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THE THIRD POLE

Climate change is coming fast and furious to the Tibetan plateau. **Jane Qiu** reports on the changes atop the roof of the world.

The Tibetan plateau gets a lot less attention than the Arctic or Antarctic, but after them it is Earth's largest store of ice. And the store is melting fast. In the past half-century, 82% of the plateau's glaciers have retreated. In the past decade, 10% of its permafrost has degraded. As the changes continue, or even accelerate, their effects will resonate far beyond the isolated plateau, changing the water supply for billions of people and altering the atmospheric circulation over half the planet.

The plateau's pivotal role is due almost entirely to its height. Being an average of 4 kilometres above sea level makes it peculiarly cold for its latitude — colder than anywhere else outside the polar regions. Lhasa, capital of the Tibet Autonomous Region, is by Tibetan standards relatively low-lying, at 3,650 metres — yet it is higher even than La Paz, Bolivia, the highest capital city of a country. Lhasa's year-round average temperature is 8 °C; at the same latitude Houston, Texas, has an average temperature of 21°C. The altitude makes Tibet cold, especially in winter; its snow and ice cover, by reflecting sunlight, make it colder still. The very bulk of the plateau affects how winds circulate above it, and its altitude also places the surface simply closer to the stratosphere than is normal.

The proximate cause of the changes now being felt on the plateau is a rise in temperature of up to 0.3 °C a decade that has been going on for fifty years — approximately three times the global warming rate. The questions are how much more change to expect in the future, and how severe the effects will be on the planet's climate as a whole. "Our understanding of global climate change would be incomplete without taking into consideration what's happening to the Tibetan plateau," says Veerabhadran Ramanathan, an atmospheric scientist at the Scripps Institution of Oceanography in La Jolla, California.

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> — Ouyang Hua

Perhaps surprisingly given its significance, the potential impact of the Tibetan plateau is still unfamiliar to many climatologists. One reason is that there are far fewer data available compared with the Arctic and Antarctic, which have seen a far greater number of scientific expeditions to plumb their secrets. Although fieldwork there can be tough, the plateau offers the same physical isolation coupled with political challenges, at least for Western researchers. "The plateau's remoteness, high altitude and harsh weather conditions make any research on the region very challenging," says Yao Tandong, director of the Institute of Tibetan Plateau Research, headquartered in Beijing, of the Chinese Academy of Sciences.

Yao and his colleagues should know: in the 1980s, they were among the few researchers persevering in difficult field conditions to gather data on the plateau's past climate history. They drilled ice cores, up to 300 metres long, from Himalayan glaciers 7,200 metres high. "It's all done manually, and we had to carry them down the mountain. There were no helicopters, no heavy equipment," he says. "It's -30 °C, with the wind cutting through us like a knife. It's no mean feat." Such ordeals seem to have paid off: in collaboration with glaciologist Lonnie Thompson of Ohio State University in Columbus, the team's work on oxygen isotopes within the cores yielded the most comprehensive temperature reconstruction for the plateau, showing a large-scale warming trend that began in the twentieth century and is amplified at higher elevations[1]. Their findings are consistent with temperature records from meteorological

stations that have made continuous measurements since the 1950s [ref. 2].

Some of this is what you would expect in a world undergoing greenhouse warming, but there are regional factors on the plateau that exacerbate the effect. In summer, dust from regional deserts blows towards and up against the northern and southern slopes of the plateau. One recent satellite study, for instance, tracked dust wafting in from the Taklamakan desert to the north[3]. "We were really surprised to find this much dust over the plateau," says Huang Jianping, an atmospheric scientist at Lanzhou University and lead author of the study. The dust layers can reach as high as 10 kilometres above sea level, where they both absorb and reflect sunlight, changing the amount of radiation that reaches the plateau.

Combining with the dust to drive climate change are emissions of 'black carbon', the soot that results when people cook with biofuels such as wood, crop waste or dung. Southeast Asia, including the Himalayas, is one of the global hotspots for black-carbon emissions[4]. Using unmanned aircraft, Ramanathan and colleagues measured the amount of sunlight absorbed by black carbon, and found that it contributes as much as 50% of the solar heating of the air[5]. "It's the second-largest contributor to atmospheric warming in the region, after

Lifting the roof of the world

The rise of the Tibetan plateau is thought to have intensified the Indian monsoon. So the history of when and how it rose could improve the understanding of climate history and long-term climate change.

Some think that the plateau rose in blocks, progressively from south to north, after the India subcontinent collided into Asia some 50 million years ago. Others suspect that this neat model might be overly simplistic. To resolve this debate, researchers have studied the elevation history of various sites on the plateau.

Geologists have inferred elevation from the composition of oxygen isotopes in ancient rain and snow that fell on the plateau, and are preserved in rocks and lake sediments. The method is based on the observation that the higher a mountain range is, the less oxygen-18 is precipitated, whereas the opposite holds for oxygen-16. Thus, the ^{18}O/^{16}O ratio can be used to deduce past elevation. Studies of sediments at various sites on the plateau show that those areas were at elevations of over 4,000 metres between 11 million and 35 million years ago[11–13].

Another way of estimating elevation is to look at the shape and size of fossil leaves (pictured, right). "The leaves of a plant represent an engineering solution to a set of environmental constraints, which is dictated by laws of physics and chemistry," says Robert Spicer, a geologist at the Open University in Milton Keynes, UK. Spicer and his colleagues found that atmospheric enthalpy — a measure of energy that depends on both temperature and moisture — was recorded in fossil leaves and could be used as a direct readout of the elevation at which the plant grew. Studies of fossilized leaves from more than 20 species from the Namling basin, in the southern Tibetan plateau, show that the elevation of the region 15 million years ago was more than 4,600 metres[14].

More recently, Wu Zhenhan, a geologist at the Chinese Academy of Sciences's Institute of Geomechanics in Beijing, and his colleagues studied two groups of ancient lake basins in the central Tibetan plateau at 4,500 metres, which were excavated during the construction of the Qinghai-Tibet railway[15]. "They are beautifully horizontal, probably untouched for about 20 million years," says Wu.

In the early Miocene time, between about 22 million and 17 million years ago, the lake basins formed two gigantic lake complexes of 100,000 and 50,000 square kilometres. "It's unlikely that lakes of that size could be uplifted to the present elevation without any distortion," he says. This suggests that the central plateau was 4,500 metres above sea level as early as 20 million years ago. **J.Q.**

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Ice cores being carried down to base camp, and Yao Tandong (right) working on a glacier.

carbon dioxide," he says. He estimates that the combined effect of black carbon and greenhouse gases may be sufficient to account for a warming trend of 0.25 °C per decade in the Himalayas, roughly what has been observed so far.

When black carbon settles on Himalayan glaciers, it darkens the snow and ice so that they absorb more heat and become warmer. "The melting seasons on the plateau now begin earlier and last longer," says Xu Baiqing of the Institute of Tibetan Plateau Research. Glaciers at the edge of the plateau tend to melt more than those in the middle; one study, for instance, showed that glaciers in the eastern part of the Kunlun Mountains retreated by 17% over the past 30 years, which is ten times faster than those in the central plateau. If current trends hold, two-thirds of the plateau glaciers could be gone by 2050, says Yao.

Floods and droughts

The melting glaciers are starting to leave behind dangerous glacial lakes, in which meltwater ponds behind a dam of debris left by the retreating ice tongue. Scientists have identified 34 such glacial lakes on the northern slopes of the Himalayas, and 20 outburst floods have been recorded in the past 50 years.

The risk of floods, though, is but a short-term danger far exceeded by long-term issues with water supplies atop the plateau. Runoff from the region's mountains feeds the largest rivers across Southeast Asia, including the Yangtze, Yellow, Mekong, Ganges and Indus rivers. If glaciers continue to retreat and snowpack shrinks atop the plateau, the water supplies of billions of people will be in danger[6].

Permafrost is also at risk, as rising temperatures cause the 'active' ground layer — which freezes and thaws every year — to thicken. That, in turn, affects how heat and moisture flow between the ground and the atmosphere, further perturbing the system[7]. Degradation of permafrost will not only put the Qinghai–Tibet Railway at risk[8], but also endangers the plateau's alpine ecosystems, which rely on permafrost to trap water in the topmost layers of soil to allow plants to thrive at an altitude that would otherwise be too hostile for them. "A large-scale thaw of permafrost would result in the loss of its water content and trigger an ecological catastrophe," says Ouyang Hua, deputy director of the Institute of Geographical Sciences and Natural Resources Research in Beijing. As permafrost stores one-third of the world's soil carbon, vegetation loss would lead to a huge amount of carbon entering the atmosphere, exacerbating global warming.

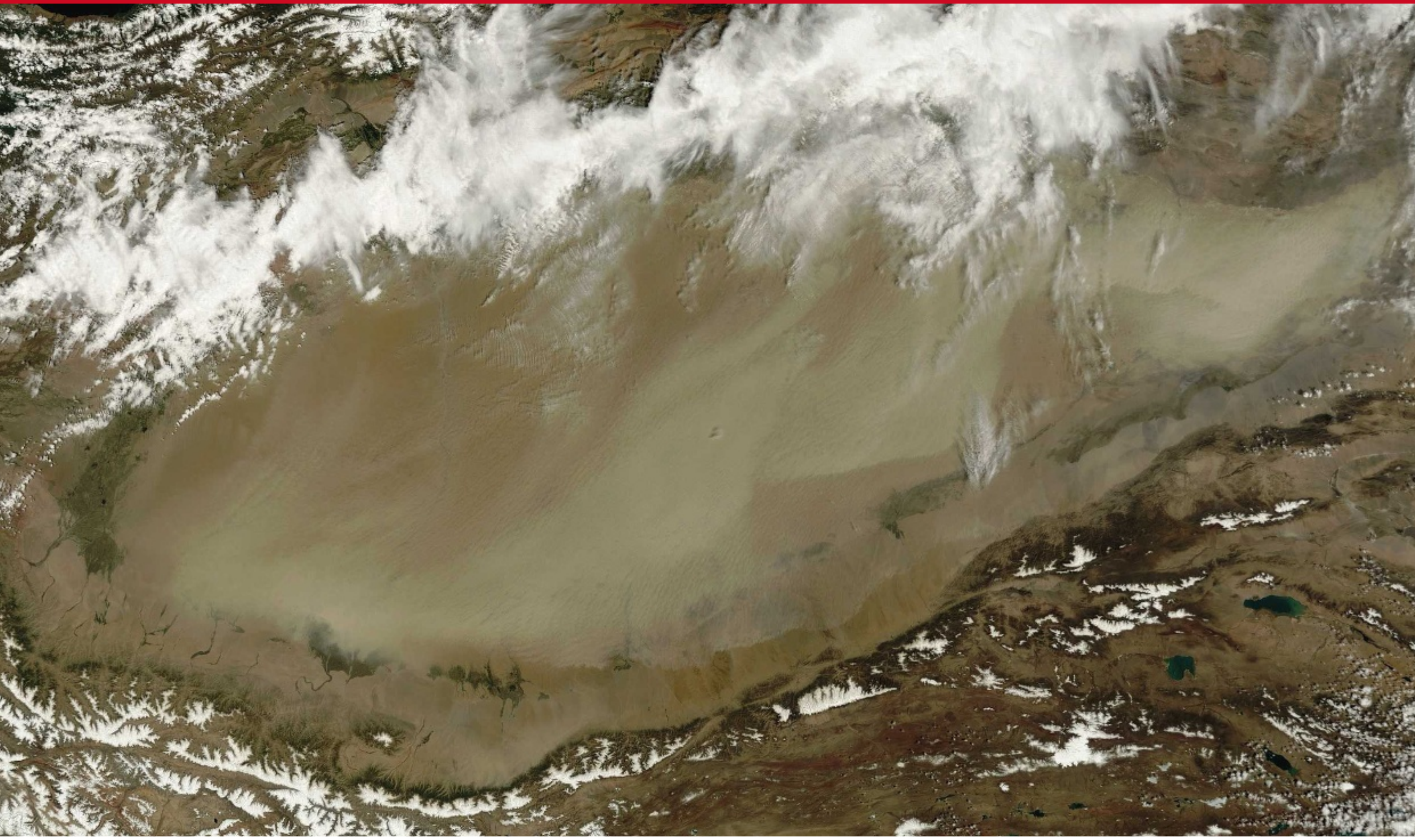
Competing forces

With all the changes the Tibetan plateau is undergoing — a warming climate, retreating glaciers, degrading permafrost and alpine ecosystems — what are the implications for the regional and global climate? The first and most important victim could be the Indian monsoon. This strong seasonal wind results from differences in the thermal properties between land and ocean. In summer, the vast land in Asia heats up more than the Indian Ocean, leading to a pressure gradient and the flow of the air and moisture from the ocean. The rise of the Tibetan plateau starting 50 million years ago (see 'Lifting the roof of the world') is thought to have strengthened this effect. As the land surface absorbs more sunlight than the atmosphere, the plateau creates a vast area of surface warmer than the air at that elevation, thereby increasing the land–ocean pressure gradient and intensifying the monsoon.

Some climate models show that global warming would lead to a greater increase in the plateau's surface temperature than over the ocean, thus augmenting the monsoon. On the other hand, some models suggest that aerosols that absorb solar radiation, and changes in land use in the region, could weaken the monsoon. "The intensity of the monsoon is likely to depend on which of these two competing forces dominates," says Ramanathan.

No matter what the causes are, some studies indicate that the weakening force may be prevailing, or has prevailed for at least the past three centuries. Duan Keqin, of the Cold and Arid Regions Environmental and Engineering Research Institute in Lanzhou, and his colleagues reconstructed a 300-year history of snow accumulation by analysing ice cores from the Dasuopu glacier[9]. They believe the ice there preserves an estimate of monsoon variations in the Himalayas. "We found that the warmer it was, the weaker the monsoon," says Duan. On average, a temperature increase of 0.1 °C was associated with a decrease of 100 millimetres in snow accumulation. But similar studies on other parts of the plateau are needed to confirm the results, he notes.

"Changes in the Indian monsoon are not the



Plumes from dust storms in the Taklamakan desert, such as this one in June 2005, can reach the Tibetan plateau and affect the climate there.

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only threat in Asia to the global climate," adds Rong Fu of the Georgia Institute of Technology in Atlanta. Her research shows that convection over the Tibetan plateau can transport water vapour and pollutants to the stratosphere[10], the atmospheric layer that is immediately above the troposphere and contains most of the Earth's ozone. "The strong, horizontal wind in the stratosphere could then spread the water vapour and pollutants globally," says Fu.

> **"Reducing emissions of greenhouse gases and black carbon should be the top priority."**
> — Xu Baiqing

Water vapour has a stronger greenhouse effect than carbon dioxide per molecule, but it normally reaches no higher than 1–2 kilometres below the stratosphere. The situation is different over the plateau, over which the convection layer is shifted some 6 kilometres further up so that its top boundary is around 18 kilometres up, in the lower stratosphere. In addition, the troposphere is thinner over the plateau, and the heat emitted by the surface can reach higher and make the air warmer at the base of the stratosphere. "So more water vapour is able to get to the stratosphere without being frozen or precipitated," says Fu. Warmer temperatures over the plateau can resulting increased glacial melting and water-vapour transport — which, in turn, causes strong convection and lifts even more water vapour up. "It's very worrying to think that a lot of it may reach the stratosphere," she says.

"Worrying", indeed, best captures the mood of researchers who work on the Tibetan plateau. They are keen to undertake large-scale, comprehensive studies and to collect as many data as possible. "We know so little about it and understand it even less," says Yao. One ongoing study is to document all the glaciers in China, recording characteristics such as their location, area, length, thickness and the position of the snow line. A similar survey was conducted between 1978 and 2002, which scientists believe could serve as a reference point to reveal any major changes. In addition, glaciologists continue to identify and closely monitor potentially dangerous glacial lakes in hopes of heading off any potential outburst floods.

Quick way out

Meanwhile, others focus on the bigger picture of how to tackle pollution problems in Asia. "Reducing emissions of greenhouse gases and black carbon should be the top priority," says Xu. Ramanathan reckons that cutting down on black-carbon emissions could be a "quick way out of the mess", given that its half-life in the atmosphere is about 15–20 days compared with the century-scale half-life of carbon dioxide. His simulations suggest that, just by removing traditional ways of cooking with wood, dung and crop residues, some 40–60% of the black-carbon emissions would be gone. This could be "a short-term fix, a low-hanging fruit that is much cheaper and faster" than reducing carbon dioxide, he says. "The key is to give villagers access to better forms of energy."

In the end, the Tibetan plateau may be a crucial testing ground for how humans and the environment collide in a globally warmed world. Can the world's third pole be saved? "Let's hope that the changes the plateau is going through are only transient," says Yao. "What we do about them probably will determine what's going to happen to it in the future."

Jane Qiu writes for *Nature* from Beijing.

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