C. BRISTOW

The dustiest place on Earth

Dust clouds can cool the Earth and halt hurricanes. But the world's biggest dust source was until recently a war zone. Jim Giles joins one of the few research teams to make the trip.

Midday, near Chicha, northern Chad. It's the dustiest time of day in the dustiest place on Earth. A dirty-white haze drifts in through the open windows of the jeep, coating our clothes with powder. Outside, in the 40 °C heat, there's an argument going on.

Adrian Chappell and Charlie Bristow have come a very long way, to a place where no one else wants to be, to have their dispute: the Bodélé depression, a low-lying region on the eastern fringe of the Sahara. Almost nothing grows here, amid the dunes, gravelly ground and the great plumes of dust that blot out the Sun. Even the local desert people avoid the area.

But it's confusion, not discomfort, that is causing Earth scientists Chappell and Bristow to disagree. After three hot and bumpy days of driving from Chad's capital, N'Djamena, they find themselves in a desert with a surprisingly compact, crusty surface. We're covered in dust, yet it's not clear how the very solid ground we're standing on can produce the clouds that surround us.

This simple and surprising observation will be the source of much discussion over the next two weeks. The team of seven scientists — one of the few groups of researchers ever to visit the Bodélé — will see their tents buried by dust storms, become accustomed to digging jeeps out of the sand, and develop a taste for goat stew and roast gazelle — the only fare in this barren land.

Their efforts will also shed light on one of the major players in Earth's climate. Dust affects storm formation and cloud cover, and provides minerals that fertilize the ocean and jungles thousands of kilometres away. "Features like the Bodélé turn out to be of planetary significance," says team member Richard Washington of the University of Oxford, UK. And yet little is known about exactly how much dust is produced, by what mechanism, and how much of an effect it has on the planet. So perhaps it's no surprise that Chappell, of the University of Salford, and Bristow, from Birkbeck College, London, are now troubled by what seems an easy question — just what causes the Bodélé to pump out dust at such a phenomenal rate?

The pair climb back in the jeep and put their debate on hold until dinner that evening. The seven-man team is camping nearby at Chicha, a place that is little more than a name on the map. Sights: one tree — the only one for tens of kilometres — and several pieces of abandoned weaponry. Apparent population: several dung beetles and one yellow snake.

The Bodélé was not always like this. Our camp would once have been submerged under Lake Megachad, a vast expanse of freshwater that stretched across much of the country, supporting numerous human communities on its shores. Six thousand years ago the lake receded south, and the people went with it. Today's travellers sometimes


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Choked: the Bodélé is covered in diatomite, which, when eroded, is the source of huge amounts of dust.

stumble across the remains of those long-gone settlements. On one trip we spy a pile of pottery fragments jumbled up with alligator bones, suggesting that an ancient Bodélian made a meal for the reptile (or vice versa). Later we find a human jawbone and a skull protruding from the gravelly ground, and we duly record their location for future study. "These people probably died around six thousand years ago," says Andrew Warren, an Earth scientist from University College London. "It's not inconceivable that we are the next people to come by."

Wind tunnel

To the northeast of the remains lies the geographical feature that makes the Bodélé so dusty: a gap between two mountain ranges that funnels winds onto the chalky-white desert. The ground here is not made up of sand or rock, but diatomite — the ground-up remains of microscopic freshwater creatures that once thrived in Lake Megachad. Judging from satellite photographs, most of the Bodélé is covered with this material. And those same pictures show that the wind kicks up clouds of diatomite dust that can stretch for up to 700 kilometres. Unlike other dust sources on the planet, the area seems to be active year-round, making it the largest single source of dust (see 'Measuring up', overleaf). This can make life unpleasant in nearby N'Djamena, but dust and other airborne particles have much longer-range effects as well.

Only over the past few decades have scientists begun to realize the range of dust's impact on the climate. They now know that aerosols such as mineral dust can reflect light from the Sun, cooling the land beneath. Particulate matter also encourages cloud formation, which again tends to reflect light back into space. But other aerosols — particularly carbon from fire and industry — absorb sunlight, heating the atmosphere but not the surface.

"If researchers could watch the formation of storms and dust clouds, and better forecast whether they'll collide, hurricane prediction should improve."

Combine these effects, and it seems that the overall impact of particulates is to cool the Earth, reining in the temperature increase caused by greenhouse gases. Yet our understanding of these effects is primitive and the uncertainties great — so great, in fact, that climate scientists cannot rule out the possibility that aerosols have an opposite and unwelcome heating effect.

But while dust has increasingly occupied the minds of researchers, no climate scientist has been to the Bodélé before now. It is easy to see why. A few kilometres away from our camp lies an unexploded bomb, its plump body and tail fin slanting upwards from the sand. We also find a Soviet-made jeep equipped with a rocket launcher, the armour pierced by bullet holes.

Libya and Chad fought for this area during the 1980s, one of many conflicts to have derailed Chad's development since it gained independence from France in 1960. Even now the area is turbulent. To the north, the Tibesti mountains remain off-limits due to landmines. East of us, fighting in the Darfur region of Sudan has spilled across the border. And Africa's deserts are often lawless places anyway. When we camped on the way to Chicha, our guides searched for a hollow away from the road — any lights at night could attract the attention of bandits.

Now here, the priorities for the climate researchers are working out which weather conditions produce dust, and how much sunlight that dust reflects. On arrival, Martin Todd of University College London and Samuel Mbainayel of the Department of Water Resources and Meteorology in N'Djamena, erect a weather station close to camp. That's complemented by a computer-controlled device, which will track the strength of the sunlight reaching the ground.

Up, up and away

Towards the end of the first day, as the heat recedes a little, Washington and his Oxford colleague Sebastian Engelstaedter begin a somewhat lower-tech experiment. The budget for the trip is extraordinarily tight — the main source of funding is a single grant of just £12,000 (US$22,500) from the Royal Geographical Society in London. So when Washington and Engelstaedter decided to map wind patterns by tracking the motion of helium-filled balloons, they were forced to improvise to cut costs.

Researchers usually follow the balloons by attaching electric bulbs and batteries and tracking them at night. But with more than 100 flights planned, this was beyond the pair's resources. Instead, Washington and Engelstaedter attach plastic cups containing candles to their balloons — they tested this system back in Oxford by driving around town holding the cups and candles out of the window of their car, to check that they wouldn't blow out. It turns out to work reasonably well; they manage to track the balloons for around 10 minutes, about half the time achievable using electric lights.

As someone who has spent the past 15 years of his holidays criss-crossing the Sahara in a 1960s Land Rover, Washington is undaunted by the prospect of spending two weeks at Chicha. But the others are less enamoured by the idea. On our second day in camp, the winds are strong by midday, raising a gritty cloud that obscures the horizon and gets into mouths and eyes. Laptop keyboards have to be covered with clingfilm.

Remote control: the team of researchers camp at Chicha, which has an apparent population of dung beetles and one snake.

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And when the temperature hits 40 °C by mid-afternoon, the team is forced to retreat to what the group has dubbed the 'University of the Bodélé': a tent containing camping chairs and a car stereo for entertainment.

Such weather isn't pleasant, but it's great for data collection. While the researchers huddle in tents, the information being gathered outside will help answer some basic questions with far-reaching impacts. It will determine how the size of the Bodélé dust cloud varies with wind speed, for example, and how much sunlight the plume reflects. Although satellite pictures have given a good indication of the relative dustiness of this desert, this is no substitute for data gathered from the ground. Armed with this information, modellers will be able to include the conditions and processes special to the Bodélé in their simulations for the first time.

The end result could have dramatic effects on predictions of extreme weather events — some of them on the other side of the globe. Across the Atlantic in Florida, for example, hurricanes batter the coast almost every summer, running up bills of billions of dollars. The hurricanes form from seedling storms off the west coast of Africa, and over the past few years researchers have discovered that hurricane risk is much reduced if the storm runs into dry and dusty air from the Sahara.

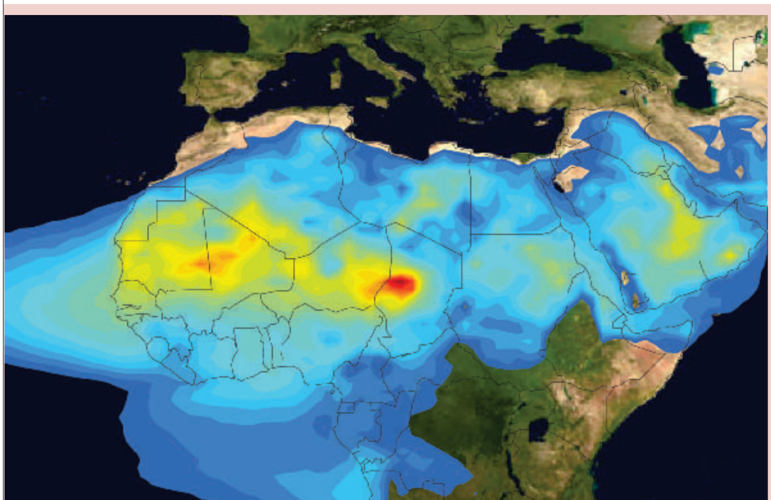
If researchers could watch the formation of seedling storms and dust clouds, and better forecast whether they may collide, hurricane prediction is likely to improve, giving extra days of warning to those on the US east coast. "We're catching hurricanes downstream now," says Jason Dunion, a hurricane researcher at the Atlantic Oceanographic and Meteorological Laboratory in Miami, Florida. "We've got to get to grips with the start of the process."

Diatomite dunes

But for the researchers out in the Bodélé, the start of that process is proving perplexing. Before the trip, they had guessed that the Bodélé was covered in talcum-powder fine deposits of diatomite. Washington has seen similar diatomite fields elsewhere in the Sahara and the team assumed that the lightweight particles could easily be whipped up into dust clouds. Wind alone will not do that — smooth air flow will flatten out and then pass over the top of fine deposits — although sand blown in from the surrounding desert could provide the necessary kick.

When we drive out in search of diatomite deposits, armed with Global Positioning System handsets and the satellite imagery as a guide, we find plenty of it, but none of it is in powder form. The white sediments are gravelly in some places, hard and chalky in others. The three Earth scientists find it difficult to fathom how even the most violent sand streams could generate dust. "You'd need an electric sander," says Chappell.

Over that evening's goat stew, the three bat around possible explanations. Bristow suggests that large particles of diatomite might collect in crescent-shaped mounds called barkhan dunes, which march slowly across the desert, blown along a few metres every year. As the wind forces grains up the gentle slope of each dune, from where they



Dishing the dirt: the Bodélé (centre) is the brightest region in this 13-year average of satellite data on the concentration of aerosols.

S. ENGELSTAEDTER

Measuring up

The Bodélé's claim to be the dustiest place on Earth rests on data from an instrument originally designed to measure ozone levels: NASA's Total Ozone Mapping Spectrometer (TOMS), launched in 1978.

TOMS measures the amount of radiation that is reflected by Earth's surface and atmosphere at ultraviolet (UV) wavelengths. Different substances in the atmosphere, including dust, reflect varying amounts of UV light at the six different frequencies that TOMS measures. Once this reflectivity signature for aerosols was identified in 1992, TOMS data could be crunched to estimate aerosol concentration.

The aerosols algorithm, developed by a team led by Jay Herman of the Goddard Space Flight Center in Greenbelt, Maryland, has now been applied to all the data generated by the four different satellites that have carried TOMS instruments since 1978. Although other satellite devices have also contributed data on dust levels, "TOMS is the only one that's truly global", says Martin Todd of University College London.

Use of Herman's algorithm reveals several hotspots. Winds send plumes of mineral dust out westwards from the coasts of Africa and eastwards from China. Land-clearing activities cause fires in equatorial Africa and southeast Asia, which also contribute clouds of smoke. But while these sources wax and wane on an annual cycle, the Bodélé pumps out dust all year round at a rate that matches the peak fluxes seen in other hotspots.

Comparing emissions from different sources is difficult, but, according to one model of global dust distribution, the Sahara produces about two-fifths of global dust emissions (P. Ginoux *et al*. *Env. Mod. & Software* **19,** 113–128; 2004), whereas the Bodélé is responsible for up to half of all the dust that leaves the west African coast (R. Washington *et al*. *Ann. Assoc. Am. Geogr.* **93,** 297–313; 2003).

A.CHAPPELL

become worried. Chappell's experiment won't produce much data on quiet days. And the climate scientists want to experience the worst the Bodélé can throw at them, so they can study the weather conditions that generate the huge dust clouds.

Back in London, I check the daily satellite imagery from the comfort of my office. And come the middle of their second week in the Bodélé, a huge plume appears. "It's a beast," Washington tells me by satellite phone. Tents were flattened and covered in sand overnight, sending the inhabitants fleeing to the jeeps at 2 in the morning. The next day, the team had to don ski goggles and masks. Out on the diatomite dunes, it was impossible to distinguish dunes from sky from ground. "It's like flying a plane on instruments," says Chappell.

Flakes and balls

But the data from those last few days, which the team is now analysing back in Britain, will make the trip worthwhile. Washington and Todd are just beginning their analysis, but they are already sure that the wind speeds needed to produce dust in the Bodélé are higher than thought. "Things start getting going at around 12–15 metres per second," says Washington. "A gentle breeze can produce dust elsewhere in the Sahara."

Bristow's theory about dust generation seems to be largely correct. The high winds seen at the end of the trip may release dust as they blow pellets of diatomite across the flat ground, he says, but most of the dust is being generated by flakes and balls of diatomite that grind against each other as the wind pushes them up and over dunes.

Chappell's data provide further confirmation. He sees more dust farther up dunes than at the bottom, and notes that the concentration of dust drops off exponentially with height above the dune tops — a pattern characteristic of a dust source.

Back in his lab in Salford, Chappell has also produced the first estimate of how fast dust flows from the Bodélé. Although the team witnessed just one major storm, the data collected revealed that an average of 40 mg of dust passed every square metre every second during that period — an emission rate that matches the highest recorded anywhere in the world.

So the satellite images that identified the Bodélé as such an important dust source seem to have proven a trusty guide. Those images can now be compared with real data from the ground — and researchers who could not join the trip are eager to get started. "All of us who look at satellite photographs are fascinated with that place," says Joseph Prospero, an expert on dust at the University of Miami in Florida. "We want to know what makes it that way." Thanks to the team from 'the University of the Bodélé' they seem to be getting their wish. ■

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plummet off the sharp edge at the top and down the protruding horns, the particles would be constantly rubbing and grinding against each other. This continual motion might break the chunks of diatomite into particles light enough to blow off the edge of the dune and into the air.

It's a good theory, but a radical one for the field. Most of the world's dust is produced by wind-driven sand bouncing over the top of dusty deposits. And barkhan dunes made from quartz sand are common in deserts, but no one has ever seen one made out of diatomite. As the rest of the camp heads to bed, most sleeping outside to enjoy the cool night, the three are still deep in debate.

But the next day we drive up to a greyish dune and discover that it is not simply coated in a fine layer of diatomite. A sample shows that it seems to be diatomite throughout, made up of chunks of particles of different sizes. "It's extraordinary," says Warren, whose 40-year career has taken him to many Saharan countries. "I don't know of anywhere else with dunes like this." As the wind picks up, we can clearly see that dust is being blown off the crest of these dunes and that the air is clearer where there are fewer dunes.

Chappell and I drive out the following day to set up an experiment that might settle the issue. Around a grey barkhan we set up ten poles, each armed with three bottles to collect sand and dust at different heights. Six poles are planted up the gentle upwind slope of the dune; four are sited off the downwind side. It's sweaty work and Chappell aims to plant 60 in all. Unexpected hitches cause further perspiration: when our vehicle becomes stuck, we shovel sand in the midday sun for an hour to free it.

Bottles on poles collect sand and dust blown off the dunes (above) while relics of the 1980s war fought between Chad and Libya remain (below).

At first, the weather is on Chappell's side. Thanks to a wind-free period, he plants poles around three dunes and the space around them in just a few days. But when the calm, clear spell continues, he and the others