"In June 2017, a giant iceberg the size of Delaware broke off the Larsen C Ice Shelf in West Antarctica, creating an 80 mile long crack in the ice. How do relatively small shifts, rifts and changes lead to a long lasting effect on our planet's climate?"

Chaos, Gaia, and the Winds of Change

Linearity predominates human interpretation. Everyday interactions appear to conform to this notion, from physical to mental exertion: the input of a process correlates to its output. Even in more quantitative fields, such as mathematical modelling, it is often assumed knowledge of approximate initial conditions will yield approximate results. But linearity is not ubiquitous: not all small deviations yield small variations. Within complex dynamical systems non-linearity dominates, and a sensitivity to initial conditions is inherent: minute changes can have colossal results. Therefore, it would seem obvious to extend this principle to a more complex system such as Earth's climate. If a simple system demonstrates sensitivity to initial conditions, there seems no reason a complex dynamical system should not exhibit a non-linear reaction to change, allowing small changes to have significant effects. To a certain extent this is correct, when studying weather, meteorological predictions struggle to predict short term forecasts, and any specific predictions over a month into the future have little credence as it impossible to consider how seemingly negligible perturbations to the system will affect it. However, though apparent that the climate does show highly complex and often unpredictable behaviour, there seems to be some global tolerance and predictability to greater change: human intervention, though often devastating in its impact on individual environments has not caused immediate worldwide catastrophe. The global climate has not fluctuated wildly or chaotically in response to changes such as increased carbon emissions. Instead a response has resulted that appears to fit a more linear understanding of the world. Even over geological time periods the Earth's climate has maintained some degree of constancy despite changes both large and small to inputs such as solar radiation. Therefore, though small changes to environments can cause large enduring effects due to the complex dynamical systems involved, on a global scale these effects appear to be mitigated as the Earth acts much like an equilibrium, with living mechanisms comparable to homeostasis, acting against change whether great or small. However, as these mechanisms become hindered or overwhelmed by change so does the planet's capacity to protect its life-sustaining environment, and sustain its sensitive 'Goldilocks' conditions; if these conditions changed drastically they would dramatically change the climate, as many components of the climate system are fragile, and sensitive to change.

The idea of chaos, or sensitivity to initial conditions, has been considered indirectly throughout history, but it first came to fruition as theory through the work of Edward Lorenz: Lorenz's computerised meteorological simulation, based on several partial differential equations, explicitly exhibited the chaotic behaviour of weather, and identified the mathematical complexities of climate. A further paper entitled 'Predictability: Does the Flap of a Butterfly's Wings in Brazil Set Off a Tornado in Texas?' suggested how small events may result in large effects, not due to direct causation, but by changing the parameters of a chaotic system. This idea considers how changes to a system may propagate far beyond the scale of that which initiated the change to any initial conditions. A paradigm of this concept is the double-pendulum, a mechanism of two connected pendulums, as small deviations to the angle of release will cause significant non-linear variation to its trajectory; the double-pendulum is considered a personification of chaos theory. Chaos has far reaching implications within Earth's biosphere: the logistic difference equation, created by Robert May, accurately models animal populations by considering the impact of this theory. The deceptively simple iterative sequence of $X_{n+1} = rX_n(1 - X_n)$, where r is a constant, contains deep mathematical and biological complexity. Small changes to the initial values could send a modelled species to mathematical fruition or extinction. Similar chaotic complexity inhabits the majority of climate controlling biotic and abiotic processes on Earth, from the turbulence controlling ocean currents to gravitational interactions between Earth and other celestial bodies. It is therefore evident that small effects can cause large and enduring changes to Earth. However, though the prevalence of chaos is apparent in nature, it does not appear to be the predominant mechanism by which the planet's climate adapts to change. Though local climates have varied significantly, global changes have been slow and to a certain degree predictable, a far cry from the pseudo-random erraticism of chaos.

The large scale processes of the Earth's climate seem far less sensitive to initial conditions than might be considered reasonable, despite the underlying chaotic systems: this can perhaps be attributed to the feedback between interplaying systems, and the equilibrium which can be established. A simple demonstration of this balancing act was created by James Lovelock in his 'Daisyworld' simulation. A theoretical planet, that is modelled to increase in temperature over time, contains only two species, white and black daisies, with the former proliferating in warmer conditions, and the latter the opposite. The planet begins as a cold world with few daisies able to survive, with the black ones predominating. When the planet increases in temperature white daisies increase in population, however, due to their white colour, this increases the albedo, the ability to reflect incident radiation, of the planet decreasing radiation absorbed, and hence its temperature. Black daisies have the reverse effect. Due to these negative feedback processes the planet will reach an equilibrium temperature, maintained by the two populations. This temperature differs from the same modelled planet without daisies. Any disturbance to the number of either variety of daisies will cause a short-term disturbance, but ultimately small changes will be buffered by the equilibrium in place. Similar analogies can be observed in chemistry, through buffer solutions. The role of feedback loops can be observed throughout climate history, with perhaps the most similar real mechanism to 'Daisyworld' being the process of global cooling as seen in an ice age: a variety of positive and negative feedback loops combined to find an equilibrium state, by primarily manipulating the Earth's albedo. Lovelock even goes beyond this simple simulation with his 'Gaia' theory, suggesting how the Earth may be compared to a living organism, with various regulatory systems in place to prevent change to the climatic conditions which permitted life. Such a theory would go some way to explain the perceived discontinuity between relatively stable climate systems, such as atmospheric composition, compared with their chaotic beginnings. However, this concept is not in contradiction to the possibility of small changes propagating to cause large results, but simply suggests that the Earth attempts to minimise any change: in many ways this concept is intuitive, an increase in carbon dioxide levels might cause a resultant increase in plant life, to absorb the excess gas. Though the position of an equilibrium may be moved there will still be effects countering, and balancing each other;

miniscule changes might still affect this balance, but it would not destroy the process, simply change the conditions.

Yet despite the relative strength of the ‘Gaia’ effect in countering significant change, once this last defence is broken the underlying climate controls appear fragile. Contributing systems of various gaseous cycles whether animal, vegetable, or mineral have inherent, or have adapted to have a small and specific range of conditions which they can survive and flourish in, and so disruption of any form to these conditions will affect their ability to exist; this causes direct change to the climate system which these individual elements control. If conditions, such as temperature, went outside the range of viability for many living organism a knock-on effect would ensue as further change propagates and causes disturbance of further systems in balance. Critical change to a system like the carbon cycle, by action such as deforestation, has far reaching consequences, as changes beyond a certain threshold go beyond any system’s tolerance to change. Even abiotic processes such as hurricane formation are equally sensitive to conditions, as a net increase in global temperature could increase their frequency and ferocity due to additional energy available; this deviation from standard climatic conditions would have further repercussions. Therefore, it is imperative for climatic conditions to stay within a limit, as change of a certain magnitude has the potential to causes large and unforeseen results due to the fragile balance of systems.

What has been observed of the planetary climate system is that the often non-linear systems which drive individual components of a climate, interact to form feedback loops, creating various equilibria, and causing apparent order from chaos. However, when these equilibria become overwhelmed, new dynamics come into play, creating new equilibria and new climatic conditions. Therefore, small change can propagate within an individual system, but to propagate to a global scale it must significantly distort the mechanism it would normally be contained by, such that it overcomes the bounds of feedback loops and establishes real change. Therefore it would appear there is some critical level of change, after which the climate can change dramatically, as the controls in place fail. Therefore seemingly small variations can cause long-lasting effects, provided any change meets certain criteria, such that the complex balance of systems in play are sufficiently compromised.

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