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Is the Political Economy Stable or Chaotic?

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Abstract Recent events in the global economy have caused many writers to argue that the market is driven by animal spirits, by irrational exuberance or speculation. At the same time, the economic downturn has apparently caused many voters in the United States, and other countries, to change their opinion about the the proper role of government. Unfortunately, there does not exist a general equilibrium model of the political economy, combining a formal model of the existence, and convergence to a price equilibrium, as well as an equilibrium model of political choice. One impediment to such a theory is the so-called chaos theorem which suggests that existence of a political equilibrium is non-generic. This paper surveys results in the theory of dynamical systems, emphasizing the role of structural stability and chaos. We consider models of celestial mechanics where the notion of chaos first developed, and then examine applications in models of climate change and economics. There is discussion of the past influences of climate on human society, and particularly how agriculture developed during the "holocene," the past ten thousand years of benign climate. The recent period of globalization is likened to the holocene, and the question is raised whether future climate change may bring economic and political chaos.

Keywords Economic uncertainty, climate change, political disorder
JEL classification H10

1. Introduction

John Maynard Keynes's work, *The General Theory of Employment, Interest and Money* (1936) was very probably the most influential economic book of the twentieth century. *The General Theory* is , in a sense, a continuation of Keynes's earlier writing on the foundation of probability, completed in the period 1906 to 1914, and published eventually as the *Treatise on Probability* (1921). In the *Treatise*, Keynes viewed probability as a degree of belief.[1] Indeed, Keynes later seemed to come to the opinion that it was impossible to construct an adequate model of how we form beliefs in an uncertain world. As a result we cannot construct adequate mathematical and stochastic models of political and economic behavior.

Macro-economics as it is practiced today tends to put a heavy emphasis on the empirical relationships between economic aggregates, while micro-economics emphasizes the logic of equilibrium and market efficiency. Keynes's views, in the *Treatise*,

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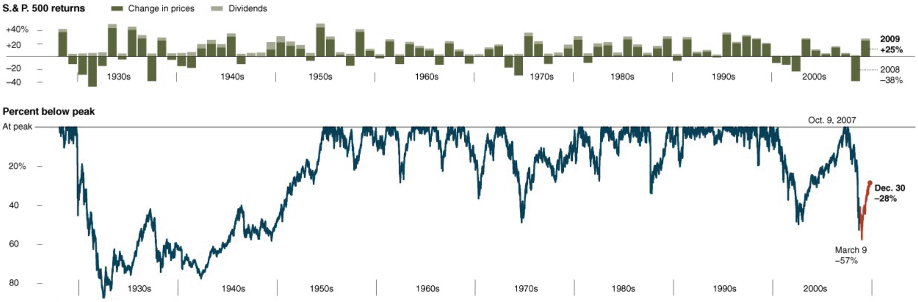
[1] The *Treatise* took as its starting point the arguments by Condorcet and Laplace, written a hundred years before, about the logic of induction and belief. Later work by Popper (1992, [1935]) took Keynes's argument further and rejected the possibility of induction.

suggest that he was impressed neither by econometric relationships nor by algebraic manipulation. Moreover, his later ideas on "speculative euphoria and crashes" would seem to be based on an understanding of the economy grounded neither in econometrics nor algebra but in the qualitative aspects of its dynamics.

It has been argued that a dominant core belief, the *economic equilibrium hypothesis*, had won universal acceptance among policy makers in the aftermath of the chaotic events of the 1970's. The International Financial Crisis of 1997–1998, involving Russia, Indonesia, Malaysia, and many countries in Latin America, indicated that the global economy faced a fundamental quandary derived from the realization that this core belief was wrong. A resolution of this quandary could be based on accepting that Keynes was correct in his understanding of the global economy. While commodities markets, governed by risk, might well display equilibrium, asset markets, governed by speculation, need not. For Keynes, asset markets display fundamental uncertainty. The events of the late 1990's indicated that fundamental reform of international institutions was necessary to avoid chaos.

The crisis of 1997–1998 was followed shortly by the collapse of the dot.com bubble. Figure 1 shows the magnitude of changes in the U.S. stock market in the long period from the 1920's to the end of 2009. (The figure normalizes the changes by setting all peaks to unity.) It is noticeable that the fall from a peak in the Dow of 11,723 on January 14, 2000, to its next low of 7,286 on October 9, 2002, was followed by a peak of 14,164 on October 9, 2007. The next low was 6,547 on March 9, 2009. On January 19, 2011 the Dow reached 11,772 again. These violent oscillations are compatible with Hyman Minsky's theory of market volatility, based on Keynesian uncertainty (Minsky 1975, 1986).[2] Minsky's argument is that periods of economic growth eventually lead to irrational beliefs about the degree of risk embedded in the market. Increasing risk taking leads to a bubble, and this eventually collapses when the true level of risk becomes apparent. Minsky's work therefore denies the core principle of market efficiency associated with the equilibrium hypothesis.



Source: New York Times, Dec 31, 2009.

Figure 1. Chaotic stock market prices 1930–2009

[2] Minsky spent many years at Washington University in Saint Louis. His work was almost forgotten, but recently there has been renewed interest in his analysis of economic disorder.

The collapse of the global property/housing bubble from late 2007 destroyed trillions of dollars of assets, not just in the U.S. but worldwide, and almost destroyed the global market itself. Rapidly rising unemployment showed that disorder in financial markets could have real macroeconomic effects.

Many theories have been put forward recently to account for this bubble. One of these is that China's mercantilism meant that its purchases of dollar assets, to maintain its cheap currency, provided cheap money to U.S. consumers, fueling the bubble and U.S. economic growth (Ferguson 2008). While there is some truth to this argument, it does not provide a basis for understanding the periods of high and low volatility apparent from Figure 1.

In this paper, I shall focus on the idea of chaos that underlies Keynes's arguments about uncertainty. To do this I shall first discuss the economic equilibrium and efficient market hypotheses. The idea of chaos first occurred in constructing models of the weather, climate and celestial mechanics, and I shall use such models to give an idea of what chaos is all about. In discussing climate, I shall argue that our civilization developed during a period known as the holocene. I conjecture that the prior period of market stability resembles the holocene, and we should prepare ourselves for a future of increasing chaos. I shall argue that the only way to defend against this future chaos depends on building dynamical models of the political economy *and* climate that are not based on false equilibrium arguments, but incorporate at least some of the complex feedback mechanisms that we now know govern our society and the planet on which we live.

The basis of the equilibrium models of the economy lies in Brouwer's (1910) fixed point theorem. This mathematical formalism is now a century old. We need to develop new mathematical models to deal with our complex world.[3]

2. Economic equilibrium or market chaos

First consider a thought experiment to about the global economy. There must be local periodicities due to climatic variation. Since hurricanes and monsoons, etc. affect the economy, one would expect small chaotic events. More importantly, however, some of the behavior of economic agents will be based on their future expectations about the nature of economic growth, etc. Thus one would expect long term expectations to affect large scale decisions on matters such as investment, fertility, etc.

It is evident enough that the general equilibrium (GE) emphasis on the existence of price equilibria, while important, is probably an incomplete way to understand economic development. In particular, GE theory tends to downplay the formation of expectations by agents, and the possibility that this can lead to unsustainable "bubbles."

It is a key assumption of GE that agents' preferences are defined on the commodity space alone. If, on the contrary, these are defined on commodities *and* prices, then it is not obvious that the Arrow-Debreu Theorem (Arrow and Debreu 1954) can be employed to show existence of an equilibrium. The point here is that how individuals

[3] Indeed, Hawking and Mlodinow (2010) argue that it is *only* through a mathematical model that we can properly perceive reality.

respond to price signals in an asset market depends on how they evaluate risk and it is not clear how best to model risk attitudes in the presence of extremely unlikely but very unpleasant events. More generally one can imagine energy engines (very like hurricanes) being generated in asset markets, and sustained by self-reinforcing beliefs about the trajectory of prices. It is true that modern decentralised economies are truly astonishing knowledge or data-processing mechanisms. From the perspective of today, the argument that a central planning authority can be as effective as the market in making "rational" investment decisions is very controversial. Hayek's "calculation" argument used the fact that information is dispersed throughout the economy, and is, in any case, predominantly subjective. He argued essentially that only a market, based on individual choices, can possibly "aggregate" this information (Hayek 1945).

Recently, however, theorists have begun to probe the degree of consistency or convergence of beliefs in a market when it is viewed as a game. In fact the issue about the "truth-seeking capability" of human institutions is very old and dates back to the work of Condorcet (1955, [1795]). Recent work suggests that there may be "belief cascades" or bubbles, which generate multiple paths of beliefs which diverge away from the "truth" (Bikhchandani et al. 1992, 1998).

2.1 Market chaos

I have in mind a dynamical representation of the economy somewhere in between macro-economics and general equilibrium theory. The laws of motion of such an economy would be derived from modeling individuals' "rational" behavior as they process information, update beliefs and locally optimize.

However, as Akerlof and Shiller argue,

> ... the business cycle is tied to feedback loops involving speculative price movements and other economic activity—and to the talk that these movements incite. A downward movement in stock prices, for example, generates chatter and media response, and reminds people of longstanding pessimistic stories and theories. These stories, newly prominent in their minds, incline them toward gloomy intuitive assessments. As a result, the downward spiral can continue: declining prices cause the stories to spread, causing still more price declines and further reinforcement of the stories. (Akerlof and Shiller 2009)

At present it is not possible to construct such a micro-based macro-economy because the laws of motion are unknown. Nonetheless, just as simulation of global weather systems can be based on local physical laws, so may economic dynamics be built up from the local "rationality" of individual agents. However, the GE models discussed in this paper are based on the assumption that the political economic world is contractible, that is, it has the topological characteristic of a ball. This seems an unlikely assumption.[4] In particular, individuals may fear economic and political disasters, so their preferences are non-convex, thus violating one of the key assumptions of the GE model.

[4] See Krugman (2009), for a recent argument that the assumptions of economic theory are unrealistic.

In addition, modern growth theory emphasizes "ideas" as the basis of productivity (Romer 1986; Jones 2002; Jones and Romer 2009), and there is no reason to suppose "ideas" exhibit the usual property of diminishing returns. Although the total set of resources may well be bounded, it does not appear to be the case that technological possibilities are similarly bounded. Indeed, the Enlightenment argument between Malthus (1970, [1798], [1830]) and Condorcet (1955, [1795]) seems, at least in the developed world, to have been carried by the optimistic Condorcet. However, the less developed world, particularly Africa and parts of the Middle East, faces Malthusian constraints that engender economic and political disorder. North (2005) argues that the growth of the developed world is due to its sophisticated institutions, what Kling and Schultz (2009) call "protocols," namely the techniques to solve social and economic problems.[5]

Although we might have reason to be optimistic about technological advance, recent economic events have caused concern about the validity of current economic theory. Since our social protocols are crucial to our society, it is imperative they work in an efficient manner. This concern has led to an extensive literature, in the last few years, dealing with the efficiency of our market protocols. This literature discusses the nature of herd instinct, the way markets respond to speculative behavior and the power law that characterizes market price movements (see, for example, Mandelbrot and Hudson 2004; Shiller 2003, 2005; Barbera 2009; Cassidy 2009; Fox 2009). Some of these analyses are based on a version of the market equilibrium theorem. In fact, much of the work on efficient markets is based on the Black-Scholes partial differential equation used to price options (see Black and Scholes 1973).[6] The recent collapse of the economy suggests that this equation is subject to chaotic singularities, whose qualitative nature is not understood.

There are thus two difficulties with GE: ideas give rise to increasing returns, which can generate explosive growth and thus market euphoria. This can lead to bubbles and chaotic collapse.

As discussed above, Minsky's interpretation of Keynes's general theory focuses on the proposition that asset pricing is subject to an extreme degree of uncertainty. The underlying idea is that individuals do not know the true probability distribution on the various states of the world, but only have personal probability distributions, in the sense of Savage (1954). They make stochastic choices on the basis of this personal uncertainty. Agents may also differ widely in how they treat "black swan" low probability events (see Taleb 2007; Chichilnisky 2009, 2010). Since investment decisions are based on these uncertain evaluations, and these are the driving forces of an advanced economy, the flow of the market can exhibit singularities, of the kind that recently nearly brought on a great depression. These singularities are time-dependent, and can be induced by endogenous belief-cascades, rather than by any change in economic or political fundamentals.[7]

More abstractly, the space in which economic and political behavior occurs may

[5] See also Stiglitz (2010) for a recent discussion of the failure of these protocols.

[6] I shall argue below that this equation is structurally similar to the Ricci flow equation in celestial mechanics, and can be regarded as a method of computing the "geodesic" of the financial economy.

[7] All of these ideas are present in Keynes's work, especially as interpreted by Minsky.

be thought of as a "manifold" of very high dimension. While GE asserts that there are "equilibria," these will depend on the dynamical domain in which they are defined. These domains are separated by singularities, where the qualitative nature of the system may be radically transformed. To illustrate this point by the stock market, shown above in Figure 1, the flow does not look like a slowly changing equilibrium, responding to exogenous changes in population and resources. A period of relative stability, or low volatility, as in the 1990's, would give a false impression of risk prior to the singularity in 2000. This stable period was followed by collapse, then euphoria, then by collapse again, then the current partial recovery. The period of disorder that occurs after passing through such a singularity we can call "chaos."

3. Chaos

3.1 Chaos in weather

"Empirical chaos" was probably first discovered by Lorenz (1963,1993). He found that slight changes in the coefficients of a simple system, with three variables and three parameters, used to model the weather, gave rise a qualitatively different dynamical process.

Given that chaos can be found in such a simple meteorological system, it is worthwhile engaging in a thought experiment to see whether "climatic chaos" is a plausible phenomenon. Weather occurs on the surface of the earth, so the spatial context, or "geosphere," is the two-dimensional sphere, the surface of the earth, $S^2 \times I$, where I is an interval corresponding to the depth of the atmosphere. Purely theoretical arguments show that a certain kind of dynamical system on $S^2 \times I$ will exhibit a critical point. Such a critical point can also be viewed as a local singularity. But as the weather systems change then the dynamical systems that are used to describe them also change. When different local weather systems collide then their impact will often be indeterminate or chaotic. So the onset of a hurricane for example can be seen as a local singularity.

The system of plate tectonics occurs in the "lithosphere" also in $S^2 \times I$, so volcanoes can also be seen as local singularities. Earthquakes and volcanoes on the tectonic boundaries are locally chaotic because of the non-linearity of the dynamical system that governs their behavior.[8] As a dynamical system changes so that a new singularity is about to come into being, we can call this neighborhood a "portal." It is within a portal that the dynamics becomes chaotic.

Climate is affected by temporal periodicities, induced by the orbit of the earth round the sun and wobbles in the earth's rotation.[9] In addition there are spatial periodicities or closed orbits in the geosphere. Chief among these must be the jet stream and the oceanic orbit of water from the southern hemisphere to the North Atlantic (the Gulf Stream) and back. The most interesting singularities are the hurricanes generated each year off the coast of Africa and channeled across the Atlantic to the Caribbean and

[8] For example, the earthquakes in Haiti on January 12, in Chile on 27 February, 2010, and in Qinghai Province, China, on April 14, 2010, as well as the eruption of the Eyjafjallajokull volcano in Iceland later in April, 2010, were completely unpredictable events.

[9] Celestial chaos is discussed below.

the coast of the U.S.A. Hurricanes are self-sustaining heat machines that eventually dissipate if they cross land or cool water. It is fairly clear that their origin and trajectory is chaotic. Understanding weather, and more generally, climate itself, involves the analysis of an extremely complex dynamical system that is affected by periodicities in the solar system. We now turn briefly to the notion of "structural stability" and chaos in the heavens.

3.2 Celestial chaos

When Galileo Galilei turned his telescope to the heavens in August 1609, he inaugurated the modern era in science. In his *Sidereal Messenger* (1610) he wrote of the myriad stars in the milky way, the moons of Jupiter, each with a different period and distance from Jupiter. Jupiter's moons suggested it was a planet just like the earth. Moreover the phases of Venus also suggested that it was a planet orbiting the Sun. These observations, together with Kepler's empirical "laws" on planetary orbits made it clear that the Copernican heliocentric model of the solar system was not just a mathematical theory but a truth. Galileo waited 22 years before publishing *Dialogue Concerning the Two Chief World Systems, Ptolemaic and Copernican*, for fear that he would be accused of heresy by the Church. Indeed, in 1633, he was found guilty of "vehement suspicion of heresy" and spent the years until his death under house arrest, while writing *Two New Sciences* (1638). Within fifty years Newton published *Philosophiae Naturalis Principia Mathematica* (1687), giving a mathematical model of physical reality, including celestial mechanics that provided the theoretical foundations for Kepler's Laws.

Even with the Newtonian mathematical model, it was unclear whether the solar sytem was "structurally stable." Although it was possible to compute the orbit of a single planet round the sun, the calculation of the influence of many planets on each other seemed technically difficult. Could these joint influences cause a planet to slowly change its orbit, perhaps causing it to spiral in to the sun? Structural stability for the orbital system of the planets means that the perturbations, caused by these interactions, do not change the overall dynamic system. The failure of structural stability means that a slight perturbation of the dynamical system induces a change in the qualitative characteristics of the system. As in the previous discussion, we can use the term "chaos" to refer to this breakdown.

It is only in the last twenty years or so that the implications of "chaos" have begun to be realized. In a recent book Kauffman commented on the failure of structural stability in the following way:

> One implication of the occurrence or non-occurrence of structural stability is that, in structurally stable systems, smooth walks in parameter space must [result in] smooth changes in dynamical behavior. By contrast, chaotic systems, which are not structurally stable, adapt on uncorrelated landscapes. Very small changes in the parameters pass through many interlaced bifurcation surfaces and so change the behavior of the system dramatically. (Kauffman 1993)

It is worth mentioning that the idea of structural stability is not a new one, though the original discussion was not formalized in quite the way it is today. The laws of motion written down by Newton in *Principia Mathematica* could be solved precisely giving a dynamical system for the case of a planet (a point mass) orbiting the sun. However, the attempt to compute the entire system of planetary orbits had to face the problem of perturbations. Would the perturbations induced in each orbit by the other planets cause the orbital computations to converge or diverge? With convergence, computing the orbit of Mars, say, can be done by approximating the effects of Jupiter, Saturn perhaps, on the Mars orbit. The calculations would give a prediction very close to the actual orbit. Using the approximations, the planetary orbits could be computed far into the future, giving predictions as precise as calculating ability permitted. Without convergence, it would be impossible to make predictions with any degree of certainty. Laplace in his work *Mécanique Céleste* (1799–1825) had argued that the solar system (viewed as a formal dynamical system) is structurally stable (in our terms) (see Galison 2003). Consistent with his view was the use of successive approximations to predict the perihelion (a point nearest the sun) of Haley's comet, in 1759, and to infer the existence and location of Neptune in 1846.

Structural stability in the three-body problem (of two planets and a sun) was the obvious first step in attempting to prove Laplace's assertion. In 1885 a prize was announced to celebrate the King of Sweden' s birthday. Henri Poincaré submitted his entry "Sur le problème des trois corps et les Equations de la Dynamique." This attempted to prove structural stability in a restricted three body problem. The prize was won by Poincaré although it was later found to contain an error. His work on differential equations in the 1880s and his later work, *New Methods of Celestial Mechanics* in the 1890's, developed qualitative techniques (in what we now call differential topology). The Poincaré conjecture, that "a compact manifold, with the same algebraic invariants as the three-dimensional sphere, is indeed a three sphere" was one of the great unproven theorems of the twentieth century. The theorem has recently been proved by Grigori Perelman (see O'Shea 2007).[10]

The earlier efforts to prove this result has led to new ideas in topological geometry, that have turned out, surprisingly, to have profound implications for a better understanding of general relativity and the large scale structure of the universe. Our physical universe is a three dimensional manifold, probably bounded and thus compact. The Ricci flow on this manifold is given by a certain partial differential equation. This equation is a way of characterizing the curvature of geodesics on this manifold. The equation has a deep relationship with the topological structure of the universe. Perelman's proof depends on understanding the nature of singularities associated with this equation.

One of the notions important in understanding structural stability and chaos is that of *bifurcation*. Bifurcation refers to the situation where a particular dynamical system is on the boundary separating qualitatively different systems. At such a bifurcation, features of the system separate out in pairs. However Poincaré also discovered that

[10] Perelman recently won a million dollar Millenium prize for his theorem from the Clay Mathematics Institute. For an outline of Perelman's result see Morgan and Tian (2007).

the bifurcation could be associated with the appearance of a new solution with period double that of the original. This phenomenon is central to the existence of a period-doubling cascade as one of the characteristics of chaos. Near the end of his *Celestial Mechanics*, Poincaré writes of this phenomenon:

> Neither of the two curves must ever cut across itself, but it must bend back upon itself in a very complex manner ... an infinite number of times .... I shall not even try to draw it ... nothing is more suitable for providing us with an idea of the complex nature of the three body problem. (Galison 2003, p. 74)

Although Poincaré was led to the possibility of chaos in his investigations into the solar system, he concluded that though there were an infinite number of such chaotic orbits, the probability that an asteroid would be in a chaotic orbit was infinitesimal. Arnol'd (1963) showed that for a system with small planets, there is an open set of initial conditions leading to bounded orbits for all time (see Message 1984). Computer simulations of the system far into the future also suggests that it is structurally stable.[11] Even so, there are events in the system that affect us and appear to be chaotic.[12] It is certainly the case that the "N-body system" can display exceedingly complex, or chaotic phenomena (Saari and Xia 1985). Although space is three dimensional, the Einsteinian universe also involves time, and the behavior of geodesics near space-time singularities may also be very complex.[13]

The point of this discussion about celestial mechanics is the we know the Newtonian laws of motion, but even these relatively simple laws generate phenomena that can defeat prediction. Analysis under the more complex Einsteinian laws of motion become even more difficult. The Black-Scholes partial differential equation, which we referred to above, can be seen as the analogue of the computation of the geodesic in cosmology. Once we have rejected the notion that the economy seeks equilibrium, then we are obliged to accept the real possibility of singularity and chaos in its behavior.

As a result of his research in celestial mechanics, Poincaré (2007, [1908]) was led to the realization that any deterministic system could, in principle, be chaotic. As he wrote:

> If we knew exactly the laws of nature and the situation of the universe at the initial moment, we could predict exactly the situation of that same universe at a succeeding moment ... but even if it were the case that the natural laws had no longer any secret for us, we could still only know the initial situation approximately. If that enabled us to predict the succeeding situation with the same approximation, that is all we require, and we should say that the phenomenon had been predicted, that it is governed by laws. But it is not always so; it may happen that small differences in

[11] Had the solar system been chaotic, then life would not have evolved on Earth.

[12] For example, asteroid collisions with the earth or Jupiter could be called chaotic, though catastrophic would be a more appropriate term.

[13] See the discussion of space-time singularities, such as black holes, in Hawking and Ellis (1973) and in Penrose (2003).

> the initial conditions produce very great ones in the final phenomena. A small error in the former will produce an enormous error in the latter. Prediction becomes impossible, and we have the fortuitous phenomenon.[14] (Poincaré 2007, [1908])

Poincaré's work led to one of the other great theorems of twentieth century century. It had seemed that structurally stable dynamical systems were typical or generic, but Smale (1966) proved that though this was true in two-dimensions, it was false in general. In essence, in the space of all dynamic systems, there seems to exist an open set of structurally stable ones and an open set of chaotic systems. A singularity characterizes the transition from one of these sets to the other.

We now turn to the possibility of chaos in climate, and its influence on humankind.

4. The Holocene

The onset and behavior of the ice ages over the last 100,000 years is very possibly chaotic, and it is likely that there is a relationship between these violent climatic variations and the recent rapid evolution of human intelligence (Calvin 1991; Fagan 2010).

More generally, evolution itself is often perceived as a gradient dynamical process, leading to increasing complexity. However, Gould has argued over a number of years that evolution is far from gradient-like: increasing complexity coexists with simple forms of life, and past life has exhibited an astonishing variety. Evolution itself appears to proceed at a very uneven rate, and Gould used the term "punctuated equilibrium" to refer to these singularities that differentiated domains of evolutionary volatility (see Gould 1989; Eldridge and Gould 1972).

By analogy with the use of the term *singularity* in the theory of dynamical systems, I shall use it to refer to a "gate" or portal between qualitatively different systems.[15] We shall use this idea to discuss the qualitative changes that can occur in weather and climate.[16]

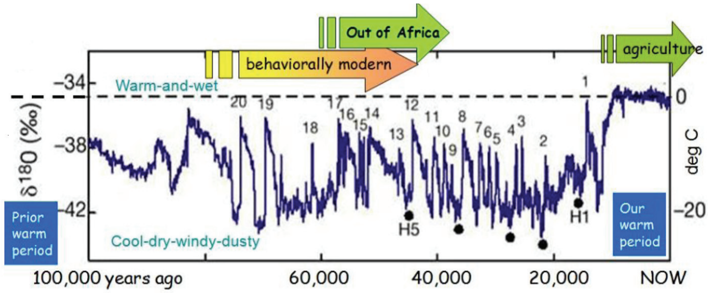
One of the concerns about climate is that it may exhibit complex singularities. For example, the spatially periodic, oceanic flow of water, including the Gulf stream, has switched off, and then on again, in the past. These switches can be interpreted as singularities that have caused catastrophic changes in climate, and have, in turn, been caused by subtle changes in the underlying periodicities of the system. Since the end of the last ice age, during the period of the *holocene* of the last twelve thousand years, humankind has benefited from a structurally stable and mild climate domain, conducive to agriculture. Figure 2 shows average global temperature for the last 100K years, taken from Greenland ice cores. There is a singularity about 90K years ago, then

[14] Poincaré's argument may hold for the formation of the solar system. It is not clear as yet whether our stable solar system is generic in some sense, or very unusual.

[15] I do not mean simply a rest point in a given dynamical system, but rather a barrier within a set of dynamical systems where general topological properties change. See Zeeman (1977) for example who used the term catastrophe.

[16] Sometimes climate does hit an equilibrium, when the planet becomes an ice ball. It only escapes such an equilibrium because of tectonic activity (Macdougall 2004).

a long chaotic period of about 80K years, and then a singularity about 12K years ago, where the chaotic behavior changed, leading to the holocene. Just before the holocene, there was a brief ice age, the "Younger Dryas," lasting approximately 1,300 years, from about 12,800 to 11,500 years ago. Broecker (1997, 2010) describes how the global climate "flickered" in a particularly chaotic fashion, over periods of between 5 and 45 years, just before passing through the singularity that heralded the holocene.[17] The dynamical system of the "biosphere," the whole system of life on Earth, is so interwined with that of the geosphere that computer-based quantitative analysis can only hint at the connections.



Source: Global-Fever.org.

Figure 2. Climate 100K BCE to now: chaos from 80K BCE to 10K BCE

As we noted above, the earth's climate is affected by periodicities in the rotation of the Earth, as well as by the oscillatory behavior of the Solar irradiation (with an eleven year sunspot cycle). The celestial cycles are associated with the eccentricity of the orbit (with a period of order 95,000 years), the Earth's tilt or obliquity (with a period of about 41,000 years), and precession (of period about 26,000 years). The changes in eccentricity are due to the perturbations on Earth's orbits induced by the other planets.[18] Hansen (2009) has charted the effects of these celestial oscillations on correlated changes in temperature, CO_2 concentration and sea-levels over the last 400 thousand years. As Figure 3 illustrates these "celestial" oscillations are periodic and non-chaotic in themselves. However, as the work of Broecker and many others illustrates, their interactive effect on the Earth can induce transformations in climatic behavior that are chaotic over certain domains. Clearly the oscillatory celestial events, as illustrated in Figure 3, cannot, by themselves, account for the climatic behavior presented in Figure 2. In other words there may be two entirely different domains, a stable one like the holocene, and a chaotic one, just before the holocene. In addition, exotic celestial events, like the collision with the asteroid, 65 million years ago, can induce major singularities and flip the biosphere into a different domain (see Alvarez

[17] There was also a very brief ice age about 8,200 years before the present.

[18] See Hays et al. (1976) for a discussion of the work of Milutin Milankovitch who hypothesised that these "celestial" oscillations affected climate.

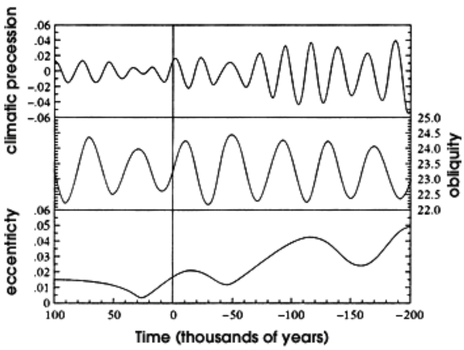


Figure 3. Oscillations in precession, obliquity and eccentricity

et al. 1980).[19]

It is increasingly understood that the dynamics of the geosphere and biosphere interact through multiple feedback mechanisms. The melting of the ice caps resulting from a temperature change modifies their albedo, reflecting less heat energy, further raising world temperature, increasing oceanic volume, affecting forest evapotranspiration as well as the global algae populations. The oceanic conveyor (and thus the Gulf Stream) can, and has, shut down. Methane can be liberated from deep ocean domains and from land, due to the decay of pemafrost. Cloud formations may change as the weather system is transformed, and intense families of hurricanes spawned in the oceans. All these possible changes are deeply chaotic because they involve fundamental transformations in the nature of the balance between our civilization, the oceans, the land and the atmosphere.

It is now well established that even relatively small changes in climate, over the last few thousand years, have had profound effects on our civilization, the *anthrosphere.*[20] Over the longer run of 100K years, our rapid evolution was the consequence of the chaotic climate prior to the holocene. The population growth from about 6 million, at 12K years ago to over 6 billion now is due, of course, to the spread of agriculture, but this was possible only because of a relatively stable climate.[21]

We have only recently realized that population growth and economic activity have induced links from the anthrosphere *to* the biosphere and geosphere. In fact it is now believed that these effects have been present since the beginning of agriculture about 12K years ago, but the relative stability of the holocene obscured this connection. It

[19] See also Benton (2003) for the much more severe Permian mass extinction about 250 million years ago. It is believed that extensive volcanic activity released enormous amounts of CO_2 and chlorine, causing a runaway greenhouse effect. The effect was further stimulated by the melting of frozen gas hydrates, and led to a global 6 degree Celsius rise in temperature. About 90 % of all species became extinct.

[20] See Fagan (1999, 2008) and Diamond (2005) on the Medieval Warm (800CE to 1300CE) and the Little Ice Age (1300 to 1850CE).

[21] World population growth rate increased from about 0.07 % 12K years ago to about 0.08 % 2K years ago to about 0.4 % in 1650. The "Malthusian barrier" was broken about 1950 with a growth rate of about 1.6 % (Kremer 1993).

is precisely because small changes can bring about a qualitatively different system of climate behavior, that we now fear that human activity may be be sufficient to "force" the biosphere through a singularity into a "hot zone."[22]

5. Concluding remarks

While GE may assert the existence of a general full-employment equilibrium, recent events seem to support the thesis presented here that economic behavior in our sophisticated markets may also induce complex or chaotic singularities in the flow of the economy. Indeed, it has dawned on us that these lurches from one crisis to another make it even more difficult to see how to plan for the future. If the onset of climate change induces the kind of chaos that occurred prior to the holocene, then we can expect economic hurricanes in the future. More to the point, before we hit a climatic singularity, there may occur totally unexpected eventualities, such as Malthusian crashes, or Katrina events. For this reason, the future we face exhibits the kind of fundamental uncertainty that Keynes emphasized.

It can be argued that the degree of uncertainty is so pronounced that we should plan for the future with extreme risk aversion (see Stern 2007; Rockström et al. 2009).[23] The global downturn, has led to severe disagreement about how to attempt to deal with climate change at the international level. It was only because of pressure from President Obama that the Copenhagen Accord was agreed to, in December 2009, by the United States together with four key emerging economies—China, Brazil, India and South Africa.

The UN Climate Change Conference in Cancun, ended on 11 December, 2010, with a declaration that it had adopted:

> … a balanced package of decisions that set all governments more firmly on the path towards a low-emissions future and support enhanced action on climate change in the developing world.

However, for further success on this issue, it is necessary to obtain agreement from the rapidly developing polities of Brazil, China and India. This will prove difficult. The relative economic stability of the past was maintained by the dominance of the United States. This period seems to have come to an end, and it may well be that without such hegemony, political and economic instability will be exacerbated.

To preserve democracy, Keynes believed that government intervention to control market volatility was the answer, coupled with the preservation of the free market in commodities.[24] But as ever, to constrain or regulate a market, it is necessary to control

[22] Metaphorically speaking, it would be like passing through a black hole into a totally different universe. The point is that the portal to the singularity would be chaotic. Indeed it has been suggested that our behavior may have brought the Holocene to an end, and we should note this by calling the new world the *Anthropocene*.

[23] This uncertainty stems essentially from the very limited horizon of predictability that we can reasonably impose on the interaction of the anthrosphere and climate.

[24] Both Keynes and Hayek believed that the free market in commodities was conducive to both efficiency and liberty.

assets sufficient to do the job, and the scale of these required assets depends on the size of the market and its inherent volatility. The decades long growth and globalization of the international economy means that the assets used for control must be of the order of many trillions of dollars. The United States does not control sufficient assets.

Schumpeter was sanguine about the consequences of market volatility. As he wrote:

> This process of Creative Destruction is the essential fact about capitalism. It is what capitalism consists in and what every capitalist concern has got to live in .... It must be seen in its role in the perennial gale of creative destruction. (Schumpeter 1942)

If the volatility of the market is no more than a cyclic phenomenon, then we can agree with Schumpeter. Minsky, a student of Schumpeter, was much less sanguine. While accepting Schumpeter's view of the transformative role of technology, he feared the consequences of financial chaos.

In fact, it seems that the globalization and transformation of the world economy in the last few decades has created much more complex feedback mechanisms in the world political economy. It is this increased complexity in the international system that has made it more susceptible to belief cascades, and to the possibility of singularity.

In a sense, our own hubris has brought this on ourselves. If we can no longer trust the market to behave in a fairly stable fashion, then we have to understand it better, in order to regulate it, or partially control it. At the same time however, we also face the possibility of climatic chaos, generated by the additional complexity of our own behavior affecting an already subtle dynamical system.

We face a quandary of uncertainty, since we neither understand the Anthropocene that we have created, nor the way in which it is affected by the biosphere and climate. This global quandary creates many localized quandaries about how to proceed in the short and medium term, not the least of which concerns the question of debt.[25]

Although President Obama seems aware of the quandary, he faces a divided Congress, and a Senate, conservative in its policy preferences, because of its use of a supermajoritarian voting rule. It would seem that facing the quandary of the future will depend on our ability to better understand the global economy that we have created. A high degree of risk aversion would seem like a good first step. But to do this requires concerted and cooperative action by all the major powers, including at a minimum, the United States, the European Union and China. An appreciation of the failure of our theories about economic equilibrium and an acknowledgement of fundamental uncertainty and chaos may help us proceed with caution.

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[25] Ferguson (2010) suggests that the American Empire, like earlier ones, may collapse in a chaotic fashion. The total U.S. federal debt is a concern. It increased from $5 trillion in 1992 to $7 trillion (about 70 % of GDP) in 2000 to $17 trillion (about 116 % of GDP) in 2010.

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