CLIMATE DYNAMICS

Land warming revives monsoon

A weakening land–ocean temperature difference, owing to a rapidly warming Indian Ocean, has seen the Indian monsoon trending downward since the 1950s. New research gives hope for a revival in monsoon rainfall as land warming catches up with, and exceeds, ocean warming.

Mathew Koll Roxy

Downward trends of monsoon rainfall over the last half century have raised grave concerns for the Indian subcontinent, which relies heavily on seasonal rains for its predominantly agriculture-based economy[1]. This reduction in monsoon rainfall has been attributed to the comparatively larger warming of the Indian Ocean compared to the subcontinent, thus reducing the land–sea temperature difference[1], a key factor that determines the strength of the summer monsoon. Writing in *Nature Climate Change*, Qinjian Jin and Chien Wang[2] reveal that the landmass has warmed strongly compared to the ocean since 2002, with the monsoon showing signs of revival.

The Indian summer monsoon develops as a response to the intense heating of the subcontinent during the spring–summer season, when the maximum solar insolation moves north from the equator. South of the landmass the Indian Ocean is relatively cool, resulting in a tropospheric temperature difference that drives the monsoon winds towards South Asia. For the 1.7 billion people living in India, Pakistan and Bangladesh, these summer monsoon winds bring three quarters of the annual rainfall to the subcontinent. As such, any slight deviation in rainfall could have wide-reaching impacts given the reliance of food, water supply, and gross domestic product on monsoon rains.

On a year-to-year basis, a major driver of monsoon variability is the El Niño Southern Oscillation (ENSO)[3]. An El Niño event, characterized by warmer-than-average ocean waters in the central and eastern Pacific, modulates tropical atmospheric circulation, thereby dampening the monsoon winds and rainfall over land. About 50% of monsoon droughts may be linked to these El Niño events in the Pacific. However, recent decades have seen a series of droughts unrelated to ENSO. Observations show that Indian monsoon rainfall has undergone a statistically significant weakening since the 1950s, with a reduction of about 10–20% observed over parts of northern and central India and the Indo–Gangetic plains[1]. The secular decline in mean rainfall has been connected to a weakening of the monsoon circulation, itself attributed to human-induced changes due to increased air pollution[4], deforestation over the subcontinent[5], and most importantly, increased fossil-fuel emissions which have led to a rapid warming of the Indian Ocean[1].

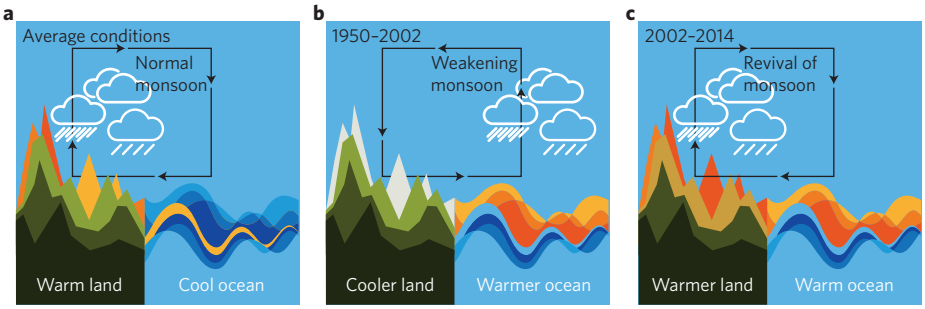

Figure 1 | Schematic illustration of changes in the Indian summer monsoon. **a**, The temperature difference between land and ocean during summer drives the moisture-laden monsoon winds, carrying water from the ocean and dumping it as rainfall over India. **b**, However, a rapid warming in the Indian Ocean during the past half century has weakened this thermal contrast, thereby reducing the amount of rainfall. **c**, Jin and Wang show that this condition has reversed since 2002, with a strong warming of the Indian landmass. This has strengthened the thermal contrast again, leading to a revival of the monsoon.

The weakening monsoon, along with both a growing demand for and a gross mismanagement of water resources, has resulted in a water crisis. Despite large investment in irrigation, more than 60% of cultivated land in India is still rain-fed. Hence, the series of droughts have resulted in economic losses since agriculture in this region is mainly subsistence farming on small land holdings. The cumulative deficit in the monsoon rainfall has also contributed to depleted groundwater resources[6]. This is aggravated by an unsustainable abstraction of groundwater for irrigation purposes. Since groundwater levels respond slowly to recharge, the ongoing decline may exacerbate the water and agriculture crises.

Given the observed decline in monsoonal rainfall and its corresponding impacts, there is clear urgency for monsoon strength to be revived. Now, using various observational datasets, Jin and Wang[2] examine whether and how the monsoon may have regained its vitality using a set of six observed rainfall datasets. Except one, all datasets render a robust signal of monsoon revival, at 0.63 mm per day per decade (1.34 mm per day per decade for the Climatic Research Unit dataset) during the 2002–2014 period. Jin and Wang[2] show that the revival in monsoon rains may be linked to an increase in the land–sea thermal contrast since 2002. Specifically, they illustrate that while surface warming was relatively higher over the ocean compared to the land during 1950–2002 (hence the decline in monsoon strength), the condition has now reversed due to strong land surface warming (0.36 °C per decade) and suppressed warming in the Indian Ocean (Fig. 1). The study suggests that this recent warming over the land, which is reflected in the entire tropospheric column, has enhanced the monsoonal circulation, and thus rainfall, during 2002–2014.

While five datasets evidence this recent revival, the positive shift in the monsoon rainfall is not observed in the data from the

India Meteorological Department (IMD). This discrepancy is a concern because the IMD dataset utilizes rainfall records from 6,995 rain gauge stations over India and is the largest of the six rain gauge datasets. However, the number of stations used in this IMD dataset is not uniform every year, and the data compiled during 2002–2014 does not include all the available stations[7] — this may be the reason why it is diverging from the other datasets. Nevertheless, a blended dataset merging satellite-based rainfall estimates and IMD observations[8] clearly suggests an increasing trend during the period.

The revival of monsoon precipitation discussed by Jin and Wang[2] spans only a decade, a relatively short period to draw conclusions regarding long-term trends in monsoon recovery. An extension of the SST data up to 2016, however, suggests that the suppressed oceanic warming may be temporary; with increasing greenhouse gases, the Indian Ocean will continue to warm. Indeed, a recent study[9] examining climate projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) indicates that pronounced future warming in the Indian Ocean may lead to a further reduction in the amount of monsoon precipitation and a shortening of the rainy season by the end of the twenty-first century.

It must be remembered, however, that many state-of-the-art climate models fail to accurately simulate monsoon processes and thus do not capture the observed changes in their characteristics[10,11]. For this reason, the Indian government has set up a US$1 billion National Monsoon Mission aided by a high-performance computing facility to improve short-term and long-term monsoon forecasts. At the moment, there is no clarity on how the monsoon will evolve in the future. Jin and Wang's study[2] suggests that the future monsoon may depend on a fierce competition between the land and ocean — on which is warming faster than the other. However, there are no winners in this game, as a warmer land might result in frequent heat waves and flash floods, and a warmer ocean may present us with severe droughts. ❐

Mathew Koll Roxy is at the Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune 411008, India.
e-mail: roxy@tropmet.res.in

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