Did the Roof of the World Start an Ice Age?

The rise of the Tibetan Plateau and the high country of the American Southwest probably helped refrigerate the globe

WHY HAS CLIMATE GONE TO POT LATELY? When William Ruddiman asked himself this question, he was not thinking of this year's drought in California or last summer's massive heat wave. Ruddiman is a paleoceanographer, which means he uses words like "lately" for somewhat longer spans of time—say, tens of millions of years. So Ruddiman was wondering what had both ended the heat wave that prevailed until about 40 million years ago and caused the world to slip into progressively colder climes until the great ice ages enveloped the Northern Hemisphere about 3 million years ago.

Ruddiman believes he has strong evidence that at least part of the answer lies in the thrusting of great mountain chains and plateaus into the lower atmosphere. Meteorologists had thought that such upheavals might so disrupt atmospheric circulation that the climate of the whole Northern Hemisphere could deteriorate, culminating in a prolonged, icy cold spell. Now Ruddiman has gathered some impressive support for that notion.

Ruddiman came to his conclusions about the effect of high mountains on climate by way of the sea floor. A few years ago, he had the normally stultifying chore of summarizing the results of a sediment-collecting leg of the Deep-Sea Drilling Project. Ruddiman's forte is compiling climate records from the remains of tiny plants and animals preserved in the muck of the sea floor; that makes him a "bug picker" in the parlance of the trade. The drilling project, with lots of bug picking, had helped decipher parts of the 40-million-year cooling, but what it showed did not seem to fit the usual explanations of the ice ages very well. Ruddiman therefore decided to test quantitatively the idea that the formation of the great mountain chains and plateaus alone might have disrupted the formerly balmy climate of the Northern Hemisphere.

To help with the detailed meteorology that he felt had been neglected by paleoceanographers, Ruddiman, who works at Lamont-Doherty Geological Observatory, turned to climate modeler John Kutzbach of the University of Wisconsin. He would supply the crucial link between uplift and climate change. But first, Ruddiman, the bug picker, played geomorphologist to show that the shape of the globe did indeed change substantially in the last 40 million years. He hit the books, and recalls now that his literature search "was a very slow thing off and on for 2 years."

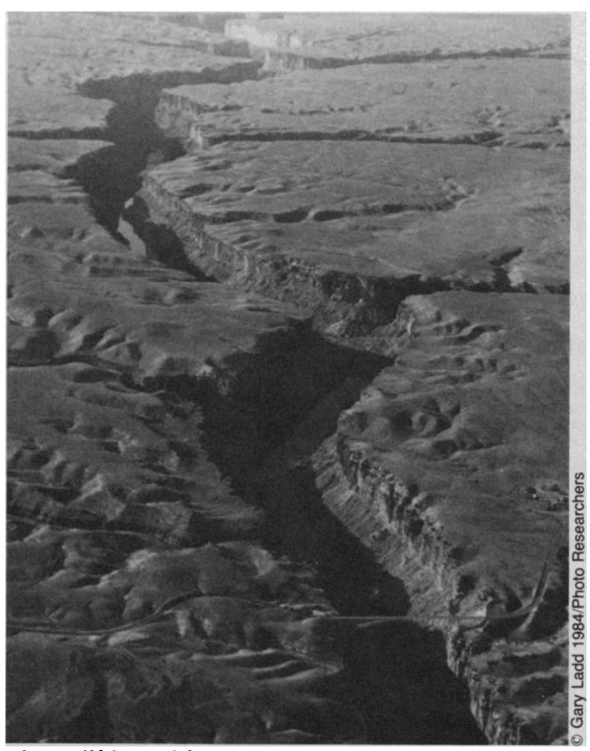
Though he was exploring largely new territory, Ruddiman gradually pieced together a consistent picture from the work of other scientists. Geologists had mapped faults where the crust broke as it bulged upward. Palynologists had found pollen from warmth-loving plants in strata now perched at high and therefore cold elevations. And geologists had shown that rivers have cut canyons faster as the rising bulge steepened.

In the end, Ruddiman pulled together evidence of impressive uplift during the past few tens of millions of years for two areas that are roughly on opposite sides of the hemisphere and at similar latitudes: the U.S. Southwest and the Tibetan Plateau.

An area of roughly 2.5 million square kilometers from the Sierra Nevada of California to the southern Rockies, which now stands 1.5 to 2 kilometers high, had risen more than 1 kilometer during the past 20 million years, explains Ruddiman. The uplift seemed to accelerate during the past 15 million years. That is quite a spurt, considering that erosion, given time, grinds away even the loftiest mountains. Reassuringly enough, Ruddiman found confirmation of his outsider's opinion. A review by real continental geologists that appeared last year near the end of Ruddiman's lonely labors implied a similarly rapid uplift.

The heights of the American Southwest may be impressive, but they shrink beside the monster Tibetan Plateau. More than half of the plateau soars above 5 kilometers; nothing at all in the lower 48 states reaches that high. This "roof of the world," as it is called, rose at an increasingly rapid rate during the past 5 to 10 million years, Ruddiman concluded; the total uplift during that time was about 2 kilometers.

What has been driving these uplifts? For the Tibetan Plateau, the answer lies in the initiation of the upward thrust sometime after India began colliding with Asia about 45 million years ago. Whether India has squeezed Tibet upward, as if it were in a vice, or slipped under it and floated it upward is not clear. But in either case, continental collision is the root cause.



An uplift's etching. *The Colorado River has cut into the plateau as the uplift progressed.*

Not so in the United States. "There are four or five competing ideas" about uplift there, Ruddiman says, "most involving one means or another of supplying additional heat beneath that part of the crust, but once I figured out what the rate of uplift was like and that there are people willing to defend each mechanism to the death, I figured I would not get into that."

The upshot of all this crashing and swelling was the rapid growth of two massive bulges on opposite sides of the Northern Hemisphere. Ruddiman then faced the question of what effect this had on climate. That was where Kutzbach the modeler came in. Kutzbach turned to a supercomputer to perform experiments impossible in the real world: he simulated Earth's climate with and without the two bulges.

The plateaus in Kutzbach's model performed much as expected from earlier, more fragmented work, but the modeling allowed a new, comprehensive view. Overall, the plateaus provoked a more complex circulation across much of the hemisphere through two mechanisms, as well as through their interaction. The first is the simple presence of an obstacle in the path of the prevailing westerly winds. Like a boulder in a river, each plateau diverted the winds, including the jet stream, around it, provoking wiggles in an otherwise smooth flow. The second is the generation of great columns of swirling air—in summer a column rising from the sun-baked plateau and in winter one of descending air dragged downward by the chill of the snow-covered heights (see box). The vertical drafts redirect winds themselves, but they also act as obstacles.

To test their model, Ruddiman needed to know if the plateau-induced climate changes matched what really happened. So he searched the climate record of the past 40 million years region by region. Did forest give way to grassland where cold winds appeared out of the north? Did moist forests appear where new winds came from the ocean? "The whole fabric of climatic differentiation is predicted remarkably well," says Ruddiman. Of the 14 climate changes simulated by the model—from drier summers on the west coast of North America to colder winters in northern Europe—he found all but two in the climate record. (The two failures seem to be due to obvious limitations of the model, such as a Gulf of Mexico that is too wide.)

For climate modelers, who know their models are far from perfect, this match is extremely good: it not only includes the right kind of changes predicted by the simulation, but also shows many of them accelerating, just as uplift accelerated.

The match between computer simulation and real world suggests that "uplift is a major factor in explaining the climatic deterioration that culminated in Northern Hemisphere glaciation," says Ruddiman. But there is a snag. Plateaus in the model cool winter temperatures by as much as 8°C and summer temperatures by 2°C, but "that's not enough for us to claim we've nailed the ice age problem," he says. The decrease in Northern Hemisphere temperature falls perhaps 5° or 10°C short of that expected for widespread glaciation.

It may be, though, that a better, more realistic model—one that includes varying snow cover, sea surface temperatures, and soil moisture—would fetch the required cooling. These added variables might well amplify the Northern Hemisphere cooling.

Ruddiman and Kutzbach intend to find out whether a better model will cool the Northern Hemisphere all the way to the ice ages, but Ruddiman has a hunch that it will not. "I think there's more than one mechanism operating. The guess is that decreased carbon dioxide is the wild card." Reduced carbon dioxide would reduce the greenhouse warming effect and cool the climate.

Climatologists agree. "I don't think anyone knows the full explanation," says Thomas Crowley of Applied Research Corporation in College Station, Texas, "but they have made a good case for uplift playing a potentially major role. They've put their finger on something."

The Southern Hemisphere is another matter all together. Antarctica got its first substantial ice sheet sometime between 40 and 30 million years ago. Thirteen million years ago something like the present continent-size ice sheet formed. What caused that climate deterioration? "I have no idea," admits Ruddiman. "It's an open question, but uplift is a possibility there, too."

■ **Richard A. Kerr**

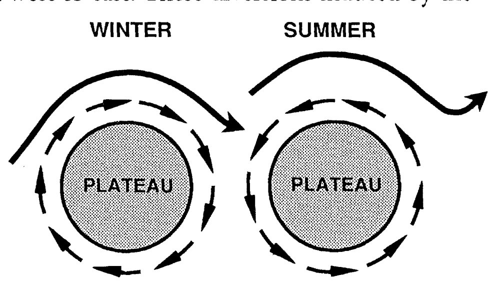
ADDITIONAL READING

Three papers on uplift and climate change by W. F. Ruddiman and J. E. Kutzbach and their colleagues W. L. Prell, P. J. Guetter, and M. E. Raymo are in press in *Journal of Geophysical Research.*

How to Stir Up a Climate Change

Thrusting two plateaus—the Tibetan Plateau and that of the U.S. Southwest—into the atmosphere turns out to alter climate in subtle and indirect ways, according to recent computer model simulations.

Throughout the troposphere—the lowermost, weather-generating layer of the atmosphere—the two model plateaus redirect winds to the north and south that would otherwise blow smoothly from west to east. These diversions induced by the plateaus are not just a local effect. By acting as obstacles to airflow, high plateaus help put wiggles in the jet stream around the world. Some of these wiggles guide storms down across the United States and direct frigid air farther south and warm air farther north than would happen otherwise. In part, the wiggle-inducing diversions are due to the rock-solid obstacle of the plateau, which acts like a boulder in a stream.



Seasonal swirls. *Plateaus divert and redirect the wind, depending on season.*

In addition to the obstruction provided by the plateau itself, prevailing winds must also bypass wind systems induced by the plateau. In the summer, this system is the fountain-like rising swirl of air that is the summer monsoon. In the simplest example of a monsoon-like circulation, the faster warming of land than sea on a summer day induces a sea breeze at the beach as warm air rises over the land and draws in air from the sea. But a plateau places the summer heating well up in the atmosphere. Because the atmosphere is thinner and less massive at those altitudes, winds can be driven faster by the same heat energy input. Given the breadth of, say, the Tibetan Plateau, the rising warm air forms an intense updraft that draws in air around its base. Under the influence of Earth's rotation, this air blows counterclockwise around the updraft, like a huge, permanent low-pressure system. Winds such as the jet stream must swing to the north to get around the low, which makes for the start of a wiggle.

During the winter, the circulation about plateaus reverses. Cooling now has the advantage, thanks to there being less atmosphere above the ground to block heat loss to space. Cold, dense air sinks off a wintertime plateau and swirls like a permanent high-pressure system, which also must be negotiated by the prevailing winds.

The diversions of winds and resulting climate shifts are not due solely to obstructions. Plateau circulations themselves also bring climate change. The air swirling into the Tibetan Plateau during the summer carries moisture off the ocean that falls as monsoon rains in southeast Asia. On the west side of the plateau, dry air blowing off Central Asia helps create the Mediterranean region's typical dry summers. And to the north, the dryness from loss of moisture to monsoon rains encourages the desert conditions of the Gobi. Wintertime plateau circulations alter climate too. For example, the U.S. plateau brings cold air from the north to the Northern Great Plains rather than milder air from the west.

These are effects at the lower end of plateau-induced circulations, but the upper end reaches even farther. The air that rises over a warmed plateau must come down eventually. The descent of such dry air in the subtropics contributes to the aridity of the Sahara, among other deserts. ■ **R.A.K.**