"When does an ice age end?"

In a new study published in Nature, scientists provide a surprisingly simple rule that predicts when, during the last 2.6 million years, Earth's climate warmed out of an ice age.

During this period, known as the Quaternary, Earth has alternated between cold and warm periods. In the cold times, ice sheets advanced over large parts of North America and northern Europe. In the warm periods like today, known as interglacials, the ice sheets retreated completely. It has long been realised that this alternation was paced by astronomical changes in the Earth's orbit around the Sun and in the tilt of its axis, which change the amount of solar energy reaching high northern latitudes in summer that is needed to melt ice. However, of the 110 incoming solar energy peaks (about every 21,000 years, when the Earth is closest to the Sun during northern summers) only 50 led to complete melting of the ice sheets. Finding a way to translate the astronomical changes into the exact sequence of interglacials has proved elusive.

Now, researchers from University College London, University of Cambridge (UK) and Université catholique de Louvain at Louvain-la-Neuve (Belgium) have put together some existing ideas to solve the problem. The basic idea is that there is a threshold for the amount of energy reaching high northern latitudes in summer. "Above that threshold, the ice retreats completely and we enter an interglacial", said Chronis Tzedakis of University College London. In the first half of the Quaternary, the threshold was reached roughly every 41,000 years, and this predicts almost perfectly when interglacials started and the ice sheets disappeared. "Simply put, every second solar energy peak occurs when the Earth's axis is more inclined, boosting the total energy at high latitudes above the threshold" says Eric Wolff from the University of Cambridge.

Somewhere around a million years ago, the threshold rose, so that the ice sheets kept growing for longer than 41,000 years. However, paradoxically, as the waiting time since the previous interglacial increased, the growing ice sheets became more unstable, lowering the threshold again. Combining these observations into a simple rule, it becomes possible to predict all the interglacial onsets of the last million years, occurring roughly every 100,000 years, as well. "Once we account for the effect of the waiting time, the data beautifully show the threshold shift" said Takahito Mitsui of the Université catholique de Louvain. The next step is to understand why the energy threshold rose a million years ago. "One idea is that this was due to a change in the concentration of CO_2, and this needs to be tested", said Eric Wolff.

The results explain why we have been in a warm period for 11,000 years: despite the weak increase in solar energy 11,000 years ago, ice sheets retreated completely during our current interglacial because of the very long waiting time since the previous interglacial (more than 100,000 years) and the accumulated instability of ice sheets. Intriguingly, the researchers found that sometimes the amount of energy was very close to the threshold, so that some interglacials were just aborted, while others just made it. "But the threshold was only just missed 50,000 years ago. If it hadn't been missed, then we wouldn't have had an interglacial in the last 11,000 years" said Michel Crucifix, also from the Université catholique de Louvain.

However, the analysis shows that the succession of interglacials is not chaotic: the sequence that has occurred is one among a very small set of possibilities. "Finding order among what can look like unpredictable swings in climate is aesthetically rather pleasing" said Tzedakis.

The research is published as "A simple rule to determine which insolation cycles lead to interglacials" by P.C Tzedakis, M. Crucifix, T. Mitsui and E.W. Wolff, *Nature* doi: 10.1038/nature21364 (2017).