instance, increased levels of carbon dioxide, the gas mainly responsible for the anthropogenically induced greenhouse effect. To understand global warming and its implications for climate in general, then, we first need to understand the dynamics of atmospheric regimes and regime change.

In theoretical work supported by observational data[1,2], Cromellin has followed Palmer's lead and provided evidence that transitions between atmospheric regimes may be related to the occurrence of a 'heteroclinic cycle' in nonlinear models of large-scale atmospheric dynamics. Heteroclinic cycles explain both the apparent stability of the blocked regimes and the sudden changes that occur when they are unblocked. The usual statistical approach views transitions between regimes as random processes, but there has been growing evidence that atmospheric regime change has a deterministic component. Cromellin's work pins this proposal down and makes it possible to test it.

Heteroclinic cycles have an element of unpredictability, but their dynamics is relatively straightforward and much of it is very predictable indeed. The cycles are characterized by occasional bursts of activity punctuated by lengthy periods of torpor. Specifically, heteroclinic cycles are sequences of connections between unstable equilibrium states — 'saddlepoints' that are stable in some directions but unstable in others. The torpid states are predictable: they occur when the system is near an equilibrium. The uncertainty lies in predicting when the torpor will cease.

For example, a pendulum has an unstable equilibrium in which it balances vertically in an upward position. If disturbed, the pendulum rotates with increasing speed to the downward vertical, and then climbs back to the upward vertical. In the absence of friction, it returns very close to the original unstable equilibrium, but approaches it from the opposite side. This is a connection between an equilibrium and itself — in the jargon, a 'homoclinic' connection.

Connections are also possible between distinct equilibria, but these are uncommon unless the system possesses a degree of symmetry. In the case of the Earth and its atmosphere, there are two kinds of symmetry. Thus any model of the system is mathematically unchanged by rotation about the same axis, or if north and south are flipped by reflection in a mirror placed in the equatorial plane. These symmetries, broken only slightly by the effect of uneven landmass distribution, can create complicated patterns of heteroclinic connections. Mathematicians have carried out much theoretical work on heteroclinic cycles; now we are starting to see the fruits of this research in applied science.

Cromellin begins by analysing 'empirical eigenfunctions', or common flow patterns, in the atmosphere. In this technique, the actual flow is approximated by the closest possible combination of a set of independent basic patterns. The complicated equations of meteorology are thereby transformed into a system of ordinary differential equations describing a finite number of variables, which represent the amplitudes of the component patterns. Heteroclinic connections can be interpreted as the persistence of various apparently stable flow patterns, punctuated by rapid switches from one such pattern to another. This apparently counterintuitive behaviour makes perfect sense in the context of a heteroclinic cycle.

Cromellin tests his theory using data on the Northern Hemisphere for the period 1948–2000. He computes empirical eigenfunctions, and uses them to approximate the weather patterns. Next, he determines the most probable patterns, which should correspond to possible equilibria in any underlying deterministic model; six of these patterns dominate the statistics. Transitions between these six patterns are not purely random, but display some systematic features, which can be described using a Markov chain — a matrix of transition probabilities. Finally, the underlying deterministic dynamics can be inferred.

This analysis demonstrates the existence of a preferred dynamic cycle connecting various regimes of blocked flow in the Atlantic region. The dynamical variable is the deviation of the atmospheric flow from its mean state, which we will refer to simply as the 'flow'. The cycle begins with north–south flows over the Pacific and North Atlantic. These merge to form a single east–west Arctic flow. This in turn elongates over Eurasia and the west coast of North America, leading to a predominantly north–south flow. In the second half of the cycle, the flow patterns revert to their original state, but following a different sequence. The complete cycle takes about 20 days. The details of the cycle suggest that, in effect, the North Atlantic and Arctic Oscillations may act as a partial trigger for each other.

Cromellin's first contribution is to provide a systematic technique for making the preferred regimes visible from real data. His second is to show that, on an appropriate scale, transitions between atmospheric circulation regimes may have an underlying

Earth science

Stressed in Alaska

AP/ALASKA DEPT TRANSPORTATION

The seismic events in central Alaska on 23 October last year, and then on 3 November when a magnitude 7.9 earthquake ruptured more than 300 km of the Earth's surface, won't rate much mention in human history. Such was the remoteness of the area that, happily, no one was killed. And despite the forces involved, as seen in this image of ground movement along a highway, and in the occurrence of many huge landslides, damage to infrastructure was comparatively light.

Now, however, analyses of the earthquakes are being recorded for scientific history. One of the first reports appears in *Geophysical Research Letters* (doi:10.1029/2002GL016724; 2003), where Greg Anderson and Chen Ji describe their modelling of stress transfer during this earthquake sequence. They conclude that the magnitude 6.7 earthquake of 23 October transferred 30–50 kilopascals of stress to the hypocentre of the second (the Denali fault mainshock) — thereby, as the authors put it, "encouraging the occurrence" of the mainshock. From other studies, it seems that levels of 10–20 kPa of stress transfer can trigger further seismicity.

Both of the earthquakes occurred along the Denali fault system, in a mountain range some 90 miles south of Fairbanks. This is a 'strike-slip' fault, where two tectonic plates are in transform movement past one another, akin to the San Andreas fault that so exercises Californians. For context, the Denali fault mainshock was about the same magnitude as the San Francisco earthquake of 1906, with surface offsets across the fault of up to 9 metres.

Like the San Andreas, the Denali fault system is complex, with many regional faults. Anderson and Ji also calculate the combined effect on those faults of the events of 23 October and 3 November. The resulting picture is varied, with minor stress release or increase on most fault segments, but in a couple of cases a massive increase of more than 400 kPa. This is well over the commonly cited threshold for triggering further seismic activity — showing that the threshold is perhaps not a 'hard floor', and that these fault segments might prove especially lively subjects for monitoring.

Tim Lincoln