Deterministic chaos model for the prediction of climatological weather cycles

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Introduction

The recently identified universal inverse power law form for the atmospheric eddy energy spectrum of the meteorological and climatological scales of temperature fluctuations indicates a close coupling between the short and long term periodicities in weather cycles (Lovejoy and Schertzer, 1986). Numerical weather prediction (NWP) models have had limited success because of the inherent nonlinearity of the governing equations which are sensitive to initial conditions and give chaotic solutions characteristic of deterministic chaos. In recent years there is growing conviction that NWP models based on conventional meteorological concepts and nonlinear partial differential equations are inherently unstable to computational approximations and round-off errors and are therefore incapable of improved performance with further increase in the resolution of the meteorological data network or computer precision and capacity (Lorenz, 1979; Weil, 1985; Mason, 1986; Lighthill, 1986; Reinhold, 1987; Shepherd, 1987; Tennekes, 1988). Accurate modelling of short and long term weather phenomena therefore require alternative conceptual models of atmospheric flows with robust computational techniques (Ottino et al., 1988). In this paper the newly emerging intensive research area of deterministic chaos is applied for atmospheric flows using the concept of 'cellular automata' computational technique. The energetics of atmospheric flows are modelled by structurally stable scale invariant governing equations which predict universal and unique spatiotemporal patterns for atmospheric flows.

Deterministic chaos in the ABL

Lorenz (1963) was the first to identify the existence of deterministic chaos in a mathematical model of atmospheric flows derived by severe truncation of the Navier-Stokes equations. Later extensive studies by other mathematical scientists revealed the existence of deterministic chaos in all mathematical models of physical systems (Fairbairn, 1986; Tavakol, 1988). The field of chaos is characterized by the strange attractor design with self-similar fractal geometrical structure. A selfsimilar object is characterized by its fractal dimension D which is equal to $d\ln M/d\ln R$ where M is the mass contained within a distance R in the object. The physics of deterministic chaos is not yet identified. Conclusive observational evidence for the existence of deterministic chaos in the planetary atmospheric boundary layer (ABL) was provided by Lovejoy and Schertzer (1986) who showed that the global cloud cover pattern exhibits fractal geometrical structure on scales ranging from the convective to the planetary scales. Further, the observed universal characteristic for shape and spectral slope of atmospheric eddy energy spectrum which follows an inverse power law of the form f^{-b} where f is the frequency and b the exponent ($\approx$1.8) is basically the 1/f noise spectrum generic to the field of chaos (Tang and Bak, 1988).

Conceptual model of deterministic chaos in the ABL

The turbulent shear flow in the ABL has an inherent mean upward momentum flux of frictional origin at the planetary surface. The turbulence scale upward momentum flux is progressively amplified in the vertical by buoyant energy supply from microscale fractional condensation by deliquescence even in an unsaturated environment and amplified further by the exponential decrease of atmospheric density with height. Helical vortex roll (or large eddy) circulations form as a natural consequence of such turbulence scale buoyant energy flux in the ABL and are manifested as cloud streets and mesoscale cloud clusters (MCC) in the global cloud cover pattern (Mary Selvam, 1988a). Townsend (1956) has derived the following relation between the root mean square (r.m.s) circulation speed W of the large eddy of radius R which grows from the turbulence scale eddy of length r and r.m.s circulation speed w

$$W^2 = \frac{2r}{\pi R} w^2 \qquad (1)$$

The rising large eddy carries the turbulent eddies as internal circulations which mix the environmental air into the large eddy volume. The steady state fractional volume dilution k of the large eddy by turbulent eddy fluctuations is given as

$$k = \frac{w_* r}{dWR} \qquad (2)$$

where w_* is the turbulence scale buoyant acceleration and dW the corresponding acceleration of the large eddy. It may be computed and shown $k > 0.5$ for scale ratio $Z < 10$ where $Z = R/r$. Therefore identifiable large eddy growth occurs for scale ratios of 10 or more only since for smaller scale ratios the large eddy identity is erased by turbulent mixing. Large eddy growth therefore occurs in successive decadic scale range intervals giving rise to the observed coherent cloud structures which consist of a hierarchy of turbulent, convective, meso-, synoptic and planetary scale eddies, the larger eddies containing the inherent smaller eddies as internal circulations. Integrating (2) for large eddy growth starting from the turbulence scale length a at the planetary surface, the growth occurring at discrete length step intervals $dR = r$ we obtain

$$W = \frac{w_*}{k} \ln Z$$

$k = 0.4$ for $Z = 10$. The model therefore predicts logarithmic spiral airflow in the ABL with the von Karman's constant k being equal to 0.4 as a natural consequence of the eddy growth mechanism by the universal period doubling route to chaos. The von Karman's constant is therefore more universal than the Feigenbaum's constants for organised chaos. The above concept of large eddy growth from microscopic domain eddy dynamical processes is analogous the computational techniques of 'cellular automata' and 'molecular dynamics' recently being applied for fluid flow simulations (Hayot, 1987; Rapaport, 1988). The strange attractor design traced by the atmospheric flow trajectories therefore consists of a nested continuum of logarithmic spiral curves, each spiral consisting of the upward and corresponding return downward flow. Further, it may be shown (Mary Selvam, 1988b) that the period doubling growth of eddies in atmospheric flows gives successive eddy lengths following the Fibonacci number sequence as a natural consequence, one complete vortex roll circulation being completed in five length step increments each on either side of the primary perturbation. The internal structure of one complete vortex roll circulation (Fig. 1) consists of balanced counter rotating circulations tracing out the quasi-periodic Penrose tiling pattern identified as the quasicrystalline structure in condensed matter physics (Janssen, 1988). The short range balance requirements of the eddy circulations with the Fibonacci winding number impose long range orientational order in the quasicrystalline structure for large eddies in atmospheric flows and is consistent with the observed long range spatiotemporal correlations of weather phenomena e.g., the El Niño Southern Oscillation (ENSO) cycle.

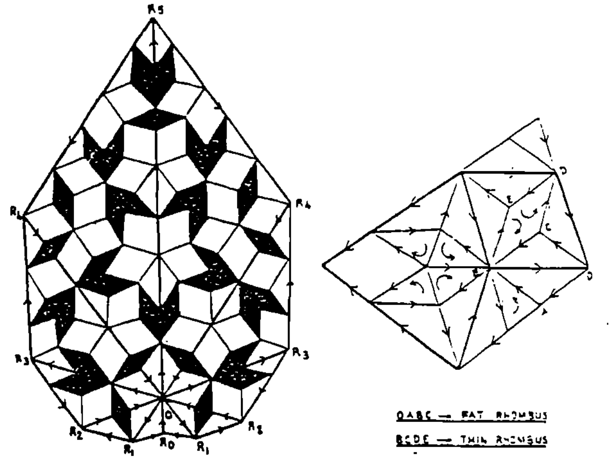

Figure 1: The internal structure of the large eddy circulation pattern in the ABL. A primary turbulence scale perturbation R_oO generates compensating return circulations on either side along isosceles triangles of successively increasing base lengths (large eddy radii) OR_1, OR_2, OR_3, OR_4, OR_5 such that the winding number $OR_2/OR_1 = OR_3/OR_2 = \ldots\ldots = \sqrt{5} + 1/2$ = golden mean. The internal structure of one complete vortex roll (large eddy) circulation with the Fibonacci (golden mean) winding number consists of the quasiperiodic Penrose tiling pattern formed by a mosaic of fat and thin rhombi as shown separately.

Dominant weather cycles (Limit cycles)

It was shown above that identifiable large eddy growth occurs for successive decadic scale range intervals. Therefore from (1) the following relations are derived for the length and time scales for the limit cycles in atmospheric flows.

$$\begin{aligned} a : R &= a : 10r : 10^2 r : 10^3 r : 10^4 r \\ t : T &= t : 40t : 40^2 t : 40^3 t : 40^4 t \end{aligned} \qquad (3)$$

The 40-50 day oscillations in the general circulation and the ENSO phenomena may possibly arise from the diurnal surface heating since they correspond respectively to the first and second decadic scale range of eddy growth (3). Similarly the QBO (Quasi-biennial Oscillation) may arise as a result of the semi-diurnal pressure oscillation (QBO $\approx$ 0.5 day x 40^2. The 20-year periodicity in solar cycle and the associated weather patterns may be associated with the newly identified 5 minute oscillation of the sun's atmosphere (20yr $\approx$ 5 min. $\times$ 40^5. The growth of large eddies by energy pumping at smaller scales, namely, the diurnal surface heating and the semi-diurnal pressure oscillation as cited above is analogous to the generation of chaos in optical phenomena (Harrison and Biswas, 1986). Spectral analysis of long term high resolution surface pressure data will give the amplitude and phase of the limit cycles in the atmospheric flow pattern.

Climate prediction

The deterministic chaos model for atmospheric flows also predicts that vertical mass exchange occurs in the atmospheric eddy continuum fluctuations extending from the troposphere to the ionosphere and above resulting in the transport downwards of negative space charges from ionosphere and the simultaneous upward transport of positive space charges from lower troposphere. The charged aerosol current generated by the vertical mass exchange is shown to quantitatively generate the observed atmospheric electric field and the geomagnetic field and is consistent with the observation that atmospheric circulation patterns closely follow geomagnetic field lines and further, that climatic variations are preceded by corresponding geomagnetic field variations, Close monitoring of the global geomagnetic field variations may enable prediction of future climatic trends (Mary Selvam, 1987).

Stratospheric Ozone and Climate

The recently identified stratospheric ozone depletion (Heath, 1988) and a tropospheric ozone increase (Penkett, 1988) may be a manifestation of increased vertical mass exchange due to global warming related atmospheric eddy continuum energy enhancement.

Conclusion

The deterministic chaos model for atmospheric flows enables to predict the observed meteorological and climatological periodicities as simple multiples of solar insolation related fundamental periodicities in the ABL.

References

Fairbairn, W., 1986: *Phys.Bull.* **37**, 300.

Harrison, R.G., and Biswas, D.J., 1986: *Nature* **321**, 394.

Heath, D.F., 1988: *Nature* **332**, 219.

Hayot, F., 1987: *Physica* **26d**, 210.

Janssen, T., 1988: *Phys. Rep.* **168**(2).

Lighthill, J., 1986: *Proc. R. Soc. A* **407**, 35.

Lorenz, E.N., 1963: *J. Atmos. Sci.,* **30**, 130.

Lorenz, E.N., 1979: *J. Atmos. Sci.,* **36**, 1367.

Lovejoy, S., and Schertzer, D., 1986: *Bull. Amer. Meteorol. Soc.* **67**, 21.

Mason, B.J., 1986: *Proc. R. Soc. A,* **407**, 51.

Mary Selvam, A., 1987: *Proc. Int. Geosci. and Remote Sensing Symp.* (IGARSS).

Mary Selvam, A., 1988a: *Proc. 8th NWP Conf. Amer. Meteorol. Soc.* USA.

Mary Selvam, A., 1988b: *Proc. III Inter-American Cong. Meteorol.* , Mexico City.

Ottino, J.M., Leong, C.W., Rising, H., and Swanson, P.D., 1988: *Nature,* **333**, 419.

Penkett, S.A., 1988: *Nature,* **332**, 204.

Rapaport, D.C., 1988: *Phys. Rev. Lett.* **60**, 2480.

Reinhold, B., 1987: *Science* **235**, 437.

Shepherd, T.G., 1987: *J. Atmos. Sci.* **44**, 1166.

Tang, C., and Bak, P., 1988: *Phys. Rev. Lett.* **60**, 2347.

Tavakol, R.K., 1987: *Sci. Prog. Oxf.* **71**, 71.

Tennekes, H., 1988: *Bull. Amer. Meteorol. Soc.* **69**, 368.

Townsend, A.A., 1956: *The structure of turbulent shear flow.* Cambridge Univ. Press, UK, 115pp.

Weil, J.C., 1985: *J. Climat. Appl. Meteorol.* **24**, 1111.