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The horizontal, shore-perpendicular change in shoreline position along the Outer Banks of North Carolina is a self-affine signal. We measure shoreline change by determining the horizontal change in position of the 0.8m contour at 20m intervals along the coast. The profiles are obtained from two LIDAR surveys performed in September 1997 and September 1998 as part of a collaborative USGS, NOAA, NASA project. For six selected sections of coast, wavelet analysis of the shoreline change signal indicates that the signal is self-affine with a scaling exponent that varies from 1.2 to 2.1. This self-affine behavior indicates that the shoreline change signal is non-stationary with long-range persistence. The scaling exponent is found to vary depending on the orientation of the shoreline, suggesting that these changes are driven chiefly by subtle gradients on alongshore transport associated with subtle deviations from a smooth shoreline. Recent modeling work has shown that when waves approach shore from deep water at relative angles greater than approximately 45°, shoreline perturbations grow, causing alongshore-heterogeneous shoreline changes on any scale at which perturbations exist. Waves approaching from deep-water angles closer to shore-normal tend to smooth out the shoreline. The patterns of change over some extended time period will result at least partly from the interactions between the roughening and smoothing influences, which will depend on the regional wave climate, including the relative proportions of high and low wave-approach angles. The observed trend in scaling exponents found for the Outer Banks, with scaling exponent varying as a function of shoreline orientation, is predicted by the alongshore transport model.

NG31A-0608 0830h POSTER

Signatures of Self-Organized Criticality as System Forcing Changes

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Because of the broad claims of applicability made for self-organized criticality (SOC), it is important to define measurable characteristics which can validate or invalidate a statement that a system or model is SOC. We examine two such measures, spectral and R/S analysis, on a SOC sandpile model with varying driving rate and very long time records and find that: 1) the length of the data record can be crucial in distinguishing SOC from random dynamics, 2) R/S analysis gives a more consistent indication of the dynamics (whether correlated or not) in a SOC system than does the power spectrum, 3) a 1/f region in the SOC power spectrum does not arise from just a random superposition of events (pulses) from a power law distribution and 4) the 1/f spectrum can be substantially altered by keeping the same events and simply changing the spacing between them. The first result implies that SOC should not necessarily be discounted as a model for a geophysical process whose data do not match SOC signatures, since many such processes have long time scales that preclude the collection of relevantly long time series. The second result is an argument for including R/S analysis in one's standard toolbox when characterizing the dynamics of any physical system. The final two results imply a test to see if a process with a 1/f signal is possibly due to SOC.

NG32A MCC: 3001-3003 Wednesday 1340h

Critical Point Theory and Space-Time Pattern Formation in Precursory Seismicity I *(joint with S, T)*

Presiding: **K Tiampo,** University of Western Ontario**; M Anghel,** Computer and Computational Sciences Division**; C G Sammis,** University of Southern California

NG32A-01 1340h INVITED

Long-Term Prediction of Large Earthquakes: When Does Quasi-Periodic Behavior Occur?

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I argue that the prediction of large earthquakes for time scales of a few decades is possible for a number of fault segments along transform and subduction plate boundaries. A key parameter in ascertaining if forecasting is feasible is the size of the coefficient of variation, CV, the standard deviation of inter-event times of large earthquakes that rupture all or most of a given fault segment divided by T, the average repeat time. I address only large events, ones that rupture all or most of the downdip width of the seismogenic zone where velocity-weakening behavior occurs. Historic and paleoseismic data indicate that the segment that ruptured in the great 1946 Nankaido, Japan, earthquake broke 9 times in the previous 1060 years yielding T=118 years and CV=0.16. The adjacent zone that broke in 1944 exhibits similar behavior as does the Copper River delta, the site of 8 paleoseismic events dated by Plafker and Rubin (1994) above the rupture zone of the 1964 Alaska earthquake. Lindh (preceding abstract) finds that many fault segments in California have similar small values of CV. Paleoseismic data for inter-event times at Pallet Creek and Wrightwood, however, indicate a large CV. Those sites at situated along the San Andreas fault near the end of the 1857 rupture zone where slip was much smaller than in the Carrizo plain, rupture in large events to the northwest and southeast overlap and deformation is multibranched as plate motion is transferred in part to the San Jacinto fault. Plate boundary slip is confined to narrow zones along the 1944 and 1946 segments of the Nankai trough but is more diffuse in the Tokai-Suruga Bay region where the Izu Peninsula is colliding with the rest of Honshu and repeat times appear to be longer (and CV perhaps is larger). Dates of uplifted terraces likely give repeat times of inter-plate thrust events that are too long and large estimates of CV since imbricate faults within the upper plate that generate terraces do not rupture in every great earthquake. The 2002 Working Group on large earthquakes in the San Francisco Bay region followed Ellsworth et al. (1999) in adopting much larger values of CV for several critical fault segments and underestimating their likelihood of rupture in the next 30 years. The Working Group also gives considerable weight to a Poisson model, which is in conflict with both renewal processes involving slow stress accumulation and with values of CV near 0.2. The failure of the Parkfield prediction has greatly influenced views in the U.S. about long-term forecasts. The model of the repeated breaking of a single asperity is incorrect since past Parkfield shocks of about magnitude 6 likely did not rupture the same part of the San Andreas fault.

NG32A-02 1355h INVITED

Hazard Forecasting by MRI: A Prediction Algorithm of the First Kind

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Seismic gaps do not tell us when and where the next earthquake is due. We present new results on limited earthquake hazard prediction at plate boundaries. Our algorithm quantifies earthquake hazard in seismic gaps. The prediction window found for M7 is on the order of 50 km by 20 years (Lomnitz, 1996a). The earth is unstable with respect to small perturbations of the initial conditions. A prediction of the first kind is an estimate of the time evolution of a complex system with fixed boundary conditions in response to changes in the initial state, for example, weather prediction (Edward Lorenz, 1975; Hasselmann, 2002). We use the catalog of large world earthquakes as a proxy for the initial conditions. The MRI algorithm simulates the response of the system to updating the catalog. After a local stress transient dP the entropy decays as (grad dP)2 due to transient flows directed toward the epicenter. Healing is the thermodynamic process which resets the state of stress. It proceeds as a power law from the rupture boundary inwards, as in a wound. The half-life of a rupture is defined as the healing time which shrinks the size of a scar by half. Healed segments of plate boundary can rupture again. From observations in Chile, Mexico and Japan we find that the half-life of a seismic rupture is about 20 years, in agreement with seismic gap observations. The moment ratio MR is defined as the contrast between the cumulative regional moment release and the local moment deficiency at time t along the plate boundary. The procedure is called MRI. The findings: (1) MRI works; (2) major earthquakes match prominent peaks in the MRI graph; (3) important events (Central Chile 1985; Mexico 1985; Kobe 1995) match MRI peaks which began to emerge 10 to 20 years before the earthquake; (4) The emergence of peaks in MRI depends on earlier ruptures that occurred, not adjacent to but at 10 to 20 fault lengths from the epicentral region, in agreement with triggering effects. The hazard enhancement in space is shaped like a Mexican hat function. The central part is the aftershock region, separated by a ring of quiescence from an outer region of increased rupture probability(Lomnitz, 1996b). In conclusion, we may speak of seismic weather prediction using MRI. Hasselmann, K. (2002). Is climate predictable? In The Science of Disasters, A. Bunde, J. Kropp and H.J. Schellnhuber, eds. (Springer, Berlin, 140-169). Lomnitz, C. (1996a). Predicting earthquakes with the MRI algorithm, Seismol. Res. Letters, 67, 40-46. Lomnitz, C. (1996b). Search of a worldwide catalog for earthquakes triggered at intermediate distances, Bull. Seismol. Soc. Am., 86, 293-298. Lorenz, E. (1975). Climate predictability: The physical basis of climate and climate modeling. World Meteorol. Org., Geneva, Report 16, 132.

NG32A-03 1410h INVITED

Characterization of space-time correlations in aftershock and seismicity patterns

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Correlations in space and time play a fundamental role in earthquake processes. The direct manifestation of the effects of correlations is the occurrence of aftershocks due to the stress transfer in the vicinity of the main shock. Less obvious and more debatable changes in correlations might occur in the background seismicity before large earthquakes. Using statistical physics it is possible to introduce a measure of spatial correlations through the correlation length. This quantity characterizes how local fluctuations in space can influence the occurrence of earthquakes over distances comparable with the value of the correlation length in a seismogenic region. Partial information of correlations is also present in the well-known Gutenberg-Richter frequency-magnitude statistics which is reflected in the change of the shape of the distribution during different time periods. Time correlations are well documented for aftershock sequences and described by the modified Omori's law. This law specifies a temporal decay of aftershocks and has power-law scaling. The physical basis of these laws will be discussed in the context of correlations. In addition we have obtained scaling laws for the spatial clustering of aftershocks using pair and density correlation functions and a radius of gyration. We have also obtained the variations in time of the correlation function and correlation length associated with the spatial and temporal processes in seismogenic regions. Applications of the correlation analysis to background seismicity will also be discussed.

NG32A-04 1425h

Spinodal Critical Points, Scaling and Predictibility

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The critical point hypothesis, that there exists a critical point in earthquake fault systems, is attractive in that it provides a physical basis for the observed scaling laws seen in the data. However, the existence of a critical point is not enough to explain other observed properties of fault systems such as the earthquake cycle, including the possible existence of runup to failure. In addition, the critical point itself provides no physical basis for prediction or forcasting. Over

the past several years we have proposed an alternative paradigm which we call the Self Organized Spinodal(SOS) Hypothesis. This is based on the fact that faults and fault systems have stress Greens functions that have a very long range. Such systems are known to be well approximated by meanfield. These systems have a spinodal critical point that marks the boundary betwee metastable and unstable states. Such spinodal points act in many ways like critical points, i.e. they generate scaling, however they also give rise to other phenomena such as nucleation which play a role in the earthquake cycle. The SOS picture then naturally generates an earthquake cycle and provides a physical basis for the forcasting algorithm developed by our group. In this presentation I will explain the SOS hypothesis and describe how it generates scaling as well as how it can be used as a basis for statistical forcasting.

NG32A-05 1440h INVITED

Long Range Earthquake Interaction in Iceland

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It has been observed that earthquakes can be triggered by similarly sized events at large distances. The phenomenon has recently been shown to be statistically significant at a range up to several source dimensions in global earthquake data. The most appropriate explanation of the phenomenon seems to be criticality of the Earths crust as e.g. changes in static and dynamic stresses would otherwise be too small to trigger remote events. I present results for a regional (as opposed to global) study of seismicity in Iceland which is based on a high quality reprocessed catalogue. Results include the time-dependent determination of the maximum range of interaction and the correlation length and also address the question whether small events can trigger larger ones. Pitfalls such as data accuracy and geometry as well as boundary effects are thoroughly discussed. A comparison with surrogate data helps to assess the statistical significance of the results.

NG32A-06 1455h INVITED

Proximity to Criticality: Statistical Mechanics, Numerical Models and Natural Earthquake Data

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Complex driven threshold systems often produce statistical fluctuations that are very similar to those of equilibrium systems, with Boltzmann fluctuations in energy that can be used formally to define an entropy S and a 'temperature term' T. In this spirit we develop a mean field formulation for the frequency-magnitude distribution of earthquakes. Based on the results of numerical models for earthquakes as a complex system (averaged over several cycles), we assume a positive correlation between the distribution of potential strain energy U in the internal system and the radiated seismic energy E. The model predicts a functional relationship between S and <lnE> that can be used to answer the question: 'How close is the system to the critical point?'. We examine this question for temporal and spatial ensembles using CMT data. The answer for the temporal ensemble (annual data) is that the fluctuations represented by the earthquakes are indistinguishable from self-organised criticality, with a linear relationship between S and <logE>, but no correlation between S and <E>. Similarly <lnE> and <E> are not strongly correlated because <lnE> is determined most by intermediate-sized events on the Gutenberg-Richter trend, and <E> is dominated by the largest events. However, the spatial ensemble (with regions as defined in the Flinn-Engdahl scheme) show a systematic curvature in the plot of S v <lnE> consistent with an intermittently (but still near-critical) critical point system.

NG32A-07 1510h

Phase-locking in Coupled Non-linear Relaxation Oscillators: an Explanation for Observed Temporal and Spatial Correlation and Anti-correlation of Large Earthquakes

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There is mounting paleoseismological evidence that large earthquakes on a given fault network tend to occur in temporal clusters. Examples include the southern San Andreas system in the Imperial Valley (Rockwell et al., in prep, 2003), the Eastern California Shear Zone (Rockwell et al., BSSA, 2000), the Garlock system (Dawson et al, in prep., 2003) and the Los Angeles area (Dolan et al., in prep., 2003). This last study has also found evidence that clusters within the Los Angeles area tend to be anti-correlated with similar clusters in the Eastern California shear zone and on the Garlock fault. This clustering behavior is expected if large earthquakes behave as coupled non-linear relaxation oscillators. As a simplest case, we consider two identical faults which are loaded at constant strain rate and which fail at a prescribed stress threshold. Each thus produces the saw-tooth stress strain curve characteristic of a relaxation oscillator. The faults are non-linear oscillators because we assume the stress-strain curve is non-linear, having the negative curvature typical of laboratory experiments and regional damage mechanics models (Ben-Zion and Lyakhovsky, 2002). The two faults are coupled by symmetric stress transfer, in that we assume each fault either increases or decrease the Coulomb stress on the other by an equal amount. We find that events on the two faults phase-lock either in phase if the Coulomb stress transfer is positive or 180 degrees out of phase if the transfer is negative. This phase-lock is driven by the non-linear stress-strain relation. When a fault is close to failure, the increment of stress transfer causes a larger increment in strain. Since time is linked to strain through the assumption of constant strain rate loading, the time shift of the impending event is larger the nearer a fault is to failure. For a positive stress transfer, this shortens the interval and leads to in-phase locking. For a negative stress transfer, the interval is lengthened and the system evolves to a 180 degree out of phase lock. Preliminary models of simple faults controlled by rate- and state-dependent friction have found that non-linearity introduced by friction has a similar effect.

NG32A-08 1525h

Which Works Best, ETAS or SAM?

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In recent years a number of models have been proposed that describe evolutionary seismicity as an interplay between aftershocks and Coulomb stress interactions. The Epidemic-Type Aftershock Sequence (ETAS) model has in particular been proposed as a possible explanation for the widely observed phenomenon of accelerating moment release before large earthquakes. This model is based on the idea that large earthquakes are the end result of a period of self-organization in the background stress field (i.e. smaller earthquakes). In contrast to this concept is the Stress Accumulation Model, (SAM) which treats the evolution of seismicity before a large earthquake as the result of loading of the main fault primarily by creep on an extension of the fault at depth. While both of these models predict accelerating seismicity before the mainshock, they make different predictions of the spatial distribution of this activity. We demonstrate that the predictions of the Stress Accumulation model are more consistent with observed seismicity than the predictions of the ETAS model.

NG32B MCC: 3001-3003 Wednesday 1600h

Lorenz Lecture

Presiding: **S F Tebbens,** University of South Florida

NG32B-01 1605h INVITED

Wonders of Planet Earth: Complexity and Order in Earth Systems

Rafael L. Bras (617-253-2117; rlbras@mit.edu)

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Much of the climate, weather and landscape of the earth is mediated by the ever present water. This talk explores the non-linearities of hydrologic processes which commonly lead to chaotic-like behavior yet beautifully organized systems. Land-atmosphere interactions are discussed first. The dynamic impact on the atmosphere and climate of land surface conditions like soil moisture and vegetation are illustrated. The ideas of multiple equilibria in vegetation and soil moisture, and of maximum evaporation at all times, are discussed. Self organization in landscape forms are the next topic. Organization in geometry and in surface texture of the river basin is achieved jointly and is the result of highly nonlinear phenomena.

NG41A MCC: 3010 Thursday 0800h

Scaling in Our Fluid Earth: Chaos and Multifractals in the Atmosphere, Oceans, Hydrology, and Climate I

(joint with A, B, GP, H, OS, PP, SA, AE, C, GC)

Presiding: **S Lovejoy,** McGill University**; D Schertzer,** Laboratoire de Modélisation en Mécanique, Université Pierre et Marie Curie

NG41A-01 0800h

Deriving Spatiotemporal Fractal And Wavelet Models In Terms Of The Generalized Random Field Theory

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A powerful unified framework is suggested in terms of generalized spatiotemporal random fields (GS/TRF), which can derive well-known models as its special cases, including fractal, wavelet and heterogeneous random field models. It is worth-noticing that the development of the GS/TRF theory precedes that of its special cases above. A G-S/TRF is typically defined in terms of a functional involving a so-called test function belonging to a space D. The choice of D is made on the basis of the physics of the atmospheric situation and the goals of the analysis. Very rich classes of moments across space and time are derived by means of the corresponding GS/TRF functionals. By properly selecting the test functions, space-time heterogeneous models are generated, termed GS/TRF-n/m, where n and m are the corresponding spatial and temporal orders of heterogeneity, respectively. Well-known fractal random fields are readily obtained from the GS/TRF-n/m which, in addition, can lead to new and richer fractal representations in space-time. By assuming test functions having properties useful in the study of important field characteristics (multiscale features, singularities caused by physical laws, sharp variations etc.), continuous space-time wavelets are derived which have a wide range of earth science and image processing applications.

NG41A-02 0815h

Multifractals and Chaos, Predictability and Prediction Skills in Geophysics

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The question of prediction - from short to very long term - and its intrinsic limits is a fundamental question in Geophysics; it cross-cuts traditional discipline boundaries. The chaos revolution emphasized the fact that nonlinearity is at the core of this question. This was widely popularized as the 'butterfly effect' with the help of the celebrated Lorenz model, which was introduced as a highly simplliefied mathematical model

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