Analysis and Modeling of Complexity in Earth System Using Fractals: What Have We Achieved?

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Understanding complex behavior of the Earth system remains a “grand challenge” and an “unsolved problem” for the geo-scientific community. Many mathematical methodologies have been suggested to model this complexity and this gave birth to a new branch of geo-science known as “Non Linear Geophysics”. According to Lovejoy et al. (EOS, 2009), many disparate phenomena of earth system show similar behaviors when seen in a proper nonlinear prism. This hints at some fundamental laws of self organization and emergence that describe the real nature instead of linear, reductive paradigms that at best capture only small perturbations to a solved state or problem. These laws are very well related to the theory of power law scaling and fractals. Thus, the fractals theory was evolved to solve a problem posed by non linearity of the earth system.

The origin of term “fractals” dates back to the 18th century in the study of non-differentiable functions by the Karl Weierstras, Georg Cantor, and Felix Hausdorff, however, the term fractal was coined by Mandelbrot (Science 1967, Elsevier 1983) in a paper published in science ‘How long is the coast of Britain?’ and later in his book ‘Geometry of Nature’. Very soon the term became popular and now finds its widespread application in all branches of geosciences viz. geophysics, seismology, geology, geochemistry, atmospheric science, hydrology etc, however the most interesting application of fractal theory is in forecasting extreme events and hazard assessment techniques. Thus a major advancement was the application of the concept of self- organized criticality.

The fractal theory has led to the development of a wide variety of physical models of seismogenesis including nonlinear dynamics and it can be efficiently used to characterize the seismicity pattern of a region. The fractal nature of the spatial distribution of earthquakes has been demonstrated in the research work of Kagan and Knopff (JGR, 1980); Hirata and Imoto (GJI, 1991); Hirabayashi et al. (PAGEOPH, 1992); and Dimri (Belkema 2000, Springer 2005). The hypocenter distribution data suggests that the changes in fractal dimension could be a good precursor parameter for earthquakes as it is a measure of the degree of clustering of seismic events. A change in fractal dimension corresponds to the dynamic evolution of the states of the system.

Another area, where fractal approach has been successfully applied is potential field. The deep bore well data around the globe have shown that the physical properties like density, susceptibility, elastic constants etc do not follow the random distribution hitherto assumed, rather they follow fractal distribution. These findings entailed to re-formulate the geophysical problems assuming the source as fractal distribution. A relation between fractal source and its response led to several applications in developing new techniques to interpret potential field data.

This lecture presents an overview of recent advancements in fractal theory and its application to various complex geo-scientific problems.