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A Tipping-Elements Expedition in the Footsteps of Alexander von Humboldt

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With 1 Figure

Abstract

When Alexander VON HUMBOLDT set out to explore the American continent, he came across terrestrial and marine (eco-)systems that are considered tipping elements today. Small perturbations linked to climate change may trigger abrupt and/or irreversible change in these systems. If Alexander VON HUMBOLDT had undertaken his expedition in modern times, he might have studied potential tipping behavior of the marine biological carbon pump, the Amazon rainforest, coral reefs in the Caribbean Sea, and the El Niño-Southern Oscillation (one of the major oceanic/atmospheric circulation modes on Earth). Likewise, when he later travelled across the vast plains of Russia, he might have been most interested in signs of approaching tipping points in boreal forests, permafrost soils, Tibetan glaciers, and marine methane hydrates off the Siberian coast. Here, we follow Alexander VON HUMBOLDT on a mental journey. We present recent scientific findings on tipping elements that are located along his expedition routes. To conclude, we sketch a research agenda whose successful completion would provide society with the knowledge and tools required to handle the risks arising from tipping elements.

Zusammenfassung

Auf dem Weg, den amerikanischen Kontinent zu erforschen, stieß Alexander VON HUMBOLDT auf Regionen und Ökosysteme – auf dem Land und im Meer –, die heute als Kippelemente im Erdsystem betrachtet werden. Kleine Störungen, bedingt durch den Klimawandel, könnten in diesen Systemen zu abrupten und/oder irreversiblen Veränderungen führen. Wäre Alexander VON HUMBOLDT heutzutage auf seine Forschungsreise aufgebrochen, hätte er wohl das Kipprisiko der biologischen Kohlenstoffpumpe im Atlantik, des Amazonas-Regenwaldes, der tropischen Korallenriffe in der Karibik und des ENSO-Phänomens (eines der bedeutendsten atmosphärisch-ozeanischen Zirkulationsmuster der Erde) studiert. Später – auf seiner Reise durch das russische Zarenreich – hätte er wahrscheinlich mit großem Interesse nach Zeichen sich nähernder Kipppunkte in den borealen Nadelwäldern, in den Permafrostgebieten, in den ostasiatischen Gletscherregionen und bei den Methanhydraten vor der Sibirischen Küste gesucht. In diesem Aufsatz gehen wir mit Alexander VON HUMBOLDT auf Reisen. Wir diskutieren neueste Forschungsergebnisse zu Kippelementen, die entlang seiner Reiserouten gelegen sind. Zum Abschluss umreißen wir eine Forschungsagenda, die darauf abzielt, die Gesellschaft mit dem notwendigen Wissen und den Werkzeugen auszustatten, um den Risiken der Kippelemente in geordneter Weise zu begegnen.

On 5 June 1799, Alexander VON HUMBOLDT left La Coruña on board of a Spanish ship, heading towards the American continent. He was accompanied by one scientific partner, the botanist Aimé BONPLAND, and with them they had taken innumerable measuring instruments. His intentions were to shed light “on the interactions of all forces, the effect of the inanimate creation on flora and fauna” (MOHEIT 1993). During the five years that followed he crossed the North Atlantic, explored the Amazon rainforest, climbed the Andean mountains, and sailed along the West coast of South America and through the Caribbean Sea.

Humboldt probably never imagined that, in the not-so-distant future, humans would become a planetary force, with the power of significantly transforming the processes and objects that he was studying. At a time when less than one billion people lived on Earth, humans – rather unsurprisingly – did not belong to the "forces", whose interactions Humboldt set out to investigate. If he had repeated his exploration along the same route in modern times, he might have called his trip a "tipping elements expedition to the Americas".

He might have intensively studied the marine biological carbon pump while crossing the Atlantic, the rainfall regime of the Amazon rainforest, parts of the El Niño-Southern Oscillation (ENSO), and tropical coral reefs of the Caribbean Sea. (The prospect of an ENSO shift towards more persistent El Niño conditions [see below], implying a vanishing Humboldt Current along the West coast of South America, would have probably worried him most …) All of these (sub-)systems fulfill the criteria of tipping elements in the Earth's climate system.

When Alexander von Humboldt, thirty years after his expedition to the Americas, toured the vast plains, extensive forests and swamps of Tsarist Russia, he also came across regional features and ecosystems that are considered potential tipping elements today. In modern times, he might have observed melting of permafrost, massive disturbance of boreal forests, retreating of Tibetan glaciers, and destabilization of methane hydrates along the East Siberian Arctic coast.

1. Definition of Tipping Elements

A tipping element is a component of the Earth system that is at least subcontinental in scale and might be switched to a qualitatively different state by small perturbations (Lenton et al. 2008). A tipping point is the associated critical threshold of a pertinent forcing parameter at which the (future) qualitative change is triggered. The formal definition of tipping elements encompasses a variety of phase transitions. The system might run through a bifurcation and show hysteresis, such that recovery is much slower than the initial state switch. Systems that produce quasi-continuous transitions with full reversibility might also qualify as tipping elements (Lenton et al. 2008, Lenton and Schellnhuber 2010). All tipping elements contain some type of internal feedback mechanism triggered by (or coupled to) the climate that gives rise to highly non-linear dynamics.

Paleoclimatic data suggests that the Earth's past climate system has many times undergone large-scale regime shifts, i.e. has passed tipping points (Alley et al. 2003). Based on these observations, one can conjecture that the forcing deployed by the anthropogenic emissions of greenhouse gases – if unchecked – might similarly bring about abrupt and possibly irreversible changes in the Earth system. Gauging the scientific deliberations about tipping elements to society's needs, Lenton et al. (2008) have proposed additional criteria that define "policy-relevant" tipping elements. In short, this subset of tipping elements are defined as those elements which (*i*) include a tipping point that could be crossed already this century, and (*ii*), as a consequence, experience a qualitative change in state within this millennium, affecting a large number of people (Lenton and Schellnhuber 2010).

2. Starting Point and Overview

Lenton et al. (2008) presented a shortlist of nine policy-relevant tipping elements. At present, the scientific community is still far from providing comprehensive risk assessments and definite conclusions on tipping elements (Schellnhuber 2009). However, since the publication of Lenton et al.'s shortlist, considerable progress has been made in identifying critical forcing thresholds and in narrowing down likelihoods of passing a tipping point. The main aim of this paper is to present advances in the science related to specific tipping elements. The update is based on recent literature, particularly a recent Special Feature of the *Proceedings of the National Academy of Sciences* on tipping elements (2009) and a review by Lenton and Schellnhuber (2010).

Figure 1 depicts a map of potential tipping elements that will be discussed. We do not present an exhaustive overview of currently investigated or suspected tipping elements. Instead, we limit our discussion to some tipping elements that are located along Humboldt's expedition routes.[1] Tipping elements, whose status is particularly uncertain, are denoted with a question mark. For each tipping element, we consider (*i*) the known internal feedback processes that can give rise to threshold behavior, (*ii*) recent advances in the understanding of these feedbacks, (*iii*) observational records of key indicators from the recent past, and (*iv*) critical temperature thresholds (if known) and the likelihood of passing a tipping point this century.

3. Tipping-Elements Expedition to the Americas

Marine biological carbon pump? – Global oceans currently absorb approximately 2 Gt carbon per year, which is equivalent to around 20 % of annual anthropogenic carbon emissions (Le Quéré et al. 2009). Sequestering of carbon by the oceans is largely mediated by the so-called biological carbon pump, i.e., the fixation of carbon by algal photosynthesis and the export of organic carbon to deeper ocean layers. Increasing temperatures and acidifying waters may affect this biological pump in a multitude of non-linear ways. Deoxygenation of large ocean domains, linked to warming, acidification and nutrient enrichment (Hofmann and Schellnhuber 2009, Keeling et al. 2010), may also contribute to triggering a qualitative change in marine biological productivity. Therefore, a rapid decline in the ocean carbon sink as well as ocean anoxia have been discussed as potential tipping points in the oceans (Lenton et al. 2008, Kriegler et al. 2009).

Recently, it has been suggested that tipping-element behavior of the biological carbon pump primarily arises from the detrimental effects of ocean acidification on marine calcifying organisms (Riebesell et al. 2009). Reduced biogenic calcification critically lowers the supply of calcium carbonate, which serves as a carrier of organic carbon and forms a critical component of the mineral ballast transport to the deeper ocean. Weakening of the biological pump translates to a positive feedback on atmospheric CO_2 concentrations and in turn on ocean acidification. However, large uncertainties about the mechanisms involved remain. The attenuation of biogenic calcification also creates a negative, stabilizing feedback on at-

1 For a complete discussion of currently known tipping elements the reader is referred to Lenton and Schellnhuber (2010).

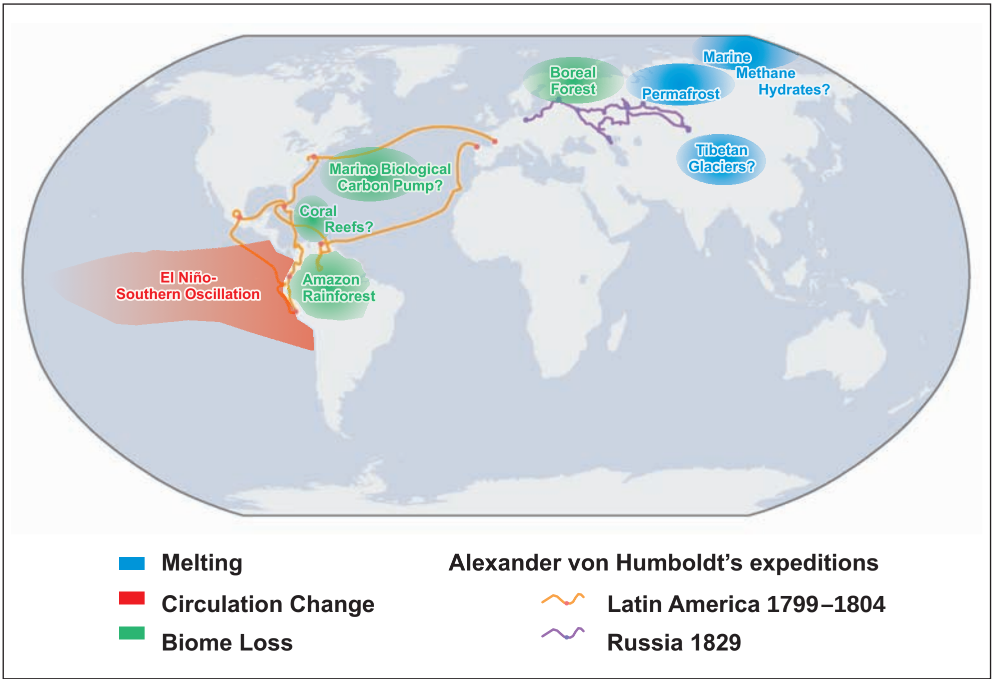

Fig. 1 Selected potential tipping elements in the Earth system alongside Alexander von Humboldt's expedition routes to the Americas and Russia. Tipping elements are large-scale features of the Earth system that may undergo a qualitative change in response to small (climatic) perturbations. Tipping elements shown in blue involve melting of large masses of ice, those shown in red involve changes in atmospheric and oceanic circulation patterns, and those shown in green involve loss of unique biomes. Source: Martin Wodinski and Veronika Huber 2010.

mospheric CO_2 levels, which according to one study (Hofmann and Schellnhuber 2009) may outweigh the positive feedback of a weakened biological pump. The loss of calcium-carbonate ballast could also be at least partially compensated by increased aggregation of organic matter and non-calcium-carbonate minerals in carbon-enriched waters (Riebesell et al. 2009). Additional feedbacks may arise from the marine nitrogen cycle, which is closely linked to the biological carbon pump and oxygen saturation of the oceans. Recent studies suggest that deoxygenated oceans could outgas more nitrogen oxide (N_2O), acting as a very potent greenhouse gas (Codispoti 2010).

It is now a well-established fact that oceanic CO_2 uptake of the last century has made the marine pH drop from 8.2 to 8.1 (Orr et al. 2005). Shell thinning in calcifying organisms has been documented in the field. However, it remains to be resolved whether the latter observation can be clearly attributed to ocean acidification (de Moel et al. 2009). Negative effects of acidification on biological calcification rates have been unambiguously demonstrated in experimental studies (Riebesell et al. 2009). It is still under debate, though, whether these are species-specific and confined to the laboratory or whether they can be generalized to entire groups of calcifying organisms and the open oceans (Ridgwell and Schmidt 2010). To our knowledge, no study has yet presented clear evidence for a weakening of the biological carbon pump due to the ocean acidification over the last century.

Under business-usual-scenarios, CO_2 concentrations might reach 800 ppm by the end of the century, implying a drop in ocean pH of 0.3 – 0.4 units (Orr et al. 2005). Bloom-forming coccolithophore species, especially important for carbon export to the deep ocean, have shown significant declines in calcification rates when exposed to 750 ppm CO_2 (Riebesell et al. 2000). In recent model studies, however, much higher CO_2 atmospheric concentrations on the order of >1500 ppm needed to be reached until considerable responses in the marine biological carbon pump could be observed (Hofmann and Schellnhuber 2009). In summary, no definite conclusions can be drawn yet on the existence of a policy-relevant tipping point in the marine biological carbon pump.

Amazon rainforest – Droughts in Amazonia tend to cause (partial) dieback of the rainforest, and a reduction in forest cover, in turn, tends to amplify the decrease in precipitation. Several processes give rise to this positive feedback loop and the possibility of tipping-element behavior of the system (Betts et al. 2004). First, deforestation reduces the local evaporative recycling of water in the Amazon basin. Second, forest dieback releases large amounts of CO_2 into the atmosphere. Third, rising CO_2 concentrations may suppress precipitation over the Amazon region by altering atmospheric and oceanic circulation patterns (towards more persistent El Niño) and by directly affecting plant physiology (involving increased stomatal closure and decreased transpiration). Additional feedbacks that amplify forest dieback arise from ecosystem disturbance processes such as increased fire frequency and pest infestation. Lenton et al. (2008) noticed that the Amazon rainforest "may exhibit bistability" (i.e., may exist in either of two distinctive states, depending on the medium-term history) and included it in the list of policy-relevant tipping elements.

The occurrence and extent of forest dieback in climate forecasts differs among models. Dieback is less sensitive to the choice of vegetation model, but not all global climate models (GCMs) project a reduction of precipitation over the Amazon basin (Salazar et al. 2007, Lenton and Schellnhuber 2010). Recently, Malhi et al. (2009) found that many GCMs underestimate current rainfall in the region. Correcting for this bias shifts forecasts in the direction of seasonal forests rather than replacement by savannah-type ecosystems. Yet a recent analysis has indicated that the Amazon rainforest may lag climate forcing significantly (Jones et al. 2009). Therefore, it may be committed to considerable dieback long before the loss of forest cover becomes apparent.

The western and southern parts of the Amazon basin experienced a severe drought in July to October 2005. Rivers fell dry, and some forested areas that had been a carbon sink turned into a source of CO_2 (Phillips et al. 2009). Reduced precipitation was linked to unusually warm sea-surface temperatures in the North Atlantic (Cox et al. 2008). Also, weakening of the tropical Pacific atmospheric circulation, affecting the length of the Amazon dry season, has been observed since the mid-nineteenth century (Vecchi et al. 2006).

Dry-season water stress is likely to further increase in Amazonia. One model predicts that the drought of 2005 may become the norm as early as 2025 (Cox et al. 2005). Several models show dieback of up to 70 % of Amazon rainforest by the end of this century (Cook and Vizy 2008). However, the likelihood of passing a tipping point this century will depend largely on whether the natural resilience of the forest can be maintained or not (Malhi et al. 2009). Fire ignition associated with logging and forest fragmentation act as nucleation points that may speed up the transition to seasonal, low-biomass forests and savannah. Experts estimate that dieback of the Amazon rainforest is more likely than not if global warming exceeds 4 °C (Kriegler et al. 2009). A recent study concludes that the risk of significant loss of forest cover in Amazonia increases rapidly for a global mean temperature rise above 2 °C (Jones et al. 2009).

El Niño-Southern Oscillation (ENSO) – The El Niño-Southern Oscillation (ENSO) phenomenon is the strongest internal climate mode on year-to-year timescales. ENSO manifests itself most conspicuously in the sea-surface temperatures of the central equatorial Pacific. The warm extreme is called El Niño, the cold La Niña. ENSO affects regional and global climate, e.g., ENSO has contributed to the record global surface temperatures of 1998. Strong feedback processes, involving sea-surface temperatures, thermocline depth, and atmospheric circulation cells, drive the oscillations between El Niño and La Nina states (Latif and Keenlyside 2009). Paleo-data suggests that warmer climates might have been accompanied by more persistent El Niño conditions (Wara et al. 2005). Lenton et al. (2008) considered there "to be a significant probability of a future increase in ENSO amplitude" with the "required warming to be accessed this century".

The first coupled model studies predicted a future shift from current ENSO variability to more persistent or frequent El Niño conditions. More recent analysis indicates that models do not produce any consistent response of ENSO to global warming (Latif and Keenlyside 2009). Some models exhibit increases in amplitude and/or frequency, some decreases, and some no change at all. If a tendency can be identified at all among models, it is a trend towards an El Niño-like mean state change of the ENSO (Solomon et al. 2007). One recent study forecasts a shift toward so-called Modiki events, which correspond to modifications of the typical El Niño pattern (Yeh et al. 2009). During these events, the warm pool shifts from the West to the middle rather than to the East of the equatorial Pacific.

Over the past half century sea-surface temperatures in the equatorial Pacific have increased, with an El Niño-like trend pattern, i.e., stronger warming in the East relative to the West. However, according to Latif and Keenlyside (2009), sea-surface temperatures do not yet provide unambiguous evidence for significant changes in either ENSO activity or mean state. At the same time, recent studies show that the canonical El Niño has become less frequent and that Modiki events have become more common during the late twentieth century (Yeh et al. 2009).

Large uncertainties persist about the response of ENSO to additional global warming of the twenty-first century. One model simulates increased El Niño amplitude when climate stabilizes at 3–6 °C higher global temperatures (Guilyardi 2006). Others suggest that tipping-element behavior, in the sense that ENSO vanishes or becomes overly strong, is very unlikely to occur until the end of this century (Latif and Keenlyside 2009). However, even a gradual change in amplitude or location of El Niño could entail severe consequences in many regions.

Coral reefs? – Experts agree that acidifying and warming oceans might trigger widespread coral bleaching and reef collapse. Yet Lenton et al. (2008) did not include coral-reef systems in their shortlist of policy-relevant tipping elements. In contrast, marine biologists now talk about a 'point of no return' as rising CO_2 emissions put coral reef system increasingly under pressure (Veron et al. 2009).

Hence the world's largest coral reef systems, such as the Great Barrier Reef and the cold-water coral-reef systems extending from Northern Norway to the West coast of Africa, may turn out to be tipping elements in the Earth system (Lenton and Schellnhuber 2010). Abrupt changes in coral reef systems are expected as ocean acidification causes the aragonite (a crystalline form of calcium carbonate) saturation horizon to shallow (Riebesell et al. 2009). Once bathed in corrosive water, skeletons and shells may dissolve and the reef could collapse. Cold-water coral reefs that grow down to 3000 m depth are particularly vulnerable to ocean acidification. Also, a clear causal link between increasing ocean temperatures and mass bleaching events in the tropical coral reefs has been established (Hughes et al. 2003). The geological record suggests that reefs take thousands to millions of years to re-establish after massive extinction events (Veron et al. 2009). Thus, they could be irreversibly lost on human timescales.

Anthropogenic penetration of CO_2 into the oceans has contributed to a shoaling of the aragonite saturation horizon by 30–200 m from the preindustrial period to the present (Doney et al. 2009). Upwelling of corrosive waters has been observed on the continental shelf off the West coast of North America, decades earlier than had been predicted by models (Feely et al. 2008). Decreasing calcification rates in corals have been recorded worldwide, most prominently on the Great Barrier Reef (De'ath et al. 2009). In response to increasing sea-surface temperatures, the extent and severity of coral bleaching in the tropics has also dramatically increased in recent decades (Veron et al. 2009).

If CO_2 emissions remain unabated, 70 % of the presently known cold-water coral reef locations may be affected by aragonite undersaturation by the end of the century (Guinotte et al. 2006). Adaptation and migration capacities increase resilience, but may not keep up with the speed of acidification (Ridgwell and Schmidt 2010). Increases in sea-surface temperature of 1 °C to 3 °C – likely to take place already this century even if ambitious global mitigation measures are undertaken – are projected to result in more frequent coral bleaching events and widespread mortality unless there is substantial (and surprising) thermal adaptation or acclimatization by corals (Smith et al. 2009, Veron et al. 2009).

4. Tipping-Elements Expedition to Russia

Boreal forests – Documented incidents of species invasions of the past demonstrate the potential for abrupt change in boreal ecosystems (Chapin et al. 2004). It is a general ecological phenomenon that species alter their environments so as to improve their competitive abilities and increase their survival chances. For example, black spruce is a strongly fire-adapted tree of the boreal zone that itself promotes fire through its high flammability. This type of internal feedback mechanisms may amplify the response of boreal vegetation to climate change. Lenton et al. (2008) explain that a combination of increased temperature and drought stress, fire frequency, and pest infestations may rapidly shift boreal forests to a new biome type, consisting of open woodlands and grasslands, once certain critical thresholds have been passed.

Besides the potential dieback of coniferous forests, the expansion of deciduous forests northwards into the tundra has recently been intensively discussed as another important consequence of climate warming in the boreal zone (Soja et al. 2007). A new model analysis shows that positive feedbacks associated with the global carbon cycle are largely driven by increasing forest cover in northern latitudes (O'Ishi et al. 2009). Expanding forests on formerly bare grounds in the Arctic region strongly reinforce regional/global warming by changes in land-surface albedo and transpiration of water vapor (Swann et al. 2010). However, albeit important as a feedback mechanism, the northward migration of the tree line is less likely to involve an abrupt switch to a qualitatively different state. In fact, the tree line is expected to move rather gradually because, at the northern limits of species ranges, competitive species interactions are less important than in central portions of the boreal forests (Chapin et al. 2004).

Mild weather conditions of recent years have brought outbreaks of insect pests damaging boreal forests all across the circumpolar region (Berg et al. 2006, Soja et al. 2007). The boreal forest in Western Canada, for example, is currently suffering from a disastrous invasion of mountain pine beetle that has caused widespread tree mortality (Kurz et al. 2008). Moisture-stress-related dieback in white spruce trees in Alaska has also been documented (Barber et al. 2000). Extreme fires have occurred more frequently and have affected larger boreal areas in all of Alaska, Canada and Siberia, concurrent with rising temperatures of recent decades (Soja et al. 2007).

According to expert elicitation, dieback of the boreal forest is more likely than not if global warming exceeds 4 °C (Kriegler et al. 2009). At least one model predicts widespread replacement by grasslands when regional temperatures reach around 7 °C above present (Lenton and Schellnhuber 2010). Further research is required to confirm these temperature thresholds and the possibility of passing a tipping point this century.

Yedoma permafrost – Perennially frozen soils in the Northern circumpolar regions may contain the gigantic amount of up to 1500 Gt organic carbon (Tarnocai et al. 2009). If only part of this carbon reservoir was mobilized, and degassed as either CO_2 or methane, a substantial positive feedback on global warming would result. Lenton et al. (2008) did not include permafrost regions in their shortlist of policy-relevant tipping elements because thawing of soils was considered to happen in a "quasi-linear" manner.

On the other hand, Khvorostyanov et al. (2008) have recently shown that during mobilization of highly labile frozen carbon deposits, so-called Yedoma, threshold behavior may arise from microbial decomposition activity that generates additional heat. In their simulations, a comparatively small amount of external heat was sufficient to trigger irreversible thawing. Yedoma consists of frozen carbon loess (windblown dust), occurring predominantly in northeastern Siberia. Once started, thawing processes could release 2.0–2.8 GtC per year over a century, transforming up to ~ 75 % of the initial carbon stock into CO_2 and methane.

When Yedoma thaws, melting of ice wedges releases large amounts of water. While part of the melt water runs off in summer, it also creates long-lasting thaw lakes, which are a significant source of methane. These so-called thermokarst lakes have expanded across northeastern Siberia, concurrent with regional warming since the mid-1970s, and have contributed to a significant increase in methane emissions (Walter et al. 2006). In the Yedoma permafrost region, the soil depth at which active cycling of carbon takes place has also increased by at least 10 cm over the second half of the twentieth century (Sazonova et al. 2004, Khvorostyanov et al. 2008).

The tipping point marking irreversible decomposition of Yedoma permafrost soils may lie at around > 9 °C additional regional warming (Khvorostyanov et al. 2008). Given polar amplification of global warming, under high emission scenarios this magnitude of temperature rise can well be reached by 2100. Thus, the Yedoma permafrost has recently been added to the list of policy-relevant tipping elements (Lenton and Schellnhuber 2010).

Ocean methane hydrates? – Estimates of the global inventory of methane hydrates in the ocean range from 700 to 10,000 GtC (Archer et al. 2009). As heat diffuses into the ocean sediment, hydrates melt and methane may be released into the ocean waters, and subsequently into the atmosphere. Destabilization of marine methane hydrates might have been an important positive feedback mechanism during major warming events in the Earth's history, such as during the Paleocene-Eocene Thermal Maximum around 55.5 Myr ago (Archer 2007) and, more controversially discussed, also during Quarternary deglaciations ("clathrate gun hypothesis"; Kennett et al. 2003, but see Sowers 2006). However, the melting of hydrates is thought to be taking place on a time scale of thousands of years (Archer and Buffett 2005). Lenton et al. (2008) did not classify ocean methane hydrates as a policy-relevant tipping element, because they considered the full draining of the reservoir – a qualitative change – "extremely unlikely to occur within this millennium".

Recent analyses have corroborated this conclusion. The only conceivable abrupt releases of methane triggered by warming oceans could originate from submarine landslides. These may be provoked by bubbles associated with the melting of hydrates. However, even the largest known landslide of the past (the Storrega slide off Norway around 8,150 years ago) has not released a climatically significant amount of methane to the atmosphere (Archer 2007). Based on current paleo-climatic evidence, the most likely impact of a melting hydrate reservoir is therefore a long-term chronic methane source (Archer et al. 2009).

Where hydrate deposits are located at great ocean and sediment depths, it will take hundreds to thousands of years until they are reached by the thermal perturbations of anthropogenic warming. The only significant release of methane from the ocean has been documented along the Arctic coastline of Siberia, where shallow shelf waters today are highly supersaturated with methane (Shakhova et al. 2005, Archer 2007). According to recent observations, the annual methane outgassing from these waters adds as much to the atmosphere as the entire methane emissions from the global oceans (Shakhova et al. 2010).

Archer et al. (2009) have estimated that, on timescales of several thousand years, the equivalent of between 35 Gt to 940 Gt carbon could be released from marine methane hydrates in response to a 3 °C uniform warming. The relatively small external forcing involved and the irreversibility of the release clearly qualify marine methane hydrates as a tipping element in the Earth system. However, unless a plausible mechanism for large-scale abrupt methane release is found, a qualitative change in the global reservoir of marine methane hydrates is extremely unlikely to occur within this millennium.

Tibetan glaciers? – The Hindu-Kush-Himalaya-Tibetan (HKHT) glaciers have recently been proposed to be a policy-relevant tipping element (Ramanathan and Feng 2008). If these glaciers disappeared, the regional impacts would be huge. Three of the largest rivers that drain these glaciers, the Indus, Ganges and Brahmaputra, alone currently supply around 500 million people with water for drinking, agricultural and industrial purposes (Kehrwald et al. 2008). The question, however, is whether the HKHT glaciers really qualify as tipping elements or whether they rather fall into the category of "high impact eventualities" that do no necessarily show threshold behavior (Lenton and Schellnhuber 2010).

To our knowledge, no study exists to date that has explicitly investigated tipping points associated with the melting of the HKHT glaciers. However, some feedback mechanisms involved in the waxing and waning of mountain glaciers have been identified. Most importantly, the snow-ice-albedo feedback that causes amplification of warming in high mountain regions (Pepin and Lundquist 2008) may generate non-linear responses of HKHT glacier melting. In addition, Oerlemans et al. (2009) have found that the deposition of dust on glacier snouts may considerably accelerate their retreat. As the glacier area decreases, it exposes side moraines that provide important sources of mineral dust. A feedback arises because mineral dust stimulates the growth of algae and lowers the surface albedo, thereby enhancing the melt rates of the glacier. Studying a glacier snout in the Swiss Alps, the authors measured a dust-caused decrease in surface albedo during a period of four years, which constituted a forcing equivalent to a rise in air temperature of ~ 1.7 °C.

The Himalayan/Tibetan region has experienced a decline in snow cover and an advance in the melt season during recent decades (Rikiishi and Nakasato 2006). Over the last half century, the Tibetan Plateau has warmed at around 0.36 °C per decade (Wang et al. 2008), more than twice as rapidly as global mean temperatures, which have risen by around 0.17 °C per decade (Solomon et al. 2007, p. 248). While a few glaciers in the HKHT region have increased in mass (Hewitt 2005), probably due to precipitation effects, loss in area and volume has been recorded at the majority of the sites (Solomon et al. 2007, chapter 4). For example, satellite data indicates that over 80 % of the glaciers in western China have retreated in the past fifty years (Ding et al. 2006). Widespread thinning of glaciers has been observed at elevations up to 6,000 m (Kehrwald et al. 2008).

Ramanathan and Feng (2008) named 1 to 3 °C global warming above preindustrial levels as the temperature range that might commit the environment to major reductions of area and volume of HKHT glaciers. However, due to inertia involved in the melting of large glaciers, it could take several hundred years until the majority of HKHT glaciers will have completely vanished (Paterson 2004). Some estimate that even small glaciers are unlikely to disappear before the end of the century (Schiermeier 2010; contrary to Parry et al. 2007, p. 493). Further research is required to elucidate whether HKHT glaciers constitute a policy-relevant tipping element, involving a temperature threshold that could be passed in the 21st century.

5. Conclusions: A Tipping-Elements Research Agenda

When still travelling in America, Alexander von Humboldt was appointed member of the Academy of Sciences based in Berlin. Later, upon return to his hometown, he became the driving force and focal point of the scientific community – in Prussia and beyond. In 1828, he organized and presided a natural science congress (‘Naturforscherkongress’), which was the first of his kind regarding interdisciplinary and international participation. If this conference had taken place in modern times, there would have certainly been a session on tipping elements in the Earth system. The great Alexander would have possibly presented an update on tipping elements that he had visited during his expeditions – just as we have done in this essay. At the end, he might have added his view on the most important research gaps. As a conclusion to our paper, we sketch three items of such a research agenda, aimed at providing society with the knowledge and tools to handle the risks arising from tipping elements.

Interactions among tipping elements – Tipping elements across the globe are closely interlinked. It is easily conceivable that abrupt changes in one of them triggers – in a domino-like process – tipping in others. For example, droughts in the Amazon basin have been related to a shift in the ENSO (Latif and Keenlyside 2009). First attempts have been made to elucidate critical teleconnections between tipping elements (Kriegler et al. 2009). However, much more research is necessary to gain a better understanding of the interactions among tipping elements and the potential additional risks arising from these interdependencies.

Impacts of passing tipping points – At some point in the future, societies may be confronted with a situation in which several tipping points are close. Limited capacities and resources (for instance, for investing in renewable energy sources or large-scale ecosystems management) might allow to avoid the passing of some, but not of all of them. A comprehensive impact assessment could then become the basis of deciding which tipping elements to focus on. Up to date, no convincing metric has been developed to properly quantify impacts of climate change, let alone of passing tipping points. Establishing such a metric is also the prerequisite for ranking tipping elements according to their associated risks today (LENTON and SCHELLNHUBER 2010). Understanding the capacity of societies to absorb environmental shocks of the kind associated with tipping-elements activation is still intellectual *terra incognita,* waiting for exploration by contemporary HUMBOLDTS.

Identification of early-warning signals – Successful early-warning systems exist for hurricanes and tsunamis. These natural catastrophes are low-probability-high-impact events, similar to the passing of tipping points. Developing reliable methods to identify the proximity of tipping points far in advance would be of the highest value for society. Science has already identified several indicators signalizing that critical transitions in dynamic systems are close. Slower recovery from perturbation, increased autocorrelation and increase variance in time-series data are considered generic early-warning signals for a wide class of systems (SCHEFFER et al. 2000). Applying these indicators (and others) to paleoclimatic time-series data will contribute to testing their general validity. As a side benefit, new tipping elements might be identified that have so far not been thought of. However, one recent study cautions that the class of natural systems which exhibit leading indicators might be limited (HASTINGS and WYSHAM 2010). Where abrupt transitions occur without warning, the only possibility to forecast sudden changes is process-based modeling and simulation.

In summary, the emerging field of tipping elements in the Earth system poses research challenges that would match the capacities of giants like Alexander VON HUMBOLDT. Unfortunately, these giants do not abound and, more worrying, there may be little time left for them to do their job before irreversible environmental changes start to unfold.

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