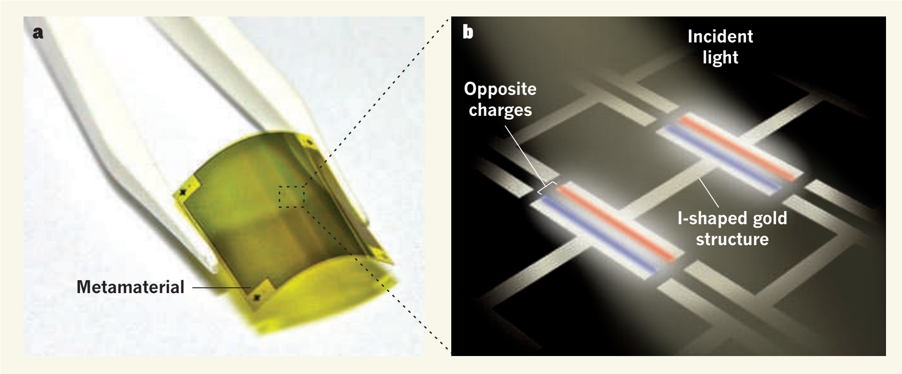

Figure 1 | Choi and colleagues' high-refractive-index metamaterial[1]. **a**, Photograph of the centimetre-sized, free-standing and flexible metamaterial. **b,** The internal structure of the metamaterial consists of a lattice of I-shaped gold unit cells, each 60 micrometres in size. When light of terahertz frequency is shone onto the material, the small gap between the bars of two adjacent I cells produces an extremely strong electric dipole of equal but opposite oscillating charges, which confers a high refractive index on the material. (Modified from ref. 1.)

sized planar layers to create bulk-like metamaterials. They formed each layer by printing arrays of thin I-shaped gold building blocks, or 'meta-atoms', onto a polymer (polyimide) substrate using the conventional lithographic technique used for printing electronic circuits. The resulting metamaterials, which are free-standing and flexible (Fig. 1a), have a very high refractive index — more than 30 at the terahertz frequency regime.

The refractive index depends on the product of a material's electrical and magnetic responses to an electromagnetic field. The authors achieved a large electrical response by placing the I-shaped meta-atoms close to one another, leaving only a small gap. Upon irradiation with terahertz light, the small gap between the bars of two adjacent I meta-atoms produces an extremely strong electric dipole that significantly enhances the electrical response (Fig. 1b). However, at the same time, the incoming light has the detrimental effect of decreasing the material's magnetic response by inducing electric-current loops that prevent the light's magnetic field from penetrating the metallic structures. The authors came up with a creative approach to minimize this effect: they thinned the metallic structures such that the area subtended by the loop current was reduced, effectively minimizing the loss of the magnetic response. In this way, the overall refractive index, which arises primarily from huge electrical dipole moments, was kept at a high value.

To measure the refractive index, Choi *et al.*[1] used terahertz time-domain spectroscopy, in which terahertz pulses are sent through the sample and the time-dependent transmitted pulses are recorded and transformed into frequency-dependent values. The detailed features of these transmitted pulses are then used to deduce the sample's refractive index. The authors found that the metamaterial's observed high index occurs over a broad band of frequencies with low energy loss in the metal. This is caused by strong interactions between the meta-atoms.

Choi *et al.*[1] estimate that a much higher refractive index — of a few hundred — could be obtained by further shrinking the gaps and embedding the layers of metamaterial in a substrate that has a higher refractive index than polyimide, for example strontium titanate. Such an index would be a remarkable amplification of the refractive indices of nature's materials. However, this requires a precision of 10–50 nanometres for the manufacture of the metallic structures into a large (centimetre-scale) area of metamaterial, which can be challenging.

A shortcoming of Choi and colleagues' I-shaped metamaterials is the fact that they are sensitive to the polarization of incident light. Although the authors also designed isotropic two-dimensional metamaterials, which are insensitive to polarization, it will be a challenge to build truly isotropic three-dimensional metamaterials with a refractive index that is both high and does not depend on polarization. But for now, the unusually high index of Choi and colleagues' materials has demonstrated a hidden potential of metamaterials, which once again beats the limitations of naturally occurring materials and will greatly extend our ability to manipulate light. ■

Xiang Zhang *is in the NSF Nanoscale Science and Engineering Center, University of California, Berkeley, California 94720–1740, USA.*
e-mail: xiang@berkeley.edu

1. Choi, M. *et al. Nature* **470,** 369–373 (2011).
2. Pendry, J. B., Holden, A. J., Robbins, D. J. & Stewart, W. J. *IEEE Trans. Microw. Theory Techniques* **47,** 2075–2084 (1999).
3. Yen, T. J. *et al. Science* **303,** 1494–1496 (2004).
4. Veselago, V. G. *Sov. Phys. Uspekhi* **10,** 509–514 (1968).
5. Shelby, R. A., Smith, D. R. & Schultz, S. *Science* **292,** 77–79 (2001).
6. Valentine, J. *et al. Nature* **455,** 376–379 (2008).
7. Fang, N., Lee, H., Sun, C. & Zhang, X. *Science* **308,** 534–537 (2005).
8. Shin, J., Shen, J.-T. & Fan, S. *Phys. Rev. Lett.* **102,** 093903 (2009).

CLIMATE CHANGE

Human influence on rainfall

Rising concentrations of anthropogenic greenhouse gases in the atmosphere may already be influencing the intensity of rainfall and increasing the risk of substantial damage from the associated flooding. **See Letters p.378 & p.382**

RICHARD P. ALLAN

The varying distribution of fresh water across the globe, involving complex patterns of rainfall in space and time, crucially affects the ecosystems and infrastructure on which human societies depend. The recent severe floods in Australia, Sri Lanka and Brazil, which were partly associated with an episodic cooling in the equatorial Pacific Ocean (La Niña), highlight the effect of natural fluctuations in atmospheric circulation systems on rainfall distributions. However, global warming resulting from anthropogenic emissions of greenhouse gases may have compounded the effects of such fluctuations, a possibility that is considered in two papers in this issue[1,2].

Min *et al.* (page 378)[1] provide evidence that human-induced increases in greenhouse-gas concentrations led to the intensification of heavy precipitation events over large swathes of land in the Northern Hemisphere during the latter half of the twentieth century. They combined a rigorous 'detection and attribution' framework with extreme-value theory (a statistical technique designed for analysing rare events) to place daily rain-gauge data and climate-model simulations on a common scale. A tentative but intriguing finding by these authors is that climate models may underestimate the effects of anthropogenic global warming on rainfall intensification, a possibility that has implications for projections of future climate.

© 2011 Macmillan Publishers Limited. All rights reserved

Climate models typically do not have sufficient resolution to satisfactorily represent processes at the level of cloud formation, and there is considerable variation in simulations of the relationship between rainfall extremes and warming in the tropics[3,4]. Pall *et al.* (page 382)[2] get around this issue by considering an event relating to a large-scale weather pattern that can be represented by high-resolution versions of such models. They link human influence on global-warming patterns with an increased risk of severe flooding that is associated with a displacement in the North Atlantic jet stream (a fast, eastward-moving ribbon of air at around 8–12 kilometres altitude). The consequence of jet-stream displacement was recurrent, unusually prolonged periods of heavy rain over England and Wales in autumn (September–November) 2000 (Fig. 1).

The authors' approach involved conducting multiple climate simulations of this event, with realistic control runs and further scenarios in which the anthropogenic warming patterns were artificially removed. Building up convincing statistics required thousands of model simulations, which were made possible through the use of idle time on personal computers volunteered by members of the public.

Feeding the precipitation simulations into river-flow models allowed Pall *et al.* to gauge the influence of anthropogenic greenhouse-gas emissions on the risk of damaging floods occurring in England and Wales during autumn 2000. They conclude that flooding risk was indeed "substantially increased" by these emissions, although the exact scale of the effect is difficult to estimate. However, their results vary with the range of anthropogenic warming patterns estimated separately from four coupled ocean–atmosphere climate models. The set of different models used to simulate the relationships between temperature, precipitation and flooding also requires further evaluation. Nevertheless, applying their technique to further severe flooding events may prove valuable for informing policies aimed at improving adaptation to climate change.

More generally, in considering changes in the pattern and intensity of precipitation, the underlying physical and geographical context provides essential background. The root cause of the reported changes in rainfall with increasing atmospheric temperature is centred on atmospheric water vapour[5]. The convergence of moisture-laden air masses leads to air uplift, cloud formation and eventual precipitation (rain, snow or hail). A warming atmosphere can carry greater quantities of gaseous water (approximately 6–7% more is carried per °C of warming near Earth's surface, as determined by the Clausius–Clapeyron equation). It has long been thought that the intensity of the heaviest rainfall is modulated through this simple relationship, again increasing at around 6–7% per °C. However, water vapour also controls precipitation by influencing the radiative cooling of the atmosphere (through the absorption and emission of infrared radiation). The temperature dependence of radiatively induced increases in total global precipitation (around 2–3% per °C of warming[5,6]) is substantially lower than the 6–7% per °C increase in intense rainfall implied from changes in atmospheric moisture.

A. DENNIS/AFP/GETTY

Figure 1 | The floods of autumn 2000. Geese take to the inundated streets of York, northern England.

Intense rainfall is inherently local, but is fuelled by a supply of atmospheric moisture from farther afield that may otherwise have contributed to more moderate rainfall elsewhere. So rapid increases in precipitation intensity in one region imply a decrease in intensity, duration and/or frequency in other regions[7]. Many climate models show this projection through an increasing intensity of rainfall in wet regions (above the 2–3% per °C rate of increase in global precipitation due to radiative cooling), together with a tendency towards diminished rainfall in the already dry subtropics[5,6]. Because of the implications for future flooding and drought, it is vital to establish the physical basis for these changes[5], and to verify theory with further observational evidence[1,3,8].

The detailed physical mechanisms determining changes in the distribution of extreme rainfall also require further investigation. Additional latent energy released within storms can invigorate vertical motion, increasing rainfall intensity to above 6–7% per °C (ref. 9). Alternatively, limitations on sources of moisture and counteracting dynamical feedbacks could explain increases in heavy-rain intensity of less than 6–7% per °C (ref. 8). One other possibility to explore is the role of atmospheric aerosols (especially those that absorb sunlight), which may influence global and regional precipitation by modulating the energy balance between the atmosphere and Earth's surface[10,11].

Predicting regional changes in the water cycle presents a considerable challenge, but that endeavour is essential in formulating strategies for adapting to and mitigating such changes. Subtle shifts in large-scale atmospheric circulation may affect local rainfall to a much greater extent than the thermodynamic processes relating to atmospheric water vapour content. Understanding the regional responses of rainfall patterns to global warming is therefore crucial. In the meantime, as these two papers[1,2] demonstrate, robust physics, combined with carefully constructed observing systems and detailed modelling, indicate that the frequency of intense rainfall events is likely to increase with anthropogenic greenhouse-gas-induced warming. ■

Richard P. Allan *is in the Department of Meteorology, University of Reading, Reading RG6 6BB, UK.*
e-mail: r.p.allan@reading.ac.uk

1. Min, S.-K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. *Nature* **470,** 378–381 (2011).
2. Pall, P. *et al. Nature* **370,** 382–385 (2011).
3. Allan, R. P., Soden, B. J., John, V. O., Ingram, W. & Good, P. *Environ. Res. Lett.* **5,** 025205 (2010).
4. O'Gorman, P. A. & Schneider, T. *Proc. Natl Acad. Sci. USA* **106,** 14773–14777 (2009).
5. Held, I. M. & Soden, B. J. *J. Clim.* **19,** 5686–5699 (2006).
6. Allen, M. R. & Ingram, W. J. *Nature* **419,** 224–232 (2002).
7. Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. *Bull. Am. Meteorol. Soc.* **84,** 1205–1217 (2003).
8. Haerter, J. O., Berg, P. & Hagemann, S. *Geophys. Res. Lett.* **115,** D17102, doi:10.1029/2009JD013384 (2010).
9. Lenderink, G. & van Meijgaard, E. *Environ. Res. Lett.* **5,** 025208 (2010).
10. Wild, M., Grieser, J. & Schär, C. *Geophys. Res. Lett.* **35,** L17706, doi:10.1029/2008GL034842 (2008).
11. Andrews, T. *et al. Geophys. Res. Lett.* **37,** L1470, doi:10.1029/2010GL043991 (2010).

© 2011 Macmillan Publishers Limited. All rights reserved