Global wind patterns are shifting, with immense consequences for us all. Anil Ananthaswamy reports

Making waves
JOELLEN RUSSELL can still feel the terror of the Southern Ocean. In 1994, at the start of her career as an oceanographer, she spent two months there on a research voyage. It was a punishing trip. The winds consistently roared at near-gale force or worse, stirring up huge waves. “The waves were so big that our 300-foot ship would slide down them as if it were surfing and dig its prow into the next wave,” she says. “The wave would fall on you like a mountain of black water.”

Today, a similar voyage could well be even worse. The waves around Antarctica are growing bigger, because the westerly winds that circle the continent are shifting southwards and growing stronger. These speedier westerlies are making waves in more ways than one. The Southern Ocean might seem a world away, but what happens there affects us all.

That’s because the Southern Ocean is the door to the deep, the place where stupendous amounts of heat and carbon dioxide can enter the oceans – or escape from them. The changing winds are affecting how much goes in and out. In the short term, the deep could soak up more heat, slowing surface warming – a bit like flinging open the door on a hot day. But there are immense dangers, too. If the door opens too wide, it could let carbon dioxide from the deep oceans escape. If it slams shut instead, the surface – where we live – will warm faster and end up even hotter.

The speed-up of the winds is just one part of a global change in air circulation patterns. As CO₂ levels go up, the planet is being rezoned. The dry belts around 30° north and south are expanding and creeping towards the poles. Russell, who is at the University of Arizona, Tucson, thinks the effects can already be seen where she lives. “We are in a 13-year drought,” she says. “Dry winters mean that there is pressure on the reservoirs; you can see bathtub rings on lakes. Our cacti are a little droopy, and we have had bark beetle infestations mowing through forests, which don’t look like they are going to grow back because it’s too dry for trees.”

Sailors were the first to discover the global wind patterns, which are produced by the heat of the sun and the rotation of the Earth. In a broad zone around the equator, the winds usually blow from the east. Beyond the latitudes of 30° north or south, though, the winds blow from the west (see diagram, page 37). The hot, humid air near the equator rises, producing lots of rain and supporting lush rainforests. As surface winds rush towards

Faster winds are blowing up a storm in the Southern Ocean
The equator to replace this air, they are deflected by Earth’s rotation and so become easterlies – the trade winds. Higher up in the atmosphere, the air that rose from the equator moves polewards and descends at about 30° latitude. Under this dry, sinking air there is hardly any rainfall, creating belts of desert around the world. These great circulatory loops are called Hadley cells. On each side of them, some of the descending air flows polewards, becoming the great westerlies.

Expanding tropics

That’s the theory, anyway. In reality, changing seasons and the presence of land and mountains make day-to-day wind patterns much more complex. But the Hadley circulation dominates, and now it is changing. Human emissions have already made both Hadley cells expand by about 200 kilometres. The evidence, such as changes in average wind speeds and atmospheric pressures, is patchy but persuasive. “Each observational data set gives us a somewhat different answer, but they all [point] more or less in the same direction,” says Thomas Reichler of the University of Utah in Salt Lake City. “They all indicate that there is a widening of the Hadley cells.”

Climate models, too, show the Hadley cells expanding as the planet warms (Geophysical Research Letters, vol 36, p L03803). “It’s a very robust finding,” says Reichler.

Put another way, the tropics are expanding (Nature Geoscience, vol 1, p 21). This will widen the wet, green belt around the equator, but it will also widen the area affected by tropical storms. And the subtropics are expected to expand and get drier, too. That is bad news for the hundreds of millions who live in the dry regions poleward of the desert belts, including the Mediterranean, the US Southwest, and the southern parts of Australia, Africa and South America. “For whatever reason, people like to live in Mediterranean climates, and they may be most affected by it,” says Reichler.

We will all be affected by the wider consequences, which will range from changes in fish stocks and farming practices to, perhaps, water wars and climate refugees. There will also be feedback effects that help determine how fast and how much the planet warms – and this is where the westerlies come in.

The observed changes in these winds are indisputable (though global warming is not the only cause – see “The ozone hole isn’t helping”, left). Over the past half-century, the westerlies have been pushed towards the poles.

THE OZONE HOLE ISN’T HELPING

The westerly winds that circle the planet are shifting and speeding up as the planet warms (see main story). Their strength has increased more in the southern than the northern hemisphere, though. Why? It appears another result of human pollution – the hole in the ozone layer over Antarctica – is also altering the Hadley circulation (see right) and boosting the westerly winds.

The ozone layer soaks up ultraviolet light, protecting us from it and warming the upper atmosphere. Without the ozone, the stratosphere cools. Climate models suggest that a colder stratosphere above the pole drives faster and more southward westerlies below.

In fact, it seems the ozone hole is the dominant force driving changes in the southern hemisphere westerlies. A study out earlier this year found that the rise in greenhouse gases may be responsible for only a third of the observed changes between 1979 and 2008, with the rest attributable to the loss of ozone over Antarctica (Science, vol 339, p 563). The Antarctic ozone hole is now shrinking, thanks to the ban on ozone-destroying chemicals, so this effect should dwindle. But greenhouse gas emissions are rising faster than ever.

What happens next isn’t clear, but according to Thomas Reichler of the University of Utah in Salt Lake City, the consensus is that these competing effects will balance each other out during the next 50 years or so. After that, the southern Hadley cell will start expanding again, pushing the westerlies southwards and intensifying them even more, with consequences for the oceans’ ability to absorb heat and CO₂.
and have sped up. And that matters because of how the changing winds affect the seas. The oceans have been acting as giant sponges, soaking up half of the excess CO$_2$ we are pumping out and 90 per cent of the excess heat the planet is absorbing because of higher greenhouse gas levels. The world would have warmed much, much faster over the past century if it hadn’t been for the oceans.

The Southern Ocean is especially important, because it is the biggest “door” between the atmosphere and the oceans. The high winds and rough seas here maximise the exchange of heat and gases between air and surface waters. Most importantly, though, these surface waters readily mix with deeper waters. Because surface temperatures in the Southern Ocean are similar to those deeper down, it is relatively easy for winds to push the surface waters down or pull up deep waters. In most other oceans, a layer of warm water “floats” on top of the colder deep waters, preventing this vertical mixing. “The heat at the surface basically makes it very difficult for the ocean to overturn, regardless of the winds,” says Russell. “It means that we have this tiny moment of grace before that sink is overwhelmed.” If and when that happens, global surface temperatures will start to rise much faster.

When it comes to CO$_2$, opening the door too wide could be as dangerous as shutting it. Over the past two decades, the Southern Ocean has been soaking up as much CO$_2$ as ever, according to a 2007 study of data from weather stations collected between 1981 and 2004 (Science, vol 316, p 1735). “The carbon sink was very stable,” says team leader Corinne Le Quéré of the University of East Anglia in Norwich, UK. That might sound reassuring but it’s actually worrying. During this time, atmospheric CO$_2$ levels have risen sharply. Since the amount of CO$_2$ that dissolves in surface waters depends largely on atmospheric levels, more CO$_2$ in the air should mean more CO$_2$ entering the ocean. “This did not happen,” says Le Quéré.

The question is, why? It could be the changing winds, Le Quéré’s team suggested in 2007. Winds that churn up only the top 1 or 2 kilometres of the ocean should increase carbon uptake, as these the waters are undersaturated with CO$_2$ relative to the atmosphere. But winds that churn up deeper waters can reduce uptake or even release CO$_2$. That’s because deep waters usually contain high levels of carbon, built up over many thousands of years as organisms living in surface waters die and sink into the depths. Stirring up these depths brings this CO$_2$-rich water to the surface.

That is exactly what is happening, according to work by Darryn Waugh of Johns Hopkins University in Baltimore, Maryland, and his colleagues. They traced water movements by measuring pollutants – in this case, the very CFCs that caused the ozone hole – in samples of seawater collected in the 1990s and the mid-to-late 2000s. CFC levels reveal the degree of churn in the ocean because they are lower in deep water that rose to the surface recently than in water that has been at the surface longer.

So the shifting winds have already opened the door to the Southern Ocean wide enough to reduce its ability to soak up CO$_2$. If the door opens even wider, the ocean could even start releasing CO$_2$. This what scientists now think happened at the end of the last ice age, when atmospheric CO$_2$ levels went up from 190 to 260 ppm. The resulting warming ended the
The Hadley circulation determines the location of the deserts zones linking the wet tropics, through continents and mountains, and east-west patterns vary complex. These dry zones are now shifting polewards, but if CO₂ levels get even higher, they might suddenly move much closer to the equator.

**FLIP FLOP**

As the world warms, the tropics are spreading. It’s happening because the great spinning loops of air that girdle the planet either side of the equator, known as the Hadley cells (see above), are getting larger. They are expected to keep growing over the next century or so (see main story). But what if global warming continues? “They can’t just keep growing forever,” says William Hay of the University of Colorado, Boulder, who studies past climates.

According to a study published last year, there could be a tipping point beyond which the cells shrink rapidly and dramatically. This would cause yet more climate chaos, with the deserts suddenly moving much closer to the equator as lush tropical regions dried up.

The evidence comes from ancient sand dunes. Hitoshi Hasegawa of the University of Tokyo, Japan, and colleagues studied “fossilised” dunes in Mongolia, China and Thailand that formed during the Cretaceous, between 145 to 65 million years ago. They worked out which way the prevailing winds blew and how far north or south the dunes were when they formed, from the dunes’ shape and magnetic properties.

At present the margin of the northern Hadley cell – where air sinks and deserts form – is at about 32° latitude. In the early and late Cretaceous, when carbon dioxide levels ranged between 500 and 1000 parts per million, it was several hundred kilometres further north, at around 37°, Hasegawa’s team found. But in the mid-Cretaceous, when CO₂ levels were between 1000 and 1500 ppm, the margin moved about a thousand kilometres south, to around 27° (Climate of the Past, vol 8, p 1323). The findings suggest that there is a threshold in CO₂ levels or temperature beyond which the Hadley circulation abruptly shrinks.

This is a surprise to other researchers. “It certainly is contrary to expectation,” says Paul Valdes of the University of Bristol, UK, who models past climates. He now plans to look more closely at models to see whether they produce this effect.

It could be that the shrinkage was caused by a factor peculiar to the Cretaceous, rather than high CO₂ levels, Valdes says. Or Hasegawa’s findings might reflect variations in prevailing winds rather than the Hadley cells. “The Hadley circulation is surprisingly difficult to see,” Valdes says.

Or perhaps they do not give a true picture, says Thomas Wagner, of Newcastle University in the UK. There are huge uncertainties in working out past latitudes, he says, and his team’s study of Cretaceous seas found no evidence of shrinking Hadley cells. “We see the exact opposite,” Wagner says.

But Hay, who recently reviewed what we know about the Cretaceous climate, thinks Hasegawa’s hypothesis is plausible. The world was very different during the Cretaceous, he points out.

“The changes taking place now fit the various things that we knew about the transition out of the last ice age,” says Robbie Toggweiler of the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. Fortunately, there is less stored CO₂ in the deep Southern Ocean today than 20,000 years ago. “We are in the state now where there is relatively little excess carbon dioxide in the deep ocean, so there isn’t as much to come out,” Toggweiler says.

But any decline in the oceanic sink, let alone release of CO₂, would be bad news. One recent study points to a disturbing picture. Before the end of the century, the world could be 2 to 3°C warmer, as it was during the mid-Pliocene warm period 3 million years ago. Studies of ocean sediments had seemed to show that the most active ocean circulation system back then was the Atlantic Meridional Overturning Circulation – in which cold, saline waters sink to the bottom of the North Atlantic and head south. Yet climate models suggest the Atlantic circulation weakens in a warmer Earth.

This contradiction has been resolved by a new study of sediments by Ninnemann and colleagues, which shows that although overturning in the Atlantic was weaker, it was stronger in the Southern Ocean. The loss of sea ice around Antarctica, along with faster winds, may have allowed mixing to occur in waters that today are cut off from the atmosphere, Ninnemann says.

If this happens again, it would be bad news. “It could stir the deep water up that has the CO₂,” says Ninnemann. In fact, it’s a double whammy, because the sinking water in the North Atlantic also carries a lot of CO₂ down into the deep ocean. “We’d be switching from a big sponge to the thing that helps release it,” he says.

It’s no wonder, then, that oceanographers are intensely studying the Southern Ocean and the winds whipping it into a frenzy. The dangers of messing with this door to the deep are immense. If we open the door too wide, we could release some of the CO₂ bottled up in deep waters. And if we slam the door shut, much more heat and CO₂ will stay in the atmosphere. What’s more, if the door does shut, there’ll be no way to open it again anytime soon. “That might be considered a tipping point,” Russell says.

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Additional reporting by Michael Le Page