derstanding the Precambrian history of the earth. Moreover, the Lesser Himalaya is the most populous zone of the Himalaya, containing forests, agricultural lands, human settlements, infrastructures, etc. Research in such fields as geomorphology and neotectonics of the Lesser Himalaya would be important in terms of understanding the mountain–human interactions.

Selected, refereed papers resulting from the workshop will be edited by the organizers and published as a volume of the *Geological Society of America Special Paper*, and also possibly in a special volume of the journal *Tectonophysics*. Financial support for the Workshop came partly from registration fees and partly from a grant from the Continental Dynamics Program of the US National Science Foundation (NSF). The NSF grant mainly supported travel funds (some partial support and some full funds) for 24 researchers from the Himalayan countries (China, India, Nepal, and Pakistan) and students from Europe. The Indian participants at the workshop were from the Wadia Institute of Himalayan Geology (Dehra Dun) and University of Roorkee. Overall, 28 of the participants were originally from the Himalayan countries (including those residing in the US or Europe). Indeed, one of the successes of the workshop was that it could provide financial support for native researchers in the Himalaya to attend this international meeting. (Nearly 100 applications were received for travel award; it was not financially possible for the committee on travel awards to respond positively to all of these requests.) Participation of researchers from the Himalayan countries is important for the H–K–T Workshops; however, not all organizers have been or will be able to obtain the necessary funds (especially in view of shrinking government budget for science in recent years). One solution is to hold the H–K–T Workshops frequently in the Himalayan countries (so far, only one of the workshops has been held in the Himalayan region, namely the Kathmandu Workshop in 1994). This solution was suggested in Flagstaff during the planning session for the 1997 H–K–T Workshop, and deserves more attention.

The 12th H–K–T Workshop will be held in Rome (Italy) in April 1997 on the occasion of the 100th anniversary of birth of Ardito Desio, a geologist who carried out pioneering research in the Karakoram mountains.

1. Sorkhabi, R. B., *Curr. Sci.*, 1995, **69**, 489–490.
2. Keay, J., *When Men and Mountains Meet: The Explorers of the Western Himalayas 1820–1875*, John Murray, London, 1977, pp. 278.
3. Patriat, P. and Achache, J., *Nature*, 1984, **311**, 615–621.
4. Zhao, W., Nelson, K. D. and Project INDEPTH, *Nature*, 1994, **366**, 557–559.
5. Jackson, M. and Bilham, R., *Geophys. Res. Lett.*, 1994, **21**, 1169–1172.
6. Burchfiel, B. C. *et al.*, *Geol. Soc. Am. Sp. Paper 269*, 1992.
7. Gansser, A., *Geology of the Himalayas*, Interscience, London, 1964, pp. 289.

Rasoul B. Sorkhabi, Department of Geology, Arizona State University, Tempe, AZ 85287-1404, USA.

Chaos – A new paradigm for comprehending nature

The earliest study of what is today known as *deterministic chaos* dates back to the paper entitled 'Deterministic Nonperiodic Flow' by E. N. Lorenz[1] in 1963. However the concepts of chaos took roots only in the seventies. By the eighties there was an exponential growth in the numbers of research articles and books. Journals devoted entirely to this dynamic new concept were started, and the number keeps increasing – especially if one considers the related areas of fractals and complexity.

A four-day Workshop on Complex Systems (chaos) was organized under the auspices of CSIR Technical Advisory Board (Physical, Environmental & Earth Sciences), hosted by C-MMACS, at C-MMACS/NAL from June 26 to 29, 1996. The motivation for holding this Workshop stemmed from the view that it would be desirable to empower CSIR scientists with a working knowledge and hands-on experience in this fascinating, new, dynamic area of physics so that they may make creative applications of these paradigms to new problems in their respective fields. Interested scientists and students from outside CSIR were also included among the participants to ensure benefits on a wider scale. The participants had a background in diverse areas of physics, biology, engineering, mathematics, computer science, etc.

Deterministic chaos is a nonlinear phenomenon and is easily understood by studying the behaviour of the simple one-dimensional nonlinear map[2], the so-called logistic map, $x_{n+1} = \mu x_n(1 - x_n)$. This is so simple that one can programme it on a hand-held calculator without much trouble. A physical understanding of this equation can be gained by considering the variable x_n to represent the normalized population of some organism in the nth generation, x_{n+1} becoming the population in the next generation. The model is discrete in time and assumes that the size of the present population depends only on the size in the previous generation (some insect species do approximate such simple dynamics). The first factor on the right hand side, μx_n, is the growth term and would lead to a runaway exponential increase but for the inclusion of the second factor. The latter, μx_n^2, represents the decay term and the limit to growth such as, for example, controlled by a finite amount of food supply. Here, we treat x_n as a normalized variable (a proportion of some maximal population) and consider values $0 < x_n < 1$. The model exhibits a range of dynamical behaviours for different values of the parameter, μ. Figure 1 shows a sequence of values of x_n, with $n = 1, 2, 3, \ldots$, namely an orbit of the system, for $\mu = 4$, and a similar behaviour is obtained regardless of any specific initial condition x_0. There is no regularity in the sequence: it looks quite random in character and is, in fact, quite unpredictable. The unpredictability is evident when one starts off with two initial conditions which are very slightly different from each other. After just a few iterations, the two sequences bear no resemblance whatsoever, and can differ from each other by arbitrary amounts within the general confinement. All the sequences are constrained to lie between 0 and 1, so the difference in absolute terms may not be large, but locally, nearby orbits diverge from each other at *exponential* rates. We have a situation where although the equation is deterministic, the outcome is neither regular nor predictable in the long run. This is characteristic of deterministic chaos.

In the early part of this century, a major paradigm shift occurred with the discovery of quantum theory, which introduced us to the uncertainty principle: that both of a pair of complementary dynamical variables (observables), such as position and momentum, cannot be measured with arbitrary accuracy simultaneously. This led to the formulation of the mathematical apparatus of the theory in terms of probabilities. However, the probability functions themselves were evolved using deterministic equations in the theory. The philosophical ramification of all this has been, and continues to be, debated extensively.

In the past decade, *chaos theory* has again confronted us with the question of limits to predictability[3]: it says that, as long as the equations of evolution are nonlinear, even if deterministic, any imprecision in initial measurements, can, during subsequent evolution, get magnified exponentially fast, so that no predictions can be made with sufficient accuracy in the long run. This is a statement with far reaching implications. Almost all systems are nonlinear in nature: linearity is most often a convenient approximation. However, until recently, most developments in science and technology have been based on this approximation. This is understandable because linear theory is analytically tractable whereas nonlinearity, in general, is not. It is only with the advent of computers that it has become possible to tackle nonlinearity directly, using numerical tools.

Quite apart from the philosophical implications, beautiful results and techniques have been spawned by the chaos theory[4]. The hallmark of chaos, namely the sensitivity to initial conditions or the exponential divergence of nearby trajectories can be quantified by the rate of divergence, which is termed the Lyapunov exponent. A positive exponent implies exponential separation of trajectories or chaos. There are as many exponents as there are phase space dimensions and, while divergence occurs in some directions, contraction can occur along other directions. For conservative systems, the net expansion is zero whereas in dissipative systems volumes contract (we deal only with the latter case here). Thus, even though nearby trajectories diverge, globally all trajectories remain confined to some subset of the phase space. This is achieved by a process of folding back of the trajectories at the boundaries. This process of local divergence and global confinement through 'stretching and folding' is typical of systems where the motion is chaotic (a good visual mnemonic of such a process is the kneading of dough by a baker). Coupled with the contraction of phase space volumes, what results in phase space is an *attractor*, namely the orbit to which progression from any initial conditions eventually converge. When the motion is chaotic, the attractor often has a fractal geometry, and is termed *strange*. Systems can have different strange attractors and fractal (non-integer) dimensions have to be used to characterize them. Nonlinear dissipative systems can have simple attractors as well, such as fixed points (steady states) or limit cycles.

A remarkable result from chaos theory has been the discovery of universal routes to chaos. As a control parameter (as for example μ in the map above) is varied, one observes qualitative changes in the dynamical behaviour and the phase space dynamics switches between the different attractors in a universal manner. Three well-defined universal routes to chaos have been documented in various experiments: the Feigenbaum scenario or the period-doubling route to chaos, intermittency and the Ruelle–Takens or strange attractor scenario. The period doubling route is characterized by a set of universal numbers, which relate to the way in which aperiodic behaviour is approached. As the parameter is varied, one observes period doubling, i.e. from a steady state to a periodic motion with period (say) T, to $2T$, to $4T$, $8T, \ldots, 2^nT$ and thus on to an aperiodic or chaotic behaviour. The parameter windows in which successive periods exist keep getting smaller and the ratio of two such successive window lengths approaches a universal number, the so-called Feigenbaum constant, which has the numerical value 4.669.... In essence, what happens is that, as the parameter varies, one limit cycle becomes unstable and a new limit cycle of twice the period is stabilized. Ultimately no cycle is stable but all exist, albeit as unstable ones. In other words, chaos can be considered as a closure of unstable periodic orbits. It is possible then to visualize chaotic dynamics as one in

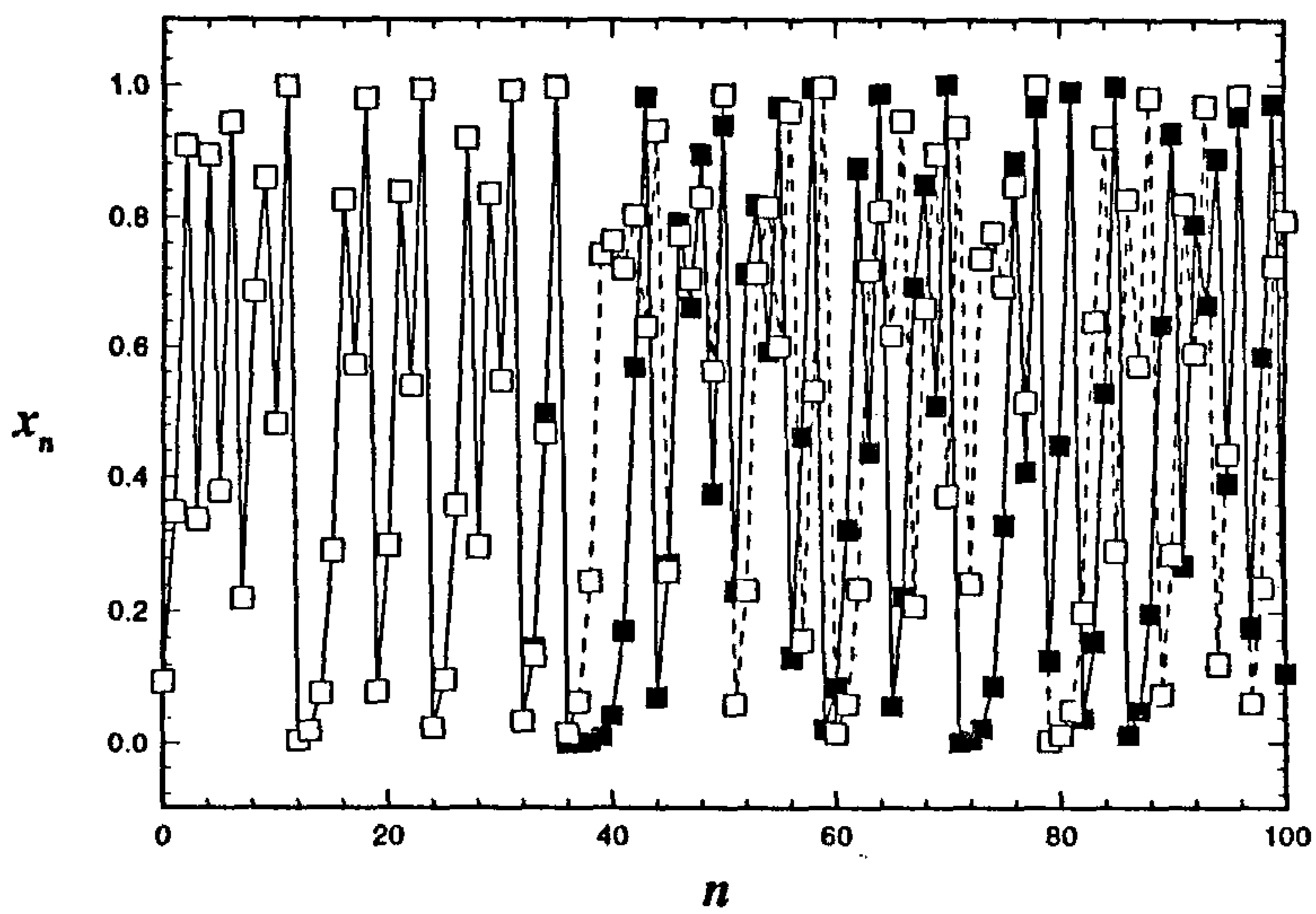

Figure 1. Sensitivity to initial conditions, hallmark of *deterministic chaos*: two sequences of iterates of logistic map differing only in the twelfth decimal place in the initial conditions.

which the phase space orbit gets kicked from one unstable orbit to another and keeps wandering in the skeleton formed by the unstable periodic orbits, unable to settle down on any of them.

Dynamical chaos can be exploited. The knowledge that there are unstable periodic orbits within chaotic regions has been used to devise beautiful control algorithms, where a nonlinear dynamical system can be made to have a desired dynamical behaviour corresponding to a particular periodic orbit. Since the system is extremely sensitive, small parameter changes are enough to manipulate the dynamics and it is possible to design a series of such small parametric perturbations to keep the system around a periodic orbit of interest. This possibility vests chaos with a desirable feature where it provides for versatile design options. For, one can thus control, simply by tuning parameters involving very small changes, and switch the system from one periodic behaviour to another, and no major design modifications are called for!

Experimental data from biological systems appear to suggest that nature has indeed incorporated some of these aspects of chaos into its engineering designs. EEG data from individuals in different stages of consciousness indicate that wakefulness is characterized by chaotic dynamics whereas different stages of sleep are marked by different periodic oscillations. Furthermore, pathological conditions in brain, for example epileptic states, are marked by periodic behaviour.

One of the most important features of deterministic chaos is that it can arise in systems of low dimensionality. In discrete systems, one-dimensional maps (if non-invertible; else two-dimensional) exhibit chaos and, in continuous systems, three variables, coupled ordinary differential equations are sufficient (nonlinearity being, of course, a prerequisite). Quite obviously, the Newtonian world view – Laplacian determinism – which attributed randomness to high dimensional, complex systems that are 'difficult' to be modelled in complete detail seems unnecessary in hindsight and recent attempts to model complex systems such as the weather or climate, biological systems like the heart or brain, etc. using low-dimensional deterministic nonlinear equations, have attained some measure of success. Simultaneously, data from such systems when analysed to ascertain the actual effective dimensionality of those systems reveal them to be indeed low-dimensional in very many cases.

The study of complex phenomena is not restricted to the dynamical regime. A significant development in the study of complex systems was the introduction of the concept of self-organized criticality by Bak, Tang and Wiesenfeld[5] (BTW) in 1987. Critical points are familiar from the study of phase transitions and they are approached by the tuning of an external parameter such as, for example, temperature in the case of water-to-ice transition. However, in self-organized criticality, there is no need to tune any parameter and the system is constantly maintained in the critical state by processes of self-organization: these are far-from-equilibrium systems[6]. The paradigmatic model that BTW studied is that of sandpiles: sand is added a grain at a time, and the slope of the pile keeps fluctuating between a minimum and a maximum value within a small range. In the steady state, the system is marginally stable and avalanches of all sizes occur as the slope keeps fluctuating. The model which is a simplified description of systems with extended spatial degrees of freedom, has generated considerable interest. An important natural phenomenon that is seen to correspond to this class of systems is that of earthquakes with their associated stick-slip dynamics.

Sandpiles are simple, paradigmatic models for complex phenomena, but, at the same time, they themselves are very complex systems from another perspective. In fact, they have been referred to as a 'new' state of matter, the *granular state*, which is intermediate between solids and liquids, having properties such as dilatancy, hysteresis, etc. A unique characteristic of sand is to sustain the evolution of bridges and arches which, unlike in liquids and gases, do not get thermally averaged away and play a significant role in stasis and dynamics. For example, due to these local formations, the stress distribution at the bottom of a sandpile is quite complicated. Again, the packing configurations are significantly affected by the presence of such formations.

The problem of turbulence is one that continues to challenge physicists. In the light of new developments, some of which have been described above, this is now described as 'fully developed chaos'. New techniques of analysis from chaos theory have been applied to turbulence data to gain some new perspectives.

Among the new techniques that have come up, a very useful one is that of phase space reconstruction. Quite often, in experimental situations, only one, or at most a few, of the variables involved in the dynamics can be measured. In the absence of a knowledge of the complete set of phase space variables, it is still possible to construct a pseudo-phase space which is topologically equivalent to the (unknown) original. The set of new coordinates for such a phase space is constructed from the available one by using time-shifted, lagged values: if $v(1), v(2), \ldots$ are the measurements of a variable v at time intervals $1, 2, \ldots$, the time series for the second coordinate can be taken as $v(1+\tau), v(2+\tau), \ldots$, with τ, an integer multiple of sampling time, chosen in an appropriate manner so as to avoid redundancy. The phase space thus reconstructed can be used to estimate dynamically relevant quantities like Lyapunov exponents, fractal dimensions, unstable periodic orbits, etc.

The widespread availability of powerful electronic computers has played a major role in many of these developments by making the simulation of complex systems tractable. Many studies of complex behaviour can be carried out with simple models that capture the essential features. Cellular automata – where space, time and all variables are taken to have only integer values – have been extensively used to model a variety of such systems. Coupled-map lattice models – where space and time are discrete – also provide a numerical methodology capable of displaying rich phenomena.

It is this fascinating, frontier area of physics that was the subject matter of the workshop. The workshop began with a keynote lecture by R. Ramaswamy (JNU, Delhi). Dissipative systems were reviewed in two lectures by V. Balakrishnan, (IIT-Madras). Neelima Gupte (IIT-Madras) gave three talks. In the first one, she introduced the basic concepts of fractals, the fascinating field of new geometry, which appears to describe natural objects such as trees, clouds, coastlines, mountain profiles, etc., all of which have non-integer dimensions. Her second lecture dealt with the control of chaos and the third was on synchronization. The latter has important applications, particularly with respect to encryption of messages (of importance in defence) where the messages are masked by synchronizing with chaotic waveforms.

T. R. Krishna Mohan (C-MMACS, Bangalore) explained the procedures for reconstruction of a phase space from single variable time series and the estimation of correlation dimension (Grassberger–Procaccia algorithm[7]) and Lyapunov exponents from the phase space dynamics. Pradhan (NIMHANS, Bangalore) discussed and explained the problems associated with ascertaining whether a time series originates from nonlinear, deterministic evolution or from a linear, stochastic process which can give rise to coloured noise having similar spectral properties. Prabhakar Vaidya (Washington State University, now visiting C-MMACS) gave a talk on methods that can be used for unambiguously confirming the presence of a nonlinear, deterministic process in time series; the methods he spoke on (trans-spectral coherence) are related to higher order spectral methods and can also be used in connection with premonition of chaos, i.e. to identify possible transition to chaotic states.

Deepak Dhar (TIFR, Mumbai) gave two lectures on self-organized criticality and sandpile models; he showed the relationship of abelian sandpile models to other related models such as Potts model, Voter model, Takayasu aggregation model and river networks.

Anita Mehta (S. N. Bose Institute for Basic Sciences, Calcutta) spoke on the complexity of granular materials, namely sand, and the relevance of ideas such as self-organized criticality to the physics of actual sandpiles. Sudeshna Sinha (Indian Institute of Astrophysics, Bangalore) discussed the general strategies of modelling spatio-temporal phenomena by coupled–map lattice models.

Three afternoon sessions were devoted to experiments. A variety of PC-based computer programs were made available to participants in order to help them understand the various concepts covered during the lectures, and to enable them further explore different aspects of chaotic dynamics and fractal geometry through numerical experiments. There were also experiments using electronic circuits to show the period doubling route to chaos, as well as strange attractors. A practical realization of the phenomenon of chaotic synchronization using two circuits was shown, and the ideas of secure communication using chaotic masking was demonstrated by Manu and Kapilanjan Krishan of Khalsa College, New Delhi.

Three evening colloquium talks marked the conclusion of the workshop activities on each day. Anita Mehta gave a general overview of the physics of sand, of the physics of granular state, in her colloquium talk, 'Probing Sand'. Rahul Pandit (IISc, Bangalore) talked on homogeneous, isotropic turbulence with emphasis on the scaling of velocity structure functions, on the multiscaling and self-similarity aspects. In another, R. Narasimha (IISc and JNCASR, Bangalore) talked on aspects of clouds as complex systems with focus on understanding of entrainment process in tall cumulus clouds where horizontal diffusion is practically nil and vertical diffusion is practically infinite! He described experiments being carried out at IISc (with Prabhu and Bhat) to study the mechanism of this strange behaviour. The large-scale vortical structures in the flow 'engulf' ambient fluid from the surroundings in the first process of entrainment, followed by 'mingling' of the engulfed fluid into the core flow and, finally, it is 'mixed' in at the molecular level. The experiments are designed to study the modifications brought about by local heating which takes place, for example, by the release of latent heat during condensation, in clouds.

1. Lorenz, E. N., *J. Atm. Sci.*, 1963, **20**, 130–141.
2. May, R., *Nature*, 1976, **201**, 459–467.
3. Gleick, J., *Chaos*, Viking, Penguin, New York, 1987.
4. Ott, E., *Rev. Modern Phys.*, 1981, **53**, 655–671.
5. Bak, P., Tang, C. and Wiesenfeld, K., *Phys. Rev. Lett.*, 1987, **59**, 381–384.
6. Prigogine, I. and Stengers, I., *Order out of Chaos*, Flamingo Fontana, London,, 1985.
7. Grassberger, P. and Procaccia, I., *Phys. Rev. Lett.*, 1983, **50**, 346–349.

T. R. Krishna Mohan, CSIR Centre for Mathematical Modelling and Computer Simulation (C-MMACS), NAL (Belur Campus), Bangalore 560 037, India.

OPINION

Monsoon: A bioclimatologist's point of view

V. M. Meher-Homji

A plant geographer's main concern with the climate is to seek correlations with the vegetation. Precipitation, temperature and evapotranspiration have been commonly used. Lesser known factors like the régime (season of occurrence of rains) have been developed here for a better understanding of eco-diversity. Briefly discussed are the different origins of rainfall in India, the variability in the climatic factors and the transition from the Mediterranean régime to the west of the Indian sub-continent to the tropical monsoon type in the peninsula, across the Thar desert. A critical review is presented on palaeopalynological studies that tried to make out monsoon fluctuations during the Holocene. Deforestation may affect the local rainfall pattern without there being a change in the intensity of monsoon as a planetary phenomenon.

The monsoon, the very pulse of the Indian economy, is a word of Arabic origin 'mausim' meaning season. The term implies the seasonal reversal of the wind systems on which depended the marine navigation for the purpose of trade. Since