Tipping elements in the Earth System

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The Earth System (ES) is defined as the conglomerate formed by human civilization and its planetary matrix (i.e., all parts of the Earth that interact with the members and manifestations of our species) (1, 2). Thus, eminently complex systems like the global economy or the human brain are just components of the ES, contributing to its overall evolution. The climate machinery is another formidable subsystem that comprises vast domains of the atmosphere, hydrosphere, biosphere, and pedosphere, involves innumerable intertwined processes, and generates fairly robust dynamical patterns like the Hadley cell. This machinery still operates in the "Holocene mode," which emerged ≈10 ka ago and is characterized by a distinctive distribution of ice sheets, wind regimes, ocean currents, biomes, and deserts, something that can be perceived as the environmental face of the Earth.

Although one of the ES components mentioned above, the global economy, is about to inadvertently transform that face through massive emissions of greenhouse gases (GHGs) and the so-induced planetary warming, one other crucial component, the human brain, struggles to advertently preserve it by constructing clumsy institutions like the United Nations Framework Convention on Climate Change (http://unfccc.int/resource/docs/convkp/conveng.pdf). The ultimate objective of this convention is to avoid dangerous climate change, a target that can be operationalized with the help of recent scientific evidence including the results presented in this Special Feature.

Now, what features establish the identity of a face; what distortions erase that identity beyond recognition? The first question can be best answered by cartoonists, whereas the second related one can be addressed in terms of mathematical mapping. An affine (i.e., linear) transformation may stretch or shear the face but cannot wipe out its character. Smooth nonlinear maps yield stronger disfigurative power by affecting proportionalities, yet we know from experience that identities even survive distorting mirrors. Only singular transformations (that remove, add, or replace constitutive traits) are able to create entirely new characters. The cardinal question of ES analysis/sustainability science (3) is whether the anthropogenic rise of global mean temperature (GMT) actually induces a singular transformation of our planet's environmental face that wipes out distinctive features and therefore undoubtedly qualifies as "dangerous."

Paleoclimatic records tell us that continuous variations of ES parameters can indeed bring about discontinuous alterations like the shutdown of the Atlantic Meridional Overturning Circulation (AMOC) (4). An interesting, although purely theoretical, phenomenon in our wider context is the flip dynamics for the number of tropospheric cells that would result from variations of the Earth's angular velocity (5, 6). Now the contemporary three-cell structure will certainly withstand anthropogenic global warming, but what about the monsoon systems, jet streams, coral mega-reefs, tropical rainforests, and iconic landscapes of the Holocene if the GMT rises by two, three, four, or more degrees? When answering these quintessential questions, it is natural to search for the most vulnerable ES components, i.e., those characteristic features that will be switched (out) first and (possibly) irreversibly as the planet warms. These features are the so-called tipping elements (TEs), a class of objects rigorously defined by Lenton et al. (7).

Lenton et al. (7) also provide a state-of-the-art review of the relevant bulk of knowledge, group the TEs according to salient criteria, and discuss their associated "tipping points," the critical warming thresholds where the respective ES elements flip into a qualitatively new state and perhaps annihilation. Note that the TE definition allows for rather slow, yet inexorable, tipping dynamics. Despite its youth, the TE field is developing quickly into a broad and relevant research frontier domain. This PNAS Special Feature accounts for that development and includes nine original articles in a collection that surpasses Lenton et al.'s work regarding depth, breadth, and topicality. Individual TEs are analyzed in great detail, additional TEs are considered (partly for the first time ever), and the recent advancements of the pertinent science are fully incorporated.

Washington et al. (8) have qualified the biggest dust source on our planet, the Bodélé Depression in Chad, as a potential TE. This 370 × 700-km area in the southern Sahara releases huge plumes, which carry ≈700,000 tons of sedimentary material toward the equatorial Atlantic and the Amazon basin and probably have major climatic and ecological impacts. Anthropogenic modification of regional wind patterns and/or surface erosivity could substantially reduce or increase the dust export from that source at time scales as small as one season.

The Indian monsoon is quintessential for the livelihoods of several hundred millions of people as it generates the necessary precipitation for the subcontinental agriculture. Levermann et al. (9) focus their TE discussion of the relevant monsoon dynamics on nonlinear moisture advection feedback processes. They introduce and use a nontrivial conceptual model based on phenomenological relations deduced from observational data.

The El Niño/Southern Oscillation (ENSO) is a well-known internal climate mode on interannual time scales, leading to significant sea-surface temperature and precipitation fluctuations in the Equatorial Pacific. Latif and Keenlyside (10) provide a thorough review of the complicated mechanisms ruling the ENSO phenomenon and discuss its TE features. They resume that current climate-system models are not advanced enough to answer the question of whether global warming will fundamentally alter the ENSO dynamics in the future.

Countless numerical experiments with ocean general circulation models have been carried out to investigate the stability of the AMOC. Almost all of them reveal a hysteresis when forcing the North Atlantic with a slowly varying freshwater flux. Because most of the models suffer from spurious diffusion it has been hypothesized that the AMOC bistability might only be an artifact. Hofmann and Rahmstorf (11) provide evidence that even models that are nearly free of those spurious effects generate a classical freshwater hysteresis for the AMOC.

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The current scientific discussion on possible anthropogenic interference with the Arctic sea ice and the Greenland and the West Antarctic ice sheet is evaluated in the article by Notz (12). He speculates about the so-called "small ice-cap instability," which could cause a sea-ice-free Arctic ocean during the entire year under extreme warming conditions. Compared with sea ice, inland ice seems much more vulnerable to regional warming owing to the lack of large internal stabilizing feedbacks. This cryosphere component is likely to reveal TE behavior that could lead to rapid multimeter rise in mean sea level.

Archer et al. (13) provide evidence that methane hydrates in deep-sea sediments should be regarded as TE in the climate system. As temperatures in the deep ocean increase, heat will diffuse into the sediment layers and destabilize the hydrates, leading to a release of methane bubbles into the water column. Using complex coupled climate system–sediment models, the study finds that an emission of 1,000 GtC from fossil fuels could cause an escape of ≈450 GtC in the form of methane from the sea floor on a millennial time scale. They introduce the term "slow tipping point" in this context.

Riebesell et al. (14) describe the oceans as a climate-system component that presently undergoes major changes. The sea is not only warming, leading to higher stratification and thus lower ventilation of the deep ocean, it also is becoming more acidic. As a consequence, unbridled anthropogenic GHG emissions could affect the oceans' CO_2-uptake capacities and might damage entire marine ecosystems. They conclude that some of the projected shifts in oceanic biogeochemistry and their impacts are rather severe. However, the current level of knowledge allows no clear answer about whether tipping points in the marine ecosphere exist.

By using 19 different global climate models, Malhi et al. (15) provide evidence that the Amazonian rainforest could also reveal characteristic properties of a TE with the tendency to change into a seasonal forest. The destructive synergies between global warming and unsustainable land-use practices are crucial in this context.

Finally, Molina et al. (16) demand "fast action" from political and economic decision makers to avoid unmanageable consequences, most notably activation of TEs, of "dangerous anthropogenic interference." They propose to strengthen the Montreal Protocol regarding substances that have high global-warming potentials. In particular, they make strong cases for an accelerated phasing out of hydrochlorofluorocarbons and a massive reduction of the emissions of black carbon (soot).

What are the analytical and political conclusions to be drawn from this body of evidence? An immediate observation is that the TE issue probably poses one of the toughest challenges for contemporary science: Practically none of the planetary cases studied can be either dismissed (by firmly ruling out a possible anthropogenic triggering of irregular dynamics) or settled (by providing relevant estimates for activation temperatures and reaction time scales). Many of the articles in this Special Feature sketch the research way forward, but it seems that we have to live with at least another decade of tantalizing ignorance concerning the most worrying potential impacts of global warming. For instance, it is disturbing that we still have no clue whether human GHG emissions can bring about a permanent El Niño regime that may suppress the Quaternary glacial quasi-cycles completely.

However, the results reported in this Special Feature confirm that the expert elicitation-assisted risk assessments by Lenton et al. (7), Smith et al. (17), and Kriegler et al. (18) deal adequately with the overall topic. Once the fog has cleared completely in some dozen years from now, one may realize that the territory in question, the true TE phase space, looks rather differently from what one imagines today. Yet the state of the scientific art as presented here resupports the views that a GMT rise beyond 2 °C might push the world into singular-change terrain and should be avoided, in line with the findings of the recent climate congress in Copenhagen (19). Whether this precautionary approach is an option at all, after two decades of failed climate protection since the 1990 Intergovernmental Panel on Climate Change Report, is more doubtful than ever. The latest study by the German Advisory Council on Global Change (20) demonstrates that even a 2-in-3 chance of holding the 2 °C line requires that the industrialized countries achieve almost-complete decarbonization by 2030 or purchase tremendous amounts of GHG permits from countries like India, Pakistan, and Ethiopia.

What are the most important scientific topics left untouched by this Special Feature on TEs? First, integrated in-depth analyses on several crucial and vulnerable ES components are still lacking, most notably appropriate assessments of the stability of GHG reservoirs in the once-permafrost areas of the Arctic and the relevant advective/convective ocean currents on the Southern Hemisphere. Second, no serious efforts have been made so far to identify and qualify the interactions between various TEs and the possibly resulting ES dynamics. In particular, the existence of self-amplifying global warming processes involving TEs needs to be addressed (and hopefully dismissed) to the best of our scientific knowledge. Third, this Special Feature was originally meant to also include "social TEs," i.e., singular anthropospheric phenomena that may be forced by (gradual or discontinuous) ecospheric changes. For example, the agro-cultures of Southeast Asia, fed by glacial meltwater and monsoon precipitation, might collapse under the regional impacts of unabated global warming. Unfortunately, the necessary scientific evidence is not yet available. Other exciting, but unexplored, dimensions of social singularity refer to the question of whether economic systems can be deliberately tipped into novel and sustainable patterns of production and consumption.

If international climate policies succeed, against all odds, in sealing an ambitious deal on the confinement of global warming to <2 °C, then the focus of TE research should actually shift to the social transformations arena: a massive acceleration of innovation processes for the decarbonization of our contemporary industrial metabolism will be the only way to deliver. In the more likely case of insufficient mitigation targets and measures, however, future TE research will rather have to predict how and when the environmental face of the Earth is going to be disfigured.

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Corrections

PERSPECTIVE

Correction for "Tipping elements in the Earth System," by Hans Joachim Schellnhuber, which appeared in issue 49, December 8, 2009, of *Proc Natl Acad Sci USA* (106:20561–20563; first published December 7, 2009; 10.1073/pnas.0911106106).

Because of a printer error, an incorrect version of this article was published in the print issue; the online version appears correctly.

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LETTER (ONLINE ONLY)

Correction for "Parameters that influence the prediction of epidemiological benefits of more-effective tuberculosis vaccines, drugs, and diagnosis," by Janakiraman Vani, Mohan S. Maddur, Sébastien Lacroix-Desmazes, Srini V. Kaveri, and Jagadeesh Bayry, which appeared in issue 46, November 17, 2009, of *Proc Natl Acad Sci USA* (106:E129; first published October 26, 2009; 10.1073/pnas.0911020106).

The authors note that on page E129, right column, first full paragraph, second line, "One of the reports suggests that >80% of current smokers or ex-smokers are positive for tuberculin skin test as compared to <3% in nonsmokers (5)" should instead appear as "One of the reports suggests that >80% of current smokers or ex-smokers are positive for tuberculin skin test and this was significantly higher than for nonsmokers (5)."

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MICROBIOLOGY

Correction for "Highly specialized microbial diversity in hyper-arid polar desert," by Stephen B. Pointing, Yuki Chan, Donnabella C. Lacap, Maggie C. Y. Lau, Joel A. Jurgens, and Roberta L. Farrell, which appeared in issue 47, November 24, 2009, of *Proc Natl Acad Sci USA* (106:19964–19969; first published October 22, 2009; 10.1073/pnas.0908274106).

The authors note that, on page 19964, left column, first paragraph, last sentence, "This desert can be viewed as nearing the cold-arid limit for life, because evidence for microbial activity in inland snow is questionable (see ref. 20)" should instead read as "This desert can be viewed as nearing the cold-arid limit for life, because evidence for microbial activity in inland snow is questionable (see ref. 64)." This error does not affect the conclusions of the article.

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BIOPHYSICS AND COMPUTATIONAL BIOLOGY

Correction for "Single molecule measurement of the 'speed limit' of DNA polymerase," by Jerrod J. Schwartz and Stephen R. Quake, which appeared in issue 48, December 1, 2009, of *Proc Natl Acad Sci USA* (106:20294–20299; first published November 11, 2009; 10.1073/pnas.0907404106).

The authors note that, due to a printer error, the legend for Fig. 4 appeared incorrectly. The second sentence, "The red curves are normalized single exponential fits given by $f = \tau^{-1}\exp(-\tau/\tau)$, where τ is the mean pause lifetime," should instead appear as "The red curves are normalized single exponential fits given by $f = \tau^{-1}\exp(-t/\tau)$, where τ is the mean pause lifetime." The figure and its corrected legend appear below.

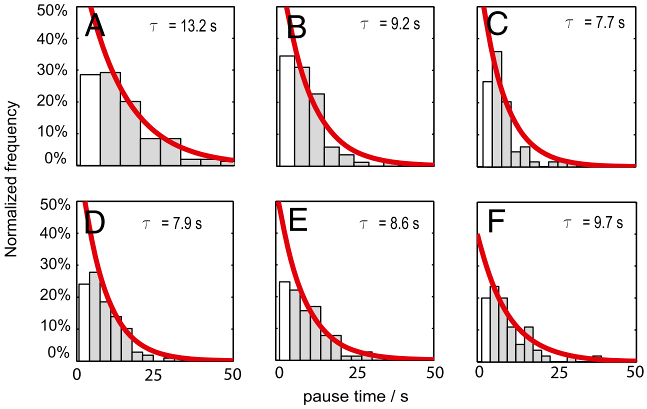

Fig. 4. Pause lifetimes for Pol I(KF) and ϕ29 were measured under different conditions for the sample and control sequences. The red curves are normalized single exponential fits given by $f = \tau^{-1}\exp(-t/\tau)$, where τ is the mean pause lifetime. Bins excluded from the fit due to undersampling are shown in white. (*A*) Pol I(KF) at 23°C with the sample template; (*B*) Pol I(KF) at 23°C with 1 M betaine with the sample template; (*C*) Pol I(KF) at 23°C with the control template, (*D*) ϕ29 at 23°C with the sample template, (*E*) ϕ29 at 23°C with 1 M betaine with the sample template, and (*F*) ϕ29 at 23°C with the control template.

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