

on poor countries is alarming (Fig. 1). Without any climate policy, the impact of climate change on poor countries' economies would be a 40% income reduction by the end of the century, compared with a 12% income reduction according to the original damage function.

What does this mean for the SCC? With the original damage function, the estimated SCC was US\$33, which is of the same order of magnitude as the value currently used by the US government¹. The authors find that the new damage function increases the SCC to a whopping US\$220. Using such a value would have a major impact in evaluations of projects that involve a change in CO₂ emissions.

So how certain are we about the new projections? Not very, judging by the sensitivity analyses. The SCC estimate by Moore and Diaz is particularly sensitive to: uncertainties in the underlying data about the relationship between temperature shocks and economic growth; assumptions about how well society can adapt to warming; and the long-term resilience to global warming. The last of these factors is the most interesting, as it has the largest impact on SCC estimates.

In fact, the SCC could even be lower than the one obtained with the original damage function if resilience strongly increases with economic growth.

The sensitivity of the SCC estimate to the long-term resilience of economies to global warming leads us to the crucial question here: why are the negative impacts of warming so much higher in poor countries? Is it because on average poor countries have a hotter climate than rich countries and therefore are more vulnerable to even higher temperatures? Or is it simply because they are poor and therefore less able to adapt? If the former, using a (much) higher value for the SCC and stronger climate action might very well be warranted. If the latter, strong policies to curb CO₂ emissions, which will lead to significant costs thereby slowing economic growth, may not be. Of course, rapid economic growth could increase the probability of catastrophic events, but current data on temperature shocks and economic growth cannot inform us about that.

Whilst a number of questions still need to be answered before policy decisions can be made, Moore and Diaz clearly show

that historical data about the effects of temperature shocks on economic growth point to a much higher negative welfare impact of climate change on poor economies than previously thought — a result that calls for increased attention to the most vulnerable nations in the world □

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References

1. Interagency Working Group on Social Cost of Carbon *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (US Government, 2013).
2. Moore, F. C. & Diaz, D. B. *Nature Clim. Change* **5**, 127–131 (2015).
3. Pindyck, R. S. *J. Econ. Lit.* **51**, 860–872 (2013).
4. van den Bergh, J. C. J. M. *Ecol. Econ.* **48**, 385–393 (2004).
5. Hof, A. F., den Elzen, M. G. J. & van Vuuren, D. P. *Glob. Environ. Change* **18**, 412–424 (2008).
6. Calel, R., Stainforth, D. A. & Dietz, S. *Climatic Change* <http://dx.doi.org/10.1007/s10584-013-0911-4> (2013).
7. Weitzman, M. L. *J. Publ. Econ. Theory* **14**, 221–244 (2012).
8. Pindyck, R. S. *J. Environ. Econ. Manage.* **63**, 289–303 (2012).
9. Moyer, E. J., Woolley, M. D., Glotter, M. J. & Weisbach, D. A. *Climate Impacts on Economic Growth as Drivers of Uncertainty in the Social Cost of Carbon Working Paper 13-02* (Center for Robust Decision Making on Climate and Energy Policy, 2013).
10. Dell, M., Jones, B. F. & Olken, B. A. *Am. Econ. J. Macroecon.* **4**, 66–95 (2012).

ATMOSPHERIC SCIENCE

Extreme La Niña events to increase

How climate change will impact the natural phenomenon La Niña, the counterpart of El Niño, has been unclear. In spite of uncertainty, now a study shows a large model consensus for an increasing frequency of extreme La Niña events.

Antonietta Capotondi

Every two-to-seven years, cooler than normal conditions in the tropical Pacific Ocean, known as La Niña, drive atmospheric circulations that generate extreme weather events in many parts of the world, such as droughts, floods, and enhanced hurricane activity. These far-reaching impacts are particularly devastating for the strongest La Niña events. During the extreme 1998–1999 event the severity of droughts, floods, mudslides and hurricanes claimed thousands of people's lives, displaced millions, and caused dramatic economic losses in many parts of the world¹. The physical mechanism of La Niña in the present climate is relatively well understood. However, there has been no consensus among climate models on how La Niña will change in a warming

world². Writing in *Nature Climate Change*, Wenju Cai and colleagues³ find a robust agreement among climate models concerning changes in La Niña — extreme events will become more frequent with global warming.

Usually, the eastern tropical Pacific is dry and cool, whereas the western Pacific is characterized by the warmest waters of the world ocean, accompanied by prodigious tropical rainfall (Fig. 1a). These average conditions are maintained by winds at the ocean surface which blow from east to west. During normal La Niña events surface easterly winds intensify, causing cooler and dryer conditions to develop in the central equatorial Pacific that lead to an increased temperature difference with the Maritime Continent, the area of the world that comprises parts of southeastern

Asia, Indonesia, and the Philippines. Tropical precipitation is shifted westwards, bringing enhanced rainfall over the Maritime Continent. These conditions are further intensified during extreme La Niña events: the central equatorial Pacific is much colder and drier, and rainfall is further enhanced in the far western Pacific (Fig. 1b).

How can extreme cold events become more frequent in a warmer climate? Climate change simulations show that the surface easterly winds, which are stronger during La Niña events and play a key role in their development, will on average weaken with global warming⁴, making the increased frequency of extreme La Niña episodes even more counterintuitive. According to Cai and colleagues there are, however, several inter-related factors that

may conspire to allow for more frequent extreme La Niña events. First, the land surface of the Maritime Continent warms faster than the central Pacific Ocean in a warmer world, and the increased temperature gradient between the two can drive stronger anomalous easterly winds. These anomalous winds not only displace warm water westward and poleward, but also bring colder water from the deep ocean closer to the surface. Since the ocean surface warms more than the deeper ocean with climate change, the temperature difference between the two is expected to increase with global warming. As a result, the deeper waters that are brought closer to the ocean surface will produce relatively colder surface anomalies. A colder central Pacific will in turn further increase the temperature gradient with the Maritime Continent and result in even stronger winds, a reinforcing feedback favouring the growth of the cold anomalies to extreme conditions. A recent study by some of the same authors⁵ has shown that El Niño, the warm phase of the El Niño Southern Oscillation phenomenon, will also be characterized by more frequent extreme occurrences in a warmer climate. Extreme El Niño events modify the subsurface ocean, and create favourable conditions for the development of an extreme La Niña event, an additional factor contributing to the increased frequency of extreme cold events. Indeed, the extreme La Niña event of 1998–1999 followed the record strong 1997–1998 El Niño event. Similarly, Cai and colleagues find that a large fraction of extreme La Niña events in the models tend to occur after an extreme El Niño event. This result has very important implications. It not only shows that events associated with devastating impacts on the world climate and economies will become more frequent, but they may shortly follow other devastating effects of somewhat opposite sign.

The study of Cai and colleagues is based upon a collection of state-of-the-art climate models. However, individual model representation of La Niña may be inaccurate⁶. Some models may, for instance, produce La Niña events that are stronger than those occurring in nature, raising the issue of whether the models operate in a realistic regime. The agreement among several different models seems to indicate that the findings of Cai and colleagues may not be affected by the details of the model simulations. Uncertainties also exist about the model representation of climate change. The increased frequency of extreme El Niño events, which plays a

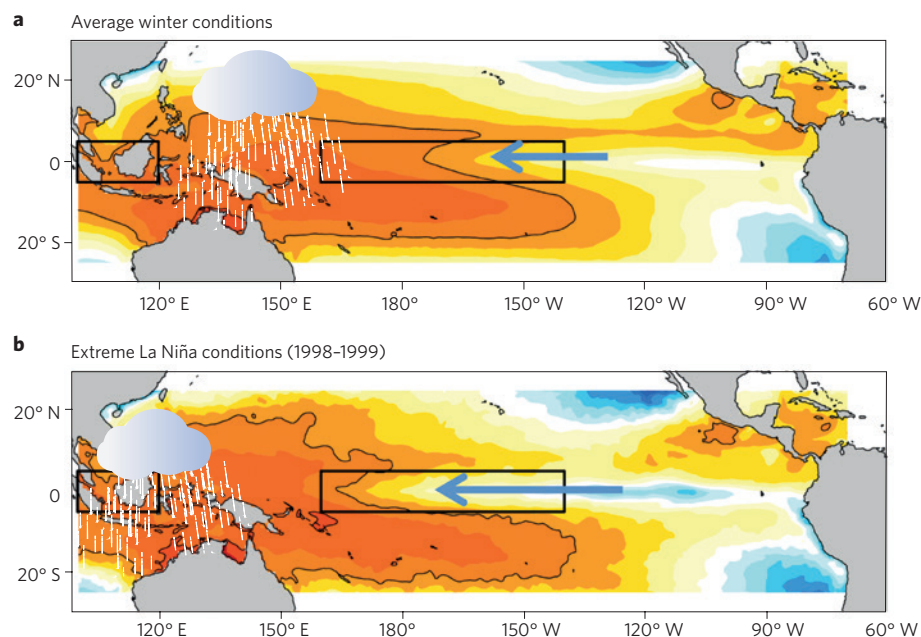


Figure 1 | Illustration of extreme La Niña conditions. **a**, Average sea surface temperature conditions during boreal winter (December–February) from 50 years of observations. Colouration indicates sea surface temperature, at increments of 1°C. Surface winds (arrow) blow from east to west, causing surface waters to be displaced westward, while colder waters from the deep ocean move closer to the surface in the eastern equatorial Pacific. Temperatures along the equator increase from approximately 24°C in the east to about 29°C in the western part of the basin. The black contour encloses waters warmer than 28°C, the area where deep convection and tropical rainfall primarily occur. **b**, Boreal winter extreme La Niña conditions. The surface easterly winds intensify, waters warmer than 28°C retreat westward along the equator, causing deep convection and rainfall to shift toward the Maritime Continent (as indicated by the box on the left). The central equatorial Pacific (box on the right) becomes cooler, and the temperature gradient between the Maritime Continent and the central equatorial Pacific is enhanced. This temperature gradient is projected to strengthen, on average, with climate change, due to the relatively greater warming of the Maritime Continent relative to the central Pacific, creating favourable conditions for the development of extreme La Niña events.

role in the occurrence of more frequent extreme La Niña events, is facilitated, in the models, by the weakening of the tropical winds. However, the weakening of the surface winds in a warmer climate, as simulated by the models, has been challenged by some recent observational studies that have instead shown evidence of a strengthening of the winds during the twentieth century^{7–9}. Other observational studies, however, support the model projection of weakening winds¹⁰.

Climate models are the only tool we have for understanding the intricacies of global warming. Despite the uncertainties on the reliability of the model projections, the study of Cai and colleagues establishes a plausible scenario of changes that may have very serious implications for society. Although their results need to be further examined in longer datasets and additional model simulations, as they become available, the possibility of more frequent

devastating La Niña events must be seriously considered as we prepare to face the consequences of global warming. □

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References

1. Bell, G. D. *et al. Bull. Am. Meteorol. Soc.* **80**, 1040 (1999).
2. Collins, M. *et al. Nature Geosci.* **3**, 391–397 (2010).
3. Cai, W. *et al. Nature Clim. Change* **5**, 132–137 (2015).
4. Vecchi, G. A. & Soden, B. J. *J. Climate* **20**, 4316–4340 (2007).
5. Cai, W. *et al. Nature Clim. Change* **4**, 111–116 (2014).
6. Bellenger, H. *et al. Clim. Dynam.* **42**, 1999–2018 (2013).
7. L'Heureux, M., Lee, S. & Lyon, B. *Nature Clim. Change* **3**, 571–576 (2013).
8. Cane, M. A. *et al. Science* **275**, 957–960 (1997).
9. Sandeep, S., Stordal, F., Sardeshmukh, P. & Compo, G. P. *Clim. Dynam.* **43**, 103–117 (2014).
10. Tokinaga, H. *et al. Nature* **491**, 439–443 (2012).

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