Predicting The Unpredictable

Will it snow over London on 23rd January 2154?

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December 2011

Introduction

Predicting London snowfall on 23rd January 2154 is no easy feat. The atmospheric conditions required are well known. However, forecasting these is subject to immediate dismissal, a testament to the unpredictability of Earth's weather and climate. To understand why this prediction is so challenging requires an appreciation of how computational limits, chaos theory and uncertainties in physical mechanisms restrict the ability to model Earth's atmosphere.

Exploring this question reveals wider implications. Society depends on weather forecasts to make everyday decisions. From commuters deciding whether to bring an umbrella to work, to authorities preparing the evacuation of towns for an approaching hurricane, its impact cannot be understated. Crucially, climate dictates weather. A changing climate will alter existing weather regimes in wide-reaching ways. Being able to predict these changes and its profound consequences is therefore vital if governments, businesses and individuals are to make informed choices in responding to climate change.

Current Forecasting Techniques

Models used in weather centres, such as the UK's Met Office, start by dividing the area of interest, say the British Isles, up into a 3-dimensional grid of boxes which span the surface to the upper atmosphere (figure 1). Atmospheric conditions, which include wind speed, air temperature, pressure and humidity, are measured and assigned to each box. Moreover, satellite and radar imaging provide detailed 'top-down' views of the atmospheric situation, supplementing ground-based measurements. With all these observations, a clear snapshot of the atmosphere's initial state is produced.

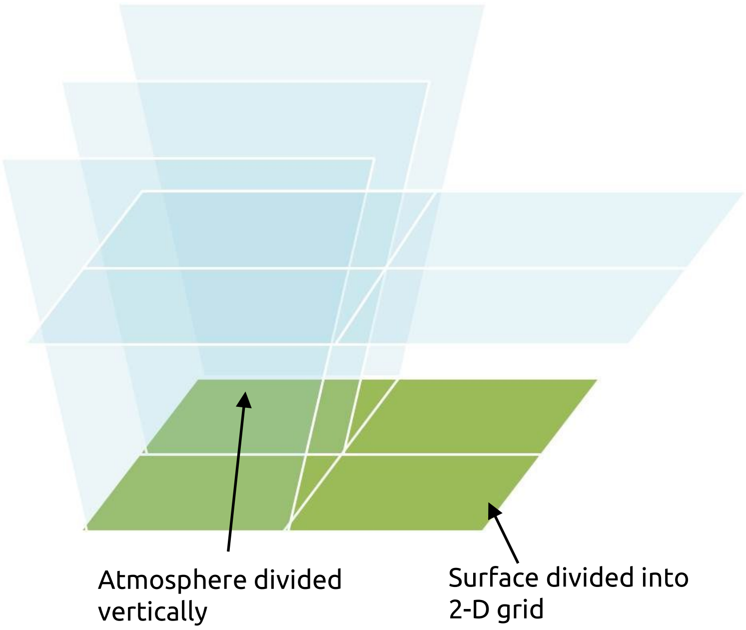

Figure 1 – Surveying The Atmosphere

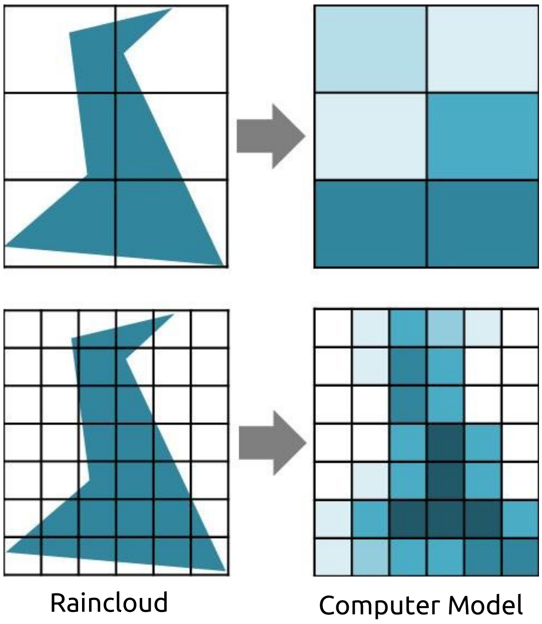

Figure 2 – Increasing Resolution

The equations used in the models are based on the study of how liquids and gases behave in motion, called fluid dynamics. Computers take the initial conditions and solve equations for each box, predicting how these variables change in a small time interval later. The computer model generates a picture of the atmosphere a few minutes into the future. It then re-runs the model, using this new set of variables generated from the first prediction, incrementing by another few minutes. This whole process is repeated, yielding tomorrow's weather forecast or next century's climate projection.

Computational Limits

From the start, there is the dilemma of how large to make each box of the 3-dimensional grid. Figure 2 shows how using smaller and more densely packed boxes allow the strangely shaped raincloud to be modelled more realistically. The resolution increased from 6 to 42. Much like how digital cameras capture more detailed images with more pixels, increasing the 3-dimensional grid's resolution produces a more realistic snapshot of the atmosphere. A greater resolution in the computer model would also allow predictions to be more precise, specifying whether snow will fall over 'London' instead of more vaguely 'South of England'.

However, a model of high precision would ideally require initial conditions for every box and it is clearly not practical to place a weather station every metre apart across the UK. In practice, atmospheric conditions do not differ much at these small scales. In figure 3, the temperatures over a grass field surveyed using a resolution of 12 elements gave very similar results. So instead of solving 12 sets of essentially identical equations, it would be computationally more efficient to sacrifice the minor inconsistencies and solve 1 set, taking an average of the area's temperatures.

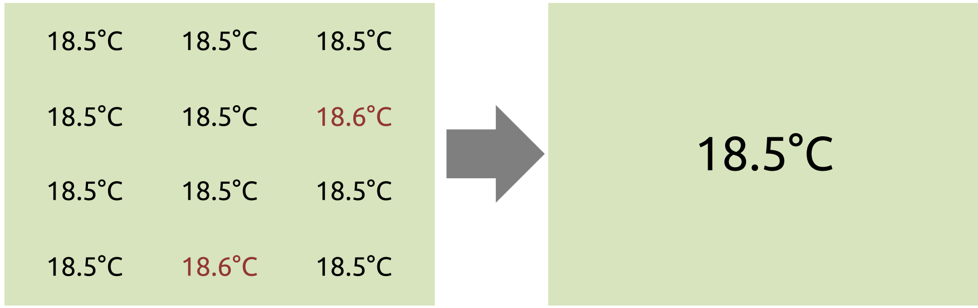

Figure 3 – Approximations

This is a sensible option given supercomputers at the Met Office can only process a finite number of equations every second. Make the boxes too small and the computer will take too long to generate predictions; too large and small local variations will not be taken into account. A balance is reached between how small the boxes should be made if an accurate prediction is to be produced in time for the evening television forecast. For short range weather forecasting, the width of a box is typically in the region of 1 kilometre. Climate projections use much larger boxes, typically hundreds of kilometres wide but can forecast much further into the future, usually decades. This disparity arises from differences in what climate forecasts predict.

To illustrate, BBC Weather quotes that in January for London, there are on average 15 'wet days'. A 'wet day' constitutes 24 hours with more than 0.1mm of rain, sleet, hail or snow. Every January, this is normally but not always close to 15. Climate forecasting capitalises on this predictability of averages. However, what cannot be said with any certainty is on which January days that rain, and indeed snow, will fall. This mismatch of predictability is in fact a consequence of chaos: over the long term, daily weather regimes become unpredictable, but regularities in averages culminate into a somewhat predictable climate.

Chaos

'Predictability: Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?' These words were coined by Ed Lorenz, an American meteorologist who pioneered chaos theory. The metaphor hypothesises slight changes in air pressure from the flap of a butterfly's wings could spark off a chain of atmospheric events escalating into a tornado thousands of kilometres away.

In the 1960s, Lorenz was developing computer models for weather prediction, similar to the modern technique outlined earlier. He soon noticed something peculiar. His computer model would generate wildly differing predictions even for tiny variations in the initial conditions. Lorenz discovered weather systems exhibit incredibly high sensitivity to initial conditions, rendering useful long term predictions impossible. This sensitivity is described as chaos, or more affectionately, the 'butterfly effect'. So how does nature use chaos to prevent prediction of London snowfall over 100 years into the future?

A good illustration of the problem is Galton's board (figure 4). Steel marbles are dropped from the top with each marble representing one run of a computer model to predict a snowstorm's trajectory. Imagine each layer of pins represents a day into the future for the snowstorm. Like an imperfect set of initial atmospheric observations, each drop of a marble will have minute starting differences and computer models accommodate this by slightly altering the temperatures or pressures say for each run. It is safe to say the marble will initially remain near the top-centre. However, the marble's sensitivity to slight differences at each collision with a pin makes it impossible to predict precisely where it will end up. Likewise this is why weather forecasts are limited to mere days, let alone 23rd January 2154, before losing predictability.

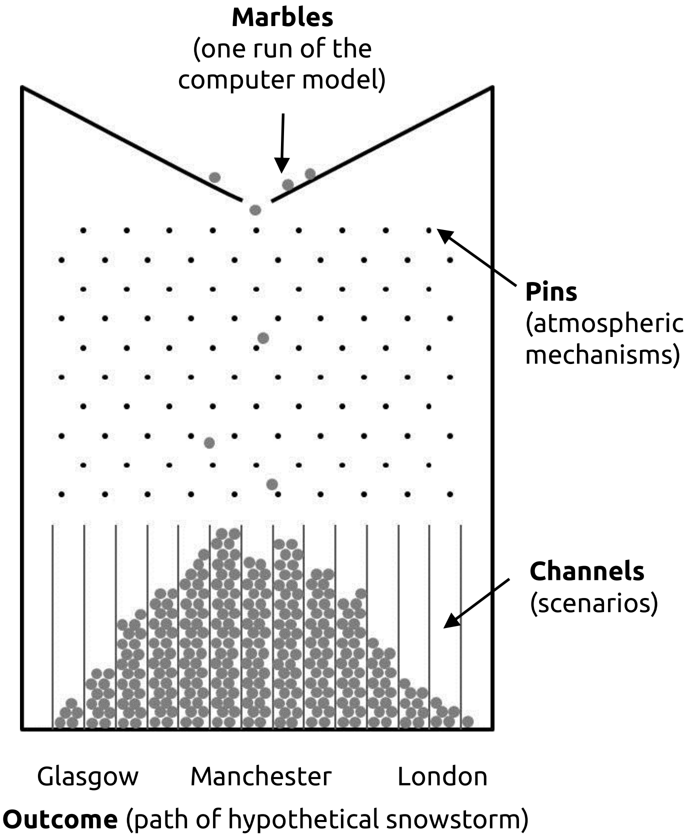

Figure 4 – Galton Board

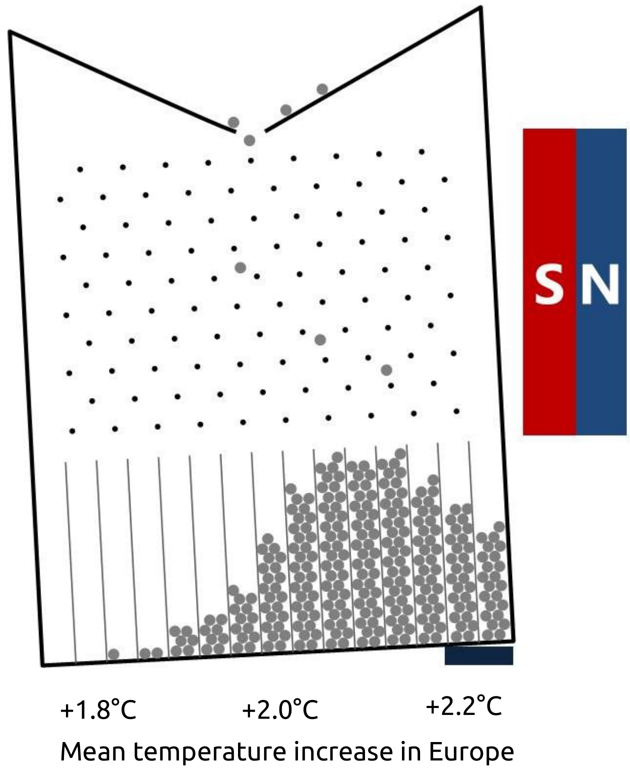

Figure 5 – Introducing Bias

Nonetheless, gravity ensures the marbles travel downwards between collisions, akin to the Westerlies, strong global winds advancing Atlantic storms eastwards to the UK. So, as more marbles are dropped, the outcome in the channels becomes increasingly clear. In this case the marbles tend to collect near the centre, indicating the snowstorm will most likely hit Manchester. Few land elsewhere, so the other scenarios are less likely. Notice the use of the words 'likely'. No single outcome can be labelled as 'will happen' or 'will not happen'. Only the probabilities of the outcomes are predictable.

Predicting an exact date for snowfall is out of the question. However, the likelihood of snowfall in January is influenced by how much the month's average temperature increases by 2154. The climate must be investigated. Now, the Galton board may be tilted, and a magnet placed to the right of the board, introducing bias (figure 5). The probabilities of the final outcomes are distorted. In this case, the marbles tend to accumulate to the right-hand side of the board. Previously, gravity represented global winds. The additional biases represent further physical mechanisms in the atmosphere which cause otherwise chaotic behaviour to favour certain outcomes over others. In this hypothetical example, the tilt could represent the cooling effect of a weaker warm ocean current called the Gulf Stream to Europe whilst the magnet, a 20% increase of atmospheric carbon dioxide over the next 100 years. The net effect of these 2 biases results in a most probable average temperature rise of 2.0-2.2 degrees. Snowfall is looking less likely.

In short, a better understanding of these physical mechanisms would allow models to be refined more realistically. Even so, many of these countless processes remain poorly understood, only adding to the uncertainties of climate forecasting.

Uncertainty In Physical Mechanisms

One of the potentially most significant uncertainties is the positive feedback of water vapour. Water vapour is the most abundant greenhouse gas, absorbing heat energy that would otherwise be radiated away into space. In the UK, its potency is most notable at night: when there is cloud cover, air temperatures remain above freezing and milder than if the night sky were clear.

Looking at figure 6, initial temperature increases release large amounts of liquid water previously locked up in glaciers and ice sheets across the world. Ice covers some 10% of the Earth's surface, reflecting a proportion of incoming light and radiation out into space, an effect called albedo. As more ice is melted, less radiation is reflected back, so the Earth warms. Further temperature increases induce greater evaporation of warmer ocean water. Air with higher temperature holds more water vapour than that with a lower temperature. This leads to a greater amount of water vapour in the air, raising the concentration of this greenhouse gas in the atmosphere.

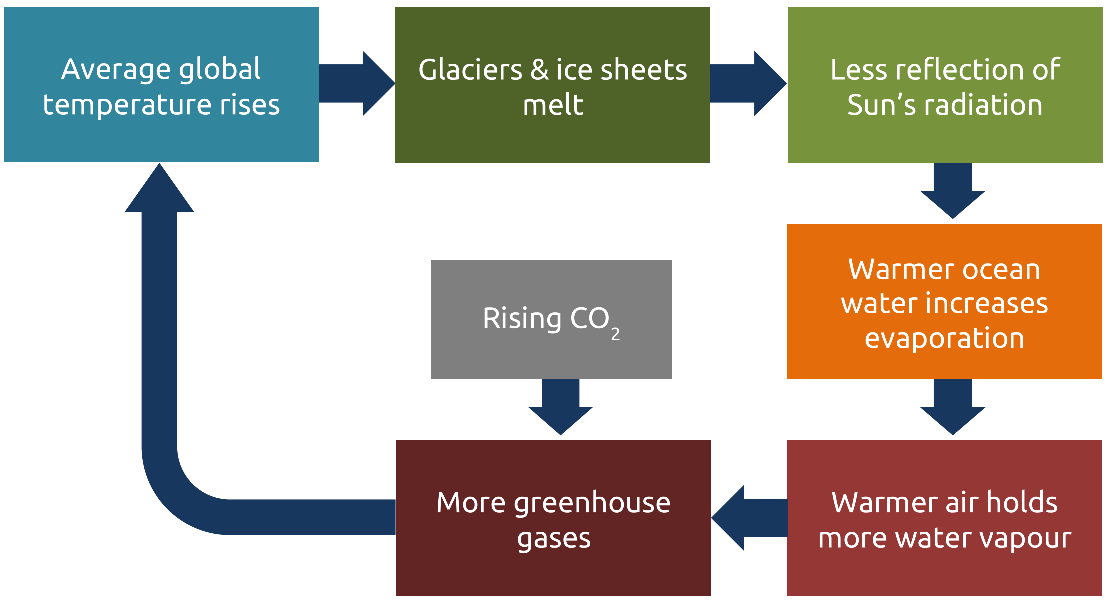

Figure 6 – Positive Feedback

Increasing temperatures trigger more mechanisms to raise temperatures further. This strong global positive feedback is like a snowball rolling downhill, collecting more snow and momentum as it does so, gradually producing something uncontrollable. The uncertainty lies in how significant this process is and better understanding of feedback mechanisms is crucial.

It is however possible to argue that increasing water vapour in the atmosphere could lead to a greater proportion of Earth covered by cloud. Clouds, like surface ice, are very reflective to infrared radiation carrying heat energy from the Sun. With more of the Earth's surface potentially covered by clouds, this could also produce a negative feedback, cooling the Earth. To what extent this counteracts the positive feedback is subject to much contention and only adds to the uncertainties already established.

How weather systems respond to an increasing concentration of atmospheric water vapour in warmer global temperatures is similarly uncertain. 'More extremes' is the generally consensus: more intense and frequent storms in some areas, more prolonged spells of drought in others. These new weather regimes may emerge unpredictably from a warming climate, affecting people on wide-reaching scales. Furthermore, the atmosphere does not act singly. It interacts with countless other processes and their contributions to climate change require more understanding. To name a few, the atmosphere's behaviour is closely intertwined with ocean currents and their global circulation, the varying solar energy that reaches Earth due to orbital variations and solar activity, and how ecosystems respond to and affect the changing climate.

Conclusion

Clearly, understanding and accounting for every mechanism is beyond the sole endeavour of atmospheric and climate physics. It is an inter-disciplinary challenge to refine ever more realistic climate models. Whether it is the technological limits of current computational power or the apparent restrictions on predictability nature imposes with chaos, countless uncertainties remain in modelling climate change.

Unexpectedly, this offers humanity a lifeline: no single destiny is a complete certainty. Perhaps unpredictability means the future climate is not pre-determined. Perhaps, through collaborative understanding and action, the world can avoid a future of so-called 'environmental catastrophes'. And ultimately, perhaps London will even see snowfall on Wednesday 23rd January 2154.