Leibniz Gemeinschaft

Anlage zum abschließenden Sachstandsbericht
Leibniz-Wettbewerb

Domino effects in the Earth system: can Antarctica tip climate policy? (DominoES)

Antragsnummer: P90/2016

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1. Executive Summary

The DominoES project, jointly led by the Potsdam Institute for Climate Impact Research (PIK) and the Leibniz Institute for the Social Sciences (GESIS), aimed to assess whether ongoing or anticipated climate tipping may lead to tipping-like transitions in domestic and global climate policies, as well as attitudinal and behavioral changes. To pioneer studying such domino effects, we pursued a threefold strategy of (i) natural science Earth system modeling, (ii) social science data analysis, and (iii) complex dynamical systems analysis with the help of process-based simulation models.

The key objectives of the four-year project (2017–2021) were to:
(1) Assess the likelihood that the tipping of some of the known climate tipping elements may lead others to cross their critical threshold as well.
(2) Identify, assemble and analyze empirical and theoretical evidence for tipping-like behavior in climate-relevant social systems with possibly large-scale consequences.
(3) Develop a conceptual, process-based simulation model of the climate-opinion-policy tipping loop, and identify conditions for potential tipping cascades.

These key objectives were successfully worked on in three work packages (WP). The first work package (WP1) concentrated on the climate tipping interactions, with focus on the interactions of three tipping elements in particular: the Greenland Ice Sheet, Antarctic Ice Sheet and Atlantic Meridional Overturning Circulation. In this context, the hysteresis behavior of the Antarctic Ice Sheet, the overall stability of the Greenland Ice Sheet, and the complex interactions between the two ice-sheets via the ocean, as well as the atmosphere and solid earth were analyzed.

The second work package (WP2) focused on the social components of climate change and potential social tipping dynamics: Based on social theory and empirical evidence, we investigated the relations between knowledge about changes in the polar ice and climate change in general, attitudes towards climate action, and behaviors in response to (anticipated) climate impacts. We further developed a framework to identify and characterize social tipping processes critical to facilitating rapid social transformations towards climate action.

To close the loop, the third work package (WP3) developed several models to understand and simulate domino effects in the whole Earth system, including climate and social tipping dynamics: We first developed a formal framework to examine interactions of generic tipping elements on arbitrary complex networks, where the tipping dynamics are described by a paradigmatic cusp bifurcation model. In an application to the climate system, we found that the risk of domino effects generally increases with global warming, and that the interactions between Greenland, West Antarctica, the Atlantic Meridional Overturning Circulation and the Amazon rainforest tend to destabilize the network of tipping elements. These results were chosen as one of the 10 New Insights in Climate Science 2021.

In order to further understand the role of climate change concern and anticipation of climate impacts, we studied how the knowledge about projected sea-level rise in different countries affects the individual willingness to engage in collective climate action. We combined future sea-level rise estimates, survey data and a social activation model to exemplify a transformative pathway where climate change concern increases the social tipping potential, and extended anticipation time horizons shift the system towards a sustainable state of climate action. The relations between climate change, opinion formation and policy changes were constituted in a process-based simulation model which lays the foundation to investigate also other potential tipping loops in the Earth system, including its natural and social components.
More than 50 scientific papers resulted from the DominoES project, several of which published in high-ranking journals including Nature, Nat. Commun. and PNAS.

Over the project period, DominoES has grown into a community effort – starting from several expert workshops held in Cologne and online, we have engaged in various international activities and research programmes bringing together experts from the natural and social sciences and the humanities. DominoES has thus paved the way to a better understanding of tipping cascades and domino effects not only in the Earth system but also in the social sphere.

Leibniz Gemeinschaft

Final Report
Leibniz Competition

Domino effects in the Earth System: Can Antarctica tip climate policy?

Application number: P90/2016

Period under review:
01.04.2017 - 30.09.2021

Leibniz Institute in charge:
Potsdam Institute for Climate Impact Research (PIK)
and GESIS – Leibniz Institute for the Social Sciences

Project leader:
Ricarda Winkelmann (PIK) with Jonathan Donges (PIK), Christina Eder (GESIS),
Jobst Heitzig (PIK) and Alexia Katsanidou (GESIS)

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1. Achievement of objectives and milestones

The overarching aim of the DominoES project was to assess the potential for tipping cascades and domino effects in the Earth system, including its natural and social components (Fig. 1).

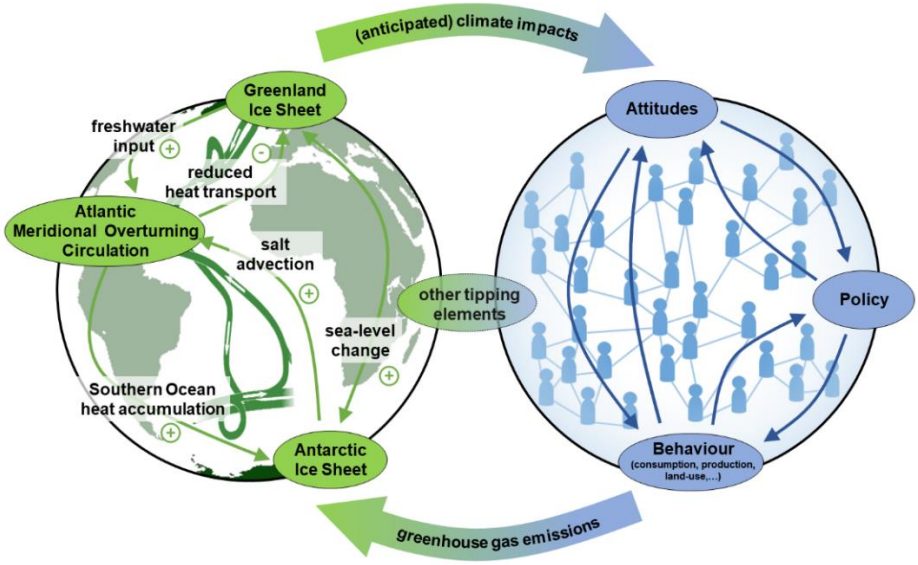

Figure 1: Domino effects in the Earth System. *Conceptual figure laying out the DominoES research agenda, with the overarching ambition of identifying and analysing tipping dynamics in the climate system and human societies [Figure R. Winkelmann, reproduced from Wiedermann / Winkelmann et al., 2019.]*

All scientific objectives within the DominoES project were successfully achieved.

WP1 – Climate tipping interactions: This work package aimed at understanding and modelling the tipping dynamics and interactions between three climate tipping elements (the Greenland and Antarctic ice sheets and the Atlantic Meridional Overturning Circulation (AMOC)), and assessing the risk of tipping cascades arising from these interactions. To this end, we investigated the underlying feedback mechanisms and critical thresholds related to the potential future decline of the ice sheets under progressing anthropogenic climate change. Since the long-term stability of the ice sheets depends on multiple factors including the surrounding atmosphere and ocean temperatures as well as sea-level changes, we worked on the two originally proposed sub-work packages within WP1 in union (using the open-source model *PISM*), which was possible not least due to the very fruitful collaboration among the project members. The deliverables for WP1 comprised at least two peer-reviewed articles in Earth system science journals – in the end, this work package resulted in 8 papers in Earth system science journals, *Nature*, *Nature Communications* and *PNAS*.

WP2 – Social tipping: This work package focused on the social components of climate change and potential tipping dynamics, in particular changes in public opinion, individual attitudes and climate-relevant behaviours as well as policies. To this end, we conducted a study on knowledge, concerns and behaviours towards polar ice loss in Germany which we built on novel data collected via the GESIS Panel and published in *Polar Geography*. Using the European Social Survey, we performed a comparative analysis of domestic energy policies and individual policy preferences in Europe that was published in *International Political Science Review*. Since the first expert workshop in 2018 was a major success, we applied for additional funding from the Leibniz-Forschungsverbund 'Krisen einer globalisierten Welt' and held a follow-up workshop in Cologne in 2019. A third workshop was held online in December 2020. This work package resulted in more than 10 published papers in high-ranking journals, well surpassing the deliverable target of 2 papers.

WP3 – Domino effects: This work package aimed at developing a general theory of tipping element interactions and a process-based simulation model of a climate → opinion → policy tipping loop. To this end, we developed a formal framework to study interactions of generic tipping elements (*PyCascades*). We further developed a taxonomy of processes and a flexible modelling framework to study tipping loops (*copan:CORE*). We then performed several model studies on a particular causal chain leading from anticipated sea-level rise and observed

extreme events via social network-facilitated activation towards reaching majority support for climate policy. This overarching work package resulted in more than 20 published papers in high-ranking journals, well surpassing the deliverable target of 2 papers.

2. Activities and obstacles

Work Package 1: Climate tipping interactions

Tipping dynamics of the Greenland Ice Sheet: In analysing the overall stability of the Greenland Ice Sheet, we investigated several positive (amplifying) and negative (dampening) feedback mechanisms and their interactions. Using the well-established Parallel Ice Sheet Model (PISM) and a newly developed diurnal Energy Balance Model for the surface mass balance, we analysed the impact of the melt–albedo feedback on the future evolution of the Greenland Ice Sheet. The related study (Zeitz et al., 2021) was chosen as a *highlight article in The Cryosphere*. We further showed how the positive-negative feedback loop due to the interacting melt-elevation and glacial isostatic adjustment feedbacks can lead to different dynamic regimes, determining the long-term stability of Greenland (Zeitz et al., under review).

Tipping dynamics of the Antarctic Ice Sheet: In a study published in *Nature*, we completed a first full-scale analysis of potential warming thresholds for irreversible ice loss and the hysteresis behaviour of the Antarctic Ice Sheet across all temperature scales (Garbe et al., 2020). We found that each ice-sheet basin displays its own characteristic warming threshold beyond which the interaction with the surrounding ocean waters and / or changing atmospheric boundary conditions can lead to widespread ice loss (Winkelmann et al., forthcoming). In certain regions this can be strongly accelerated due to changes induced by melting from the Greenland Ice Sheet and subsequent sea-level rise and changes in ocean temperature.

Tipping interactions: Furthermore, we developed a network model of four interacting key tipping elements (Greenland and West Antarctic Ice Sheet, AMOC, Amazon rainforest), which is designed to assess the risk of potentially dangerous tipping events and cascades under global warming. We found that the processes linking the tipping elements tend to destabilize the climate system. Furthermore, we were able to show that in potential tipping cascades, the polar ice sheets would often act as initiators, while the AMOC would rather act as a mediator transmitting cascades. The related study (Wunderling et al., 2021a) published in *Earth System Dynamics*, has been chosen as one of the *10 New Insights in Climate Science 2021*.

Work Package 2: Social tipping

Abrupt changes in opinions & policy due to actual and anticipated climate change (WP2.1): To study opinion and policy changes linked to climate change, we first collected original survey data to better understand the relation between knowledge of polar ice, attitudes towards polar ice loss, and behavioural changes in Germany using the GESIS Panel as well as data on climate risk perceptions in the USA. This data was employed in a paper in *Polar Geography* (Smith et al., 2020), as well as a team-authored piece on the wanted social tipping points (Smith, Eder et al., in prep.). We made further contributions to the field of climate change attitudes and behaviours, understanding the role of risk perceptions and different forms of trust (Smith and Mayer, 2018a), the differing effect of political factors in English speaking, Western European and Eastern European states (Smith and Mayer, 2018b), how climate fatalistic views can inhibit individual climate change actions (Mayer and Smith, 2019), and the role of special political interest groups (such as evangelical Christians) in climate change attitudes and behaviours (Smith et al, 2018: Hempel and Smith 2019). Current research projects look at the asymmetric polarization of political factors over the past four decades in the US (Smith et al., under review), the interactive role of values and politics shaping climate change attitudes and behaviours in Western European States (Smith and Hempel, accepted) as well as on public attitudes on energy policies in Europe (Stadelmann-Steffen and Eder, 2020,).

Inventory of climate-relevant social tipping elements (WP2.2): We organized three DominoES workshops, collaborating with over 20 well-renowned experts to (1) understand how social tipping dynamics are related, but distinct from, the more established climate tipping

dynamics (June 2018, Cologne), (2) create an inventory of archetypical tipping clusters (June 2019, Cologne), and (3) assess the role of criticality in social tipping processes (December 2020, online). Resulting from these workshops, we have collaborated with the participants to develop several papers: one of the core DominoES papers presents an agenda-setting framework for the definition and identification of social tipping dynamics towards climate action (Winkelmann, Donges, Smith, Milkoreit et al., 2022). Further, we are currently developing a paper systematically characterizing five clusters of social processes – financial and other markets, energy and technical infrastructures, demographics, political systems, and practices and dispositions. Lastly, we worked together with a group of political scientists from the first DominoES workshop to introduce a social tipping dynamics framework employing the case of the chlorofluorocarbons phase out (Stadelmann-Steffen, et al., 2021).

Work Package 3: Domino effects

Towards a general theory of tipping element interactions (WP3.1): In order to gain a better general understanding of tipping element interactions, we have developed a formal framework to study interactions of generic tipping elements (described by a paradigmatic cusp bifurcation model) on arbitrary complex networks (Krönke et al., 2020). Our results show that certain small-scale network motifs foster global tipping cascades (Wunderling, Stumpf et al., 2020), which allows us to assess the vulnerability and resilience of a given system as a consequence of the underlying network topology. Under certain circumstances, the dynamics of a large network of tipping elements can be condensed into a single aggregated tipping element (Kohler et al., 2021). Based on these studies, we have developed the open-source model *PyCascades* (Wunderling et al., 2021b), which allows us to simulate generic networks of interacting tipping elements. Based on this approach, we investigated in detail the emergent dynamics of two coupled tipping elements and were able show that such systems may tip into new states even before the individual tipping points of the isolated subsystems are crossed (Klose et al., 2020). We further outlined the effectiveness of temporal early warning signals for different types of tipping cascades (Klose et al., 2021). Based on these insights and the work in WP1, we applied the newly-developed framework and model to study interactions in a network of climate tipping elements to assess the risk of domino effects and global tipping cascades in the physical Earth system with respect to the interaction strength and certain levels of global warming (Wunderling et al., 2021a; Wunderling et al., 2020b).

Process-based simulation model of a climate → opinion → policy tipping loop (WP3.2): We consolidated our understanding of interactions between natural and social tipping dynamics (Smith, Eder et al., in prep.) and developed a blueprint for a coupled model of key processes in both spheres (see Fig. 1). To this end, we conceptualized social tipping processes with an extended version of Granovetter's threshold model incorporating individual attitudes/opinions and resulting tipping in collective behaviour via social influence and network effects (Wiedermann et al., 2020). We recently expanded this model to an empirical cross-national analysis, adopting country-level survey data and projections of future sea-level rise to illustrate different clusters of tipping potential across 81 countries (Wiedermann, Smith et al., under review). As a further extension, we studied the influence of the geographic network structure and cross-border effects by replacing the macro-approximation of network effects by a micro-simulation of activation on a realistic spatially resolved global social network, and the interaction between anticipated sea-level-rise based activation on the coasts and observed extreme events based activation further inlands (master thesis Dunker 2021, publication in preparation). To facilitate the unification and flexible combination of such model components, we also completed a theoretical and software framework for World-Earth modelling (Donges et al. 2021, Donges/Heitzig et al. 2020).

Obstacles related to the project work

The COVID-19 pandemic and its consequences, such as reduced ability to travel and additional organizational workload, slightly delayed publication processes in the final stage of the project. While all project members actively took part in and organized several workshops and conferences online (see Appendix), the circumstances made it difficult especially for the

early-career scientists to fully engage in the international network. The GESIS project team further had to compensate for times of parental leave by Alexia Katsanidou (8/2017-5/2018, and 12/2020-07/2021) and Keith Smith (01/2019 – 04/2019). These times of absence resulted in some delays in publication processes over the course of the project. Furthermore, Marc Wiedermann's working hours were reduced by 20% from July 2019 onwards, and unused travel funds were re-allocated to extend his contract in a cost-neutral manner for the period from 04/2020 to 01/2021.

3. Results and successes

With more than 50 peer-reviewed publications, 16 completed theses and dissertations, the organization of several high-level workshops and conferences and engagement in further initiatives, the DominoES project was overall highly successful. Many of the published research results were also picked up by the media, including interviews for instance in the Guardian, SPIEGEL, ZEIT, Science News, Forbes, NYT and others. Most importantly, the project has sparked the formation of a very active international community of scholars (including many early-career scientists) working on related topics on climate and social tipping. Detailed information on the scientific results, a full list of publications, conferences and workshops as well as an overview of completed theses and dissertations can be found in the appendix.

4. Equal opportunities

Achieving equal opportunities within and around the team was a key objective of the DominoES project. That applies to gender balance within the project, the recruitment process and the promotion of women, young academics, and international researchers in the form of special support programs. With 5 female and 5 male project members, we were able to achieve gender balance within the project. For the open positions to be filled, promoting equal opportunities and qualified women in science was one of the staff selection criteria. As Leibniz Institutes, GESIS and PIK comply with the respective rules and regulations given by the Leibniz Association, the DFG, and the Joint Sciences Conference. These include active recruitment of women for leading positions, individual support options, transparent and plannable career options, equal opportunities for part-time employees as well as support with respect to work-life-balance. Since 2010, GESIS holds the certificate 'work and family' of the Hertie Foundation and is thus one of the pioneers among non-university Research and Service Institutions. PIK was awarded the Total-E-Quality and Diversity award in 2010, 2013, 2016, and 2019.

The DominoES project became an important stepping stone for our female as well as male PIs: Lead-PI Ricarda Winkelmann and PI Alexia Katsanidou were promoted to full professor during the project period. Ricarda Winkelmann also became lead of the Earth Commission WG1 on Earth and Human Systems Modelling, and Alexia Katsanidou was promoted to Head of department at GESIS. Christina Eder became Co-Team lead. Ricarda Winkelmann, Jonathan Donges and Jobst Heitzig were named FutureLab and Working Group leads at PIK. Keith Smith accepted a position as senior researcher at ETH Zurich.

5. Structures and collaboration

Structure of internal collaborations: The work within the project was organized through regular meetings. Early-on, we established a weekly "DominoES lunch" at PIK with all project members and associated members which offered time for exchange about the project work. Pre-pandemic, the entire team met three to four times each year in either Cologne or Potsdam. As part of the project, we engaged in two novel survey data collection projects (online), both studying respondents from the United States context. The first survey (2020) identified different patterns of participation in climate change collective actions during times of the COVID-19 pandemic, and the second survey (2021) focuses on socio-political barriers and mechanisms of climate change attitudes and behaviours.

External collaborations: Over the period of the project, we established a growing network of collaborations within the Leibniz Association and with other German and international research institutions. The initial DominoES workshop in Cologne in 2018 was the starting point for a

number of activities resulting in community publication projects. Based on this very successful first workshop, we were able to acquire funding for two additional workshops (Cologne/2019; Bad Belzig/2021). A fourth workshop was held online in 2020. The DominoES team led three community papers – one presenting a conceptual framework for social tipping towards climate action (Winkelmann, Donges, Smith, Milkoreit et al., 2021); one characterizing social tipping clusters (Smith, Eder et al., in prep.); and one on criticality in social tipping dynamics (Smith, Donges et al., in prep.), bringing together scientists from different disciplinary backgrounds, ranging from mathematicians to ecologists to political economists and social scientists. Results from the DominoES project have also entered larger international scientific initiatives such as the Earth Commission, the Earth Resilience and Sustainability Initiative and Future Earth-AIMES.

6. Quality assurance

Already prior to the beginning of the project, a Scientific Advisory Board (SAB) was established to ensure the quality of our work, give advice and supervise the activities and progress, with renowned scientists Michael Ghil (UCLA), Timothy Lenton (U Exeter), J. Doyne Farmer (U Oxford), and Isabelle Stadelmann-Steffen (U Bern). The project team and SAB met in Cologne in 2018 for the first time, and during the following DominoES workshops. We also provided regular updates including a report to the SAB, who provided invaluable support and advice.

We presented our ideas and findings at scientific conferences and exchanged ideas with other researchers. Both PIK and GESIS used their expertise in the field of research data management to facilitate model validation. We aimed at publishing our research in gold standard open access journals. Model codes and scripts for data analysis have been published as open source software with detailed documentation on public repositories such as *GitHub*, *PyPI*, and *Zenodo* (including our main models *PyCascades*, *PISM* and *copan:CORE*).

7. Additional in-kind resources

The principal investigators at PIK and GESIS made several in-kind contributions, including the project management, publications, supervision of doctoral, Master and Bachelor students, working meetings, and the conception and organization of workshops and conferences. These contributions amount to about 30% work-force each by Ricarda Winkelmann and Jonathan Donges, and 20% by Jobst Heitzig at PIK, as well as 20% by Christina Eder and Alexia Katsanidou at GESIS. The project also profited from considerable contributions by several bachelor and master students not funded by the project. For the numerical simulations, especially in WPs 1 and 3, the PIK high-performance computer cluster was used during the entire project duration, supported by *the European Regional Development Fund (ERDF), the German Federal Ministry of Education and Research, and the federal state of Brandenburg*. In addition, we were able to include some items into Wave ED of the 2017 GESIS Panel to address the knowledge, concern, and willingness to make behavioural changes as a response to polar ice loss amongst German citizens. The data collection is fully funded by GESIS.

8. Outlook

With the completion of the DominoES project, the foundation is laid for further research and collaborations on tipping cascades, domino effects and resilience in the Earth system: together with colleagues from several different research institutions, the DominoES team is currently working on two community papers, characterizing social tipping clusters (Smith, Eder et al., in prep.) and identifying processes that make the system more prone to social tipping (Smith, Donges et al., in prep.). The project has further sparked the formation of several research initiatives and collaborations on the theoretical understanding, empirical work and modelling of domino effects, including social tipping for positive change. Based on our understanding of tipping dynamics and potential tipping cascades both in and between the natural and social spheres, we can now address the question which sensitive intervention points and amplification mechanisms within the social system might lead to rapid transformation towards a more sustainable future.