VANCOUVER – A CENTURY OF SELF-ORGANIZED RAIN

Nigel Skermer, Skaha Consultants, Penticton, British Columbia
Ken W. Olive, Municipal Insurance Association of B.C., Vancouver, British Columbia
Tony Barber, City of North Vancouver, North Vancouver, British Columbia

Abstract

The frequency of heavy rainfall is somewhat important in knowing when to expect and prepare for landslides, particular on the steep mountainous land bordering Vancouver's North Shore. This paper examines rainfall data based on current notions in physics dealing with Self-Organized Criticality. Rainfall is shown to be fractal exhibiting power law distributions that predict the probability of extreme events. The probability of even more extreme events is predictable, not just flooding, but also the possibility of drought. Once the idea of instability at the critical state is accepted and occasional catastrophes are seen as inevitable, better planning of resources and outlay of money may be feasible. This follows because self-organized critical phenomena appear to follow statistical scaling laws. It is of interest to the insurance industry which operates almost exclusively on the statistical properties of events.

Résumé

La fréquence d'un fort niveau de pluviométrie est important pour être en mesure de prédire des glissements de terrain et de faire face à ceux-ci, particulièrement en terrain raide et montagneux bordant la rive nord de Vancouver. Cet article examine des données pluviométriques basées sur des notions actuelles de la physique touchant la criticalité auto-organisée. La pluviométrie présente des caractéristiques des fractales exhibitant des distributions de loi de puissance, lesquelles prévoient la probabilité d'événements extrêmes. La probabilité d'événements encore plus extrêmes est prévisible, par exemple les inondations, mais aussi la sécheresse. Une fois que l'idée d'instabilité à l'état critique est acceptée et que des catastrophes occasionnelles puissent être inévitables, alors une meilleure planification des ressources et des dépenses budgétaires peut être possible. Cela s'explique du fait que les phénomènes de criticalité auto-organisé semblent obéir aux lois statistiques d'échelonnage. Cela présente un intérêt pour le domaine de l'assurance puisque celui-ci se base presque exclusivement sur les propriétés statistiques des événements.

1. INTRODUCTION

The title of the paper sounds quite definite. Actually, however, the question is posed whether rainfall can be self-organized. That is to say in the sense of the new theory in physics of Self-Organized Criticality (SOC), the brainchild of Per Bak (1991).

According to Bak, large interactive systems naturally evolve to a critical state in which many small events are interspersed with a few very large events and the occasional event of catastrophic proportions. His classic model is a pile of sand growing at the critical angle of repose with slippages on the face of the sand pile occurring at all scales. Earthquakes in a region are an example. He puts it this way (Bak 1996): "Self-organized criticality is a new way of viewing nature. The basic picture is one where nature is perpetually out of balance, but organized in a poised state – the critical state – where anything can happen within well-defined statistical laws. Self-organized criticality explains some ubiquitous patterns existing in nature that we view as complex".

He goes on to say:
"We see complex phenomena around us so often that we take them for granted without looking for further explanation…. complex behavior in nature reflects the tendency of large systems with many components to evolve into a poised, "critical" state, where minor disturbances may lead to events, called avalanches, of all sizes. Most of the changes take place through catastrophic events rather than by following a smooth gradual path. The evolution to this very delicate state occurs without design from any outside agent. The state is established solely because of the dynamical interactions among individual elements of the system: the critical state is self-organized".

In a new book (Hergarten 2002) the author poses the question, what is SOC, and defines it thus: "A system exhibits SOC if its phase space contains a strange attractor where events of all sizes occur, and where the size distribution of these events follows a power law." This definition may suit physicists better, but engineers may find Bak's description adequate.

Either way, the concept has arisen out of the earlier invention of fractals by the mathematician Benoit Mandelbrot.

Fractals are fairly common knowledge by now, but for an up-to-date definition (Hergarten 2002): "A fractal is an object that looks the same on all scales, and is statistically similar." Fractals are self-similar. SOC is still controversial in many ways, whereas it is probably true to say that fractal geometry is not. This paper offers up an answer to the original question by using fractals to look at, apparently random, patterns of rainfall to see if they display scale invariance such that power laws are obeyed. To be clear what this means examine the pure geometrical shape known as a Koch's curve, see Figure 1. It is simple to show that the length of the sides versus the length of the outline follows an inverse power law, as the outline changes form from a triangle to the Star of David and is subdivided further and further down to the snowflake shape. In a similar vein, Mandelbrot (1967) raised the question of the true length of the coastline of an island, considering fractal dimensions smaller and smaller down to the size of a grain of sand and less.

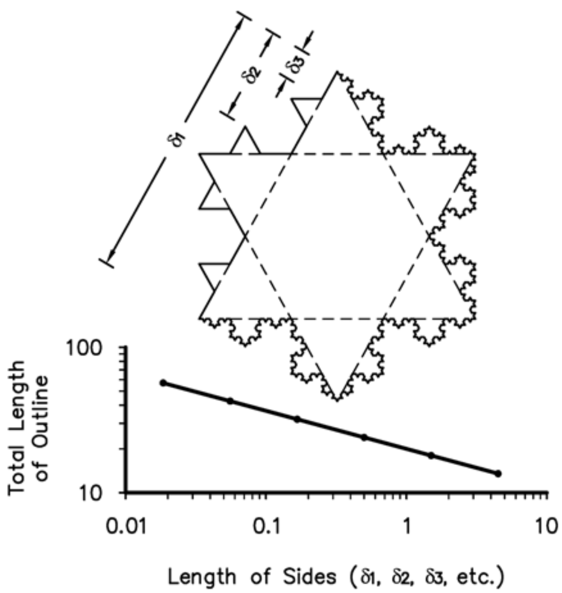

Figure 1. Fractal Geometry of the Star of David

2. RAINFALL

Vancouver has a first class weather station at the airport. The records extend from 1937 to present. Nearby at Steveston a weather station used to exist which provides records from the latter half of 1896 to 1970. Comparing the two records the airport was about 6.8% wetter on average than at Steveston over the period of overlap 1937 to 1970, see Skermer (1988). By adjusting the Steveston data upwards by 6.8% is it possible to obtain a century long record for analysis. Both stations being on the delta of the Fraser River are somewhat removed from local orographic effects of the mountains flanking the north shore of Vancouver. Fitting the two records together therefore probably causes little error.

The records analyzed here are total annual precipitations. Rather than working with calendar years, however, it is better to work with water years as used originally by the US Weather Service. The Water Year extends from the beginning of October of the preceding year to the end of September thereby incorporating one whole winter, rather than the latter half of one winter at the beginning of the calendar year and the first half of the next winter at year end. In B.C. this is more important with coastal weather than with interior weather where the precipitation tends to be more evenly distributed throughout the year. The record for the Vancouver Water Years (VWY) 1897-2002 appears on Figure 2. VWY 1996 – 97 stands out as an extreme. Calendar year precipitation 1997 was also the record high, but not as prominent.

These outliers such as VWY 1996 – 97 are becoming increasingly important considering the issue of climate change. Similarly also are the implications of continuous dry years such as those leading up to 1929. Dryness is more disastrous than wetness in many instances. To demonstrate this point the data is plotted another way, as cumulative departure from the mean (CDM) see Figure 3.

Compared to the arithmetic mean for the century, actually 106 years, the first third of the period looks like a recipe for disaster, which in fact it was for many parts of North America culminating in the Dust Bowl years, (Tannehill 1947). The century CDM plot for Vancouver displays three broad periods. In the first period most years are drier than the mean with the accumulating downwards trend. The middle third looks more like average conditions, wet and dry years being more or less evenly distributed about the mean. The last period shows increasing wetness which most of us by now take for granted, and some prefer to see as a portent of doom. The same pattern is displayed by CDM plots for other regions of the province.

Before leaving CDM it is worth reflecting on a simple random process, coin tossing. Despite the fact that the probability of heads or tails on every toss is 0.5, cumulative departures can appear that resemble Figure 3. Beltrami (1999) for example shows a figure where more than 4000 tails result from 5000 tosses of a fair coin.

Extreme values of rainfall and floods are of great interest in engineering, not merely for design purposes but also in assessing the likelihood of hazards such as landslides. An estimate of the frequency with which precipitation of a given magnitude is exceeded, or may be exceeded in future, is based on analyses of frequency magnitude relationships. Precipitation totals, however, are not distributed in normal Gaussian form. Usually the distributions, instead of being bell shaped, are strongly asymmetric. Plotted on a normal distribution, VWY 1996 – 97 is an outlier, see Figure 4, and it is highly doubtful if the claim, attributed to Carl Friedrich Gauss, is true that skewdness of curves such as this, for rainfall, would disappear if the samples were large enough. After all Gauss was dealing with random errors in geodetic survey. Hydrologists have known this for years and numerous empirical methods of analysis attempt to take it into account. A wide range of techniques can be used including, Gumbel, log Gumbel, log Pearson, log normal, cube-root probability, and finally power law (fractal) which is the method investigated in this paper.

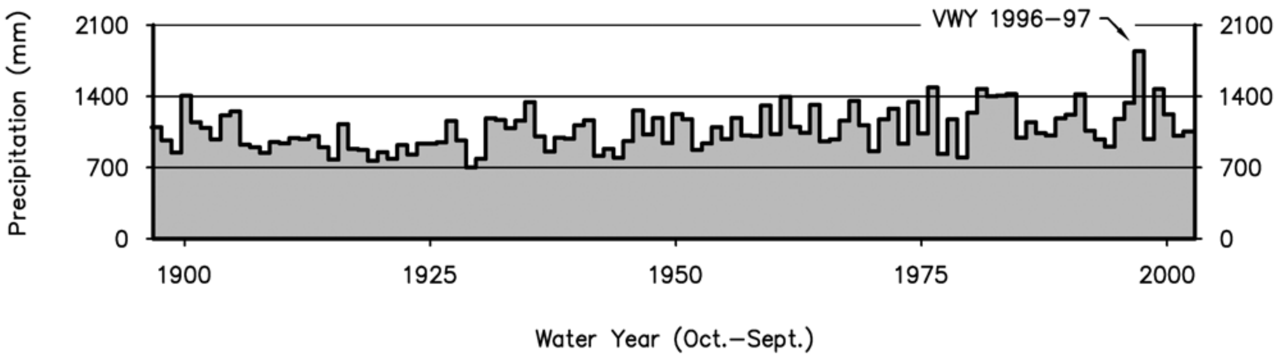

Figure 2. Vancouver Airport Total Precipitation 1897 – 2002.

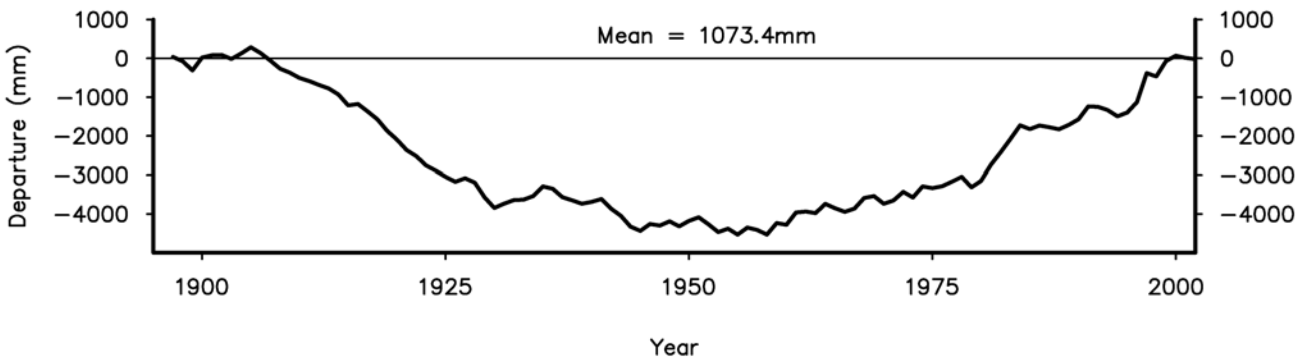

Figure 3. Cumulative Departure from the Mean.

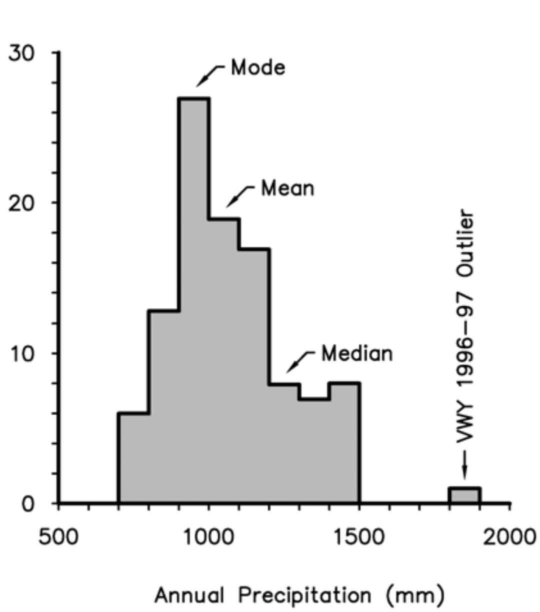

Figure 4. Histogram of Water Years 1897 – 2002.

Power law distributions are the foundations of SOC, see Bak (1996). Power laws are log-log distributions and plot as straight lines on double log paper. Applying this to the precipitation presented here, the log of the precipitation for water years is plotted against the log of the number of times exceeded over the period of record. Figure 5 show the plot for Vancouver airport with precipitation ranked in 100 mm intervals, i.e. 700 – 800 mm e.t.c. Incidentally the same plot results if the intervals are narrowed to 25 mm. The plot shows the number of times precipitation of a given rank is exceeded.

Note that Figure 5a is nothing more than the cumulative values on Figure 4 plotted on a log-log graph.

Figure 5a demonstrates that VWY 1996 – 97 had in fact a 1% chance per year of occurring. Even more interesting is to plot the data for the partial period 1897 – 1976, Figure 5b. This shows that the same probability of occurrence of 1850 mm of precipitation is predicted by the slope of the straight line portion of the plot. But of course it had not yet occurred! The slope of the straight line, the generator, is the same in both plots.

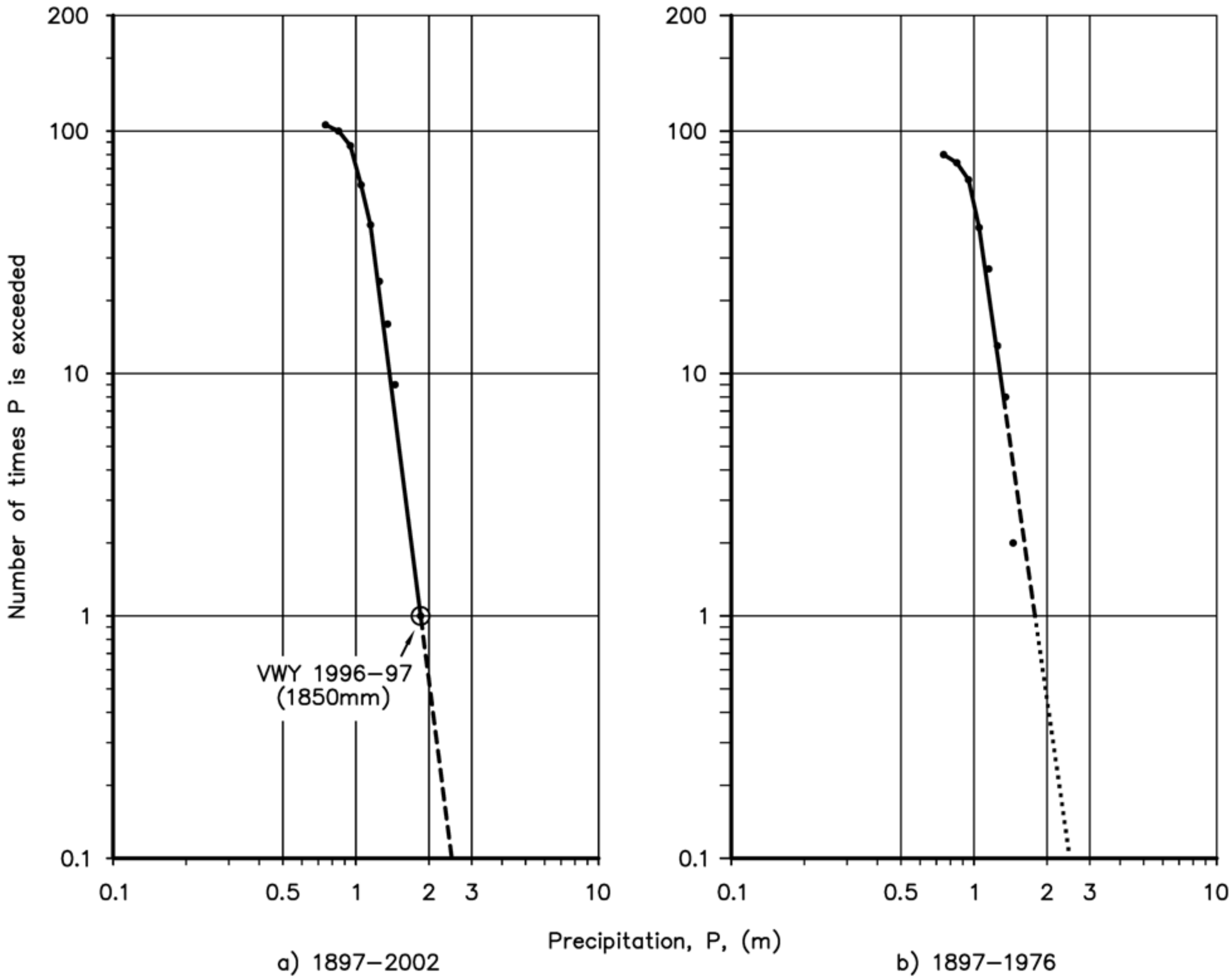

Figure 5. Power Law Distribution or Annual Precipitations for Vancouver Airport.

The conclusion is that VWY 1996 – 97 is not an outlier, or freak occurrence, but was in fact predictable on a probability basis, prior to the onslaughts of rain in the El Niño landslide years of the 1980's and 1990's. This lends support to the idea that precipitation obeys the principle of self-organized criticality, at least for this particular set of data. If so it is predictable that Vancouver precipitation at the airport could reach a yearly high of 2500 mm, but likely not more than once in 1000 years!

That is to say if Vancouver is lucky. However, 2500 mm could occur next century and the doomsayers would become convinced. But would they be correct? Not in the twilight world of probability. Thinking back to coin tossing, many patterns can emerge with the same fixed probability of 0.5 on each flip of the coin.

A more artificial interval of time is a month, and repeating the analysis for monthly totals of precipitation for the same data set for the years 1897 – 2001 yields the plot shown on Figure 6. Although far from linear at the top, the plot looks well behaved and conforms to linearity in the tail. Quite clearly there is a 1 in 10 chance Vancouver airport will get a foot of monthly rain in any year, albeit it mainly in the winter.

Monthly time intervals however are artificial in the sense that large storm events or heavy seasonal rains do not conform to the man-made calendar. The largest event can well straddle the months November-December for example. So an alternative approach using data on a near diurnal basis was made for a station in the District of North Vancouver examining discrete, 1-2 day storm events exceeding 25 mm (1 inch), the data set covering the years 1963 – 1994. The plot on Figure 7 is linear over two orders of magnitude. During the 30 year period of record a 228 mm (9 inches) storm occurred once. This was early on in the record. On a probability basis during a century a 280 mm (11 inches) storm could occur. And so on!

The time scales in these records are not *'historical'* in the sense of being orders of 10^3 years. Rather they are merely *'secular'* on a scale 10 – 10^2 years.

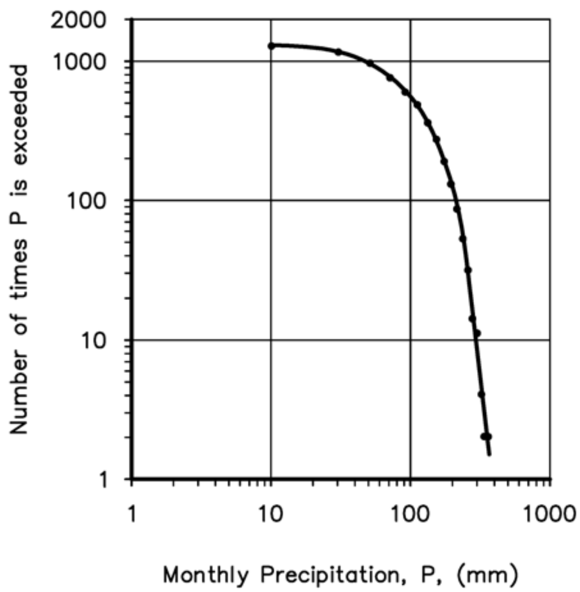

Figure 6. Power Law Distribution
for Monthly Precipitations for Vancouver Airport.

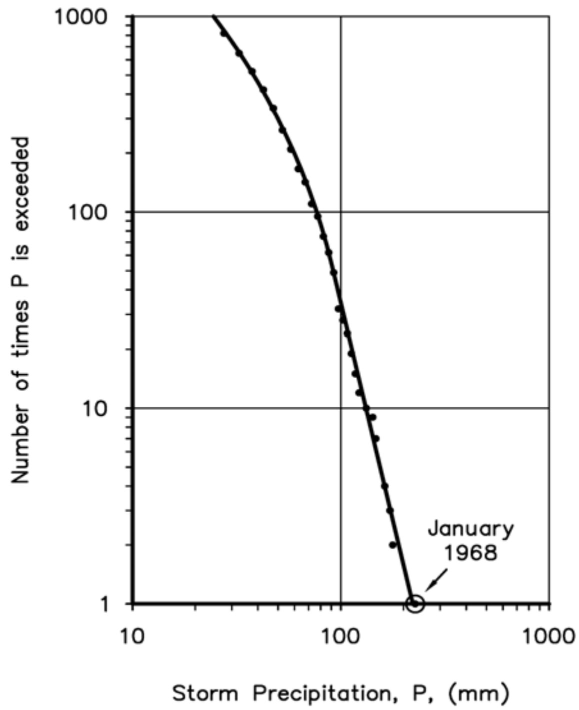

Figure 7. Power Law Distribution for 1-2 Day
Storm Events, North Vancouver District Hall.

3. ARGUMENT

The wetness of VWY 1996 – 97 appeared unexpectedly – un coup de foudre! Even the snowstorm that hit Vancouver at the end of December 1996 was said to be the worst on record. The effects were felt province wide. Heavy snow falls and heavy spring rains on snow in 1997 led to what was probably the worst year for landslides for B.C. in a century. The natural inclination to such events is to say that the climate is changing. It probably is, but then again it probably has always done so. Certainly the argument is not new; see the following letter in the 1930's to the American Society of Civil Engineers from a consulting engineer in San Francisco: "The recent series of dry and hot summers in many parts of the United States has attracted more than usual attention to matters of weather. In parts of the Pacific Coast there have been seventeen years with precipitation below the average-below normal. The question is, "Do we know what is normal? Is this dry period normal or were the earlier years of relatively high precipitation more nearly normal?"….. An "unprecedented drought" is the explanation. Such disasters occurred not only in 1934, but for several preceding years. Are they "unprecedented"? Are they likely to occur soon again? The climate is changing, say some", (Means 1936).

SOC indicates that VWY 1996 – 97, although unusual, was not abnormal and on a probability basis was to be expected. SOC may shed better light on such issues. Assume that the total volume of water on earth in its various forms is constant. Assume then that this is analogous to a pile of sand of constant mass, the sand avalanching to the bottom being returned to recharge at the top of the pile. The delicate, poised angle of repose of the sand is then equivalent to the delicate balance between the amounts of water in the sea, on land and in the air. The two analogous systems are at the critical state. "Avalanches" of water should then be analogous to avalanches of sand in the sand pile. Reports so far by different workers suggest that the flows of rivers and variations in sea level with time do in fact exhibit fractal behavior, so also does turbulence and rain (Lovejoy and Mandelbrot 1985, Peters et al 2002). The delicate, poised balance in the critical condition continually varies a little over time.

In the sand pile the critical angle of repose is generally around the mean values of 37º (75%), but sometimes, as sand is added, local steepening occurs to say 39º, before avalanches occur leaving locally flatter slope angles at say 35º. The process goes on endlessly as sand is added to the pile. It is also scale invariant. Sand poured in a pile on the laboratory bench is much the same as sand and gravel stockpiled at an aggregate plant, as is, on a grand scale, a high talus slope. The analogy with climate is that avalanches of sand off the face of the pile are the equivalent of floods on rivers, precipitation events or changes in sea level, all exhibiting fractal behavior defined by power laws.

This paper looks at only a couple of weather stations over the last century. Analyses of many more stations may show similar patterns. If so new insights into climate change and the impacts may be forthcoming. Realization that catastrophic events are inevitable should guide our response to arguments about Kyoto and perhaps prevent overreaction or worse still putting scarce resources in the wrong place. Catastrophic flooding in Vancouver may not be as serious a problem as an unforeseen period of drought, running in parallel with an ever expanding population. The population of Vancouver prior to WWII was less than ¼ million. Nowadays Greater Vancouver is close to 2 million and the major expansion has coincided with years of increasing wetness! Imagine if by chance the dryness of the period 1906 – 1929 reappeared in the 21st century. Needless to say readers of this paper in Alberta require little reminding of the effects of drought.

Further insights on flood-drought issues come from the Noah-Joseph Effect (Mandelbrot and Wallis 1968). This is based on classic studies of long flood records on the Nile River carried out by Harold Edwin Hurst. The Noah Effect refers to the fact that extreme precipitation can be very extreme indeed, VWY 1996 – 97. The Joseph Effect, the Biblical seven fat and seven lean years, means that long periods of high or low precipitation can be extremely long – look no further than Figure 2.

4. CONCLUSIONS

The following tentative conclusions are drawn:

- Koch's curve on Figure 1 could have been drawn as tiny rectangles forming parts of bigger rectangles and it could have been straightened out in linear fashion. Keeping this in mind and comparing it to Figure 2, both are seen to be fractal patterns. One is a pattern varying in two-dimensional space, while the other is a pattern varying in time. One is regular, or periodic, the other is not. However, both fractal shapes have been shown to obey power laws. This strongly suggests therefore that the weather pattern on Figure 2 is by definition self-organized at the critical state.

- Further investigation of weather data, including places with longer records, by means of the techniques suggested by SOC, could lead to useful, fresh insights into climate variability.

- The Water Year 1996-97 caused record precipitation related damages for B.C.'s Lower Mainland Municipalities, and doubtless others. Insurance underwriters, particularly underwriters of natural hazards, may wish to include what was previously considered only a freak occurrence in their long-term risk financing models.

- The general public and surprisingly many an engineer and scientist appear to be tuned into the present, with rather a short-term memory. The public tends to react to individual events, and needs to rationalize events or find cause. This very human trait appears to apply equally to traffic fatalities, cancer diagnosis as well as climatic events. This new means of organizing data may help to reveal the bigger picture.

This paper finishes by citing the French mathematician Marquis de Laplace (1749 – 1827) from his Théorie Analytique des Probabilités: "The most important questions of life are, for the most part, really only questions of probability ….. It is remarkable that a science which began with the consideration of games of chance should have become the most important object of human knowledge."

5. ACKNOWLEDGEMENTS

Review by Benjamin Ainsworth and Bill Hodge is greatly appreciated. Figures were prepared by Jon Bokic. Research assistance was provided by Nycolas Skermer at the University of British Columbia and paper preparation by Christina Gatchalian-Skermer.

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