Network analysis

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Connected climate tipping elements

Valerie N. Livina

Tipping elements are regions that are vulnerable to climate change and capable of sudden drastic changes. Now research establishes long-distance linkages between tipping elements, with the network analysis offering insights into their interactions on a global scale.

It is not uncommon in science for novel ideas to undergo several stages of development in different areas, which at first do not seem obviously related. When Henri Poincaré was developing the bifurcation theory, he would not think of climate tipping points as one of the possible applications[1]. Yet tipping elements in the climate system are currently an important topic of interest in climatology, and how they interact is an ongoing discussion, with an increasing number of applications of mathematical bifurcation theory. Writing in *Nature Climate Change*, Teng Liu and colleagues[2] apply complex network analysis to tipping elements, a new approach in climatology, and discover non-trivial spatial dependencies on the global scale, thus identifying vulnerable interlinked areas under climate change.

Nowadays, climatologists are well familiar with the Hopf bifurcation (or rather, Poincaré–Andronov–Hopf bifurcation) observed in climatic variables. In the 1960s–1970s, an intuitive idea of a bifurcation appeared in social sciences as the term 'tipping point', mentioned by many sociologists, such as Everett Rogers, Morton Grodzins, Thomas Schelling and others. Their understanding of tipping was in the context of adding a small amount of something to a balanced system until it suddenly topples, or tips. Bearing in mind that they were talking about spread of innovations in a social system, at that time there were no analytical models to link the idea of social tipping with the mathematical works of Poincaré.

Malcolm Gladwell went further with developing this trend in his bestselling book *The Tipping Point: How Little Things Can Make a Big Difference*[3]: he expanded the approach to biophysical systems (for example, to the spread of sexually transmitted diseases), but he still used the language of social science to formulate "the three rules of the Tipping Point: the Law of the Few, the Stickiness Factor, the Power of Context".

But it was not long before the idea of tipping was brought back to natural sciences: in 2008, Lenton et al. published the seminal paper on tipping points in the Earth system[4], in which the main tipping elements — vulnerable regions and subsystems of the climate system — were identified and described. This work gave an onset to multiple publications in geophysics and palaeoclimate, focussing on early warning signals of tipping points. These papers aimed to develop mathematical techniques that would allow one to detect and quantify upcoming transitions and/or bifurcations in a time series of a climatic variable that is the signature for a tipping element (bifurcations differ from transitions in terms of the structure of the system potential[5]).

Many early warning signal (or critical slowing down[6]) indicators are based on temporal scaling (autocorrelations[7]) in time series that can be quantified using scaling exponents[8]. Interestingly, stochastic models with a Hopf bifurcation are used for developing early warning indicators of tipping, and this brings back the connection with the classical bifurcation theory developed more than a century ago.

The next stage of development of tipping points in climatology was to look at spatial early warning signals within the area of interest[9]. From the initial understanding of a single tipping in one recorded variable, research efforts moved to studying interdependencies of tipping points and their possible cascades[10], in which tipping points could trigger each other. Still, this was expected to be observed in adjacent tipping elements with obvious dependencies.

The study by Liu and colleagues applies the advanced network analysis to establish long-distance connections (teleconnections) across the globe. The tipping elements considered are the Amazon Rainforest area, the Tibetan Plateau and the West Antarctic Ice Sheet, and the research has identified strong correlations across long distances between these regions. This is the first time that the theory of complex networks has been applied in the context of tipping points, and the synergy of the two research areas provides an important insight into the global climate dynamics. This work opens a new area of tipping point analysis at a global scale.

In particular, Liu and colleagues have established the propagation pathway between the Amazon Rainforest area and the West Antarctic Ice Sheet, and this teleconnection is across almost 10,000 km. The authors explain the path by the steady and strong ocean currents and westerly winds near the West Antarctic area, with transportation of dust and carbonaceous aerosols causing the teleconnection. The network methodology for tipping elements will help detect various teleconnections, which will then be analysed by climatologists to uncover linkage mechanisms, thus providing exemplary synergy of disciplines.

Recent developments in space-based Earth observations provide rich data for such studies, and it has become possible to analyse large surface regions using reanalysis data. Modelled data (Coupled Model Intercomparison Projects) and reanalysis data, which combine satellite and in-situ observations into global estimates using advanced modelling and data assimilation systems, make it possible to systematically study global climatic processes. By combining tipping point analysis and abundant real data, it is possible to conduct global studies in the context of climate change. Liu and colleagues establish a new direction of research, which promises high-impact applications in geophysics.

The IPCC recognizes the growing importance of understanding tipping points and is planning a Special Report on 'Climate Tipping Points and their Implications for Habitability and Resources', which will be prepared in the framework of the IPCC's Seventh Assessment Cycle, scheduled to start in 2023. Hopefully, the forthcoming report will address the teleconnections between tipping elements and analyse the mechanisms of their dynamic linkages.

Valerie N. Livina
Data Science Department, National Physical Laboratory, Teddington, UK.
e-mail: valerie.livina@npl.co.uk

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Competing interests

The author declares no competing interests.