and what indicators of climate impact should be used remain undecided. Although emissions, concentrations and radiative forcing are essential and much used, people are more concerned about changes to temperature, precipitation and sea level, not only as global annual means, but also in terms of regional and temporal variability.

A broad set of components have disturbed the climate[9], short- and long-lived, causing both warming and cooling effects (Fig. 1), and it is not obvious which of these to include in calculations of the contributions of countries. The set of gases regulated by the Kyoto Protocol is one option. But what about SO_2, which causes cooling? Should climate credits be given for air pollution?[2,4] These choices have large impacts on the calculated warming contributions.

Most countries support the principle of common but differentiated responsibilities and respective capabilities. When it comes to putting the principle in policy, however, interpretations diverge — often as a reflection of countries' material interests[10].

Searching for a single formula to define responsibility is therefore unlikely to succeed[11]. The Lima call for climate action instead asks countries to define what they consider to be a fair contribution[12]. In this setting, research to explore the implications of different ways of operationalizing fairness principles, including one based on warming contributions, is useful.

Matthews finds that with a wider range of emissions beyond CO_2, some countries change from creditors to debtors. This illustrates a further challenge in applying calculated warming contributions in a political context: The methodological choices have substantial implications for the calculated warming contributions and potentially also for policy.

Matthews' calculations also focus on short time scales; that is, start dates of 1960 and 1990. These time scales only cover approximately 66 and 36%, respectively, of total accumulated CO_2 emissions from 1750 to 2013[13], thereby omitting a large share of historical drivers of anthropogenic climate change (Fig. 1). Choosing earlier start-dates would have captured the early emissions related to deforestation and the Industrial Revolution, which changes the picture[2,3].

Research has a crucial role to play in informing the policy debate on differentiation of climate policy contributions. Matthews' research represents one of the multiple approaches that can serve this function. However, there are problems with using the concept of carbon and climate debts to inform debates over "who should pay" for the costs of mitigation[6], adaptation or loss and damages in countries with lower historical emissions. Instead, research on warming contributions and capabilities that encompasses a broad set of lenses could better help negotiators reach an agreement in Paris. ❐

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References

1. *United Nations Framework Convention on Climate Change* (UN, 1992); http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf
2. Den Elzen, M. *et al. Environ. Sci.Policy* **8,** 614–636 (2005).
3. Höhne, N. *et al. Climatic Change* **106,** 359–391 (2011).
4. Ward, D. S. & Mahowald, N. M. *Environ. Res. Lett.* **9,** 074008 (2014).
5. Prather, M. *et al. Geophys.Res. Lett.* **36,** L05707 (2009).
6. Matthews, H. D. *Nature Clim. Change* **6,** 60–64 (2016).
7. Neumayer, E. *Ecol. Econ.* **33,** 185–192 (2000).
8. Müller, B. *et al. Clim. Policy* **9,** 593–611 (2009).
9. Myhre, G. *et al.* in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al.*) Ch. 8 (IPCC, Cambridge Univ. Press, 2013).
10. Lange, A. *et al. Euro. Econ. Rev.* **54,** 359–375 (2010).
11. Underdal, A. & Wei, T. *Environ. Sci. Policy* **51,** 35–44 (2015).
12. *Report of the Conference of the Parties on its Twentieth Session, Held in Lima from 1 to 14 December 2014* (UNFCCC, 2014); http://unfccc.int/resource/docs/2014/cop20/eng/10a01.pdf
13. Le Quéré, C. *et al. Earth Syst. Sci. Data* **7,** 47–85 (2015).

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SOUTH ASIAN MONSOON

Tug of war on rainfall changes

Precipitation associated with the South Asian summer monsoon has decreased by approximately 7% since 1950, but the reasons for this are unclear. Now research suggests that changes in land-cover patterns and increased emissions from human activities have contributed to this weakening, which is expected to continue in the coming decades.

Deepti Singh

The onset of the South Asian monsoon in early June brings with it a burst of life across the region — children playing on the streets, blossoming flora, flowing rivers, and sowing of agricultural lands. The monsoon supplies ~80% of South Asia's annual rainfall, supporting the region's primarily rain-fed agriculture and recharging rivers, aquifers and reservoirs that provide water to over one-fifth of the global population. Since the 1950s, the monsoon has weakened[1] and become more erratic, with increased occurrence of extreme rainfall events[2]. This has led to crop failures and water shortages with severe socio-economic and humanitarian impacts across South Asia. Writing in *Climate Dynamics,* R. Krishnan and colleagues[3] suggest that anthropogenic greenhouse gas (GHG) emissions, aerosol emissions and agricultural land-cover changes are responsible for the observed changes in rainfall patterns. They predict that the monsoon weakening will continue through the twenty-first century, threatening the livelihoods and resources of over 1.6 billion people in the region.

Simplistically, the South Asian monsoon can be viewed as a system of moisture-carrying winds driven by the land–ocean thermal contrast that develops as the land heats up faster than the ocean in the summer and by the contrast in sea surface temperatures between the northern and southern Indian Ocean (Fig. 1). As the land heats, the warm, moist air rises over the Indian subcontinent. Heat released from condensing moisture further warms the atmosphere, feeding the monsoon. Increasing emissions from fossil fuel combustion, which include GHGs (such as carbon dioxide) and aerosols (such as sulphates, black carbon and nitrates), can affect the monsoon by modifying these thermal contrasts as well as moisture availability. Relative atmospheric warming near the equator due to GHG emissions reduces these temperature differences, weakening the thermally driven monsoon circulation[4] (Fig. 1). But near-surface warming over the oceans increases the

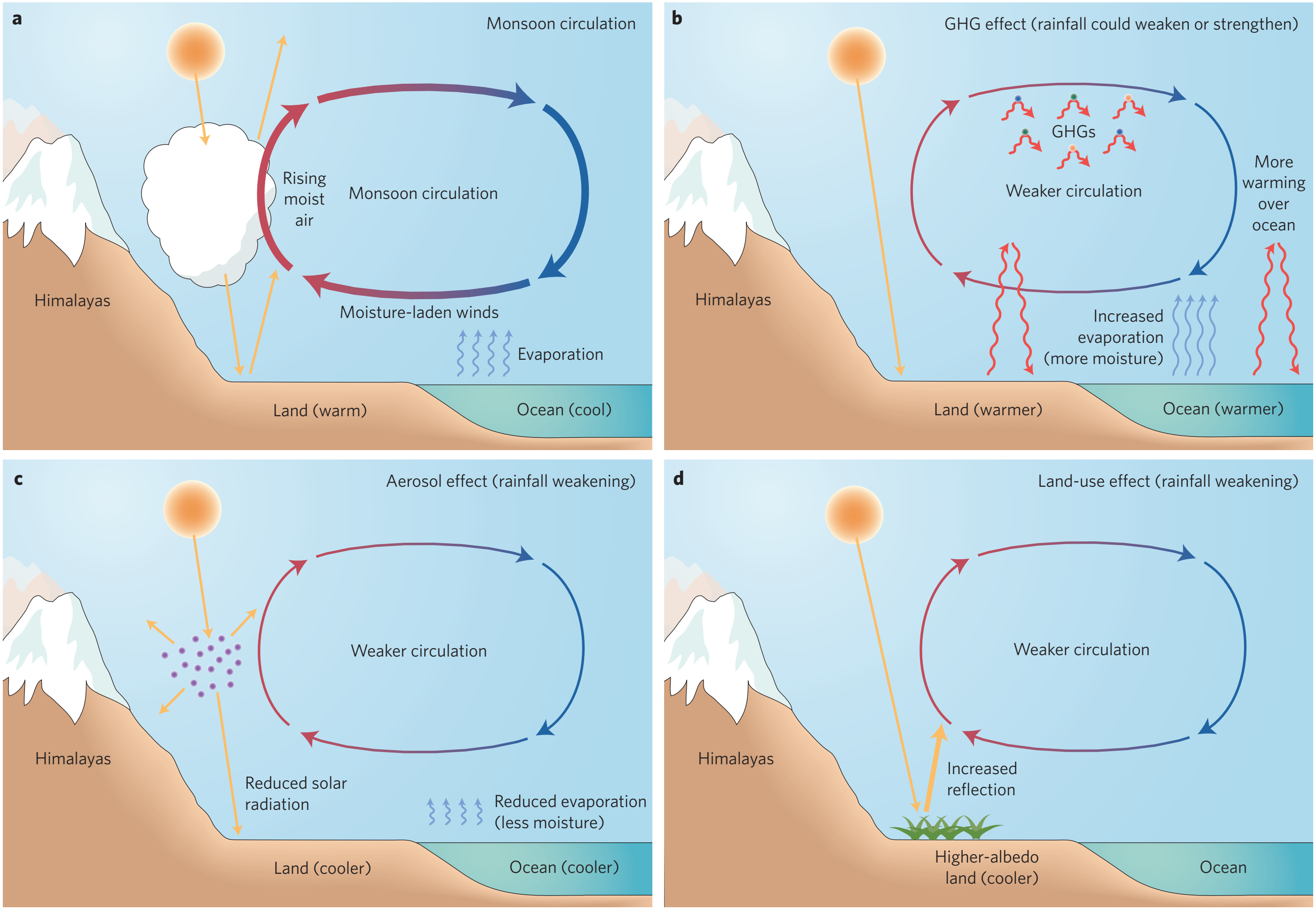

Figure 1 | Different anthropogenic factors have competing influences on the South Asian monsoon. **a**, The monsoon circulation, driven by the land–ocean thermal contrasts, brings in warm, moisture-laden winds near the surface. Over land, this air rises and the moisture condenses, releasing heat that warms the atmosphere. **b**, Trapping of radiation by GHGs warms the atmosphere, increasing moisture availability but reducing the thermal contrast due to greater warming of the atmospheric column over the tropical oceans relative to land. Rainfall changes depend on the magnitude of these opposing effects. **c**, Scattering and absorption of incoming solar radiation by aerosols results in surface cooling, reducing the thermal contrast that causes the circulation and rainfall to weaken. **d**, Increasing crop cover causes surface cooling by reflecting more radiation than a tree-covered landscape (increasing the surface albedo). This weakens the monsoon circulation and rainfall.

amount of moisture carried by the winds (Fig. 1). The interaction between these thermal wind-driven and moisture-driven effects determines the overall response of the monsoon rainfall to GHGs. Dust and anthropogenic aerosols accumulating over the Indo-Gangetic plains reduce incoming solar radiation at the surface, resulting in local surface cooling in northern India and the northern Indian Ocean. This reduces the land–sea temperature contrast and also suppresses evaporation, reducing moisture in the winds (Fig. 1). Together, these two effects weaken the monsoon circulation and rainfall[1,5]. Moreover, land-use changes are expected to have a similar effect to aerosols by increasing the surface reflectivity of solar radiation, causing near-surface cooling and weakening the monsoon (Fig. 1). This could be potentially important over South Asia, where crop cover has increased by ~45% and tree fraction decreased by 30% in the past century[3].

Although GHGs have caused warming and increased atmospheric moisture over South Asia, mounting evidence points to the importance of anthropogenic aerosols from South Asia and China in changing the timing, spatial distribution and strength of the monsoon[1,5–7]. The weakening effect of the aerosols has probably masked the otherwise positive response of monsoon rainfall to increasing moisture associated with GHG warming. In addition to understanding the competing effects of these external influences (forcings), there are some inherent challenges in attributing historical changes of the monsoon. First, global climate models are typically too coarse (~100 km) to resolve the complex topography, temperature and moisture gradients in the region that can influence the monsoon circulation. Second, the suite of models previously used does not simulate the full range of natural climate variations (internal variability) that could affect the response. And finally, these models do not include the effect of historical land-cover changes due to agricultural intensification and expansion, urbanization and deforestation.

Krishnan *et al.*[3] tackle two of these challenges using a state-of-the-art climate model with a high resolution over South Asia (~35 km) and prescribed land-use changes. The observed declining rainfall trend was only reproduced in the model when anthropogenic forcings (GHGs, aerosols and land-cover change) were included in addition to natural forcings (solar and volcanic). This suggests that anthropogenic forcings are responsible for the historical (1950–2005) monsoon weakening. They also investigate the effect of the different anthropogenic forcings by comparing the GHG-only forced climate with the combined aerosol and land-cover forcings. Without aerosol and land-cover changes, GHGs would have caused an intensification of seasonal rainfall over India. This implies that the non-GHG (aerosols and land-use) anthropogenic forcings are responsible for the observed changes in seasonal rainfall. Running the model forward, the observed weakening of monsoon rainfall continues through the late twenty-first century.

This study confirms that aerosols have substantially weakened the monsoon and masked the effect of GHG warming. However, although seasonal rainfall has weakened, extreme rainfall events (>100 mm d^{-1}) over central India have become more frequent due to the increased atmospheric moisture availability associated with GHG emissions[8]. The results of Krishnan *et al.*[3] also highlight the role of land-cover change as a substantial weakening influence on regional rainfall, but their modelling experiments do not effectively distinguish the effect of land-cover change from the effect of atmospheric aerosols — thus the relative contribution of these non-GHG anthropogenic forcings to monsoon changes in the present and future climate still needs to be quantified.

Most global coarse-resolution modelling studies project that monsoon rainfall will increase in response to future increases in GHGs, as increasing moisture will overcome the weakening of thermally driven winds. In contrast, this study shows a continued weakening of rainfall into the twenty-first century in response to increasing GHG forcing, suggesting that the wind-weakening effect dominates, consistent with another high-resolution model[9]. However, this study is not concrete evidence that the monsoon will weaken. The different responses need further investigation; they could be a consequence of the improved representation of finer-scale processes, feedbacks and orography, highlighting their potential importance in governing the response of the monsoon circulation to external forcings. Alternatively, internal variability of the monsoon could be a major confounding factor, as this alone could cause differences in the direction of future rainfall trends. A larger number of high-resolution simulations are needed to determine whether the decreasing trend is a robust response to anthropogenic forcing or a result of internal variability, whereas this study uses only a single model run.

The findings of Krishnan *et al.*[3] have substantial socio-economic implications for the region, as well as policy implications for enforcing stringent controls to reduce aerosols from fossil fuel and biomass burning. Over South Asia, biomass and agricultural burning contribute over 50% of total aerosol emissions[10]. The relatively short lifetime of aerosols (weeks) relative to GHGs (~80 years) provides scope for reducing their negative impacts relatively quickly. The results also highlight the uncertainty in the future of the monsoon to increasing anthropogenic forcings, pointing to an urgent need to reduce these uncertainties to support adaptation efforts. Improved predictions of monsoon characteristics, aided by studies such as this one, will help people to better prepare for future disasters and adapt to anthropogenic climate change. ❐

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References

1. Bollasina, M. A., Ming, Y. & Ramaswamy, V. *Science* **334,** 502–505 (2011).
2. Singh, D., Tsiang, M., Rajaratnam, B. & Diffenbaugh, N. S. *Nature Clim. Change* **4,** 456–461 (2014).
3. Krishnan, R. *et al. Clim. Dynam.* http://dx.doi.org/10.1007/s00382-015-2886-5 (2015).
4. Ueda, H., Iwai, A., Kuwako, K. & Hori, M. E. *Geophys. Res. Lett.* **33,** L06703 (2006).
5. Ramanathan, V. *et al. Proc. Natl Acad. Sci. USA* **102,** 5326–5333 (2005).
6. Lau, W. K. M. & Kim, K.-M. *Geophys. Res. Lett.* **37,** L16705 (2010).
7. Bollasina, M. A., Ming, Y. & Ramaswamy, V. *Geophys. Res. Lett.* **40,** 3715–3720 (2013).
8. O'Gorman, P. A. & Schneider, T. *Proc. Natl Acad. Sci. USA* **106,** 14773–14777 (2009).
9. Ashfaq, M. *et al. Geophys. Res. Lett.* **36,** L01704 (2009).
10. Gustafsson, Ö. *et al. Science* **323,** 495–498 (2009).

CRYOSPHERE

Warming ocean erodes ice sheets

Antarctic ice sheets are a key player in sea-level rise in a warming climate. Now an ice-sheet modelling study clearly demonstrates that an Antarctic ice sheet/shelf system in the Atlantic Ocean will be regulated by the warming of the surrounding Southern Ocean, not by marine-ice-sheet instability.

Kazuya Kusahara

The polar regions are undergoing change as atmospheric concentrations of greenhouse gases increase[1]. The Antarctic and Greenland ice sheets are two of the most important subsystems of the Earth's climate system. These ice sheets are large reservoirs of fresh water, and more than 60% of all fresh water on the Earth's surface is pinned as ice over the Antarctic continent. If all the Antarctic ice sheets melted, global mean sea level would rise by more than 60 m. Therefore, although Antarctica is very far from human civilizations, its ice sheets could impact on our lives through sea-level change. Thus, the potential contribution to sea-level rise from Antarctic ice sheets has received much attention, both scientifically[2] and socially. Recent satellite observations have revealed accelerated ice flow from Antarctic ice sheets[3] and significant thinning of the Antarctic ice sheets/shelves[4]. At this moment, future change in the mass balance of Antarctic ice sheets represents a large uncertainty for sea-level projections[1]. Writing in *Nature Climate Change*, Matthias Mengel and colleagues[5] use a state-of-the-art ice sheet/shelf model to demonstrate that the Filchner–Ronne Ice Shelf (FRIS, one of the largest Antarctic ice shelves) and the background ice sheet respond almost linearly to the magnitude of warming in the Southern Ocean.

The Antarctic ice sheet is divided into eastern and western parts by the Transantarctic Mountains running across the continent. The West Antarctic Ice Sheet is smaller than the East Antarctic Ice Sheet, containing only about 10% of the total ice