these additional feedbacks, to justify their 350-p.p.m. target. But is it coherent to include these feedbacks? If stabilizing at 350 p.p.m. would prevent the collapse of the polar ice sheets, why use a value for climate sensitivity that assumes the ice sheets melt?

The same problem applies to the radiative forcing boundary of one watt per square metre (W m^{-2}) suggested by Rockström *et al.* We cannot categorically rule out the possibility that our descendants may need to steer CO_2 levels back below 350 p.p.m. or reduce radiative forcing to less than 1 W m^{-2} to avoid dangerous climate change, but it would be equally wrong to suggest that current evidence indicates this is the most likely course they will have to take.

There is, however, one important respect in which aiming for 350 p.p.m., even without a date attached, may be a helpful target. For reasons that do not depend on carbon-cycle models, 15–20 per cent of CO_2 emissions remain in the atmosphere more or less indefinitely, until removed by chemical weathering or active sequestration (*Proc. Natl Acad. Sci. USA* **106,** 1704–1709; 2009). Because of this lingering CO_2, emitting 1 trillion tonnes of carbon over the entire 'anthropocene' era — half of which has already been released — would increase the long-term equilibrium CO_2 concentration to at least 350 p.p.m. Hence 'target 350' implies, at a minimum, that we limit net anthropogenic carbon emissions to less than one trillion tonnes. But there is no need to invoke a long-term climate sensitivity of 6 °C or to speculate about multi-century draw-down of CO_2 to justify limiting cumulative carbon emissions to less than one trillion tonnes: this is simply what we need to do to keep the most likely peak CO_2-induced warming below 2 °C (*Nature* **458,** 1163–1166; 2009).

The importance of cumulative emissions implies that, as far as climate change is concerned, the atmosphere should be treated as an exhaustible resource, which does not seem to fit into the framework of 'planetary boundaries within which we can safely continue to operate indefinitely' at all. Indeed, attempting to define time-invariant boundaries on atmospheric composition and radiative forcing focuses attention on quantities such as the long-term climate sensitivity that are very difficult to constrain, implying that the science is less certain than it actually is. There is no need to speculate about the behaviour of the climate system into the next millennium to make the case that emission reductions are urgently needed to avoid dangerous climate change.

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Identifying abrupt change

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Five per cent is a reasonable limit for acceptable ozone depletion, but it doesn't represent a tipping point.

The use of planetary boundaries to estimate a safe operating space for humanity is a very interesting and useful concept. In this week's issue of Nature, Rockström *et al.* (*Nature* **461,** 472–475; 2009) define acceptable limits for Earth-system processes in such a way that crossing a boundary would risk triggering abrupt or irreversible environmental changes that would be very damaging or even catastrophic for society.

As a boundary for stratospheric ozone depletion, they choose a five-per-cent decrease in column ozone levels — that is, in the total amount of ozone in the atmospheric column — for any latitude, with respect to 1964–1980 levels. Their choice is reasonable, but a bit arbitrary.

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Although Rockström *et al.* also identify the appearance of the Antarctic ozone hole as a tipping point, it is not connected to this five-per-cent boundary, which is still well within the bounds of linear behaviour for global ozone loss.

Arguably, a more relevant tipping point is reached when certain substances containing chlorine and bromine trigger massive ozone depletion at all latitudes. This abrupt change results from the same non-linear behaviour of ozone-depleting chemical reactions that causes the Antarctic ozone hole. Such potential change was referred to early on as the 'chlorine catastrophe' and has been more recently analyzed by Newman *et al.* (*Atmos. Chem. Phys. Discuss.* **8,** 20565–20606; 2008). They show that if chlorofluorocarbons (CFCs) had not been regulated by the Montreal Protocol, ozone-hole chemistry would appear in the tropical lower stratosphere in about 2052, leading to complete lower-stratospheric ozone loss by 2058, assuming growth of three per cent per year in the manufacture of CFCs. This corresponds to about a 60-per-cent decrease in column ozone levels, triggered by an atmospheric concentration of effective equivalent stratospheric chlorine (EESC) of about 30 parts per billion (p.p.b.). EESC is calculated by summing total stratospheric chlorine and bromine levels, and it quantifies their combined effect on ozone depletion in the stratosphere. The Montreal Protocol limited EESC to about 4 p.p.b., leading to a maximum total ozone loss of roughly five to six per cent.

So while the choice of a five-per-cent decrease in column ozone levels as the boundary for stratospheric ozone depletion appears reasonable, one could argue that a more realistic boundary is 10 or even 20 p.p.b. of EESC. Either of these boundaries would still maintain a safe distance from the 30-p.p.b. tipping point that would lead to massive ozone loss; a 10-p.p.b. EESC boundary, for example, would lead to about 15 per cent total stratospheric ozone loss.

World leaders decided to ban the industrial production of CFCs early enough that the decrease in stratospheric ozone was limited to about five per cent. Although the non-linear behaviour of lower-stratospheric ozone loss was not even a consideration in the discussions that led to the CFC ban, the decision was well-justified in light of the potential damage to human health and to ecological systems from an ozone loss greater than five per cent. It also made sense because of the CFC ban's relatively small cost to society, given that replacement compounds could be developed.

In summary, the planetary boundary concept is a very important one, and its proposal should now be followed by discussions of the connections between the various boundaries and of their association with other concepts such as the 'limits to growth'. Importantly, this novel concept highlights the risk of reaching thresholds or tipping points for non-linear or abrupt changes in Earth-system processes. As such, it can help society to reach the agreements required for dealing effectively with existing global environmental threats, such as climate change. Stratospheric ozone depletion was properly dealt with well before crossing the boundary that would trigger an abrupt change of global proportions, but well after reaching the tipping point that caused the Antarctic ozone hole — a regional, episodic event. A five-per-cent decrease in ozone might be appropriate as a planetary boundary, but that's only true if the concept is expanded to include limits that are well within the linear regime for that Earth-system process.

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The devil is in the detail

DAVID MOLDEN

A global limit on water consumption is necessary, but the suggested planetary boundary of 4,000 cubic kilometres per year is too generous.

Planetary boundaries are a welcome new approach in the 'limits to growth' debate. For one thing, they shift our attention to the scale of planetary systems being altered by human activity. As a scientific organizing principle, the concept has many strengths. What scientists persistently ignore is the unpleasant fact that a good scientific concept isn't necessarily a good communications platform. In that sense, it will take much more than the presentation of a novel concept to spur action. It is imperative that we act now on several fronts to avert a calamity far greater than what we envision from climate change alone.

The key element in the planetary boundary framework is the provision of numerical target values for process variables that represent the boundaries. Rockström *et al.* (*Nature* **461,** 472–475; 2009) provide first estimates for seven of nine environmental parameters by synthesizing available knowledge. It could be argued that with our limited understanding it is impossible to present reasonable numbers, or that the borders are much more malleable than the boundaries suggest, and with better or worse management, boundaries can be moved. Moreover, global values mask important issues at regional and local scales and conceal variability. On the other hand, the numbers are important because they provide targets for policymakers, giving a clear indication of the magnitude and direction of change. They also provide benchmarks and direction for science. As we improve our understanding of Earth processes and complex inter-relationships, these benchmarks can and will be updated.

So what are we to make of the water boundary suggested by the authors? Here at the International Water Management Institute, experience tells us that there are physical limits to human intervention into