshening, acidification and alterations to food web structure. However, to identify tipping points and provide evidence of these being trespassed requires high-quality monitoring programs, and these are few and far between for Arctic ecosystems (Fig. 3). This accounts for the relative paucity of footprints of realized impacts of climate change on Arctic marine biota (Wassmann et al. 2011).

On-going rapid changes in the physical environment of the marine Arctic, combined with increased access and human activity, are also likely to push some of the region's existing social-ecological systems—small and large—beyond tipping points and into new regimes (Carmack et al. 2012 [this issue]). Carmack et al. (2012 [this issue]) pose three distinct, but interrelated challenges: First to explore existing connectivity between components of the marine system; second to seek indicators (if they exist) of approaching regime change through observation and modelling; and third to build functional resilience into existing systems through adaptation-oriented policy, having in hand transformative options when tipping points are crossed and new development trajectories are required. These challenges are all scale dependent, and each requires a deepened understanding of connectivity within existing systems and their response to external forcing. An approach founded in 'resilience thinking' is proposed, to allow northern residents living in small coastal communities to participate in the

observation, adaption and—if necessary—transformation of the social-ecological system in which they live.

Arctic communities may also experience their own economic and political 'tipping points' (Fig. 4). Huntington et al. (2012 [this issue]) make the simple case that climate change incurs costs to society, but because economic resources are not limitless, we must choose among potential actions regarding climate change impacts. As climate changes and impacts increase, more and more resources will be required to respond to change, leaving fewer resources available to prevent further change. If and when those resources are insufficient to pay for prevention, we will have reached a tipping point and lost the option of prevention. Because political will to invest in prevention is often lacking, we may reach the real tipping point even sooner. This is illustrated with an example from Arctic Alaska: Many villages are threatened by erosion and flooding, but relocation is expensive. To date, critically threatened villages have not yet been relocated, suggesting they may already have reached a political-economic tipping point.

GOVERNANCE AND ANTICIPATION

The interacting forces of climate change and globalization are transforming the Arctic. Triggered by the non-linear

Fig. 4 Lenin tirelessly inspects the abandoned Soviet mining town Pyramiden in Isfjorden, Svalbard. Photograph: Christian Wexels Riser

shift in the behaviour of sea ice, there has been a burst of interest in prospects for exploiting the region's natural resources. A suite of environmental, economic and political concerns arise in conjunction with this. Young (2012 [this issue]) analyses the governance implications of these changes, pointing to limitations of existing governance arrangements and exploring ways to adjust these arrangements to meet changing needs. He recommends the development of an Arctic regime complex featuring flexibility across issues and adaptability over time. This would include an enhanced role for the Arctic Council, both in conducting policy-relevant assessments, and in promoting synergy in interactions among the elements of the emerging Arctic regime complex. The aim would be to maximize the fit between the main features of the Arctic treated as a complex socio-ecological system experiencing transformative change, and the character of the governance arrangements needed to steer this system towards a sustainable future.

Within this regime complex, the governance of Arctic marine ecosystems is a particular concern (Hoel and Olsen 2012 [this issue]). Whereas coastal Arctic nations have recently agreed principles of responsibility for search and rescue across the Arctic Ocean, a similar assignment of responsibilities for monitoring changes in the Arctic marine ecosystem and mitigating impacts is still pending. The combined forces of climate change, pollution and

increasing economic activities necessitates comprehensive approaches, centring on the concept of ecosystem-based ocean management. Hoel and Olsen (2012 [this issue]) provide a case study of the Norwegian experience of introducing ecosystem-based ocean management, emphasising how climate change is addressed in the plan, seen as a major long-term driver of ecosystem change. Understanding the direct effects of climate variability and change on the ecosystem is essential for adaptive planning to be useful in the long-term management of the marine environment. The prospect of passing tipping points in the Arctic marine ecosystem adds urgency to this.

Shifting to a more anthropological perspective, in a reflective closing article, Nuttall (2012 [this issue]) considers how tipping points affect how we think about the future. In this special issue and elsewhere, climate is represented as having the power to influence our lives in ways we have never before experienced or imagined, suggesting something transformative, disruptive and decentring. Yet, at the same time, the complexity of the human world is explained in terms of scientific models that suggest a return to climatic determinism. Nuttall (2012 [this issue]) addresses what we mean when we use terms like 'tipping point' to imagine, describe, and represent the world and what relevance they have for anticipatory knowledge and anticipatory practice, i.e. the art of future knowledge and future procedure developed from existing or predicted trends.

OUTLOOK: RESILIENCE THINKING

To comprehend the future of the Arctic in a systemic way, which is accessible to traditionally separated disciplines such as physical science, ecology and governance, requires integrative concepts and models. Here we follow several contributions to this special issue and introduce resilience as such an integrative concept. Resilience is a general term that can have numerous definitions, but in the current context it is the capacity of a system to absorb disturbance and reorganize while undergoing change, so as to retain essentially the same function, structure, identity and feedbacks. It is the positive capacity of a system to cope with pressures and adversities such as exploitation, warming, governance restrictions, competition, etc. Resilience embraces human and natural systems as complex entities continually adapting through cycles of change.

The ‘adaptive cycle’ model of resilience (Gunderson and Holling 2002) describes this cycle of change (Fig. 5). Under various forms of forcing, any system will have at the start a building, accumulation or exploitation phase that leads to an increasing build up of energy, wealth or resources (r ; see Fig. 5). Over time and with increasing forcing, the carrying capacity of the system is reached,

marking the locked-in or conservation phase (K). If forcing goes further, a tipping point is reached, followed by a break down in the sustainability of the system (Ω). Once the forcing ceases, the system can re-establish and reorganise itself (α) and enter a new cycle.

However, when tipping points are also points of no return (e.g. bifurcation points) more complex dynamics can emerge (Fig. 6). When a point of no return is reached, after the destruction phase, a system switches to a new state or regime. This new regime can then develop around its own adaptive cycle. It may reach anew a further point of no return (second bifurcation point), which in some cases at least can switch the system back to the original regime. We suggest that every field covered in this volume could apply a conceptual model like one of those depicted.

Resilience thinking involves both the ecosystem and the humans it supports. In such a multidisciplinary setting, resilience has several meanings. It can be the capability of a strained system to recover its function after exposure to pressure, or the ability to recover from or adjust easily to misfortune or change. Wise system management should attempt to ease pressures and keep the system along an r to K pathway and away from the tipping point. This r to K

Fig. 5 Conceptual model of the adaptive cycle, illustrating how a system, subjected to forcing, develops through two principle phases: r and K . Transgressing a tipping point may result in the system facing a destruction phase Ω before it renews itself, if the forcing decreases, in the α phase. Redrawn from Gunderson and Holling (2002)

Fig. 6 Altered conceptual model of adaptive cycles where the tipping point is now a point of no return. The original regime (*red*) switches over to a new regime (*blue*) and then back again to the original regime. There can exist a multitude of regimes with potential switches between them. Here we only display two to illustrate the principle in an easy-to-follow manner

pathway is characterized by linearity in response and often by empirical time series data, i.e. this phase is known, predictable and thus manageable. The goal of sustainable management is thus to avoid tipping points (end of K and Ω phase, Fig. 5) or points of no return (Fig. 6).

SUMMARY

The main objective of this volume is a better and more balanced understanding of the pan-Arctic region and its specific challenges. Beyond this, we hope that the multi-disciplinary nature, the integrating terminology and overarching nature of the special issue contributes to more holistic approaches, which appear indispensable in the quest for increased resilience and proficient management of Arctic systems, even during an era of strong climate change. Achieving practices where humans are not opposed to nature as a solitary, alien player, but rather act as an integrated and amalgamated part of ecosystems, are part of the challenge of our times (Figs. 1, 2, 3).

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