For Want of an Iceberg

RCSU Science Challenge Prof. Lord Oxburgh’s Question

It is often the case that transformations of our physical world can be traced back to a single instant in time. In much the same way as the mighty echoes of tsunami waves across the oceans may be triggered by a momentary shudder of the Earth’s crust, the soft rolling of a boulder down a mountainside may not have happened but for a single, sharp gust of wind. In such instants a tiny nudge, well-timed and well-placed, shoves an equilibrium of forces long-held in balance into disarray – potential energies become kinetic, and a chain of events unfolds that leaves a lasting impact.

One such instant took place in 2010, on a day like any other on the Antarctic Peninsula, when a crack suddenly formed in the Larsen C ice shelf. Over the next 7 years, this small crack would race 80 miles across the shelf, jerk by jerk, widening and lengthening until June 2017, when off into the ocean broke a chunk of ice weighing one trillion tonnes [1]. It may be said that such calving of icebergs (and the rise of sea level they contribute to) is an inevitable consequence of both natural and anthropogenic heating of the Antarctic surface and waters [2]. Yet studying such large-scale, long-term processes – global warming, plate tectonics, erosion, etc. – only gives us half of the picture, for the make up of our world is ultimately the legacy of innumerable tiny shifts, rifts, and changes. At the heart of understanding how these two scales connect are three phenomena we will discuss here – chaos, wherein tiny changes can knock a system’s evolution far off course, positive feedback, which allows small perturbations to grow exponentially, and the Law of Unintended Consequences, under which the response of a complex system to a change is different or even opposite to that anticipated.

Change One Thing, Change Everything*

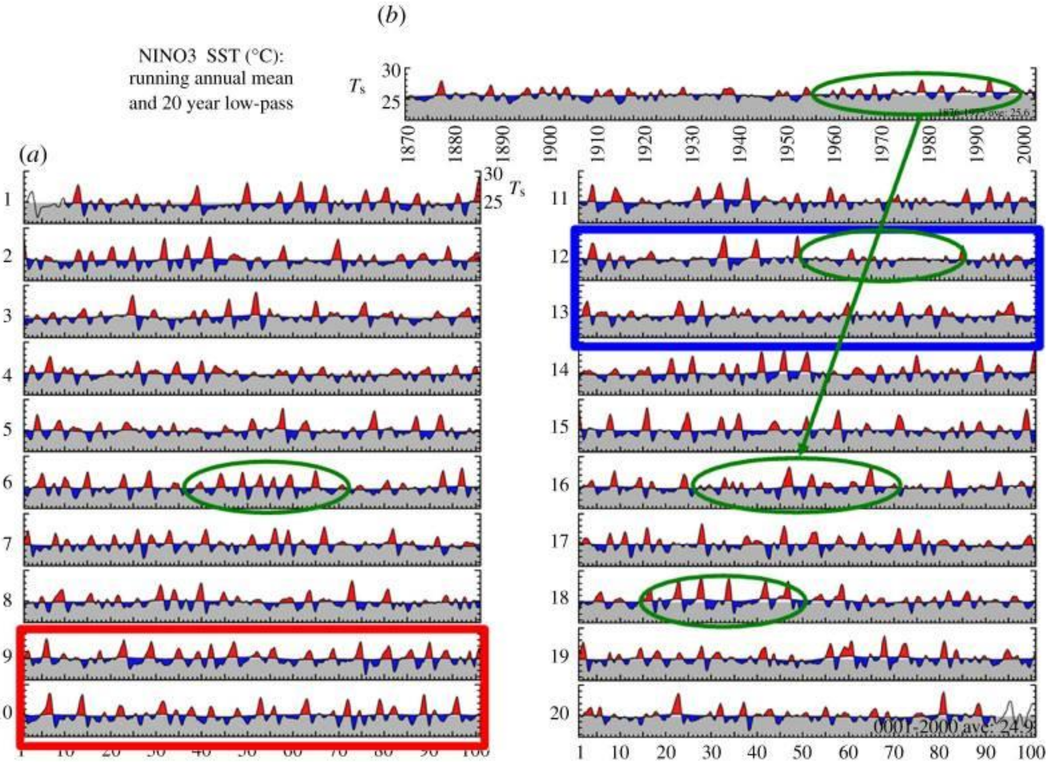
There are few domains of mathematical physics that have captured the collective imagination quite like chaos theory, the theory of systems that are highly sensitive to initial conditions. Indeed, the ‘Butterfly Effect,’ the notion that ‘the flap of a butterfly’s wings in Brazil might cause a tornado in Texas’ is so mainstreamed that it has become a cultural trope, showing up frequently as a plot point in TV, film and literature [3]. Unlike most applications of physics theory to fiction, however, the effects of chaos are generally understated, showing up in small ways, often after time-travel was used to alter something in the very distant past. In reality, the effects of chaos can be profound. Because of chaos, a

*tagline – The Butterfly Effect (2004)

trick shot in billiards that involves more than six collisions is virtually impossible, as at this point the gravitational attraction on the ball, not by the Earth or even by the moon, but by the **people around the table** becomes significant enough that the ball's trajectory can no longer be predicted [4]. Given this, we might imagine than when dealing with so complicated a system as human society, or the climate, even the tiniest change in the comparatively recent past might have led to a world today that is wholly unrecognisable.

Climate and chaos have a long history together – indeed Edward Lorenz, the pioneer of chaos theory, first identified the effect when studying atmospheric models. He found that when he accidentally inputted his model with initial conditions that had been rounded, a forecast resulted that was, after a few weeks, completely different to that resulting from the un-rounded figures. Based on these findings, Lorenz went on to conclude that long-range weather forecasting is impossible [5].

We must of course distinguish weather and climate, which describe short and long timescale atmospheric phenomena respectively. Indeed, we find that in averaging atmospheric behaviour over long periods of time, much of the chaotic behaviour disappears, and prediction of general climactic trends becomes possible. However, the chaotic, nonlinear properties of the atmosphere still have bearing on climate prediction, and we only need to examine the last 2000 years of El Nino behaviour to see that it possesses a richness of variety, over decades and centuries, that only a fundamentally chaotic system could yield [6]. While humanity can produce better and better models of how the climate will evolve, ultimately what precisely nature will see fit to bear out remains at the mercy of the flap of a butterfly's wings.



Simulated (a) and observed (b) sea surface temperatures in the equatorial east Pacific. Figure from: V. Ramanathan, GFDL, Princeton, NJ, USA

If the Camel Once Gets His Nose in the Tent, His Body Will Soon Follow†

> *"I'd need rest to refresh my brain, and to get rest it's necessary to travel, and to travel one must have money, and in order to get money you have to work… I am in a vicious circle… from which it is impossible to escape."*
>
> - Honoré Balzac, 19th century novelist and playwright

We are all familiar with 'vicious circles' in our daily lives. Some spontaneous event (e.g., one drinks too much coffee) brings about a negative consequence (one sleeps poorly that night), which sets off a chain of events that reinforce that same negative condition (one needs even more coffee to continue functioning). This is the positive feedback loop, and it another of the processes that allows small changes to have profound effects.

Climate science is rich with examples of positive feedback loops. This is unfortunate for humanity, as many of these tend to result in small changes to the climate spiralling dangerously out of control. One of the most frightening of these is the terrifyingly-named 'Clathrate Gun Hypothesis', which posits that global warming may result in the rapid release of methane from methane clathrate – a compound in which methane is trapped in the crystal structure of water – found in sediments on the ocean floors. Methane, a potent greenhouse gas, would then bring about more warming, setting off a runaway positive feedback loop that could cause dramatic increase in temperatures over the course of a human lifetime [7]. Other examples of positive feedback effects causing runaway warming include: the melting of ice lowering the planet's albedo, the drying out and burning of peat releasing nitrous oxide, and modification to the distribution of clouds resulting in more reflection of infrared radiation down to Earth [8].

Much like the effect of chaos, positive feedback permits a small initial perturbation to a system to result in more and more perturbed system behaviour as time goes by. Indeed, often chaotic behaviour is in fact driven by positive feedback loops. However, not all feedback loops result in behaviour that is unpredictable. Indeed, the explosive growth of a population of rabbits is a classic example of positive feedback, and one which evolves very predictably.

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† Arabian Proverb

Many Are the Strange Chances of the World‡

Rabbits are not native to Australia, and were first introduced in 1859 for hunting purposes. The initial population of 24 rabbits grew so quickly that within 6 years of introduction the population had exploded to millions [9]. Today, rabbits remain so widespread and damaging that over the past 150 years, numerous large-scale control measures have been attempted by the Australian government, ranging from poisoning, to biological warfare, to building a giant fence. This is a classic example of the Law of Unintended Consequences, which says that intervention in a complex system tends to create unanticipated outcomes. While this law is generally only applied to human intervention in complex systems, we can reframe it in terms of the unanticipated outcomes that changes in the environment have on the climate, and how positive feedback can drive these changes to have lasting impacts.

An ongoing environmental change that has an unanticipated consequence is the decline in arctic sea ice, which potentially causes weakening of the jet stream, causing it to dive further south and drive wet summers over northern Europe [10]. Reduced arctic sea ice also affects weather patterns at lower latitudes in other ways, such as by altering the frequency of extreme weather events and reducing the amount of available water in the American west [11].

Another, possibly more surprising example is the increase in the size and frequency of volcanic eruption due to glacial retreat. This causes reduced confining pressure to be exerted on the volcano, and the resultant increase in outpour of volcanic gases further contributes to the greenhouse effect [12]. This process is exacerbated by another warming-induced effect – the rise of sea levels increasing the crustal stress at the base of coastal volcanoes. Fascinatingly, it is also believed that the melting of ice in West Antarctica is likely to alter the Earth’s rotational period enough to shift its axial tilt by hundreds of metres, further increasing crustal stress changes [13].

We can therefore conclude that someday, the atmospheric concentration of greenhouse gases will be increased by a volcanic eruption made more probable by the recent break-off of an iceberg from the Larsen C ice shelf. An unexpected consequence, driven by a positive feedback loop, which chaos shall enable to completely transform the meteorological destiny of Earth. A long process which started with a single, solitary crack.

But oh, what lasting effects that crack will have.

‡J R R Tolkien - The Silmarillion

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