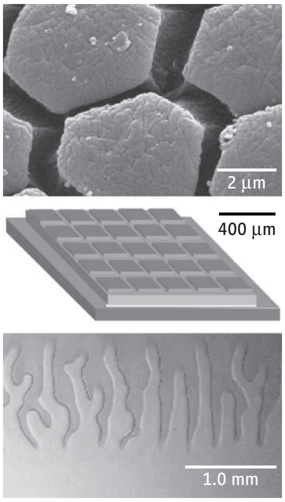
Majumder *et al.* started from the discovery that micropatterned structures resembling the toe pads of tree frogs and crickets can enhance adhesion (see the third figure). Normal adhesive tape detaches when cracks spread into the adhesive from the point of peeling. When all the energy is concentrated at a single crack, peeling occurs readily, but micropatterning can increase the force required to produce peeling by up to a factor of three. Cracks form wherever there is a groove in the pattern; when the energy is spread between many cracks—as is the case in a micropatterned tape—more force is required to produce separation (*10*, *11*).

The authors take this principle a step further. They have investigated the role of subsurface structures such as air- and oil-filled microchannels. The channels have similar crack-arresting properties as some of the patterned surfaces studied in (*10*, *11*), but the effect is much more dramatic. Depending on several factors—such as the thickness of the adhesive layer, the channel diameter, the interchannel spacing, and whether the channel is filled with air or oil—adhesion can be increased by up to a factor of 30. Under different conditions, the adhesive can act as a quick-release coating so that the tape, while sticking well, can be peeled off easily. The adhesive remains elastic and can thus be used again with no reduction in adhesive efficiency.




**The power of ridges.** The adhesive surface of the smooth adhesive pad of the cricket *Tettigonia* contains a hexagonal pattern of grooves (**top**) (*12*). On an elastic film incised with a related pattern (**middle**), cracks spread differently during peeling (**bottom**) than they would on an unpatterned surface (*10*).

Future smart adhesives like that reported by Majumder *et al.*, designed to do particular tasks, are also likely to be inspired by the remarkable mechanisms developed by climbing animals over millions of years of evolution. In this area of materials science, biomimetics is certainly coming of age.

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ATMOSPHERE

# Monsoon Mysteries

**Jagadish Shukla**

**Today's climate models cannot adequately predict the mean intensity and the seasonal variations of the Asian summer monsoon.**

The Asian summer monsoon, manifested in all its glory and fury over the Indian subcontinent, is the largest seasonal abnormality of the global climate system: During the monsoon, the equatorial region is colder than the regions to the north. The summer monsoon rains that result are critical for food production, water supply, and the economic well-being of the Asian society. There is thus great interest in predicting the waxing and waning of the Asian monsoon.

What are the prospects for predicting monsoon rainfall over India and the surrounding regions? Why has the accuracy (or "skill") of monsoon forecasts been so low? What are the projected impacts of global warming on the Asian summer monsoon? In July of this year, a conference at the Indian Institute of Sciences, in Bangalore, addressed some of these questions (*1*).

A review of the current status of short-range (1 to 10 days) forecasting presented at the conference shows that the weather prediction centers in the world have made steady progress in improving the skill of 5-day forecasts. But India somehow missed the revolution in numerical weather prediction. According to A. K. Bohra and S. C. Kar (*1*), there has been no improvement in the accuracy of the 5-day forecasts over India for many years.

Monsoon forecasting has a long history in India. After the subcontinent had experienced a devastating drought and famine in 1877, the British Government asked the recently established India Meteorological Department (IMD) to forecast monsoon rainfall. The earliest methods of forecasting the summer monsoon were based on the snowfall in the preceding winter in the Himalayan region (*2*). In the early 20th century, Sir Gilbert Walker—an applied mathematician at the University of Cambridge who became director-general of observatories in India in 1904—identified empirical relationships between the monsoon rainfall and global circulation features in data from other British colonies around the world. He devised a forecasting methodology using a linear regression model with past data (*3*).

Normand showed over 50 years ago that the forecasts made by Walker had no skill (*4*). (A forecast has no skill if it is no better than forecasting each year's rainfall to be the same as the long-term average rainfall.) Yet, the IMD continues to forecast monsoon rainfall over India using the same basic methodology as Walker did. Verification of forecasts for seasonal mean rainfall over India for the recent 1990 to 2006 period also shows that there is no skill (*5*). The problem is that the IMD uses too many nonindependent predictors, giving artificial skill in explaining the past data and poor skill in actual forecasts (*6*).

What determines the predictability of monsoon rainfall? More than 25 years ago, Charney and I proposed (*7*) that seasonal mean monsoon rainfall is influenced by the slowly varying boundary conditions of sea surface temperature (SST), soil wetness, and snow cover. Many global climate models have since been used to test the validity of this hypothesis, but none have been successful in making skillful predictions of Indian monsoon rainfall. It remains an open question

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whether the problem is with the hypothesis or the models. At present, the biggest stumbling block in predicting monsoon rainfall appears to be the deficiency of models. In particular, the models fail to capture the detailed spatial structure of monsoon rainfall (see the figure).

The lack of success in predicting Indian monsoon rainfall with climate models can be attributed to two major causes. First, the models have large errors in simulating the seasonal mean rainfall. The year-to-year standard deviation of Indian monsoon rainfall is less than 10% of the mean rainfall, yet the errors in simulating the mean rainfall are larger than these observed year-to-year changes. It is therefore not surprising that models cannot predict the departures from the mean that are relevant for societal applications and policy. Second, the climate models cannot simulate monsoon rainfall variations within seasons, and therefore perform very poorly in predicting fluctuations in the mean rainfall.

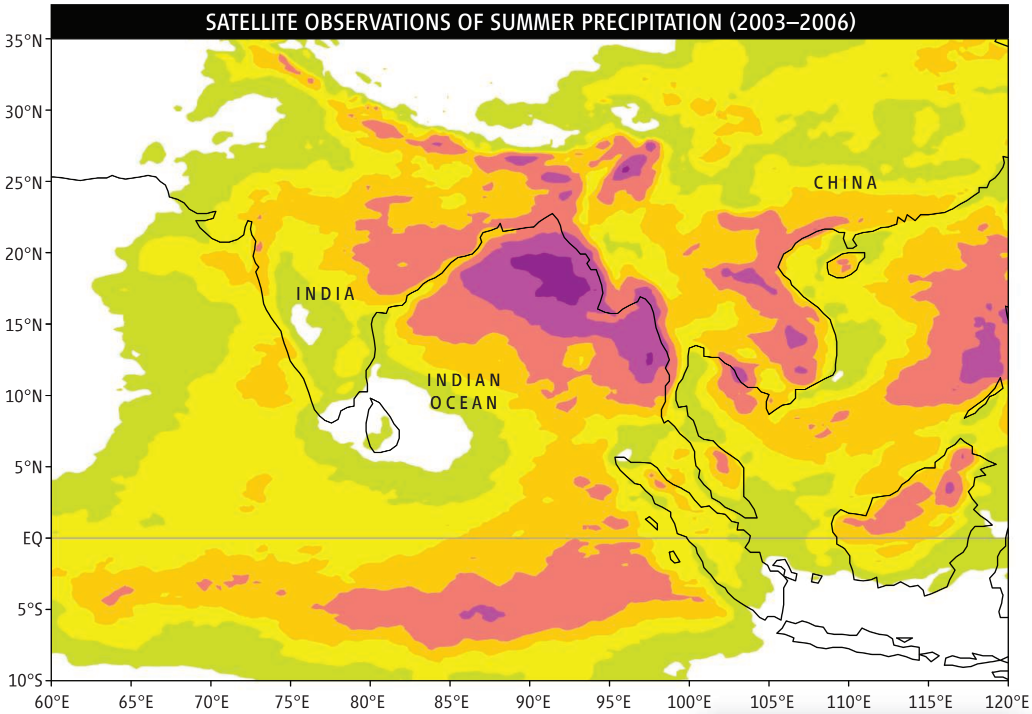
There is considerable debate in the research community whether mean monsoon rainfall is indeed determined by the slowly varying SSTs. If so—and if we had better models that capture crucial couplings between ocean, atmosphere, and land processes (*8*)—then we could make skillful predictions of monsoon rainfall. However, if the intraseasonal variations are fundamentally unpredictable, then seasonal mean rainfall is also not predictable (*9*).

At the Bangalore conference, presentations by S. Gadgil and S. Nigam (*1*) reaffirmed that there are statistically significant relationships between SST changes over the Pacific and the Indian Ocean and monsoon rainfall averaged over India, and that the combined effects of the SST anomalies over both of the ocean basins are most important for predictions of summer monsoon rainfall over India.

The prediction of the seasonal mean rainfall averaged over all of India, although of great value to the national policy-makers, is of limited value to the farmers and water managers in any of the individual states. It is therefore important to develop methods of predicting fluctuations of rainfall within the season over different regions of India. Several papers at the conference showed real progress in understanding the structure and the mechanisms of intraseasonal variations. Although the current climate models remain quite deficient in simulating the structure and life cycle of intraseasonal variations, the prospects of empirical prediction of intraseasonal variations look promising, because intraseasonal variations have a well-defined structure and tend to propagate from south to north.

Nearly half of the world's population is affected by the Asian monsoon. How reliable are the projections of changes in monsoon in a changing climate? What if the Asian monsoon rainfall, which has not changed by more than 10% in hundreds of years, decreases abruptly and substantially because of increased rainfall over warmer oceans due to global warming? These questions affect the future of global societies, and yet there are no adequate climate models to investigate them. None of the climate models assessed by the Intergovernmental Panel on Climate Change can simulate the observed monsoon rainfall and its interannual and decadal variability. If it is not possible to simulate the mean monsoon rainfall and its variability nor to make skillful seasonal predictions with existing climate models, one cannot expect the projections of regional climate changes to be reliable. What adaptation and mitigation strategies should monsoon countries adopt in the face of such large uncertainties?

Climate models can now describe and predict extratropical cyclones, but not the tropical cloud systems. To simulate the monsoon and its variability at intraseasonal, interannual, and decadal time scales, the next generation of climate models must be able to resolve the cloud systems with embedded deep convection, and to simulate mean rainfall and its variability in space and time. The stakes are high, involving food production and water availability for billions of people. Every effort should be made to produce reliable projections of monsoons and regional predictions of rainfall.




**Monsoon rainfall variability.** Observed summer (June to September) precipitation (in mm/day) from satellite data for 2003 to 2006. The large spatial variability of monsoon rainfall over land and ocean cannot yet be reproduced by models, and forecasts lack accuracy. Figure generated with the NOAA CPC Morphing Technique, see www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html.

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