(1971–2000) and possible future (2041–2070) climate conditions.

As shown in previous studies, the authors find that more-intense storms occur in a warmer world. However, the ability of the model to simulate hail generation in thunderstorms enables them to directly estimate future proportions of rainfall and hail. The results indicate that in a warmer world hailstones melt, with few ever reaching the ground. This is not entirely a good news story, however, because the disappearance of hail is accompanied by substantial increases in rainfall intensity, as the hail is converted into rain. Therefore flash flooding appears to be more likely, potentially exacerbating an existing concern in this region[6].

In all numerical modelling studies of this kind, confidence in such a prediction is improved if the model in question is able to skilfully simulate the current climate, and in this study there remains some room for improvement. The simulated freezing level in this study is higher than observed, and so all other things being equal, this would mean that their simulated hailstones would be more likely to melt in the current climate than occurs in reality. Add the additional warmth due to climate change and the stones would be even more likely to melt. Thus the prediction that summer hail will largely disappear from Colorado in the future may be overstated. To improve confidence in this result, it will need to be confirmed using other modelling systems and for other locations with similar climates.

The importance of the work of Mahoney and co-workers is that it predicts that increases in thunderstorm intensity owing to climate change will not necessarily be accompanied by more-damaging hailstorms. Even so, it seems hard to avoid the conclusion that rainfall intensities will probably increase in many thunderstorm-prone locations worldwide, with consequences for infrastructure and emergency-management strategies. ❐

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Figure 1 | Hail-producing storm clouds. Hailstones from storms such as this cause significant property and crop damage each year. Although these clouds are imposing in the landscape, the processes involved in their formation are small compared with the 100-km scale of global climate models, making prediction of changes with climate change challenging.

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References

1. IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field, C. B. *et al.*) (Cambridge Univ. Press, 2011).
2. Mahoney, K., Alexander, M. A., Thompson, G., Barsugli, J. J. & Scott, J. D. *Nature Clim. Change* **2,** 125–131 (2012).
3. Phillips, V. T. J., Pokrovsky, A. & Khain, A. *J. Atmos. Sci.* **64,** 338–359 (2007).
4. Niall, S. & Walsh, K. J. E. *Int. J. Climatol.* **25,** 1933–1952 (2005).
5. Xie, B., Zhang, Q. & Wang, Y. *Geophys. Res. Lett.* **35,** L13801 (2008).
6. McKee, T. B. & Doesken, N. J. *Colorado Extreme Storm Precipitation Data Study* Climatology Report 97–1 (Colorado State Univ., 1997).

SOCIO-ECONOMIC DEVELOPMENT

Carbon emissions and sustainability

An analysis shows that when consumption-based emissions are accounted for in a sustainable-development framework, carbon-exporting countries are systematically disadvantaged relative to carbon-importing countries.

Tapas Mishra

If you had asked a common man in the pre-industrial era what worried him the most in life, the reply would have been 'income'. Fast forward the clock one and a half centuries to the present day and the answer may well now be 'pollution'. As well as reflecting on the negative effects of mass consumption and production, this answer also sheds light on the role of trade on greenhouse-gas emissions and consumption. Emissions produced, consumed and exported beyond national boundaries significantly affect socio-economic conditions. Writing in *Nature Climate Change*, Steinberger and colleagues[1] extend research on trade's growing impact on greenhouse-gas emissions[2], and introduce an empirical strategy to unravel many hidden dynamics and pathways of human development for both developed and developing countries.

When people talk of emissions they usually mean emissions produced within the territories of a particular nation. In contrast, consumption-based emissions accommodate the uncertainties due to the nature of production and pattern of consumption resulting from international trade, and therefore transcend national boundaries. Both developed and developing economies are facing the dilemma of how to maximize both economic growth and long-term sustainability. Importantly, legal enforcement of emission standards leads developed economies, which have historically been high polluters, to importing products from developing countries rather than producing them at home. As developing economies need to catch up and converge with the developed ones, a high volume of production with improved technology and growth gains through exporting seems to be the only option.

Both strategies, however, significantly affect the development pathways across nations, enabling some to gain more in terms of socio-economic development than others. Steinberger *et al.*[1] have tried to identify blocks of countries enjoying better development gains, and the specific level of income required for both environmental sustainability and a high level of development. An important aspect of the study is the way that it combines environment, demography and economics together. Analysing these systems together is not straightforward, because they have distinct characteristics. Previous studies have investigated links between pollution and economic growth, economic growth and human population demography, or population and emissions. The simultaneous integration of the three systems requires either consideration of a common factor (in this case, emissions from consumption and production, which directly affect economic growth and, indirectly, life expectancy, fertility and mortality rates), or studying the properties of these systems together over a specified period of time. The latter can be achieved by modelling how an unexpected change affects the system as a whole[3]. Based on recent research, however, Steinberger and colleagues follow the former approach.

The main contribution of the study is to quantify the effect of consumption-based emissions on economic development (measured as per capita income) and human development (proxied by life expectancy at birth). The authors test the hypothesis that, in contrast to territorial emissions, consumption-based emissions — which include the carbon embodied in all goods and services consumed in a country — should reflect socio-economic benefits. The methods used by Steinberger and colleagues are well established, and the results are intuitive and fascinating. For instance, the authors find that life expectancy (the indicator of human development) is compatible with low carbon emissions, but that high incomes are not. This result reflects recent findings in population biology — for example, it has been found that male and female fertility are severely affected by environmental pollution[4]. Their result also conforms to the environmental Kuznets curve hypothesis, which postulates an inverted U-shaped relationship between environmental quality and per capita income[5].

The central development question addressed by Steinberger and colleagues is whether it is developed or developing countries that gain more from trade of carbon-embodied goods and services. They find that carbon-exporting countries perform worse than carbon-importing countries in terms of socio-economic advancement, exceptions being India and China, which are relatively close to the global trend. They classify carbon-importing countries according to socio-economic status and find that the poorest classes are hit the most because they have to import not just energy itself but also carbon-intensive goods and services from the global market. Steinberger and colleagues argue that, when trade is taken into consideration, countries with low income levels require higher carbon emissions than previously assumed in international policy debates.

Many of the study's results depend on the examination of pair-wise relationships (such as carbon emissions and life expectancy, and carbon emissions and income) for both territorial-based and consumption-based emissions under the assumption of unidirectional causality. However, there is no *a priori* reason to believe that unidirectional causality would be maintained over the years. The unique feature of the analysis, however, is the simultaneous consideration of emissions, income and human development that makes it possible to study how a change in any of the three dimensions affects the whole system.

Recent work[6] has shown, for example, that for developed countries the demography–economic growth and emissions relationship is quite stable over time, but for developing countries it is highly volatile. This may tie in with the great diversity in national emissions pathways and their responses to human development found by Steinberger and colleagues.

It has been argued that nations could achieve low carbon emissions, high life expectancy and high income simultaneously. The evidence provided by Steinberger and colleagues suggests that it is possible to achieve simultaneous environmental and social sustainability (in the form of low carbon emissions and high life expectancy), but only at levels of income below US$12,000 per capita. Although certain desirable outcomes are possible in view of current development perspectives — such as high life expectancy and low carbon emissions — economic and environmental goals seem to be at odds with each other, at least at the highest levels of per capita income. The main outcome of the work by Steinberger *et al.* is that consumption-based carbon emissions can better reflect human-development and income pathways. The onus is now on national heads at the international negotiation table to take responsibility rather than strategically passing the buck. ❐

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References

1. Steinberger, J. K., Roberts, T., Peters, G. & Baiochhi, G. *Nature Clim. Change* **2,** 81–85 (2012).
2. Peters, G. P., Minx, J. C., Weber, C. L. & Edenhofer, O. *Proc. Natl Acad. Sci. USA* **108,** 8903–8908 (2011).
3. Coondoo, D. & Dinda, S. *Ecol. Econ.* **65,** 375–385 (2008).
4. Strokum, H. *J. Indust. Med.* **24,** 587–592 (1983).
5. Kuznets, S. *Am. Econ. Rev.* **45,** 1–28 (1955).
6. Azomahou, T. & Mishra, T. *Stochastic Environmental Effects, Demographic Variation, and Economic Growth* UNU-MERIT Working Paper Series 016 (United Nations University, Maastricht Economic and Social Research and Training Centre on Innovation and Technology, 2009).

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