FANC proteins). This is consistent with genetic evidence that FANC proteins are required in the two-tier system that protects against acetaldehyde damage. However, the authors unexpectedly discovered that about half of the crosslinks are fixed by a second, faster mechanism. Further investigation revealed that this second route also involves DNA replication, but is independent of the FA pathway.

Surprisingly, in the fast repair route, no cuts are made to the DNA strands; instead, the ICL is probably cut within the crosslink. This mode of repair results in the reversion of the crosslink to an undamaged base on one of the DNA strands, but leaves an adduct on the other strand (Fig. 1), which specialized DNA-replication enzymes can bypass to complete repair. This mechanism is reminiscent of the one that fixes ICLs generated by the drug psoralen[11], but involves different enzymes. By avoiding DNA breaks — which are associated with genomic rearrangements, one of the hallmarks of cancer and ageing — the fast repair mechanism has an important advantage over the FA pathway. Taken together, Hodskinson and colleagues' findings provide a holistic glimpse of how acetaldehyde-derived crosslinks are cleared from DNA, and support the idea that these lesions contribute to FA.

The authors do not identify a protein that cleaves the crosslinks in the newly described repair route. One can therefore only speculate as to whether cleavage occurs spontaneously as a consequence of mechanical forces generated during replication as the DNA unwinds, or is the result of enzymatic activity. If it is indeed an enzymatic process, identifying the components of the pathway will be a challenge, but could open up opportunities for therapies: stimulation of the pathway might alleviate the symptoms of FA, or reduce the incidence of alcohol-derived cancers.

The identification of the protein(s) involved in the crosslink cleavage would also allow *in vivo* experiments to test whether impairment of the alternative repair route increases acetaldehyde toxicity, especially under conditions in which this molecule is not detoxified by metabolism. Furthermore, mutations in the genes encoding proteins involved in this pathway might reveal the existence of a new group of people who have an FA-like disorder. In the meantime, Hodskinson and colleagues' study underlines the need to develop better assays to study ICLs and other types of DNA damage in cells. By studying the repair of specific DNA lesions induced by compounds such as acetaldehyde, or other mutagens that arise in the body, we are likely to uncover other cellular defence mechanisms against cytotoxic DNA damage.

Irene Gallina and **Julien P. Duxin** are in the Faculty of Health and Medical Sciences, Novo Nordisk Foundation Center for Protein Research, University of Copenhagen, DK-2200 Copenhagen, Denmark.
e-mail: julien.duxin@cpr.ku.dk

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Atmospheric science

Jet stream stops shifting as ozone layer recovers

Alexey Yu. Karpechko

The Antarctic ozone hole shifted the jet stream in the Southern Hemisphere poleward, leading to hemisphere-wide climatic changes. But the Montreal Protocol, which banned ozone-depleting substances, has halted the shift. **See p.544**

The discovery[1] of a hole in the springtime atmospheric ozone layer over the Antarctic in the mid-1980s revealed the threat posed by human-made ozone-depleting substances (ODSs): the damage caused by these compounds exposes people and Earth's ecosystems to harmful ultraviolet radiation. A related, unexpected effect was revealed in the early 2000s, when studies[2,3] showed that the Antarctic ozone hole, which resides at altitudes of around 10–20 kilometres, has affected atmospheric circulation all the way down to the surface in the Southern Hemisphere — most notably, by shifting the summertime jet stream poleward. The production and use of ODSs was banned by the Montreal Protocol of 1987 and its subsequent amendments. Atmospheric ODS concentrations are therefore decreasing, and the first signs of ozone-layer recovery have emerged[4,5]. On page 544, Banerjee *et al.*[6] report that the hole-associated circulation effects have paused since ozone recovery started.

Stratospheric ozone absorbs ultraviolet solar radiation, and the absorbed energy heats the stratosphere, the atmosphere's second-lowest layer. Consequently, ozone depletion and the related lack of heating cool the stratosphere — indeed, the Antarctic springtime stratosphere cooled by about 7 °C between the late 1960s and late 1990s as a result of the ozone hole[2]. This cooling increased the north–south temperature gradient between the southern mid-latitudes and the Antarctic, which strengthened the stratospheric westerly winds in the Southern Hemisphere and, in turn, caused a poleward shift of the jet stream in the troposphere (the lowest layer of the atmosphere).

It is not obvious why changes to stratospheric winds affect circulation in the underlying troposphere. The stratosphere represents only about 15% of the atmospheric mass, and therefore, when in motion, has much less momentum than the troposphere. Yet observations and computational modelling confirm that the tropospheric jet stream is sensitive to changes in stratospheric winds at monthly, seasonal and decadal timescales, and that the cooling of the polar stratosphere is associated with a poleward shift of the tropospheric jet stream[7].

By the end of the twentieth century, the summertime tropospheric jet stream had shifted by about 2° of latitude, altering the transport of atmospheric heat and moisture. This contributed to warming of the Antarctic Peninsula, Patagonia and New Zealand, and to drying of western Tasmania and western New Zealand, and affected the circulation, temperature and salinity of the Southern Ocean[8,9]. A cessation of the tropospheric-circulation trends since the beginning of the twenty-first century has previously been noted[10], but Banerjee and colleagues are the first to formally attribute it to the effects of the Montreal Protocol.

The authors had to overcome several difficulties to demonstrate that the poleward shift has paused, and to attribute the pause to changes in stratospheric ozone levels. First, the natural year-to-year variability of atmospheric circulation in the mid- and polar latitudes is large, which makes it challenging to detect atmospheric-circulation trends in those regions[11]. Therefore, even though no

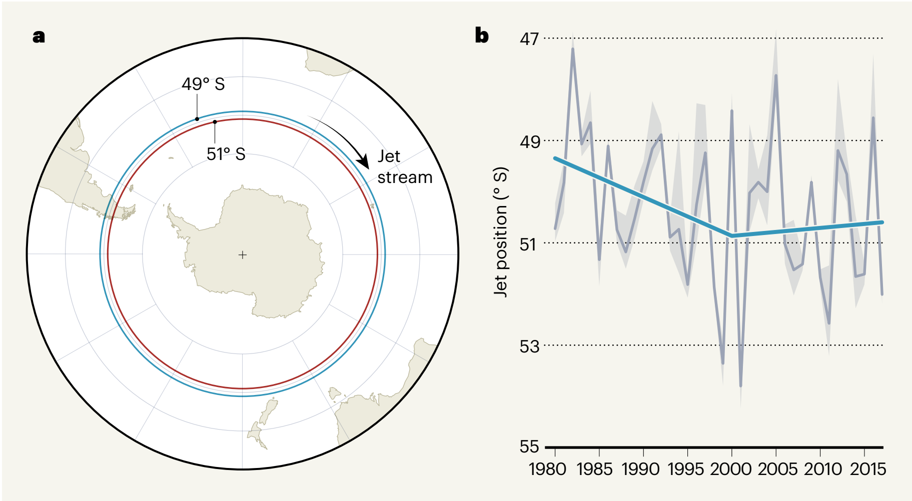

Figure 1 | Changes in the summertime jet stream in the Southern Hemisphere. a, The jet stream in the Southern Hemisphere forms a near-circle around Antarctica in the troposphere — the lowest layer of the atmosphere. **b**, Banerjee *et al.*[6] have reanalysed data that record the position of the summertime jet stream during the past few decades. The grey line shows the average position determined from their analysis; the envelope around the line indicates the minimum to maximum range. The blue line indicates the underlying trend, and shows that the jet stream shifted from about 49° S to 51° S between 1980 and 2000 — the years when the stratospheric ozone layer over Antarctica was becoming depleted. The trend alters after 2000, when the ozone layer began to recover as a result of the Montreal Protocol, which banned ozone-depleting substances; the position of the jet stream did not alter significantly during this period. Banerjee and colleagues show that ozone recovery is the cause of the pause in the jet-stream shift. (Graph from Fig. 1b of ref. 6.)

statistically significant poleward shift has been observed since 2000 (as Banerjee and co-authors report; Fig. 1), this is the first time that the lack of statistically significant trends has been shown to represent a genuine pause in the shift.

Another difficulty is working out which of the many factors that simultaneously affect atmospheric circulation is responsible for the pause. Banerjee and co-authors addressed this problem by carrying out multiple computational simulations using climate models. One group of simulations aimed to reproduce the observed climate change, and thus accounted for all known factors: anthropogenic factors such as increasing greenhouse-gas concentrations, and changes in atmospheric levels of ozone and ODSs; and natural factors, such as volcanic eruptions and solar cycles. These model simulations faithfully reproduced observed climate variability, including the poleward shift of the jet streams during the ozone-depletion period (from the late 1970s to 2000), and cessation of the shift thereafter.

Further experiments were conducted in which only one or a few factors at a time were included in the models. This allowed Banerjee and colleagues to estimate the contribution of each factor to the circulation trends. They found that only simulations that accounted for changes in ODS levels and associated changes in ozone concentration reproduced both the poleward shift of the jet streams during the depletion period and the subsequent pause. Increases in greenhouse-gas concentrations, by contrast, pushed the tropospheric jet poleward during both ozone depletion and recovery periods. Other factors, such as changes in aerosol levels or solar variability, did not have a statistically significant effect on the simulated trends.

Banerjee *et al.* also showed that their results are relatively insensitive to the details of the model formulations. For example, some models included atmospheric chemical reactions and explicitly calculated the amount of ozone depletion and recovery from ODS emissions. However, these models did not include interactions between the ocean and the atmosphere, and therefore would miss any ocean–atmosphere feedbacks that might affect the tropospheric trends of interest. Another set of models did include ocean–atmosphere interactions, but did not include interactions between atmospheric chemistry and physics, and thus could not reproduce any chemistry–climate feedbacks. Regardless of the nuances of the models, a similar picture emerged: the tropospheric circulation trends stopped when ozone recovery started.

"The results provide a clear signal that human actions can affect Earth's climate."

So, what are the implications of these findings? First, the results show that — at least, during the past 20 years — ozone recovery exerted a strong enough force on the tropospheric circulation to overcome the opposing effect of greenhouse-gas increases. This is a crucial contribution to the long-standing debate about the relative role of these two factors in past and future circulation trends[12]. There is, however, no guarantee that the effects of ozone will dominate these trends in the future. As ozone levels continue to recover, their rate of change and the associated influence on climate will weaken, increasing the relative role of greenhouse-gas increases, especially in 'business-as-usual' scenarios in which nothing is done to abate future greenhouse-gas emissions. Such emissions increases might therefore dominate future tropospheric-circulation changes, and push the jet stream back towards the pole.

Second, the findings add to the evidence that stratospheric changes can affect the climate in the troposphere. This is important because, despite decades of research, the exact mechanism of stratosphere–troposphere coupling is poorly understood[7]. The lack of understanding does not compromise Banerjee and colleagues' results, but more research is needed to increase confidence in future climate-change projections.

Finally, the authors' results provide a clear signal that human actions can affect Earth's climate: the Montreal Protocol has paused the climate change associated with ozone depletion. This is an object lesson in how the international community should react to global environmental challenges. Restricting dangerous emissions and changing business practices is also the way to combat global warming caused by greenhouse gases.

Alexey Yu. Karpechko is at the Finnish Meteorological Institute, Meteorological Research Unit, PO Box 503, Helsinki FI 00101, Finland.
e-mail: alexey.karpechko@fmi.fi

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