On forecasting the Indian summer monsoon: the intriguing season of 2002

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This year, the rainfall over India during the first half of the summer monsoon season was 30% below normal. This has naturally led to a lot of concern and speculation about the causes. We have shown that the deficit in rainfall is a part of the natural variability. Analysis of the past data suggests that there is a 78% chance that seasonal mean rainfall this year will be 10% or more below the long-term average value. We discuss briefly how forecasts for seasonal rainfall are generated, whether this event could have been foreseen, and share our perspective on the problems and prospects of forecasting the summer monsoon rainfall over the Indian region.

THE monsoon governs the very pulse of life in India. It is no wonder, therefore, that the public and the media in particular, are very much concerned when there is a deficit in monsoon rainfall. This year, the rainfall during the first half of the summer monsoon season (June and July) has been much less than the average (Figure 1 from the web-site of the India Meteorological Department (IMD), New Delhi – http://www.imd.ernet.in) and fears are being expressed about a possible collapse of the monsoon.

We attempt to address these concerns in the light of the rich historical data of the Indian monsoon and the recent advances in our understanding of the system. First, it is important to assess whether the deficit in rainfall is truly something abnormal, an unprecedented catastrophe, or is a part of the natural variability of the monsoon. If it is a part of the natural variability, then can we, on the basis of past observations, assess the chances that this deficit will be made up in the second half of the season (August–September)? After addressing these questions, we discuss briefly how forecasts for seasonal rainfall are generated, whether this event could have been foreseen, and share our perspective on the problems and prospects of forecasting the summer monsoon rainfall over the Indian region.

Natural variability of the Indian summer monsoon

Fortunately, IMD has a rich data set of meteorological observations from which the nature of variability of the summer monsoon (June–September) rainfall over about 130 years can be elucidated. Mooley and Parthasarthy[1] and Parthasarathy *et al.*[2] derived the time-series of all-India average rainfall on seasonal and monthly time-scales as a weighted average of the data at 306 stations obtained from the IMD. This data set (extended up to 2000 by scientists at the Indian Institute of Tropical Meteorology (IITM), Pune and available on-line at http://www.tropmet.res.in) reveals that four out of 130 years, the rainfall during the first half of the season was less than that received this year. Clearly, what we have experienced this year is not an unprecedented catastrophe, but an event close to the lower limit of the observed variation in the June–July rainfall, i.e. a part of the natural variability of the system.

For each year during 1871–2001, the departure of the all-India summer monsoon rainfall (ISMR) from the long-term average (expressed as a percentage of the average), is shown in Figure 2. A year with a deficit (excess) larger than the standard deviation (which is about 10% of the average) is considered to be one with drought (excess monsoon). During the other years, the rainfall is said to be 'normal'. In the past 130 years, there have been 21 years with drought, 92 (i.e. 70%) normal rainfall years and 18 years with excess rainfall. It can be seen that the frequency of droughts has varied on the decadal scale. For example, whereas ten droughts occurred during 1965–87, in the last 13 years the rainfall has been normal. Such extended runs of normal rainfall occurred twice in the past–during 1878–90 and 1921–32 (Figure 2).

What are the chances of recovery by the end of the season, from such a large deficit in the first half? It is seen from Figure 3*a* that it is difficult to predict the rainfall during August–September on the basis of historical data, since its correlation with the rainfall in June–July is poor. However, it is seen that during the years in which

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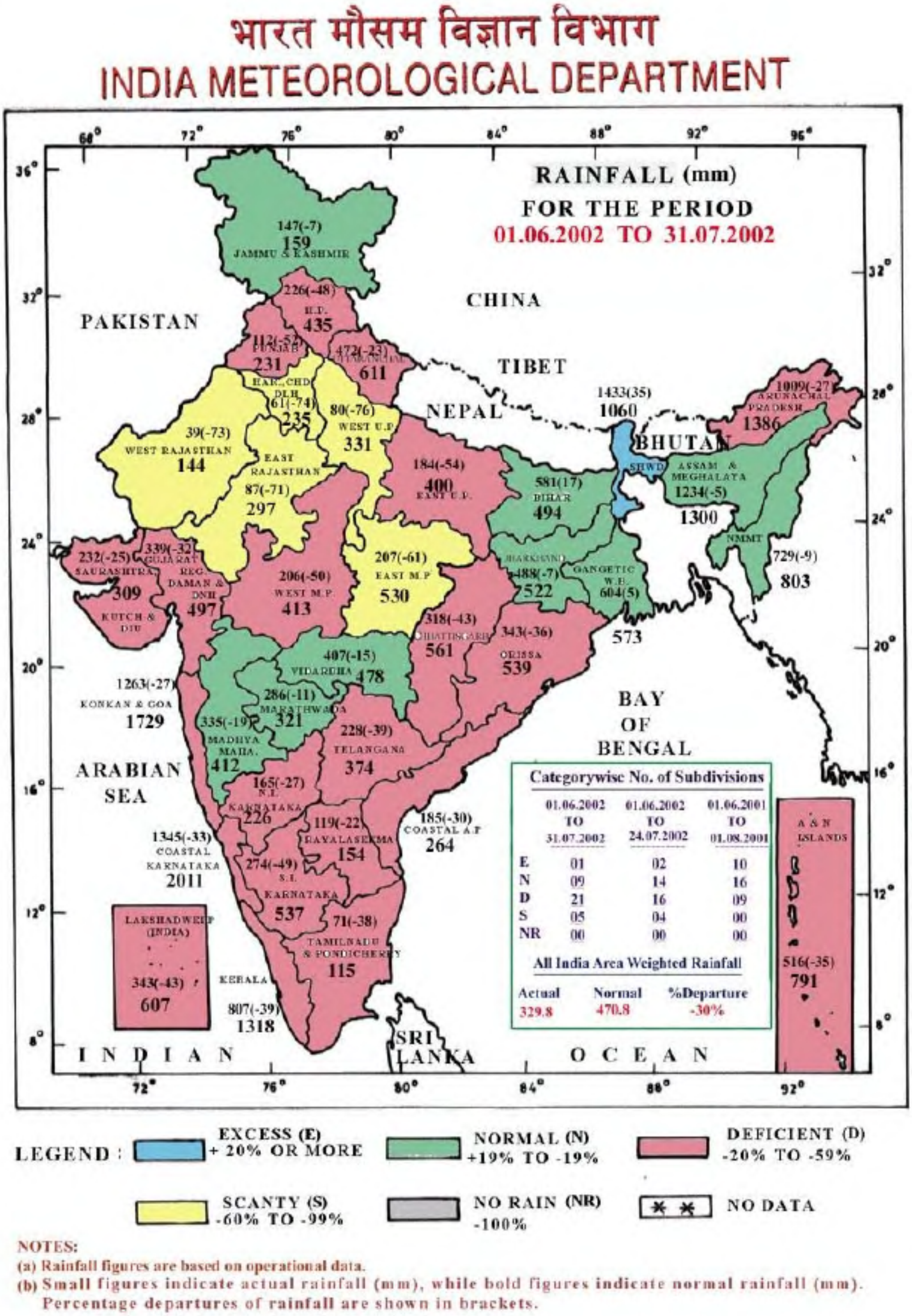

Categorywise No. of Subdivisions

	01.06.2002 TO 31.07.2002	01.06.2002 TO 24.07.2002	01.06.2001 TO 01.08.2001
E	01	02	10
N	09	14	16
D	21	16	09
S	05	04	00
NR	00	00	00

All India Area Weighted Rainfall

Actual	Normal	%Departure
329.8	470.8	-30%

NOTES:

(a) Rainfall figures are based on operational data.

(b) Small figures indicate actual rainfall (mm), while bold figures indicate normal rainfall (mm). Percentage departures of rainfall are shown in brackets.

Figure 1. Rainfall distribution during June and July 2002 over India. Small numbers show the actual rainfall, bold numbers represent normal rainfall and % departure from mean is shown in parenthesis for each meteorological subdivision.

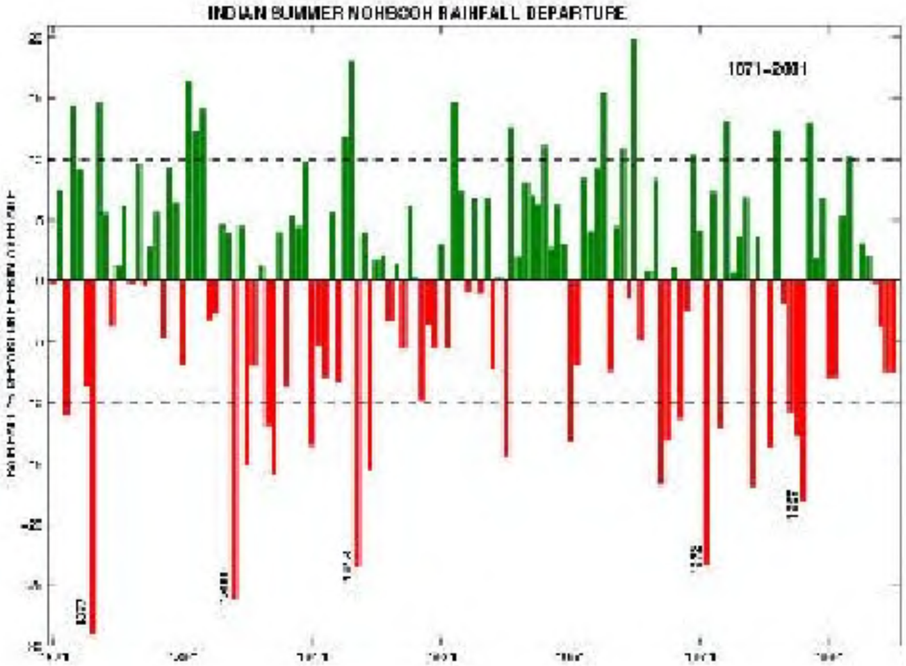

Figure 2. Indian summer monsoon rainfall as percentage departure from the mean during 1871–2001. Dotted lines indicate the standard deviation of the rainfall (as %) about the mean.

the rainfall in the first half of the season tends to be low, the rainfall in the second half is also low. In fact, all the four years in which rainfall during June–July was lower than that received this year (1877, 1918, 1972, 1987) turned out to be major droughts (Figure 3*b*). Analysis of the variation in the last 130 years shows that, when the deficit in rainfall during June–July is more than one standard deviation (i.e. 11.7%), the probability of the summer monsoon rainfall being normal is only 0.33, that of a drought 0.67, with almost zero probability of above normal rainfall. In fact, this year the deficit in June and July is about 30%, while that of July alone is at an unprecedented level of 49%. The probability of adequate rainfall in August and September so as to make the seasonal rainfall within the normal range, is only about 22%.

Thus on the basis of the observed variation, it appears that this season is likely to be a drought and the IMD prediction of a normal monsoon may turn out to be inaccurate. If this happens, then it will be important to understand why the approach adopted by IMD, that yielded successful predictions for the last 13 years, has failed this year.

How do meteorologists generate forecasts?

Scientists and laymen often find it difficult to understand the reasons for the painfully slow progress in forecasting the weather and climate in the modern-day milieu of satellites and computers. When solar eclipses can be predicted to fractions of a second and the position of a satellite pinpointed millions of miles out in space, it is not readily understandable why reliable weather predictions cannot be made for a day, week, month, season or years in advance. The problem of generating predictions of meteorological events (such as heavy rainfall over a region) is more complex than that of generating predictions of planetary orbits. This is because the atmosphere is unstable and the systems responsible for the events that we are trying to predict, such as clouds or a monsoon depression (in which thousands of clouds are embedded) are the culmination of the instabilities and involve nonlinear interaction between different spatial scales from kilometres (as in a single cloud) to hundreds of kilometres (as in a monsoon depression or a hurricane). The climatic variables on the monthly or seasonal scales, such as the monsoon rainfall over the Indian region, are the total effect of a series of such systems occurring during the season. The problem of generating long-range predictions (such as those of monthly/seasonal rainfall) is according to the late von Neumann, 'the second-most difficult problem in the world'; human behaviour presumably being the first[3].

Meteorological forecasts are generated for three timescales, viz. short-range (1–2 days ahead), medium-range (3–10 days ahead) and long-range forecasts for monthly and seasonal scales. In India, IMD generates the short- and long-range predictions, whereas the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi is responsible for the medium-range predictions. The short- and medium-range forecasts are for

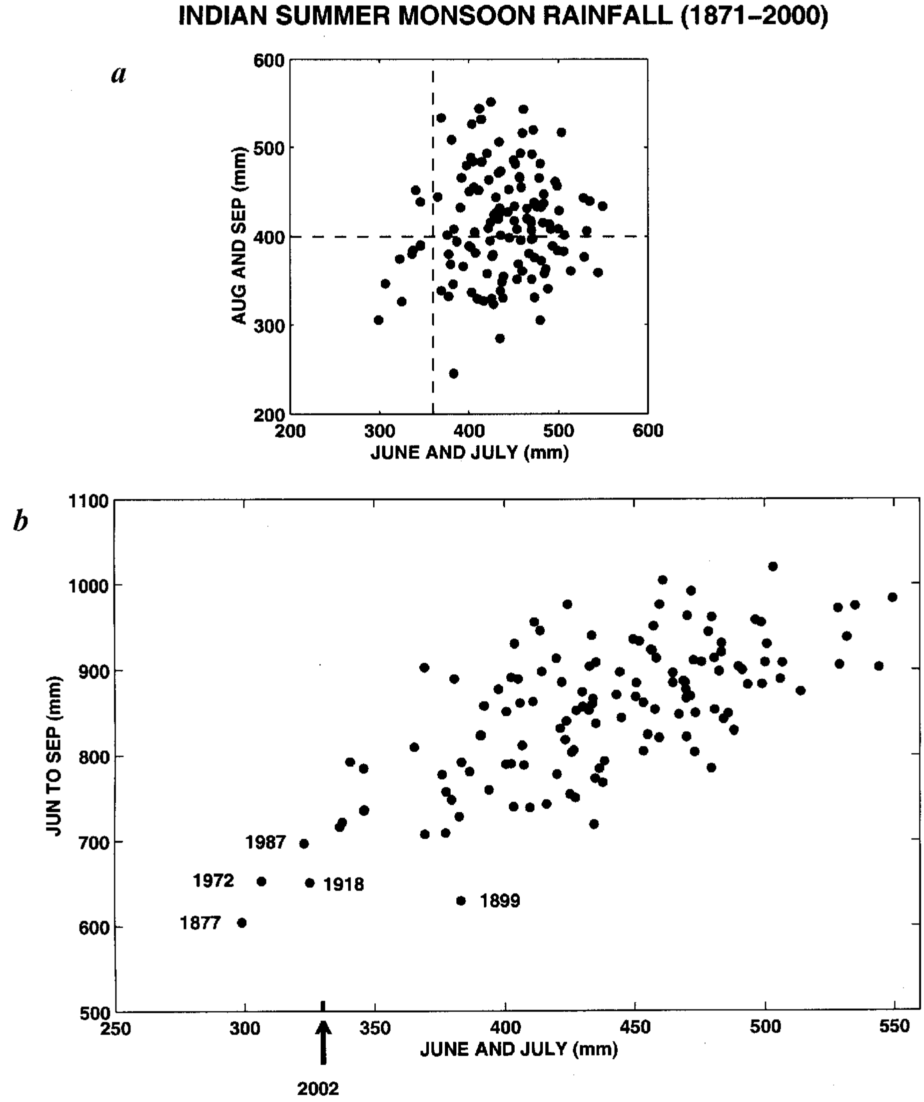

Figure 3. Scatter plot of *a*, August–September rainfall (mm) vs June–July rainfall (mm); and *b*, June–September rainfall (mm) vs June–July rainfall (mm). Arrow indicates the cumulative rainfall during June and July of 2002.

weather (i.e. temperature, rainfall) over meteorological subdivisions of India (shown in Figure 1). Since space- and time-scales are inexorably linked, long-range forecasts are made for larger regions such as the all-India scale or two or three subregions of the country.

The first weather forecasts were made by meteorologists with empirical knowledge of how weather maps evolved from day to day. By the 1950s, development of physical models of the atmosphere on the one hand and detailed observations of the system on the other, led to insights into the physics of the variation on the scale of a few days. With the advent of satellites and computers, the density of observations increased enormously and complex models of the atmosphere, that could simulate the short- and medium-range variation realistically, were developed by the 1980s. Now, the integration of such models with initial conditions obtained from the worldwide observation network, is a major input for weather prediction on these time-scales. Atmospheric models are run regularly for this purpose at IMD and NCMRWF.

It is well known that there is a limit to predictability of weather of about 7–10 days because the system is chaotic, i.e. solutions of the governing equations corresponding to initial conditions which are arbitrarily close, diverge significantly over this time[4]. However, the variation of climatic elements on longer time-scales, e.g. the seasonal rainfall over the Indian region from year to year, responds to conditions at the lower boundary of the atmosphere such as the sea surface temperature (SST) or snow cover over Eurasia. Hence such variables can be used as predictors for this time-scale. Thus seasonal forecasting is primarily a boundary-value problem, while short- or medium-range weather forecasting is an initial-value problem. Hence ensemble runs of atmospheric models with specified boundary conditions and varying initial conditions are used to generate predictions on the seasonal to interannual scale. Since oceans evolve more slowly than the atmosphere, the conditions at the surface of the ocean could be specified for these runs. The unravelling of the physics of El Nino and Southern Oscillation in the 90s (ref. 5) has given a major thrust to programmes for generating long-range predictions by atmospheric models with specified boundary conditions or by coupled models in which the oceans also evolve.

For long-range predictions, an alternative approach is the traditional one, which involves developing empirical models for prediction on the basis of past observations of that variable (in our case rainfall) and/or other variables such as pressure, temperature of the atmosphere or ocean, etc. We now consider these two approaches for prediction of the ISMR.

Forecasting the Indian summer monsoon rainfall

Empirical models

A major drought and famine occurred in India in 1877 (Figure 2) soon after the IMD was established. The first long-range prediction in the world was made by Blanford, who was the Chief Reporter of IMD, at the request of the colonial government in the wake of this drought. The predictor used was the extent and depth of the Himalayan snow cover in the preceding winter[6]. In the early part of the last century, Walker[7–9] initiated extensive studies of the worldwide variation of weather elements (e.g. pressure, temperature, etc.) to develop models for monsoon prediction. During this endeavour, he discovered a major feature of the tropical atmosphere over the Pacific called the Southern Oscillation (SO) which, in the 1960s, was found to be linked with the El Nino. After the discovery of strong links between the El Nino and the Indian monsoon[10–12], the empirical models for monsoon prediction have developed rapidly.

Since excellent reviews of the empirical models used for prediction of the ISMR are available[13–16], we mention only a few important facets here. In the tradition of Walker, a large number of potential predictors have been identified by analysis of the ever-increasing data from conventional and satellite observations on many atmospheric and oceanic variables, and their lag correlation with the ISMR. Some of these parameters are related to El Nino and SO, others to snow over the Himalayas and Eurasia, and some to global and regional conditions on spatial scales ranging from one station (e.g. surface temperature at De Bilt in Holland)[14] to hemispheric (e.g. northern hemispheric surface air temperature in January and February). However, it has been found that the relationship of several of these parameters varies with time on the decadal scale[17–19]. Rajeevan[16] showed that the correlation of the ISMR with the first principal component derived from five important parameters (representing ENSO forcing, land surface conditions over Eurasia and the heat low over northwestern parts of India) exhibited decadal variation similar to that of the ISMR, and that in extended periods with normal monsoon rainfall, the relationship between the ISMR and the predictors tends to be weaker.

Different types of models are used for generating predictions. From 1924 to 1987, multiple regression models were used. In the last two decades new techniques based on auto-regressive integrated moving average method (ARIMA)[20], power (nonlinear) regression models[21,22], dynamic stochastic transfer models[15] as well as neural network models[23,24] have been used. In addition, a model – the so-called parametric model – which utilizes qualitative input (favourable/unfavourable) from 16 parameters to provide qualitative predictions (drought/normal/excess monsoon) on the basis of the fraction of favourable parameters has been developed[21,22]. The power regression model for quantitative prediction of the ISMR is based on the same set of 16 parameters. Since the model uses such a large number of parameters, it is likely to have the problem pointed out by Lorenz[25], that in spite of a good fit in the 31 years from which the model was developed, it is likely to give large errors for other years. In 1995, Krishna Kumar *et al.*[14] proposed a linear regression model with just three parameters – all regional circulation parameters, which performed as well as the 16 parameter nonlinear regression model. In particular, these two models were able to simulate the droughts and excess monsoon years in the validation periods[14,15].

It must be noted that the autocorrelations of the ISMR with lags varying from 1 to 5 years are not statistically significant[26]. However, a neural network model has been developed, which uses only information on past history of rainfall variation[24]. It has been used to generate predictions in the last five years, but it is not clear whether this model can predict droughts or excess monsoon years.

The official forecast of the IMD is based on the parametric and the quantitative models, particularly the 16-parameter, power regression model. It must be noted that the world over, long-range forecasts are generally made by taking inputs from various forecasters and different models[27]. From 1988 to 2001, IMD generated correct qualitative forecasts (normal/excess, etc.) of the summer monsoon rainfall. For the quantitative prediction of the total rainfall during the summer monsoon, the root mean square error was 7.6%.

Physical models

Models based on equations governing the dynamics and energetics of the atmosphere have been used for simulation and prediction of variation over different timescales.

Simulation of variability: Since El Nino involves major changes in SST patterns and the Indian monsoon is known to be linked to the El Nino, we expect some success in prediction of the interannual variation of the monsoon with this approach. However, before an atmospheric model can be used for this purpose, it is important to examine whether it is capable of simulating reasonably well, the observed response of the monsoon to changes in the SST patterns. Several atmospheric general circulation models from all the leading centres of the world were run with SST specified from observations during 1978–88 under an international programme called the Atmospheric Model Intercomparison Project (AMIP). Analysis of the AMIP simulation of thirty models by Gadgil and Sajani[28] showed that a large number of models could not simulate the rainbelt over the Indian region in the summer monsoon season. Simulation of the seasonal mean rainfall pattern over the Indian region has turned out to be a more difficult problem than that over the rest of the tropics. This is because over the Indian longitudes, there are two favourable zones for the rainbelt to occur – one over the heated subcontinent (over our monsoon zone) and another over the warm waters of the equatorial Indian ocean[29]. In the presence of multiple equilibria, the simulated rainbelt in the models tends to get locked into one or another location, whereas in nature it fluctuates between the two. It was found that very few models are able to simulate the year-to-year variation of the monsoon[28].

The knowledge gained during the first phase helped to improve the models. The second phase of AMIP (AMIP-2) is presently being conducted with all the models considered simulating the period of 1979–1995. During this period India experienced three years of drought (1979, 1982 and 1987) and two years of high rainfall (1983 and 1988). About twenty models were part of the AMIP-2. We consider here the simulations by three models, viz. National Centers for Environmental Prediction (NCEP, USA), European Centre for Medium Range Weather Forecasts (ECMWF, the European Community) and Center for Ocean, Land and Atmosphere Studies (COLA, USA) for these extreme years. These models were chosen because they are in use for medium- and long-range forecasting – NCEP by USA, ECMWF by the European Community and COLA in Brazil (the only other tropical country with medium range forecast capability other than India). It should be noted that one version of the NCEP model is being presently used in NCMRWF, New Delhi.

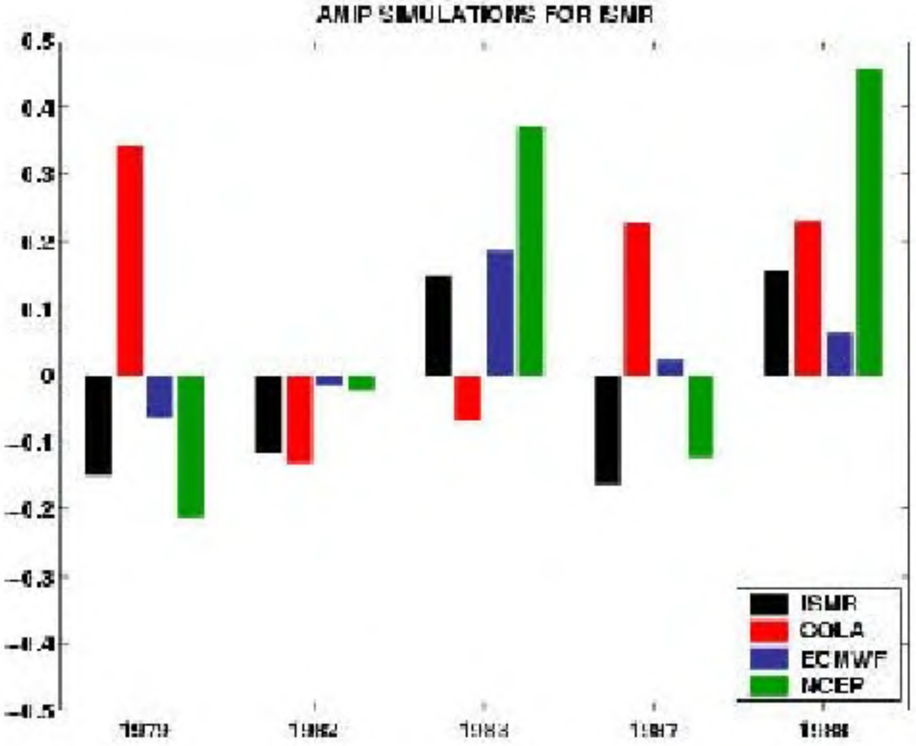

Figure 4. Comparison between the observed rainfall (ISMR) and model-simulated rainfall for the five extreme years between 1979 and 1994 for three physical models (viz. COLA, ECMWF and NCEP). Departure of rainfall from the mean normalized by the respective averages is also shown.

A comparison of the ISMR for the summer monsoon seasons of 1979, 1982, 1983, 1987, 1988 by these three models is shown in Figure 4. It can be seen that whereas NCEP was able to get the correct sign of the departure from average (i.e. whether it is deficit or excess) during all the five years, ECMWF got it right in four out of five years, whereas COLA got it right in only two out of five years. It can also be seen that the magnitude of the deficit/excess is not realistically simulated by any of the models, with NCEP overestimating it in three out of five years and ECMWF underestimating it in four years.

Prediction of year-to-year variations was generated with atmospheric models under a coordinated European project (PROVOST) for the period 1979–93. Here also it was found that the error was large for several years, including the droughts of 1979 and 1987 (ref. 16). Magnitude of the systematic error in simulation of the seasonal mean monsoon was identified as a major contributing factor to poor predictability[30]. Although some models are not able to simulate/predict the variation of the ISMR from year to year, Krishnamurthi *et al.*[31,32] have shown that by using a 'super ensemble', the simulations improved significantly. When AMIP simulations by the different models in the super ensemble were combined, the resulting values matched closely with observations not only for the control run of eight years (from which the coefficients were determined) but also for the remaining two years. Thus, as the models improve, reasonable forecasts could be generated by combination of different models.

Most forecasting centres have started issuing seasonal forecasts from 2001. The forecasts are generated with coupled atmosphere–ocean models from an ensemble of runs with varying initial conditions. It has been pointed out that there could be considerable errors in the forecasts and hence they should not be used indiscriminately. With the rapid increase in computational power and improvement in the modelling of physical processes, we can expect the forecasts from such numerical models to improve significantly over the next decade.

However, given the difficulties faced in simulating the interannual variation of the monsoon, empirical methods will continue to play an important role in generating predictions. In fact, in a recent review of long-range forecasting methods, Goddard *et al.*[33] have stated that empirical methods for prediction of the ISMR continue to outperform methods based on physical models. This is because most of the atmospheric models have not been able to simulate accurately the interannual variability of the ISMR.

The summer monsoon season of 2002

We have shown that what we have experienced this year is a part of natural variability. We believe that considerable research is required before we can pinpoint the factors and mechanisms that led to the large deficit in rainfall in the first half of the season. However, the unprecedented deficit in July, has led to several speculations about the possible causes. For example, some have attributed the drought to global warming. It is important to note that the time-scale on which global warming occurs is of the order of a century. We expect the effects of global warming to be manifested as a slow change in the mean seasonal rainfall and in the frequency of droughts and/or floods. A single event such as a drought in 2002 cannot be attributed to these long-term changes. Furthermore, most of the climate models suggest that global warming will be associated with increased monsoon rainfall and an increase in the frequency of floods. This is consistent with the expectation that global warming will intensify the hydrological cycle. Clearly, there is no basis for attributing the drought of 2002 to global warming. The other speculation is that the aerosol haze present over the Indian region in winter can cause a reduction in monsoon rainfall. There is no scientific basis for this speculation either. It is important to note that most of the aerosols present in winter over India are usually washed out by the first monsoon rains. Secondly, even if some black carbon aerosols remain during the monsoon, model simulations show that they will lead to heating of the atmosphere and hence increase in rainfall over the Indian region.

One special feature of the monsoon season of 2002 is the scarcity of cloud systems over the Arabian Sea and large deficits in rainfall over the west coast (Figures 1 and 5). Another is the increased clouding over a coherent belt across the tropical Pacific Ocean (Figure 5) with a large number of typhoons over the west Pacific. It is believed that there is a competition for convergence of moist air (and hence rainfall organized over large scales) between the atmosphere over the Pacific Ocean and that over the Indian region. Hence it is not surprising that increased cloudiness over the Pacific Ocean is associated with deficit monsoon rainfall. However, as in many instances in meteorology, while the association between events over different regions is clear, it is difficult to discern the cause–effect relationships. It is clear that further insights into the physics of the variation of the monsoon from year to year are required before we can fully understand the evolution of the monsoon in 2002. For this, multi-pronged efforts with detailed analysis of data, including those from satellites, buoys, model simulations and new observational experiments in critical regions (such as the Bay of Bengal Monsoon Experiment BOBMEX – during the summer monsoon of 1999)[34] are necessary. The second observational experiment under the Indian Climate Research Programme, viz. the Arabian Sea Monsoon Experiment (ARMEX) during which detailed observations have been made for July–August 2002, should provide some insights into why the monsoon over the Arabian Sea failed during July 2002.

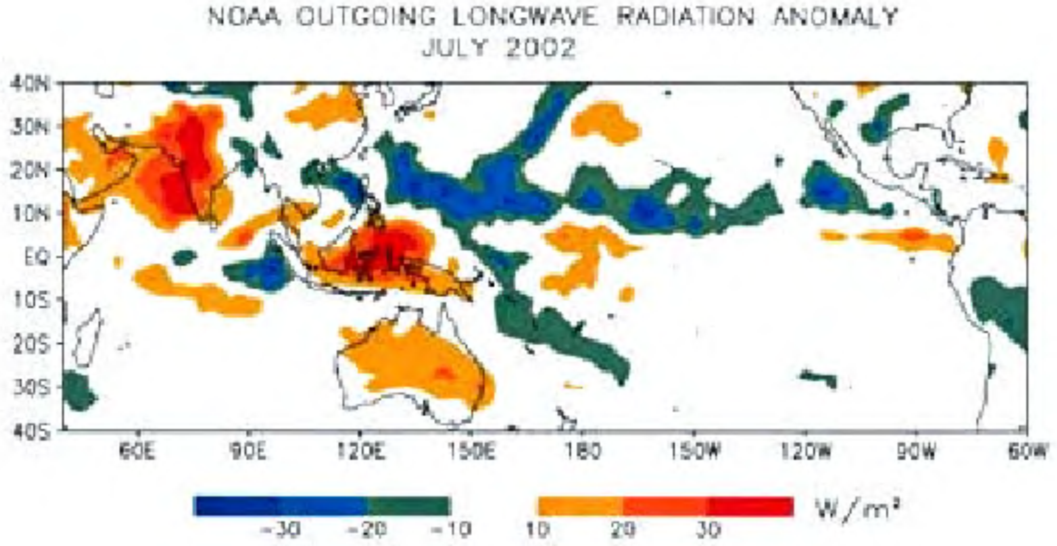

Figure 5. Outgoing Longwave Radiation (OLR, a proxy for rainfall) anomaly (i.e. departure from mean) during July 2002. Higher OLR implies lower rainfall. Note the high positive OLR anamoly (implying lower rainfall, shown in red) over the Indian region, and the large region of negative OLR anamoly (shown in blue, implying high rainfall) over the equatorial Pacific region.

It is clear that the large deficits experienced during this monsoon season were not anticipated. By the end of May, two predictions were released to the public. IMD predicted ISMR of 101% and CMMACS[35] of 99% of the long-term average. Estimates from several other empirical models also suggested above-average rainfall for this season, since most of the parameters were favourable. For example, the three-parameter model of Krishna Kumar *et al.*[14] suggested ISMR of 110%. As a matter of fact, the slew of empirical models developed over the years at IITM indicated a consensus forecast of 105% for the season of 2002. It is important to note that extensive testing of forecasts of most of the empirical models has been done mainly in the last decade during which the variation from year to year was not large. We have seen that based on past experience, the chance of recovery of the monsoon from the deficit of 30% in June–July to the normal range is only around 22%. In fact, the ISMR will come to close to the long-term average only if the rainfall in August–September is near the maximum observed in the past 130 years. Thus it appears that the rainfall during the summer monsoon of 2002 will be well below the predictions of IMD and CMMACS.

Why did the empirical models fail to predict the large deficit in July? The empirical models are based on the premise that the evolution of the complex system from the pre-monsoon season to the monsoon season is similar in the years from which it was developed and years for which predictions are made. Specifically, it is assumed that the precursors identified by analysis of the observations over the few years used for development, contain information about the forecasting monsoon season. Meteorologists are aware of the limitations of this approach and have documented secular changes in correlation of different predictors with the ISMR. So several parameters and models are considered in the expectation that when there is convergence in the predictions, the consensus prediction may be reasonably accurate. This season has proved to be a major exception for reasons we do not understand. One possibility is that it is a manifestation of the changes that are supposed to have occurred in the last decade in the relationship between the Indian monsoon and other phenomena in the tropics such as El Nino[36].

The forecast for June, July and August by the ECMWF model with initial condition in May suggested some deficit only over the southwestern peninsula and near-normal rainfall over the rest of the country (Figure 6*a*). The forecast in May, from the International Research Institute for Climate Prediction (based on the forecasts of several models) also suggested normal rainfall over the entire country. However, the forecasts generated with initial conditions in June, did suggest major deficits over the northwestern parts of the country (Figure 6*b* for the ECMWF forecast). Thus it appears that the large deficit in June–July, and the expected deficit for the season as a whole, could not have been foreseen in May, when the official predictions were made. This suggests that some unforeseen changes in atmospheric circulation on the planetary scale occurred in May, and hence the atmospheric models with initial conditions of June could provide a reasonable simulation of deficit rainfall.

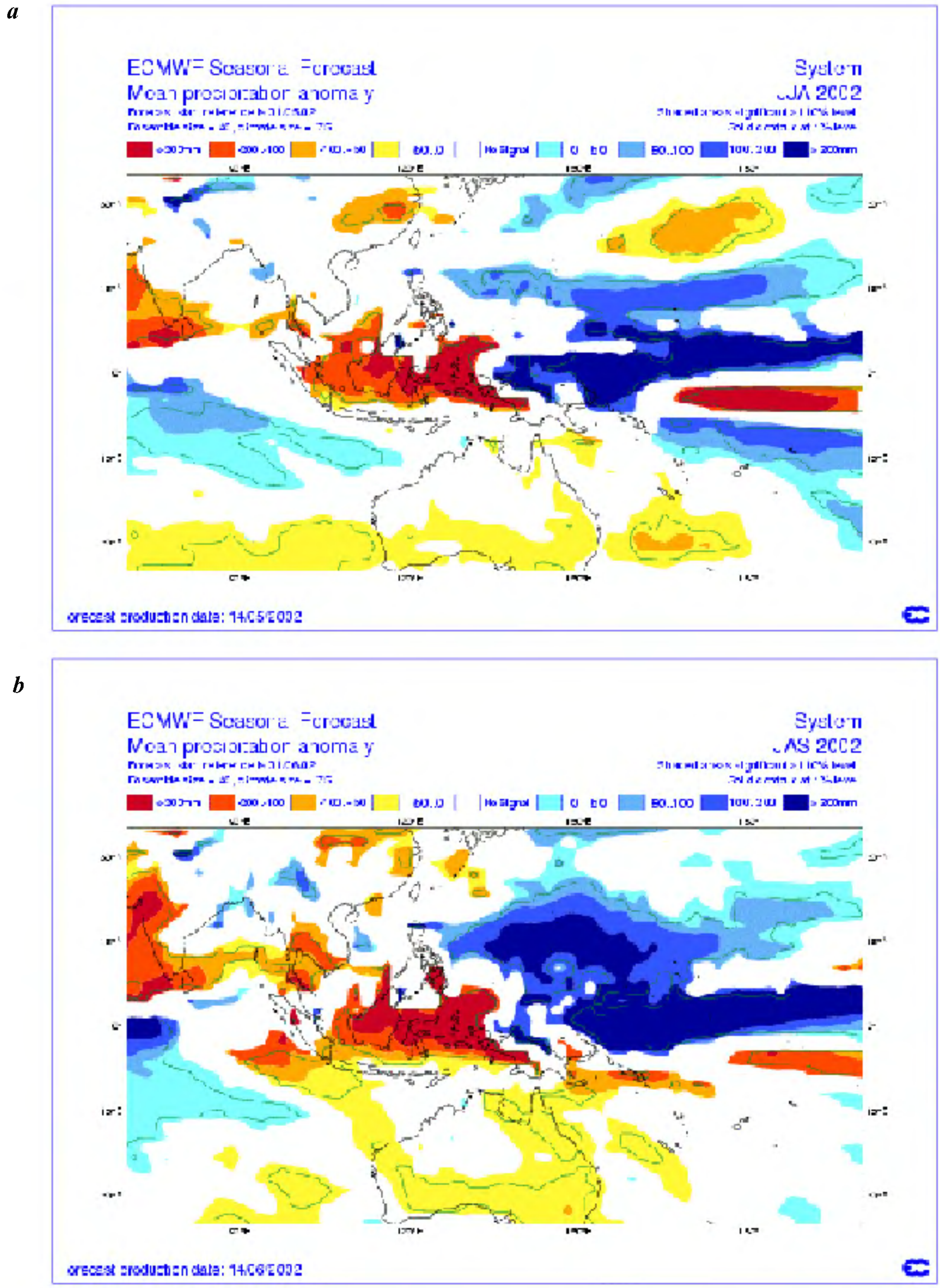

Figure 6. Forecast of rainfall (departure from the mean, mm) by the ECMWF-coupled model for ***a***, June–August using initial conditions of May; and ***b***, July–September using initial conditions of June.

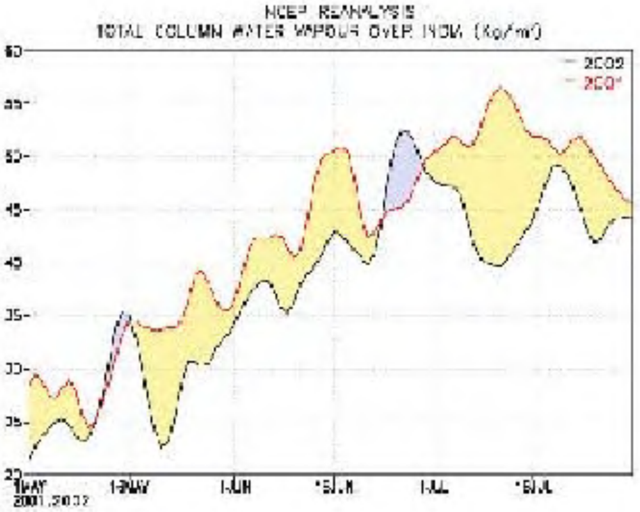

Figure 7. Variation of total water vapour in a vertical column of air over India during May–July in 2001 and 2002. Three-point smoothing has been applied.

Srinivasan and Nanjundiah[37] have shown that both in 1983 and 1997 the conditions in May were similar to those of a drought year, but the appearance of westward migrating cloud systems in June to the Bay of Bengal changed the course of the monsoon (which turned out to be above-normal). Thus events on time-scales of weeks during the evolution of the monsoon can have an impact on the seasonal rainfall. In fact, in the season 2002 an important parameter for atmospheric convection and rainfall, viz. the total water vapour in the air column over India decreased markedly in the third week of May and remained below the value in 2001 most of the time, right up to the end of July (Figure 7). Whether the large rainfall deficit in the monsoon 2002 is related to the major depletion of water vapour content in May, needs to be investigated. However, it is clear that important parameters need to be monitored on time-scales of weeks rather than months, not only in the pre-monsoon season but during the evolution of the monsoon in June as well.

As more data become available from satellites and buoys, the empirical models are expected to improve. With advances in our understanding of important facets of physics, such as interaction between ocean and atmosphere, and the role of clouds and surface processes, the physical models will also perform better in future. We expect significant improvement in our understanding of the variability of the monsoon and hence forecasting, in this decade. However, even with overall decrease in errors of prediction, the models, whether physical or empirical, will fail occasionally. When dealing with complex and chaotic systems, one must be ready for surprises.

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Frankia–actinorhizal symbiosis with special reference to host–microsymbiont relationship

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The status of current knowledge on the *Frankia*–actinorhizal plants symbioses has been reviewed with special reference to the physiology of the nodule, the plant and *Frankia* genes involved in the symbiosis, nodulation and the effects of plant, *Frankia* and the combination on the regulation of symbiosis.

SYMBIOTIC associations that develop between microorganisms and higher plants have received recognition due to their effects on plant morphogenesis, nutrition, protection against infectious diseases and study of basic cell biology. These associations cater to the nutritional needs of the biosphere and are responsible for generating almost 50% of the fixed nitrogen annually. *Rhizobium*–legume symbiosis has almost become synonymous with plant–microbe symbiosis. This is not surprising because legumes occur widely and *Rhizobium* is a fast-growing microbe, and easy to obtain in pure cultures. But there are other symbiotic systems which are equally relevant and interesting. These are *Frankia*–actinorhizal trees, *Bradyrhizobium*–*Parasponia*, *Nostoc*–Azolla and others. These systems are distinct and each displays characteristic similarity and differences from the *Rhizobium*–legume system. Particularly intriguing is the case of *Frankia*–actinorhizal tree symbiosis, which is the subject of this review.

The Actinomycete genus *Frankia* belongs to the recently emended family, Frankiaceae[1]. Its members are Gram-positive bacteria that nodulate about eight plant families representing about 25 genera of woody, dicotyledonous, perennial angiosperms, collectively called actinorhizal plants[2]. The term actinorhiza is given to root nodules that are formed by *Frankia*.

Actinorhizal plants are popularly used as pioneer plants in the regeneration of waste lands[3]. Prominent among these are *Alnus*, *Shepherdia*, *Elaeagnus* and *Hippophae*, which play a vital role in soil reconstruction. Some actinorhizal plants are used as windbreaks[4], pulpwood[5], timber[6] and fuel wood[7], while others have use in the human diet[3] and as forage for livestock (*Ceanothus* and *Purshia*). *Myrica* spp. are used in traditional Indian medical system for prevention and cure of flu, common cold and others. Actinorhizal trees are also valued for landscaping, providing shade, and contributing to the beautification of parks and cities[7]. Apart from these practical aspects, the *Frankia*–actinorhizal plant system provides enough food for thought to those interested in cell biology. The parallels between *Rhizobium*–legume and *Frankia*–actinorhizal tree systems are striking. *Rhizobium* is a Gram-negative, free-living bacterium and infects legumes only, while *Frankia* is Gram-positive and filamentous, and can nodulate a diverse range of host genera. Both *Rhizobium* and *Frankia* produce root nodules in which dinitrogen is converted to ammonia. The quantum of fixed nitrogen produced by the two systems is comparable. The *nif* genes in both bacteria share sequence homology[8]. These similarities raise many questions about the nature of symbiotic interactions in general, and *Frankia*–actinorhizal tree symbiosis in particular. For instance, why is *Frankia*, a slow-growing bacterium, able to nodulate such a diverse range of host genera, while *Rhizobium* infects only legumes? Which features are common to the host species that associate with *Frankia*? What is unique about *Frankia*–actinorhizal tree symbiosis? What are the common features with other systems? Which genes are conserved between the two systems and which genes are different? The questions are many and the answers are not forthcoming, since it is only in 1978, that the pure cultures of *Frankia* became available[9]. This means that specific tools for analysing the molecular biology cannot be easily developed. But some problems have been solved by cloning *Frankia* DNA into *E. coli.* As a consequence, some genes can be identified from a *Frankia* gene library by comparing with other genes. However, a major advance in *Frankia*–actinorhizal tree molecular biology will require the use of cloning vectors as well as the development of a transformation system. Meanwhile, another approach to the study can be to look into the salient features of host–microbe specificity and try to understand the peculiar characteristics of this partnership.

In general, a nodule is a modified lateral root. *Rhizobium*, *Bradyrhizobium* and *Frankia* infect and form nodules by different ways. *Frankia* infects the roots primarily by root-hair infection. Nodules formed have an internal anatomy similar to that of lateral roots with a cortical cylinder of vascular tissue, a cortical region in which the infected cells are found[10] and a typical outer

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