

# Global Warming Shifts Monsoon Circulation

The impression that South Asia has been getting dryer over the last 50–60 years is supported now by analysis of the trends in the widely used All-India Monsoon Rainfall (AIR) index. The 110-year-old AIR index is computed from stations well-distributed throughout India, and begins the 20<sup>th</sup> century with alternating dry and wet phases lasting 30–40 years. The last wet phase was from 1930 to 1960, but the next one, which might have been expected to begin in the 1990s, has not set in. Indeed, the AIR index shows monsoon rain has fallen by 8–10% from 1961 to 2009.

After studying various aspects of the changes in the Asian summer monsoon, IPRC researchers **H. Annamalai**, **Jan Hafner**, **K.P. Sooraj**, and **P. Pillai**

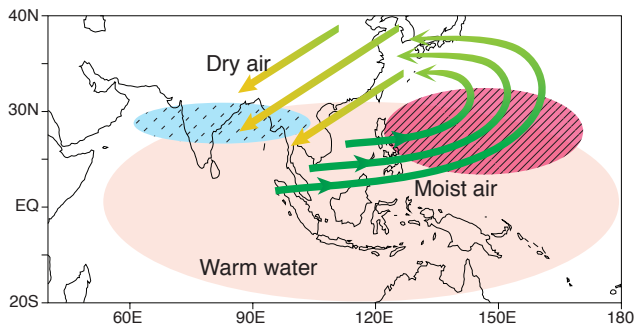
conclude that the monsoon atmospheric circulation now brings more rain to the western Pacific and less to South Asia than before. The proximate cause appears to be warming sea surface temperatures (SSTs) across the whole region that affect the regions of monsoon convection differently. The rising SSTs are plausibly attributed to global warming resulting from increased atmospheric greenhouse-gas concentrations.

## Monsoon Changes in Observations

The team's examination of monsoon-related measures from 1949 to 2000 in a range of climate products draws a remarkable picture. SST rose in both the tropical Indian Ocean and

the western tropical Pacific (10°S–30°N, 60°–150°E), in the former region by ~0.75°C and in the latter by ~0.5°C. Even though the SST increased more in the Indian Ocean, sea level pressure (SLP) there rose instead of falling, the climatological southwesterly low-level monsoon winds weakened, and rainfall over India decreased by 10% from 1951 to 2000, a decrease comparable to the AIR index. By contrast in the tropical western Pacific, SLP has dropped, and the low-level westerlies and cyclonic circulation have strengthened. Direct rainfall observations are not available, but the drop in SLP and the increased sea surface salinity (SSS) and atmospheric water vapor content over the last decades suggest that the region is seeing more rainfall than before. In short, the observations point to a shift in the monsoon circulation that has resulted in less rainfall over South Asia and more over the western tropical Pacific. The shift does not appear to reflect changes in the El Niño – Southern Oscillation (ENSO) because SST in the equatorial central and eastern Pacific has not increased.





The rise in SST over the tropical Indian Ocean and western Pacific (pink oval) increases moisture transport (green arrows) towards the western Pacific (red oval) resulting in increased rising motion and rainfall. This circulation change drives a northeasterly wind (green-yellow arrows) bringing dry, cold air from the north, reducing monsoon convection and rainfall over India (blue oval).

## Monsoon Changes in a Climate Model

Annamalai and his team also studied the monsoon changes in historical runs of the latest version of the coupled climate model of the Geophysical Fluid Dynamics Laboratory (GFDL\_CM2.1) included in the Fourth Climate Assessment Report of the Intergovernmental Panel on Climate Change. The model was forced with time series of the estimated historical record of well-mixed greenhouse gases, tropospheric sulfate and carbonaceous aerosols, volcanic aerosols, ozone, solar irradiance, and land-use changes.

These forced historical simulations paint a picture similar to the observations, capturing the South Asian monsoon interannual variability and the regional rainfall distributions from 1861 to 2000 together with the SST rise across the warm-pool region. In South Asia the model simulates a wet period beginning 1930 and then around 1945 a drying trend (~10% reduction during 1945–2000). In the western Pacific, the model simulates the increased rainfall from 1940 to 2000 together with the stronger low-level cyclonic circulation and lower SLP. The model also captures the timing and amplitude of the ENSO – monsoon relationship. Because ENSO, the major contributor to the year-to-year variations in South Asian monsoon rainfall, is simulated so well by the model, and because the long-term rainfall changes are significantly greater than year-to-year variations, the simulated shift in monsoon rainfall in the model is credible.

## Global Warming and the Monsoon Circulation

A 200-year control run *without* forcing from increased greenhouse-gas and aerosol concentrations simulates dryer

and wetter monsoon decadal periods, but not the rise in SST and changes in the rainfall pattern. Thus, man-made emissions seem to be at the root of the long-term rainfall changes.

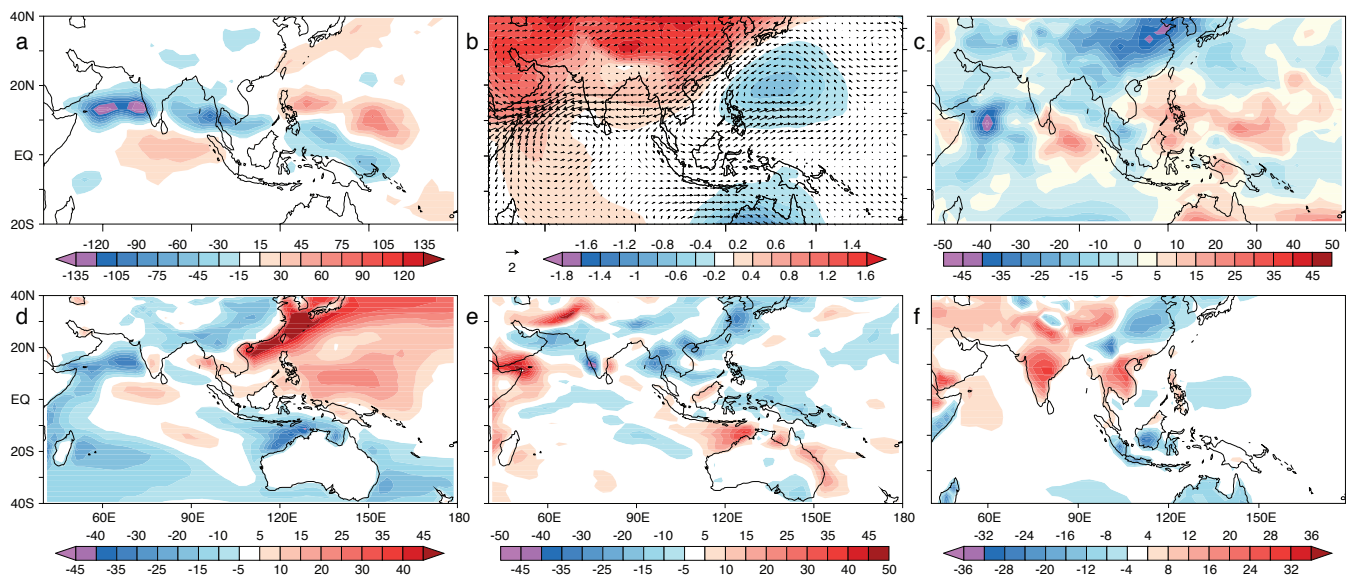
Could the circulation changes come about because SST warming due to greenhouse gases altered the interaction among the three main regions of deep convection of the Asian summer monsoon: the western tropical Pacific, the Bay of Bengal extending into the Indian subcontinent, and the tropical Indian Ocean? In a further experiment with the atmospheric component of CM2.1, the scientists forced the model with monthly increments in observed SST trends from 1949 to 2000 in (1) the western Pacific only, or (2) the Indo-Pacific, or (3) the whole tropics. Compared to a control run forced with climatological SST over the period, all 3 experimental runs showed a wetter tropical western Pacific and drying over South Asia. Since the western Pacific experiment by itself simulated this pattern, the rise in western Pacific SST appears to have initiated the monsoon circulation changes.

Analysis of the moist static-energy budget in the western Pacific model-run reveals that the rise in SST increases humidity in the lower troposphere, leading to deep convection in the tropical western Pacific. The strong low-level circulation enhances evaporation and rainfall, which in turn strengthens the low-level winds, setting up a positive feedback loop. Over South Asia, the budget shows that evaporation and advection of dry air contribute about 40% to the reduced rainfall trend, with only small contributions from other processes.

The increased rainfall in the western Pacific is thought to excite a Rossby wave (see schematic). The northerly component of this wave brings dry air from the continental subtropics into South Asia, particularly into the Bay of Bengal and the plains of Indochina. This dry, cool air reduces rainfall over the Bay of Bengal, damping convection there and reducing the moisture laden cross-equatorial monsoon flow. The weakened monsoon results in decreased evaporation, sustaining a dryer circulation over South Asia.

## Regional and Global Perspective

Some scientists propose the decadal swings in rainfall over South Asia are related to the Atlantic multi-decadal oscillation (AMO). Since the AMO is currently in a warm phase, the monsoon should be in a wet phase. The drying trend over India, thus, contradicts the AMO connection. Others propose that the increase in black carbon aerosols from 1950 to



The 52-year trend (1949 – 2000) during boreal summer (June through September) simulated by the GFDL atmosphere model (AM2.1), forced by the observed SSTs over the tropical Indo-Pacific warm-pool region. The trend is obtained by subtracting the values from a control run that was forced by climatological SST: (a) precipitation ( $W/m^2$ ), (b) sea level pressure (hPa) and 850 hPa wind (m/s), (c) vertically integrated moist static energy divergence ( $W/m^2$ ), (d) surface evaporation ( $W/m^2$ ), (e) vertically integrated moisture advection ( $W/m^2$ ), and (f) vertically integrated temperature advection ( $W/m^2$ ). Note that precipitation unit conversion is  $28 W/m^2=1.00mm/day$ .

2000 has narrowed the north-south SST gradient in the tropical Indian Ocean. This should have moved the monsoon trough southward toward the equator, drying northern regions of South Asia and increasing rainfall along the equator. The observations and modeling experiments here, however, all point to an eastward, not southward shift in monsoon rainfall. Since the shift in monsoon rainfall is seen only in the run with increased greenhouse-gas concentrations, this forcing very likely resulted in the surface warming of the Indian and western Pacific oceans, the latter, in turn, producing the atmospheric circulation shift.

As mankind's use of greenhouse-gas emitting energy is not expected to wane over the next decades, the drying trend is likely to continue, and appropriate adaptation strategies are urgently needed for this densely populated region.

*“The Indian summer is long and relentless. ... But...eventually... a prolonged and punishing summer attracts new elements in the sky: the clouds. A visible mass of droplets rise from the horizon and begin to dissipate in a thin and almost imperceptible vapour over the sky fast turning gray. Perceptibly, the horizon gathers blackness, and the sun finds its glory diminishing ... With sun's splendour veiled from human sight by a long gloomy period of storm and turbulence, the masses of heavy clouds begin to appear far more frequently, and come howling over the southern coast of India. As the days pass, the portentous bodies of water continue to roll over the peninsular India and then gradually envelop the entire landscape ... Apart from the wondrous play of raw elements of nature, the monsoon also means absolute sustenance for more than two-thirds of Indian population. During the normal duration of monsoon - roughly 100 days beginning from 1st June - about 75,000 million tonnes of water vapour are transported across the west coast of India every day. Out of which a third ... is converted into rain ... bringing joy to the farmers. Monsoon means singing crops. It guarantees the food for the rest of the year. It means extra income. It means trouble-free education for the children for yet another year.”*

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