Interacting tipping elements increase risk of climate domino effects (Display D2308)

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Further displays on conceptualized tipping elements at EGU:
- Klose AK, Karle V, Winkelmann R, Donges JF: Display D 2300
- Donges JF, Wunderling N, Kurths J, Winkelmann R: Display D 2254

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Methods and Background

Conceptual tipping elements:
Each node represents a tipping element consisting of a non-linear differential equation with two stable states (individual dynamics term) linked via a saddle-node bifurcation. The tipping elements are coupled to others via linear couplings (coupling term)

\[
\frac{dx_i}{dt} = -4(x_i - 0.5)^3 + (x_i - 0.5) + c_i + d \sum_{j \neq i} a_{ij}x_j
\]

- \( x_i \) = state of tipping element
- \( c_i \) = critical value
- \( d \) = coupling strength
- \( a_{ij} = 1 \) if connection between nodes exists, 0 otherwise

Fig. 1: Bifurcation diagram of one paradigmatic tipping element (a). The tipping element has a bistable regime. As soon as the critical parameter \( c \) of a certain tipping element surpasses a certain value \( c_{\text{crit, high}} \), the respective tipping element transgresses into the tipped state. (b) Network of connected tipping elements that are linearly coupled. Since the tipping elements are interacting, the network structure can be decisive for the emergence of tipping cascades (see structures of vulnerability).

For more details: Krönke et al., 2020, PRE (accepted) "Dynamics of Tipping cascades on Complex Networks"
Structures of Vulnerability: Network motifs

Fig. 2:

a) Dynamics of each node in the network, b-e) Micro structures (Motifs) within a larger network of tipping elements enhance its vulnerability.

Fig. 2:
The effect of the coupling strength on the proportion of networks that show any cascading effect shown for an Erdős-Rényi network of 100 nodes and an average degree of three (panel f) and four (panel g). Tipping cascades due to feed forward loops (dark red), weak motifs (orange) and due to no motifs (red line).

- Local interaction structures (Motifs) are responsible for the emergence of global cascades and the stability of the network as a whole (Linking Micro to Macro)
Motifs in the moisture recycling network of the Amazon rainforest

Fig. 3: Number of motifs that point to a certain location in the 2x2 degree grid. Regions in the North, close to the Andes and in the South-East show an increased number of motifs. These are the regions where a decreased robustness due to tipping cascades can be expected. a) Feed forward loop, b) Zero loop, c) Neighboring loop, d) Secondary feed forward loop.

Take-home
1. Motifs can explain Micro behavior and emergence of global cascades in the network.
2. Motifs in the Amazon rainforest show spatial coherence of moisture-recycling network and might hint at increased vulnerability at these locations.

Example 2: Climate tipping cascades

More details: Wunderling, Stumpf et al., 2020, Chaos “How motifs condition critical thresholds …”

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FutureLab: Earth Resilience in the Anthropocene
Tipping cascades in the Earth system

For details: Wunderling et al., ESD disc. (in review)

"Interacting tipping elements increase risk of climate domino effects under global warming"
Tipping cascades in the Earth system

Methods (see paper for details)

$$\frac{dx_i}{dt} = -x_i^{3} + x_i + \frac{\sqrt{4/27}}{T_{\text{limit},i}}\Delta GMT + \frac{d}{10}\sum_{j \neq i} s_{ij}(x_j + 1) \frac{1}{\tau_i}$$

$$\Delta GMT = \text{Increase of global mean temperature}$$
$$T_{\text{limit},i} = \text{Critical temperature}$$
$$d = \text{Interaction strength}$$
$$s_{ij} = \text{Link weight}$$
$$\tau_i = \text{Typical tipping time}$$

Simulations

- Large scale Monte Carlo simulation (1.1 mio. ensemble members)
- All results are results from equilibrium simulations

Limitations

- Set of tipping elements and their interactions (strength) uncertain
- Conceptualised nature of tipping elements
- The role of ENSO

Merits

- Estimating tipping cascades in the Earth system consistently based on expert elicitation (Kriegler et al., PNAS, 2009)
- Large scale Monte Carlo ensemble propagates all uncertainties (for details see paper)
- Comprehensive Earth system models cannot yet adequately represent all tipping elements and their interactions

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Fig. 5: Shift of critical temperatures due to normalised interaction strength. (a) Critical temperatures as taken from the literature (Schellnhuber et al., NCC, 2016). (b) Critical temperatures for the polar tipping elements. (c) Critical temperatures for the equatorial tipping elements. The standard deviations are shown in shaded colours.

In general the temperature at which a critical transition occurs goes down with increasing interaction strength. For Greenland this is the other way round due to the strong negative feedback loop between Greenland and the AMOC.
Thank you!

Please comment and ask questions 😊

Sources


