neither are floods and droughts; however, when aiming to go a step further and actually attribute an individual extreme event to a particular cause, the scientific community needs to tackle some challenges.

One of the harder challenges is based on the fact that we expect that the probability of all these heatwaves and extreme rainfall events occurring will only increase under the assumption that all else remains equal; in other words, that climate change does not affect the atmospheric circulation. But as Coumou and Rahmstorf[1] point out, this may not be the case. Identifying changes in the dynamical drivers of extreme weather events requires climate models that can reliably simulate these drivers. Not all general circulation models are up to this task, which led some scientists to conclude we should not even try[8]. Recent studies, however, have shown that it is possible to disentangle thermodynamic and circulation changes[9,10], but these studies are conditional[1] on the ability of the model to adequately represent the atmospheric circulation. Although this is a well-established fact, model evaluation has been remarkably absent in many attribution studies (such as ref. 11) — however, further scrutinizing reveals that general circulation models suitable for this purpose do actually exist (for example, ref. 12), and that robust attribution of the overall change in risks of devastating extreme events is far from impossible today[13].

But when analysing such changes in the overall risk, we consider an event as a class, and not as an individual entity — exactly as it happened. Recently, there has been some controversy over whether a very narrow definition of an event can lead to informative attribution studies, given that each event is unique and will never occur again[14]. One consequence of the uniqueness of individual extreme events is that we will never be able to say a single event could not have occurred without anthropogenic climate change. Here Coumou and Rahmstorf[1] were wrong; we simply can never say this with certainty.

Coumou and Rahmstorf[1] proposed a few different approaches to attributing extreme weather events, all of which have since developed into complex methodologies[13]. At the same time, a realization set in that if the climate science community really wants to respond to stakeholders asking for more concrete information on extremes, we have to go beyond meteorological variables. The temperatures reached in the 2010 Russian heatwave may not have set it apart from other similar events, but the large impacts it had on grain prices might justify the extra attention. Attributing such impacts is more difficult, as many factors other than the weather can influence grain prices, and vulnerability and exposure are crucial. But there are steps between single model studies on a single meteorological variable and complete end-to-end attribution analysis from such variables to their impacts. The event attribution community has come a long way towards applying different methodologies and combining meteorological variables to indices of relevance to people (for example, ref. 15), making impact attribution the challenge for the coming years.

Impact attribution was not on the to-do list that Coumou and Rahmstorf[1] compiled for advancing the field. That it would be there today shows how much progress has been made, and it highlights the importance of their paper. We, the community that has emerged in the past five years, have worked from their list and made advances on all points. If we now want to make comparable progress on the analysis of the impacts of events that really matter, we will need to start with major advances in what Coumou and Rahmstorf[1] presented as a prerequisite to every attribution study: high-quality observational data. We can make progress there, but to do so we will need to enlarge the community to include scientists from all regions of the world. ❐

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## References

1. Coumou, D. & Rahmstorf, S. *Nature Clim. Change* **2,** 491–496 (2012).
2. WMO: 2015 likely to be warmest on record, 2011–2015 warmest five year period. *World Meteorological Organization* (25 November 2015); http://go.nature.com/ua8JqV
3. Allen, M. *Nature* **421,** 891–892 (2003).
4. Stott, P. A., Stone, D. A. & Allen, M. R. *Nature* **432,** 610–614 (2004).
5. Dole, R. *et al. Geophys. Res. Lett.* **38,** L06702 (2011).
6. Rahmstorf, S. & Coumou, D. *Proc. Natl Acad. Sci. USA* **108,** 12905–17909 (2011).
7. Otto, F. E. L., Massey, N., van Oldenborgh, G. J., Jones, R. G. & Allen, M. R. *Geophys. Res. Lett.* **39,** L04702 (2012).
8. Trenberth, K. E., Fasullo, J. T. & Shepherd, T. G. *Nature Clim. Change* **5,** 725–730 (2015).
9. Grose, M. R., Black, M. T., Risby, J. S. & Karoly, D. J. *Bull. Am. Meteorol. Soc.* **96,** 158–162 (2015).
10. Delworth, T. L. & Zeng, F. *Nature Geosci.* **7,** 583–587 (2014).
11. Herring, S. *et al. Bull. Am. Meteorol. Soc.* **96,** S1–S172 (2015).
12. *Attribution of Extreme Weather Events in the Context of Climate Change* (National Academies Press, 2016).
13. Shepard, T. *Curr. Clim. Change Rep.* **2,** 28–38 (2016).
14. Stott, P. *et al. WIREs Clim. Change* **7,** 23–41(2016).
15. Sippel, S. & Otto, F. E. L. *Climatic Change* **125,** 381–398 (2014).

## Additional information

Supplementary information is available in the online version of the paper.

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TROPICAL STORMS

# The socio-economics of cyclones

Understanding the potential social and economic damage and loss wrought by tropical cyclones requires not only understanding how they will change in frequency and intensity in a future climate, but also how these hazards will interact with the changing exposures and vulnerabilities associated with social change.

### Ilan Noy

On 20 February 2016, tropical cyclone Winston made landfall in Fiji; the strongest cyclone ever recorded to hit the South Pacific nation, with estimated sustained winds of 230 km h⁻¹. For many communities, the consequences of tropical cyclones are cataclysmic. Recent storms such as Sandy (the USA in 2012), Haiyan (the Philippines in 2013) and Pam (Vanuatu in 2015) — which all caused terrible damage — clearly demonstrate this. Writing in *Nature Climate Change* in 2012, Mendelsohn *et al.*[1] suggested that the dramatic increase in the global impact of tropical cyclones over the past few decades was largely due to an increase in the exposure and vulnerability to cyclones, rather than an increase in their intensity or frequency. They also predicted an increase in damages in some geographic regions associated with future climatic influences.

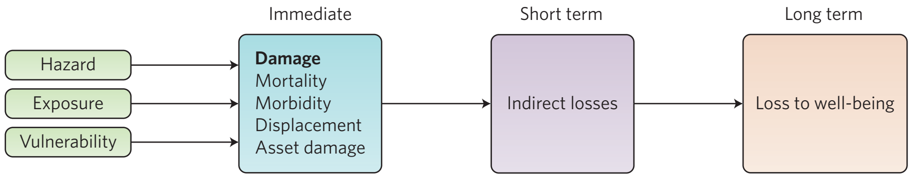

**Figure 1 |** The dynamic socio-economic consequences of cyclones at different timeframes.

At the same time, Peduzzi and colleagues[2] showed that there was a growing awareness that future tropical cyclone occurrences and, most importantly, tropical cyclone mortality would be affected by climatic change, potentially doubling the impacts. It seems that we will be witnessing a trade-off: a global decline in the frequency of cyclones that may go hand-in-hand with an increase in tropical cyclone intensity and, given the non-linearity in damage functions, more extensive aggregate expected damage to assets[3].

These two studies complement each other and bridge the gap between the physical science and the socio-economic impact assessment of tropical cyclones. We now understand that slowly changing climatic conditions, especially surface and water temperature, are likely to have an impact not only on the frequency and intensity, but also on the trajectory of tropical cyclones and on the damage they inflict. Identifying trends in the historical data is difficult, as tropical cyclones are low-probability events, and the time series required to identify trends in such events are much longer than the range of the available data[4]. It is also still difficult to attribute single extreme events to changing climatic conditions, despite the significant methodological advances in recent years[5].

Compounding the difficulty of identifying the trends associated with tropical cyclone hazards is the well-established idea that tropical cyclone risk is determined by three distinct factors[6]: the characteristics of the hazard (violent rainfall, winds and storm surges), the exposure of people and assets (their presence in coastal regions and flood-prone areas) and their vulnerability once they are exposed to these hazards (Fig. 1). With regard to hazards, the models used by Mendelsohn *et al.*[1] and Peduzzi *et al.*[2] have focused mostly on measurements of wind speed as a proxy for the intensity of tropical cyclones. But more recent research has shown that the size of the storm footprint and the speed of the tropical cyclone are also very important in determining its destructiveness[7], and that sea-level rise is associated with potentially significant increases in the impacts of storm surges[8]. Atolls and low-lying delta regions will undoubtedly experience increased damage associated with tropical cyclone hazards as a result of sea-level rise, as happened in Tuvalu and Kiribati as a consequence of tropical cyclone Pam in 2015.

Even though there is much uncertainty with regard to tropical cyclone hazard trends, it is clear that exposure is continually increasing: population density is rising in most places; people are moving to exposed regions along coasts and to the margins of large urban centres; and the number and value of assets being built in exposed areas is increasing. Less is known about vulnerability, as there is little agreement on how to measure it, with most researchers appraising vulnerability through measures of per-capita income or poverty, and broad measures of governance[2]. Comparisons across countries, however, clearly indicate that vulnerability can be impacted by deliberate policy, irrespective of these broader characteristics. Bangladesh, for example, is very poor, but also frequently mentioned for its successful reduction of vulnerability to tropical cyclone impacts (especially mortality and morbidity) in comparison with its geographic neighbours[2]. It is clear that the ability and willingness to institute successful risk-reduction policies are also determined by previous experience with a specific hazard. Therein may lie the most important, and most overlooked, potential impact of climate change. If climate change were to alter the trajectory of storms significantly, these events would increasingly hit regions that are less prepared for them.

Recent events in the Philippines are representative of this danger. In the past few years, three very large storms have hit the southern regions of Visayas and Mindanao (Bopha in 2011, Washi in 2012 and Haiyan in 2013), areas that have significantly less experience with tropical cyclone hazard than the northern Luzon region. As a direct result of the authorities' lack of experience, evacuation was ineffective and all three storms led to very high, and preventable, death tolls. For the South Pacific, to use another example, the tropical cyclone range is anticipated to extend to the north and south of the current 'tropical cyclone belt' and similar changes are to be expected elsewhere[9,10].

Another issue that is less studied and often ignored, at our peril, is the longer-term vulnerability of economies to tropical cyclone events (Fig. 1). Mortality, morbidity, population displacement and damage to assets and infrastructure may all have potentially adverse effects on economic activity, with some recent case study evidence suggesting that such effects may persist for decades[11]. Potentially, such effects could be a multiple of the immediate damage; yet global quantification and adequate understanding of the forces that shape these long-term effects is still in its early stages[12]. Although there are reasonably reliable measures of the expected annual average losses resulting from tropical cyclones (with or without accounting for climate change), and their relative importance to the national economy and its capital stock[13], we are still lacking the tools to quantify the human consequences of such losses[14] and, most critically, to prevent them.

The forecasting of tropical cyclone events within the context of climatic change has clear implications for the way we form our expectations of future risks. Mendelsohn *et al.*[1] and Peduzzi *et al.*[2] laid the foundations for understanding the socio-economic impacts of tropical cyclones, spurring others to also examine these hazards in the context of climate change and its socio-economic consequences. This wide-ranging effort[15] has led to signatories in the Paris Climate Agreement of 2015 (Article 8) to "recognize the importance of averting, minimizing, and addressing loss and damage associated with the adverse effects of climate change, including extreme weather events"[16]. This 'addressing', through the Warsaw International Mechanism for Loss and Damage of the United Nations Framework Convention on Climate Change (UNFCCC) has the potential to shape policy and to finance many of the commitments undertaken by the international community in the Sendai Framework for Disaster Risk Reduction earlier in 2015[17]. This will surely be welcomed by Fijians, just hit by the strongest storm ever recorded in their part of the world, but the issue is also likely to become much more prominent in many other areas of the globe in the years to come. ❐

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## References

1. Mendelsohn, R., Emanuel, K., Chonabayashi, S. & Bakkensen, L. *Nature Clim. Change* **2**, 205–209 (2012).
2. Peduzzi, P. *et al. Nature Clim. Change* **2**, 289–294 (2012).

3. Kang, N.-Y. & Elsner, J. B. *Nature Clim. Change* **5,** 661–664 (2015).
4. Crompton, R., Pielke, R. A. & McAneney, K. J. *Environ. Res. Lett.* **6,** 014003 (2011).
5. Herring, S. C., Hoerling, M. P., Kossin, J. P., Peterson, T. C. & Stott, P. A. (eds) *Bull. Am. Meteorol. Soc.* **96,** S1–S172 (2015).
6. Crichton, D. in *Natural Disaster Management* (ed. Ingleton, J.) 102–103 (Tudor Rose, 1999).
7. Zhai, A. R. & Jiang, J. H. *Environ. Res. Lett.* **9,** 064019 (2014).
8. Woodruff, J. D., Irish, J. & Camargo, S. *Nature* **504,** 44–52 (2013).
9. Ramsay, H. *Nature* **509,** 290–291 (2014).
10. Kossin, J., Emanuel, K. & Vecchi, G. *Nature* **509,** 349–355 (2014).
11. Caruso, G. & Miller, S. J. *J. Dev. Econ.* **117,** 134–150 (2015).
12. Hallegatte, S. *The Indirect Cost of Natural Disasters and an Economic Definition of Macroeconmic Resilience* (World Bank, 2016); http://go.nature.com/k2Xpsy
13. *Global Assessment Report 2015* (UNISDR, 2015).
14. Noy, I. A. *Glob. Policy* **7,** 56–65 (2016).
15. IPCC *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (eds Field, C. B. *et al.*) (Cambridge Univ. Press, 2012).
16. *Adoption of The Paris Agreement* FCCC/CP/2015/L.9/Rev.1 (UNFCCC, 2015); http://go.nature.com/45AnVU
17. *Sendai Framework for Disaster Risk Reduction 2015–2030* (UN, 2015); http://go.nature.com/UzllpO

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OCEANOGRAPHY

# Leading the hiatus research surge

The recent slowdown in global warming challenged our understanding of climate dynamics and anthropogenic forcing. An early study gave insight to the mechanisms behind the warming slowdown and highlighted the ocean's role in regulating global temperature.

Shang-Ping Xie

The rate at which global mean surface temperature (GMST) was increasing slowed down during 1998–2012 by a factor of 2 compared with the preceding 15-year periods. This was despite a comparable rate of increase in atmospheric $CO_2$ concentration. The apparent inconsistency between the unabated intensification of anthropogenic forcing and the early-2000s surface-warming hiatus has generated intense scientific and political debates[1]. Early on, internal variability emerged as a plausible hypothesis — climate models produce decade-long hiatus periods[2], albeit usually not at the observed timing.

In a study published in *Nature Climate Change* in 2011, Jerry Meehl and colleagues[3] took a crucial step forward by demonstrating that in model simulations, hiatus periods are associated with a La Niña-like cooling pattern over the tropical Pacific Ocean (Fig. 1a). This is consistent with the observational fact that GMST increases a few months after the peak of El Niño, as occurred following the strong El Niño event of 1997. Through atmospheric convection, a change in tropical Pacific sea surface temperature (SST) is felt by the entire tropical troposphere. Pacemaker experiments that forced tropical Pacific variability to follow the observed evolution successfully reproduced the early-2000s hiatus[4–5], providing an explicit demonstration of the tropical Pacific effect on GMST. When such constraints were removed and the Pacific was able to evolve freely, the same models simulated a much faster increase in GMST in the early 2000s compared with observations.

Unlike first-order spatially uniform anthropogenic warming, the negative swing of tropical Pacific SST that slowed down the GMST increase left clear regional fingerprints (Fig. 1a) — including the intensified equatorial Pacific trades[5], the weakened atmospheric low pressure system over the Aleutians of the North Pacific, and the decadal drought of the Southwest US[6]. The intensified Pacific trades, in addition, halted sea level rise on the west coast of the Americas while accelerating it in the tropical

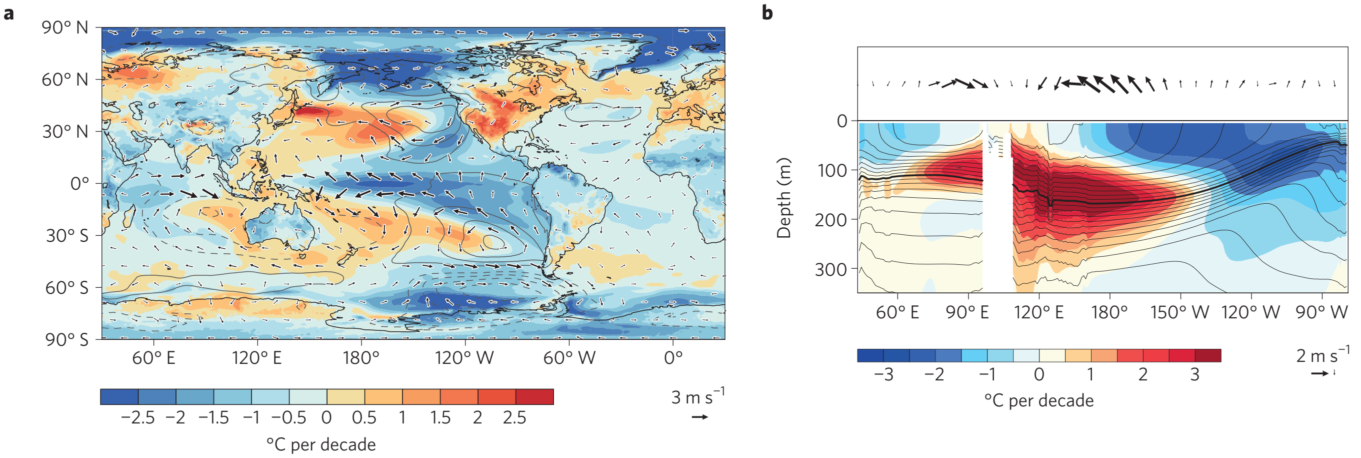

**Figure 1 |** Ocean–atmospheric trends during hiatus periods. **a**, Decadal trends of surface temperature (colour shading, °C), surface wind velocity vectors ($\mathrm{m\,s^{-1}}$) and sea level pressure (contours at 1 hPa intervals). **b**, Trends of horizontal wind velocity (vectors at the top) and ocean temperature (colour shading) at the Equator, along with temperature climatology (black contours at 1 °C intervals; the 20 °C isotherm thickened). Trends are the composite difference between four pairs of hiatus and surge decades during which GMST increase slows down and accelerate, respectively. The data is from the analysis of a large-ensemble coupled model simulation[10].