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UNRAVELLING THE MYSTERY OF THE INDIAN MONSOON

➤ Prof. Sulochana Gadgil, an Indian Meteorologist, retired from the Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science (IISc), Bengaluru. She has contributed significantly to the understanding of monsoon dynamics, tropical convection, coupling of the tropical atmosphere to the oceans and agricultural strategies for a variable climate. She has spearheaded the development and execution of the Indian Climate Research Programme with major programmes over the Bay of Bengal, the Arabian Sea and Indian monsoon zone.

She is a Fellow of the Indian National Science Academy, the Indian Academy of Sciences, the Indian Meteorological Society and has received several awards including the Vikram Sarabhai Award, the Norman Borlaug Award.

Recognising her outstanding contribution to Earth System Science, the Ministry of Earth Sciences (MoES) honoured Prof. Sulochana Gadgil with “Life Time Excellence Award in Earth System Science” for the year 2016.



MY journey in science began a little over 50 years ago when I embarked on the endeavour to understand the fascinating phenomenon known as the monsoon. I have thoroughly enjoyed the journey so far and expect to continue to do so to the end, as the monsoon is still the most challenging problem in atmospheric science. The invitation to write this has given me the opportunity to walk down the long memory lane.

I was born and brought up in Pune. My education in science began as an undergraduate student at Fergusson College. My favourite subject was mathematics, so I got BSc with that as one of the subjects and after that MSc (Applied Mathematics) from Pune University. Unforeseen circumstances played a major role in my further education in science.

While studying for MSc, I got engaged to Madhav Gadgil. Madhav who was also a student at Fergusson was then studying for his MSc in Marine Biology at Mumbai. He wanted to study for a PhD in Biological Oceanography at a good university in the US. After completing his MSc he asked me whether I would also like to study further by going with him to the US. I liked the idea very much. Since my subject was applied Mathematics, I could work on modelling in any field. So I chose to apply for admission to the PhD programme in Physical Oceanography. We applied to a few universities and one of the two universities which gave both of us admission was Harvard University, one of the topmost universities in the world.

The first two years at Harvard involved a lot of coursework, with excellent courses in Applied Mathematics, Fluid Dynamics, Geophysical Fluid Dynamics, Physics of Atmosphere and Oceans taught by Professors who were the top scientists in the field. This training in fundamentals made it possible for me to interact with scientists in Fluid Dynamics or mechanical engineering as well as meteorologists and oceanographers on my return to India. We also had a special course of lectures on tropical dynamics and convection by Prof. Jule Charney who has made the most fundamental contributions to

this field of great relevance to tropical phenomena like the monsoon.

I learnt about the dynamics of ocean circulation and did a thesis on the meanders of the Gulf Stream under Prof. Robinson who was my advisor. He insisted that as a graduate student at Harvard I should get a broad background in science. So, In addition to the courses relevant to the field I wanted to work in, I ended up auditing courses in Physics by Professors who later were awarded the Nobel prize. So, I also got exposed to the problems dealt with in totally different areas of Physics.

While carrying out the theoretical work on the Gulf Stream meanders, suggested by Prof. Robinson, I became interested in the problem of jets which are prominent features in circulation in the atmosphere and ocean and worked on the problem of the structure of jets in rotating systems which also became a part of my thesis.

Madhav finished his PhD a year before me and was offered a faculty position at Harvard. So, we decided that he take up the offer for two years so that I could work as a post-doctoral fellow for one year before we returned to India. I had decided that I would like to focus my research on the monsoon after my return to India. So to get deeper insight into tropical dynamics and convection, I requested Prof. Charney to let me work with him for a year and he offered me a post-doctoral fellowship. I learnt a lot in that year since Prof. Charney had just published a set of lectures on 'Planetary Fluid Dynamics' and was then working on the dynamics of the so-called 'Intertropical Convergence Zone (ITCZ)', the system responsible for the large-scale rainfall over the tropical oceans and, as we showed a decade later, for the Indian monsoon rainfall as well.

Another field of science I was exposed to at Harvard was Evolutionary Biology. Some of the important work on natural selection was done by Ronald Fisher, who has written an excellent book on the subject of which a considerable part was mathematical. Because in our educational system, biology students do not get an opportunity to study

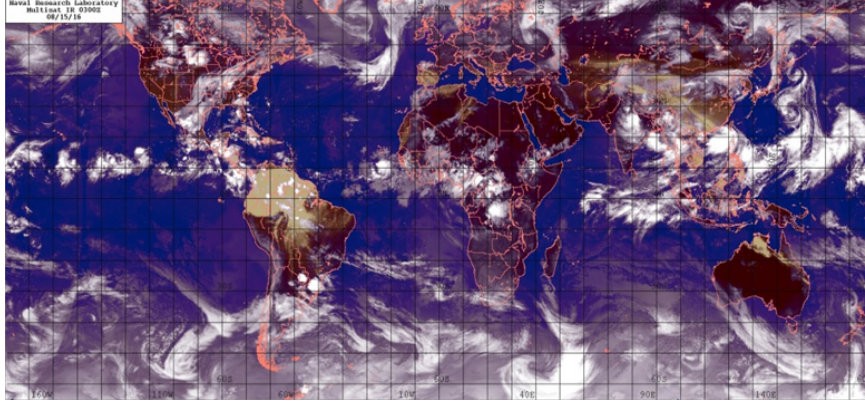
mathematics, Madhav did not have sufficient knowledge of mathematics to understand parts of Fisher's book. So we read it together and understood and appreciated it. Thus began my long and enjoyable association with another fascinating subject – mathematical modelling of totally different phenomena – which has continued throughout my journey in collaboration with faculty at IISc.

The atmosphere at Harvard and MIT was stimulating, not only because of the high level of expertise of the Professors but also because I made friends with some bright students from all over the world who were also working for a PhD in Atmospheric and Oceanic Sciences. They continue to be my friends to this day. Many of them are now leaders in the field and I have benefitted from this friendship in my research as well.

On returning to India in 1971, I joined the Indian Institute of Tropical Meteorology (IITM) at Pune as a CSIR pool officer. At IITM I heard that Prof. Dhawan, Director of the Indian Institute of Science (IISc) was interested in hiring scientists working on the monsoon. It so happened that just then the Centre for Theoretical Studies (CTS) had been established at the IISc. Madhav and I applied to Prof. Dhawan and were both offered faculty positions at CTS. We joined IISc and worked there very happily till retirement.

At IISc the fluid dynamicist, Prof. Narasimha took great interest in my research and founded the Centre for Atmospheric Sciences (CAS). I taught many courses and guided several students at CAS. Several outstanding scientists from other departments were associate faculty at CAS. I enjoyed learning from and collaborating with Prof. Narayana Iyengar on rainfall analysis. My interaction with Prof. J. Srinivasan has been extremely fruitful. Initially, it was a collaboration on monsoon modelling, but that on physics of the monsoon has continued till today. We have also worked together on many national programmes such as the Indian Climate Research Programme.

Over the past five decades, I have done research on many facets of the monsoon dynamics and ocean-atmosphere interaction. I carried out



genuinely interdisciplinary studies in climate variability and agriculture in collaboration with an ecologist and farmers, in which I have addressed problems posed by farmers cultivating rainfed crops such as deriving the sowing strategies which are appropriate for the observed rainfall variability of the region. I have made a quantitative assessment of the impact of the monsoon on food-grain production and GDP. I have also worked on evolutionarily stable strategies for competing animals.

Monsoon Research

The focus of most of my research is the monsoon. Fortunately, when I joined IITM as a pool officer, I was asked to share an office with D.R. Sikka, the most knowledgeable monsoon meteorologist in the country. I have learnt a great deal about the monsoon from him and collaborated with him extensively over the next few decades.

Our first collaboration was the study of the daily satellite imagery over the Indian region, to document the nature of variation of the major cloud bands over the land and the surrounding oceans during the summer monsoon season. Sikka had his personal collection of satellite photographs (both infrared and visible). The work involved identification of the cloud band with deep clouds organised over scales of 1000 km or more over the Indian longitudes (land and Ocean between 70°E-90°E) which we called the Maximum Cloudiness Zone (MCZ) and noting its location at 70°E, 80°E and 90°E, for each day of five summer monsoon seasons. Although the work sounds tedious, it taught me a lot and also gave me great pleasure because the cloud bands in satellite pictures are so beautiful.

We discovered several important features of the variation of MCZ. We showed that (i) the MCZ is responsible

for the large-scale monsoon rainfall and that dynamically the system is identical to that which gives large scale rainfall over the tropical oceans i.e. a Tropical Convergence Zone (TCZ); (ii) there are two favourable locations for the TCZ over the Indian longitudes, one over the heated subcontinent, the Continental Tropical Convergence Zone (CTCZ) and another over the warm waters of the equatorial Indian Ocean-the oceanic ITCZ; (iii) throughout the summer monsoon season, the oceanic ITCZ propagates northward onto the monsoon zone, as in the onset phase, at intervals of 2-6 weeks.

The result that the system responsible for large-scale monsoon rainfall is the tropical convergence zone implies that the popular theory that the monsoon is a gigantic land-sea breeze driven by land-ocean contrast in temperature, has to be discarded. This is supported by other studies that have shown that the observed variability of the monsoon rainfall is in the opposite direction to what is expected from the variability of land-ocean contrast. On the other hand, our suggestion that the basic system is the tropical convergence zone is supported by analysis of the observed variability and is getting accepted in the community.

Most of the monsoon rainfall occurs due to the propagation of cloud systems generated over the surrounding oceans. Hence variability of the monsoon is strongly linked to the variability of the cloud systems over the ocean. Hence a critical question is what determines the variability of cloud systems over the tropical oceans.

Variability of Organised Cloud Systems

It had been known that the Sea Surface Temperature (SST) of the ocean beneath plays an important role in tropical cyclogenesis and precipitation

on Canton Island in the central Pacific. However, the nature of the relationship of organised convection to SST had not been elucidated yet because of the lack of sufficient data on clouds over the Oceans. By the late 70s, Sadler at Hawaii had generated digital data on cloudiness from satellite imagery.

I wrote to my friend and fellow student at Harvard, Dennis Moore, who was in Hawaii, requesting him to send me that data which he did immediately! Hence it became possible to study the relationship with SST for which data was available from ship reports, which had been investigated by P.V. Joseph, another stalwart in Monsoon meteorology. I collaborated with Dr P.V. Joseph and Dr Joshi, a colleague at IISc, to analyze the relationship of cloudiness with SST of the Indian seas and the equatorial Indian Ocean.

We found that the relationship between organised cloudiness and the SST of the ocean beneath is highly nonlinear with a threshold of about 27.5°C for organised convection. Soon after our study, it was shown that this result is true also for convection derived from radiation measurements by satellite, and holds for other tropical oceans as well. The results have been verified with subsequent studies with far superior data on convection also.

Equatorial Indian Oscillation Variation of Monsoon Rainfall

Sikka showed in 1980 that there is a strong relationship between El Nino, Southern Oscillation (ENSO) over the Pacific and the monsoon rainfall. Since then, the major input for the prediction of the monsoon is the ENSO, although rainfall in a few years is different from what is expected from the phase of ENSO.

In collaboration with a colleague Vinayachandran, who had done extensive work on the Indian Ocean dipole and my student Francis, I showed that the equatorial Indian Ocean Oscillation (EQUINOO) also plays an important role in the interannual variation of the monsoon. ENSO and EQUINOO together can explain all the extremes of the monsoon i.e. droughts and excess rainfall seasons. Hence, the future holds great promise for better prediction of the monsoon when the physics of EQUINOO is unravelled and methods of predicting it are developed.

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Nurturing Atmospheric and Oceanic Science

At the level of the Institute, I have contributed towards developing CAS into a unique Centre of Excellence with experts in not only atmospheric and oceanic dynamics and modelling, radiation and climate but also in laboratory modelling and instrumentation as faculty. In the sixties, the atmospheric and oceanic science community recognised the need for special observational programmes aimed at understanding special phenomena or special regions and several international programmes such as the International Indian Ocean Experiment and MONEX were organised under the World Climate Research Programme. The science plans for these programmes were prepared by international committees with some participation of Indian scientists. Many Indian scientists participated in the observational programmes and benefitted from the interaction with the international experts.

But as Sikka commented, 'the Indian scientists participating remained on the periphery as they were not well prepared for research studies and hence much of the real credit of the excellent research emerging out of these programmes went to the US scientists;

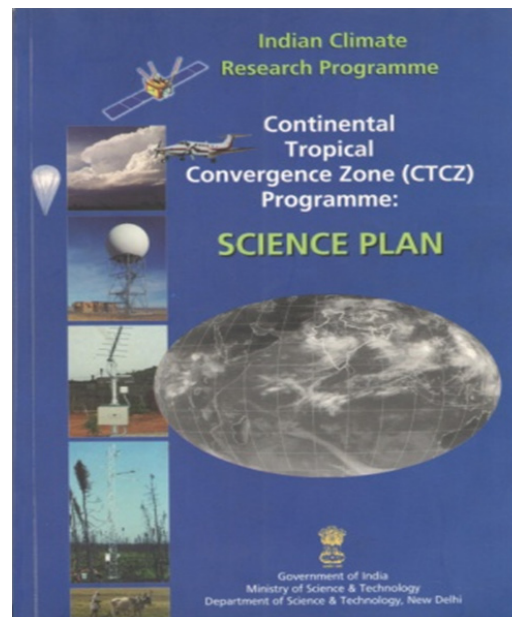
clearly, it is essential for India to build its own capabilities for launching field programmes.'

Fortunately, considerable progress was made in different institutions in the country in the 80s in atmosphere, ocean dynamics and modelling and even in the capabilities of handling and using modern instrumentation and making special observational studies. A small national observational experiment was conducted to study the atmospheric boundary layer in 1979 under the leadership of Prof. Narasimha and Sikka.

At our Centre, we also had active interaction between meteorologists and oceanographers from different institutions in the country discussing challenging problems such as convection over the Bay of Bengal. Some of us (Profs Narasimha, J. Srinivasan, Sikka and myself) felt strongly that we must have an Indian Climate Research Programme (ICRP) with science plans prepared by Indian scientists and observational experiments planned and conducted by Indian scientists. I took the major responsibility of preparing the science plan of ICRP with valuable inputs from Sikka, and other leading meteorologists and oceanographers in different institutions in the country and support from DST in 1995.

One of the major objectives of ICRP is understanding the variability of the monsoon and the oceans particularly the Indian seas and the equatorial Indian Ocean. A multi-pronged approach involving analysis of existing observations, development and implementation of new surface-based and space-based observational techniques, special observational experiments in critical regions such as the Bay of Bengal and the Indian monsoon zone and development and investigation of a hierarchy of models of the atmosphere and coupled atmosphere ocean systems, was adopted for attaining the objectives.

The first observational experiment under the ICRP was the Bay of Bengal Monsoon Experiment in 1999, under the leadership of G.S. Bhat (a young faculty member of CAS), which turned out to be a great success and gave many new insights. The second was the Arabian Sea Monsoon experiment



and the last was the CTCZ programme. With the success achieved in all these, our scientists are now leaders in international programmes such as the Indo-UK programme.

The simulations of the Indian summer monsoon rainfall with atmospheric general circulation models driven by observed oceanic conditions began to be generated even at some institutions in our country in the late 90s. The simulations could be considered to be acceptable only for some of the models and for some years, pointing to the need to assess the reliability of the different models used for monsoon prediction.

With support from DST and CDAC, Prof. Srinivasan and I organised a national project (Seasonal Prediction of the Indian Monsoon, SPIM) in 2005 in which modellers from six Indian Institutions participated and made runs for the monsoon seasons of 1985-2004 on the supercomputer at CDAC. This project promoted active interaction between all the modelling groups in the country and gave interesting results on common biases and their relationship to the phase of ENSO and EQUINOO, which persist even in the state-of-art coupled models. A logical next step was the national programme Monsoon Mission launched in 2007 aimed at improving the forecasts with dynamical models. I have also contributed to the work on the Monsoon Mission over the last five years.

INDIAN CLIMATE RESEARCH PROGRAMME Science Plan



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