Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability

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Abstract

Since 1990 extensive funds have been spent on research in climate change. Although Earth Sciences, including climatology and hydrology, have benefited significantly, progress has proved incommensurate with the effort and funds, perhaps because these disciplines were perceived as "tools" subservient to the needs of the climate change enterprise rather than autonomous sciences. At the same time, research was misleadingly focused more on the "symptom", i.e. the emission of greenhouse gases, than on the "illness", i.e. the unsustainability of fossil fuel-based energy production. Unless energy saving and use of renewable resources become the norm, there is a real risk of severe socioeconomic crisis in the not-too-distant future. A framework for drastic paradigm change is needed, in which water plays a central role, due to its unique link to all forms of renewable energy, from production (hydro and wave power) to storage (for time-varying wind and solar sources), to biofuel production (irrigation). The extended role of water should be considered in parallel to its other uses, domestic, agricultural and industrial. Hydrology, the science of water on Earth, must move towards this new paradigm by radically rethinking its fundamentals, which are unjustifiably trapped in the 19th-century myths of deterministic theories and the zeal to eliminate uncertainty. Guidance is offered by modern statistical and quantum physics, which reveal the intrinsic character of uncertainty/entropy in nature, thus advancing towards a new understanding and modelling of physical processes, which is central to the effective use of renewable energy and water resources.

Only the small secrets need to be protected. The big ones are kept secret by public incredulity.
(attributed to Marshall McLuhan)

1. Climate and climate change impacts

Since 1990, major funds of the order of billions of euro have been spent in Europe and worldwide on research into projected climate change, its impacts, and emerging vulnerabilities. Earth sciences including climatology and hydrology have played a central role in this scene and benefited significantly. Technological advances in satellite observations and supercomputing have also been beneficial to these scientific disciplines. On the other hand, scientific progress has been arguably incommensurate to the effort and funds spent, perhaps because these disciplines have been perceived as "tools" subservient to the needs of the climate change enterprise rather than autonomous sciences. Despite generous funds, the targets set have not been achieved. Uncertainties in projections of future climate change have not lessened substantially in past decades (Roe & Baker, 2007). The value added by the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC, 2007) to that of the Third Assessment Report (TAR; IPCC, 2001) is, in effect, marginal. According to IPCC AR4, "A major advance of this assessment of climate change projections compared with the TAR is the large number of simulations available from a broader range of models. Taken together with additional information from observations, these provide a quantitative basis for estimating likelihoods for many aspects of future climate change." We maintain that a large number of simulations and a broad number of models without validated results is not necessarily scientific progress and could even be regression, if not combined with sound scientific thinking, free from "political" goals and financial objectives. Interestingly, the "additional information from observations" in the period between the two reports does not really support IPCC's conclusions. According to data presented by the Climatic Research Unit (CRU), the global temperature was stable in 2002-2005 and had a slight decreasing trend since then; i.e., the last years were cooler than about 10 years ago, and the highest global temperatures were recorded 11 years ago, in 1998 (Fig. 1).

One should also keep in mind that according to IPCC AR4 (Randall et al., 2007) general circulation models (GCM) have better predictive capacity for *temperature* than for other climatic variables (e.g. *precipitation*) and their quantitative estimates of future climate are particularly credible at *continental scales and above*. Hence, the fact that the historical evolution of *temperature* at the *global* scale resists GCM predictions may also indicate that the predictive capacity of GCMs for other variables and scales is even poorer.

Despite this recognized lower predictive capacity of GCMs for precipitation (Randall et al., 2007), hydrologists have not put into question the GCM future rainfall projections but they use them as if they were credible. A recent investigation (Koutsoyiannis et al., 2008) showed that the credibility of GCM projections at the local scale is questionable even for temperature (see Fig. 2). Applying hydrological models and using as input data the GCM outputs for rainfall, hydrologists have attempted to predict the impact of climate change on freshwater (Kundzewicz et al., 2007) and particularly surface water (runoff) on regional scales. However, the changes predicted may be too small in comparison to the natural variability and uncertainty of runoff, which has been underestimated by current mainstream hydrology. For, hydrologists and climatologists have not assimilated Hurst's (1951) discovery (based on the long records of the Nile) of the behaviour known as the Hurst phenomenon or Joseph effect, scaling behaviour, long-term persistence, long-range dependence, long memory, and Hurst-Kolmogorov dynamics (where the latter name aims to give proper credit to Kolmogorov's (1940) invention of the mathematical model of this behaviour some ten years earlier than Hurst's study). This behaviour has been verified in most long geophysical data records (Koutsoyiannis & Montanari, 2007) and implies dramatically high variability and uncertainty of hydroclimatic processes (Koutsoyiannis, 2003, 2006b; see also Fig. 7). Thus, changes to runoff even larger than those produced and reported in IPCC AR4 would have been obtained by stochastic methods admitting stationarity along with long-term persistence (Koutsoyiannis et al., 2007). As in climate research, the recent progress in water sciences and their interface with climate has been minimal. This is indicated by the fact that new research targets set by IPCC AR4 (Kundzewicz et al., 2008) are the same as the old ones: to improve understanding and quantitative estimation of climate change impacts on freshwater resources and their management, to reduce uncertainty, etc.

Furthermore, the current "climate" in the environmental scientific community, which favours (almost fanatical) ideological views of scientific issues, is genuinely becoming an issue of concern. Scientists arguing against "orthodox" and established "beyond doubt" views on the climate are often mistreated (and examples unfortunately abound). This non-scientific "climate" is at odds with the basis of scientific inquiry and puts its credibility at risk. Scientific progress presupposes diversity, rather than dominance of a single group or idea. Falsification of current research trends is a likely possibility (cf. Miller, 2007) and history teaches that, sooner or later, myths collapse (cf. the "predecessor" myth of "global cooling", which prevailed in the 1970s; Gwynne, 1975; Ponte, 1976).

2. Sustainability, energy and water

Sustainability has been a highly promoted principle in the last two decades (Brundtland & World Commission on Environment and Development, 1987) and significant efforts have been made to embed it into several aspects of natural resources management and environmental preservation. For example, the number of recent papers indexed in Web of Science with either of the words “sustainability” or “sustainable” in their topic exceeds 45 000, out of which about 7 000 appeared in the last year. Given that the notion of sustainability has been often associated with economic growth, the current severe economic crisis may indicate that growth is an illusionary goal for sustainability. In other words, an exponential economic growth, associated with increasingly greedy consumption, could not be sustained on the long run on a planet with finite resources.

In particular, given that global economy is dominated by the energy sector, which, in turn, is dominated by oil and fossil fuels that are naturally unsustainable (finite rather than renewable), the whole enterprise is illusive. Inevitably, the unsustainability of energy management will become the core problem of the next decades and will span all aspects of life, economy, society, demography and science. IPCC has underrated this problem giving emphasis to CO_2 emissions, as if fossil fuel reserves were bottomless; IPCC scenarios (IPCC, 2000), and hence results, are dated by more than a decade. Recent developments in terms of oil production and oil price for the last 12 years, for which detailed data are readily available, are depicted in Fig. 3. The data indicate a stagnancy of oil production since 2005 (at around 31 billion barrels per year), despite the increase in demand, and an almost ten-fold increase in price since 1998 (the abrupt drop of prices in the last quarter of 2008 due to the economical crisis was not enough to downshift the mean annual price in 2008). These may support the plausibility of the Peak Oil hypothesis (Hubbert, 1956, 1982; Grove, 1974; Kerr & Service, 2005; van der Veen, 2006). Recent opinions reviewed in *Science* (Kerr & Service, 2005) and official reports (Hirsch, 2005) locate the time of peak for oil production within the next 20 years. The Peak Oil hypothesis, first made in 1949 by M. King Hubbert (regarded by many as the father of geophysics; US National Research Council, 1991), claims that the fossil fuel era of energy production would be short lived. According to this hypothesis, the critical time is not located at the end of the exploitation (running out) of fossil fuels but at the peak. Even after taking into account alternative sources of fossil fuels (coal-to-oil, tar sands, etc), and related extraction technology development, the fact that the fossil fuels era will come to an end is inescapable and its implications on global economy and demography may be profound (some view these implications as catastrophic, e.g. Duncan, 2001, 2005/2006). To address this emerging problem, there is a growing recognition that adaptation will require substantial energy saving and development of renewable energy sources (see e.g. Ediger et al., 2007). The argument against our continuing dependence on fossil fuels is further supported by the realisation that widespread burning of fossil fuels damages the biosphere and presents increasing economic and security problems (Smil, 2005, 2006).

The intense and unsustainable use of fossil fuels was the background of the explosive population growth in the 20th century (from 1.65 billion in 1900 to 6.6 billion currently). Food production to sustain this population absolutely depends on energy use (Pfeiffer, 2004). Cheap energy and the implied change of social and economic conditions resulted in sprawling urbanization with increasing environmental impacts and consequences (Vlachos and Braga, 2001). All in all, increased human population, economic development, and energy exploitation, have had global environmental effects, which are so prominent that geologists coined the term "Anthropocene" to refer to a new geological epoch, successor of Holocene, dominated by human activity (Zalasiewicz et al., 2008).

It is then puzzling that the ambiguous term "climate change" has dominated the scientific and popular vocabulary over the more defendable terms of "environmental change" and "demographic change" (Fig. 4). This is not purely a semantic issue: more importantly, energy-related problems have not been positioned at the heart of scientific, technological research and, instead, CO_2 emissions, a by-product ("symptom") of the unsustainable energy policies and practices, have been given a primary focus.

The importance of energy issues and their linkages to climate have recently started to be explored (cf. the Panel Discussion on "Climate Changes and Energy Challenges" of the 2008 Council for the Lindau Nobel Laureate Meetings, 2008[1]). However "climate change" is still regarded as the primary research objective, to which other objectives should be aligned. For example, the Specific Programme for Energy under the Seventh Framework Programme for Research and Technological Development of the European Union has the objective "to address the pressing challenges of security of supply and climate change" (European

[1] The panel discussion held in the framework of the 2008 Meeting of Nobel Laureates at Lindau on Physics was available online at the web addresses that we indicate in Koutsoyiannis et al. (2008d, p. S1967); however,

Commission, 2005). Science and technology currently invests more effort to study and remedy the "symptoms" of a major "illness", than on trying to treat the "illness" itself. Unfortunately, this approach is misleading, obscuring real cause and effect, and thus cannot be effective on the long run. The role of science is to deal with the true causes of problems, to lead developments and provide society with the ability to react promptly (before a crisis appears) and in an informed way. In this case, science should point out that the "therapy" for the "illness", lies with the replacement of finite, fossil fuel-based energy sources with sustainable, renewable sources, which will also remedy the "symptoms".

Renewable energy sources, including hydropower, wind, wave, tidal and biofuel energy, are all based on solar energy. The latter has the largest, by orders of magnitude, intensity of all renewable sources (Smil, 2005, 2006). The amount of solar energy reaching Earth in only one hour is equivalent to the current energy use for all human activities in one year (460 EJ = 460×10^{18} J; Crabtree & Lewis, 2007). The transformation of renewable sources into usable energy spans human history and modern devices converting natural energy to electricity have a long history already: hydropower and wind turbines are in use since 1890 and photovoltaic cells since 1960 (even earlier for non-commercial use). In recent years, significant technological developments have improved the efficiency and reduced the cost of these energy sources (Kerr & Service, 2005; Lewis & Crabtree, 2005; Crabtree & Lewis, 2007; Schiermeier et al., 2008) and their improvement continues at a growing pace. We can now regard all renewable energies as technologically, commercially and politically proven (Scheer, 2006). Some regard nuclear energy as a viable alternative, also characterizing it as "clean" or even "green", but this can hardly be convincing. According to Smil (2005, 2006) nuclear fission remains a flawed and highly uncertain choice, and nuclear fusion should not be even included among realistic options.

Contrary to fossil fuels, which gave us the luxury of a fully controllable and deterministically manageable energy production, with the flip of a switch, renewable energies are uncertain, often unavailable at the time of demand and incompliant with the specifications of demand. For example, wind and solar energy are highly variable, dependent on atmospheric and climatic conditions and unpredictable. However, hydroelectric energy, if combined with water storage in reservoirs, proves to be an exception because it allows

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regrettably, the material is no longer available online for the public (Christian Rapp, Council for the Lindau Nobel Laureate Meetings, Communications and Organisation – personal communication).

regulation of production and, even more importantly, energy storage. This energy storage potential can be used in combination with other renewable energy sources, such as wind turbines or photovoltaic cells helping to balance supply with demand. In their state of the art review, Crabtree & Lewis (2007) classify the cost effective storage of electricity well beyond any present technology, failing to mention the storage potential provided by water. Indeed, electricity is easy to transport but difficult to store, while water is exactly the opposite. This characteristic can be exploited (with due consideration to issues related to electricity grid configuration) by pumped storage: pumping water to an upstream location consuming available energy, which will be retrieved later as hydropower. This is a proven technology, with efficiencies surpassing 90%. Importantly, both forms of hydroelectric energy production, direct and through pumped storage, do not consume water; only convert its dynamic energy and thus water itself can then be used for other purposes. In addition, production of biofuels is also related to water but in a consumptive manner, since plants use and evaporate water in their photosynthetic energy production. Finally, all of the above are inherently dependent upon climatic and weather conditions, in contrast to fossil fuels.

Due to its unique characteristics among all renewable resources, i.e. its ease of storage, the high efficiency in energy conversion, and its relationship with the biosphere, water is going to play a principal, integrating and regulating role in this future energy scene. In this role, water is not only the medium of hydroelectric energy generation but also the regulating medium of all renewable energies through storage. Obviously, to undertake this role, water reservoirs are needed, which have been criticized for their environmental impacts, and sometimes characterized as “unsustainable”. While such environmental concerns legitimately trigger technological progress to resolve existing problems, and demand attention to preserve and enhance ecosystems, they should not be a barrier to the exploitation of water’s role in sustainable energy production through hydraulic projects and hydropower (see also Klemes, 2007).

3. Hydrology, uncertainty and risk

It follows from the previous discussion that a future technological landscape, where natural elements such as water, wind, sunshine, and plants are the sources of energy, with water in an additional integrative and regulating role, becomes very plausible and desirable. This extended role of water should be considered in parallel to its traditional uses: domestic, agricultural and industrial. Hydrology, the science of water on the Earth, and its interface with atmospheric sciences and energy technologies, should necessarily take an enhanced role in this new paradigm.

Engineering hydrologists understood early that the design of engineering projects based on deterministic approaches would largely be a hopeless task and appreciated the usefulness of probabilistic approaches. Yet, during the last two decades hydrology, following other geophysical disciplines, changed perspective and invested its hopes in deterministic descriptions and models. The trend towards the so-called "physically based models" (Abbott et al., 1986) allowing for detailed descriptions of spatial variations (a reductionist approach) signifies this change of perspective. The hidden assumption behind these is that modern computational means would eventually allow the full description of the detailed physics of the hydrological cycle using mechanistic model structures and "first principles", i.e. Newton's laws and their particular formulations in fluid mechanics (Navier-Stokes equations). However, from the first steps of these modelling attempts, it was argued that there are fundamental problems in their application for practical prediction in hydrology, which result from limitations of the model equations relative to a heterogeneous reality (Beven, 1989). According to Beven (1993), application of such models "is more an exercise in prophecy than prediction" and attention should focus on the value of data in conditioning such hydrological "prophecies". For a recent validation of this argument see Makropoulos et al. (2008), where a simplified lumped modelling approach provided the best predictive capacity for a complex modelling problem while a physically based approach provided the worst.

Nonetheless, the aspiration of achieving powerful deterministic modelling through a reductionist approach still dominates. The relative myth, promising models that will not need data for calibration and will sharply reduce uncertainty, has been "officially" formulated in the formative steps of the IAHS Decade on Prediction in Ungauged Basins (PUB; Sivapalan et al., 2003; see Fig 5) and states that the "cacophony" of theories and models existing prior to 2003, which need calibration, will be replaced by a "melodious harmony" of new innovative models based on increased understanding that do not require calibration. In this way, "convergence of a plurality of approaches towards the single objective of reducing predictive uncertainty, with a single-minded focus" is predicted. While to date (seventh year of the 2003-2012 decade) the PUB movement has engaged hydrologists world-wide and has made significant progress, the stated philosophical aspirations have not been approached. A more pragmatic setting would acknowledge the necessity of data, both for understanding and modelling, and the indispensability of measurements, whether these measurements are from the catchment of study or from other catchments with some similarity. Quoting K. Beven from Tchiguirinskaia et al. (2008), “we need those better measurements, and not necessarily better models”, “the answer is in the data and a new theory alone would not be enough” and “the focus in the future should be oriented on new and more accurate measurement techniques”. Thus, contrasting data and calibration with understanding and investing hopes in a sharp reduction of uncertainty in natural phenomena is a flawed scientific direction that should be abandoned.

In essence, this scientific direction reflects a general philosophical and scientific view of the 19th century, in which determinism is almighty and uncertainty is a subjective element that could be eliminated (or sharply reduced) with better understanding of mechanisms that are regarded to follow a “sharp” causality. This general view fails to recognize the radical advances in physics, mathematics and natural sciences of the 20th century such as: (a) dynamical systems theory, which has shown that uncertainty can emerge even from pure, simple and fully known deterministic (chaotic) dynamics, and cannot be eliminated; (b) quantum theory, which has emphasized the intrinsic character of uncertainty and the necessity of probability in the description of nature; (c) statistical physics, which used the probabilistic concept of entropy (which is nothing other than a quantified measure of uncertainty defined within the probability theory) to explain fundamental physical laws (most notably the Second Law of Thermodynamics), thus leading to a new understanding of natural behaviours and to powerful predictions of macroscopic phenomena; (d) developments in mathematical logic, and particularly Gödel’s incompleteness theorem, which challenged the almightiness of deduction (inference by mathematical proof) thus paving the road to inductive inference; (e) developments in numerical mathematics, which highlighted the effectiveness of stochastic methods in solving even purely deterministic problems, such as numerical integration in high-dimensional spaces (where a Monte Carlo method is more accurate than a classical deterministic method, and thus preferable for numerical integration, in spaces with more than four dimensions) and global optimization of non-convex functions (where stochastic techniques, e.g. evolutionary algorithms or simulated annealing, are in effect the only feasible solution in complex problems that involve many local optima); and (f) advances in evolutionary biology which emphasize the importance of stochasticity (e.g. in selection and mutation procedures and in environmental changes) as a driver of evolution.

Several modern thinkers (Ravetz, 1986; Funtowicz & Ravetz, 1993; Casti, 1994; Rescher, 1995; Peterson, 1998; Laskar, 1999; Chaitin, 2005; Taleb, 2007) point to randomness and uncertainty as intrinsic to science, nature and life. Most of these developments are relevant to hydrological sciences and thereby to renewable resources management. Lessons from dynamical systems and quantum theory could be used to recognize the structural (objective rather than subjective) limitations in predictions. The notion of entropy from statistical physics could be used to understand hydrological processes and explain properties regarded as peculiarities (Koutsoyiannis, 2005a,b, 2006a). Combined with the notion of incompleteness (at least as a metaphor), the entropy concept could be used to understand the impossibility of hydrological modelling without data, and the appreciation of the necessity of induction, i.e. model calibration (see illustration in Fig. 6). The developments in numerical mathematics could help to understand the power and indispensability of stochastic methods in solving practical problems, from model fitting to resource management, whether the problem formulation is deterministic or stochastic. All the above support a conclusion that, when dealing with complex real-world systems, deterministic thinking and mechanistic analogues may become obstacles in understanding. In contrast, understanding of natural behaviours necessarily relies on probability (as is the case, for instance, in thermodynamics). Thus, clichés that deterministic approaches are the only ones to provide insight and to describe cause-effect relationships, whereas stochastic approaches provide just blind data-driven models, are mistaken and should be abandoned.

Uncertainty necessarily results in risk, but under-appreciation of uncertainty results in even higher risk. Current modelling philosophies, e.g. using deterministic hydrological models linked to the outputs of deterministic climate models, underrate the structural character of uncertainty and may increase risk, by promoting misleading ideas of a predictable distant future and of dispensability of data. Likewise, earlier modelling philosophies putting deterministic upper limits to natural phenomena, e.g. the concept of probable maximum precipitation (see Koutsoyiannis, 1999), and promising risk-free constructions or practices, are equally misleading and ultimately non-scientific.

The key scientific tools able to describe and quantify uncertainty and risk rely on probability. Probability has also given the tools to make induction (inference from data) as objective as possible (Jaynes, 2003). Hydrology has never been divorced from probability theory. On the contrary, owing to its strong technological and engineering roots, hydrology has always had a close relationship with uncertainty description and management. Perhaps it is the scientific discipline that has studied uncertainty in Nature more and in greater depth than any other discipline. However, the state of the art in probabilistic, statistical and stochastic concepts in hydrology is far from satisfactory. This is mainly because these concepts have been based, to a large extent, on the classical statistical paradigm rather than on the study of natural behaviours (cf. Fig. 7). A coin tossed several times, thus making a repeatable experiment, is the prototype of thinking in classical probability. Two characteristic properties in this experiment are the constancy of the coin properties at all times and the independence of the different outcomes; both support the notion of repeatability of experiments. In natural systems, these properties are invalidated. There can be no repeatability: the system evolution or trajectory in time is unique. There is no reason that the system properties remain unchanged in time: an event that has 50:50 odds to occur now may not have the same odds next year. And there is no independence: every occurrence affects all future occurrences. In some hydrological tasks, time dependence has been admitted but its common representation by typical Markov-type stochastic models is insufficient or inappropriate (Koutsoyiannis, 2003). For, the Hurst-Kolmogorov behaviour discussed above, which has been detected to be omnipresent in long time series of hydrological processes and seems to be consistent with the principle of maximum entropy (Koutsoyiannis, 2005b), is not represented by classical Markov-type models and is completely unaccounted for in classical statistics.

Therefore, we claim that hydrology must move toward a new paradigm by radically rethinking its fundamentals, which are unjustifiably trapped in the deterministic myth of the 19th century and the illusive promise of uncertainty elimination, and in the simplistic way of treating uncertainty, typical of the second half of the 20th century. Guidance is offered by modern statistical and quantum physics, revealing the intrinsic character of uncertainty and the dominance of entropy in nature, thus advancing towards a new understanding of physical processes and, thereby, a new paradigm for thinking about and managing renewable natural resources.

4. Conclusions

Summarizing the above discourse and extracting the key future implications, we can state that:

1. The climate will most probably change, as it has consistently done during the 4.5-billion-year history of Earth. Current climate research cannot predict what this change will be. A scientific approach to future climate exploration is feasible only in terms of a probabilistic description.

2. The sustainability target would be better served by abandoning the misleading notion of "climate change", and reframing the issues around the (more defendable) notions of environmental and demographic change, both being influenced by the unsustainable production and use of energy.

3. Carbon dioxide emissions are a "symptom" tightly linked to the fossil fuel era of energy production, which is approaching its end.

4. A "therapy" that can ensure socio-economic and environmental sustainability should necessarily focus on integrated, renewable resource management and energy production and use. Within this framework, water has a new integrative and regulating role to play.

5. The variability of these natural sources of energy and the resulting uncertainty in all scales, will necessitate new theoretical and methodological approaches to allow for the design and management of the engineered systems required for their exploitation. This presupposes deconstruction of myths currently dominating the climate and hydrological sciences, and development of a new hydroclimatic theory that will recognize the structural character of uncertainty in these processes and will build upon it.

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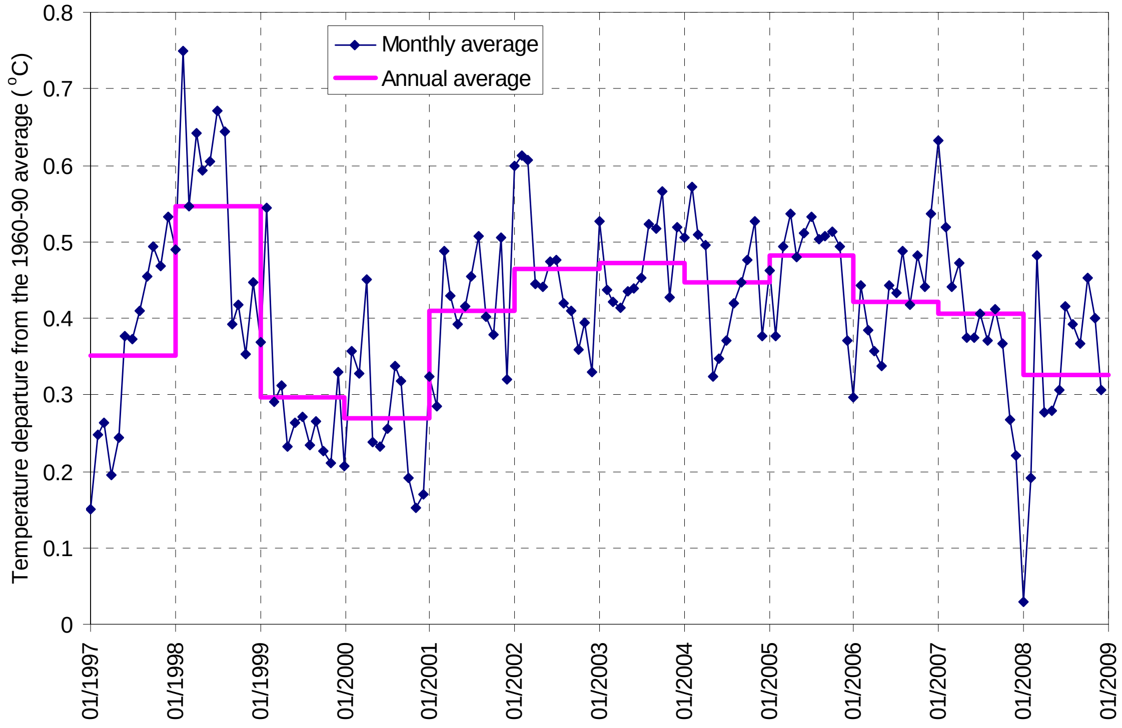


Figure 1: Evolution of the global temperature in the last twelve years (data from CRU; combined land and marine temperatures; www.cru.uea.ac.uk/cru/data/temperature/hadcrut3gl.txt).

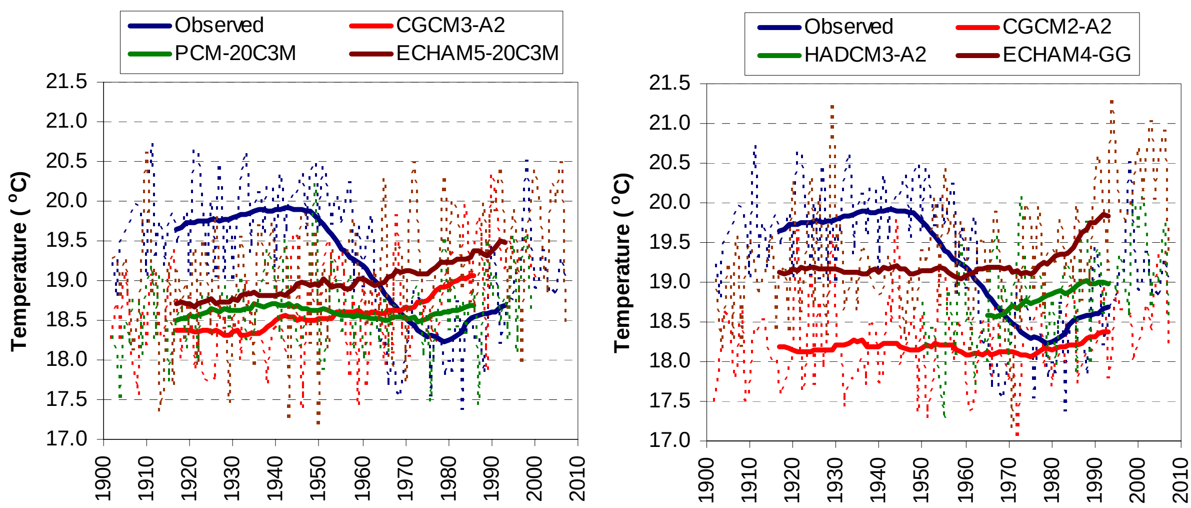


Figure 2: Plots of observed and GCM modelled annual (doted lines) and 30-year moving average (continuous lines) temperature time series at Albany, USA (left AR4 models; right TAR models; reproduction of the original Fig. 5 from Koutsoyiannis et al., 2008, with kind permission of IAHS Press).

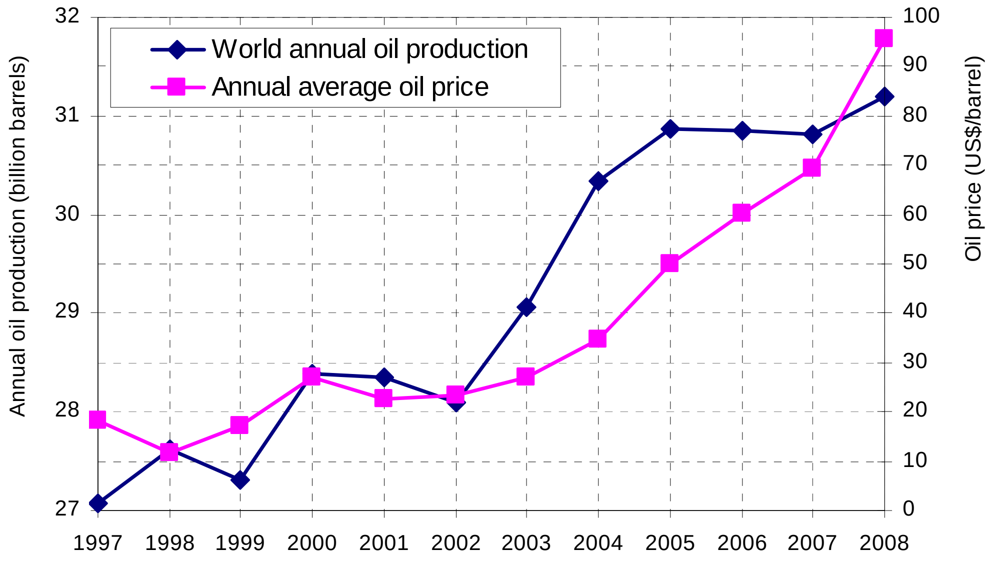


Figure 3: Evolution of world annual oil production and oil price in the last twelve years (data from www.eia.doe.gov/emeu/ipsr/ www.eia.doe.gov/steo; and tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm).

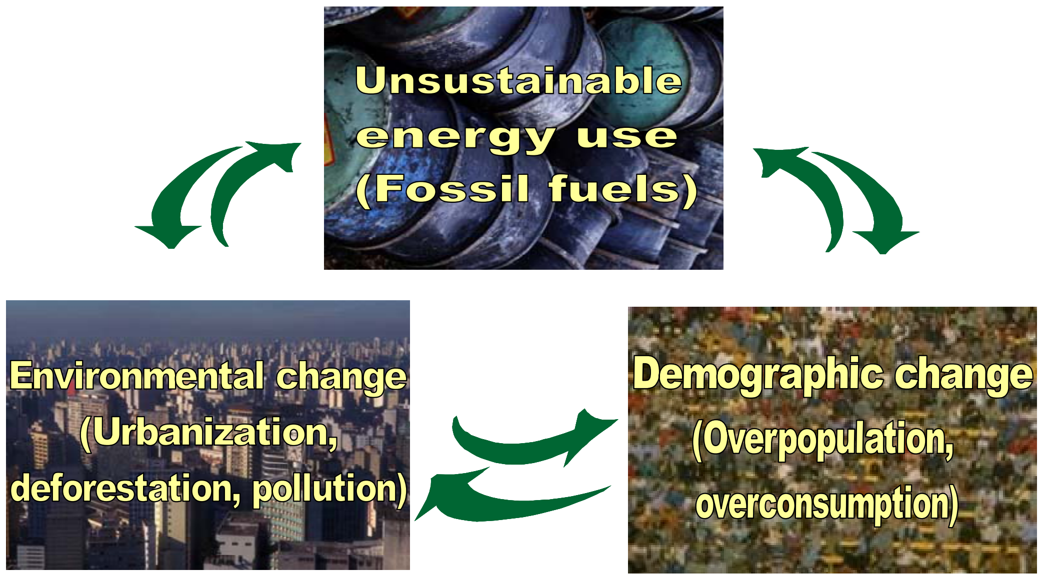
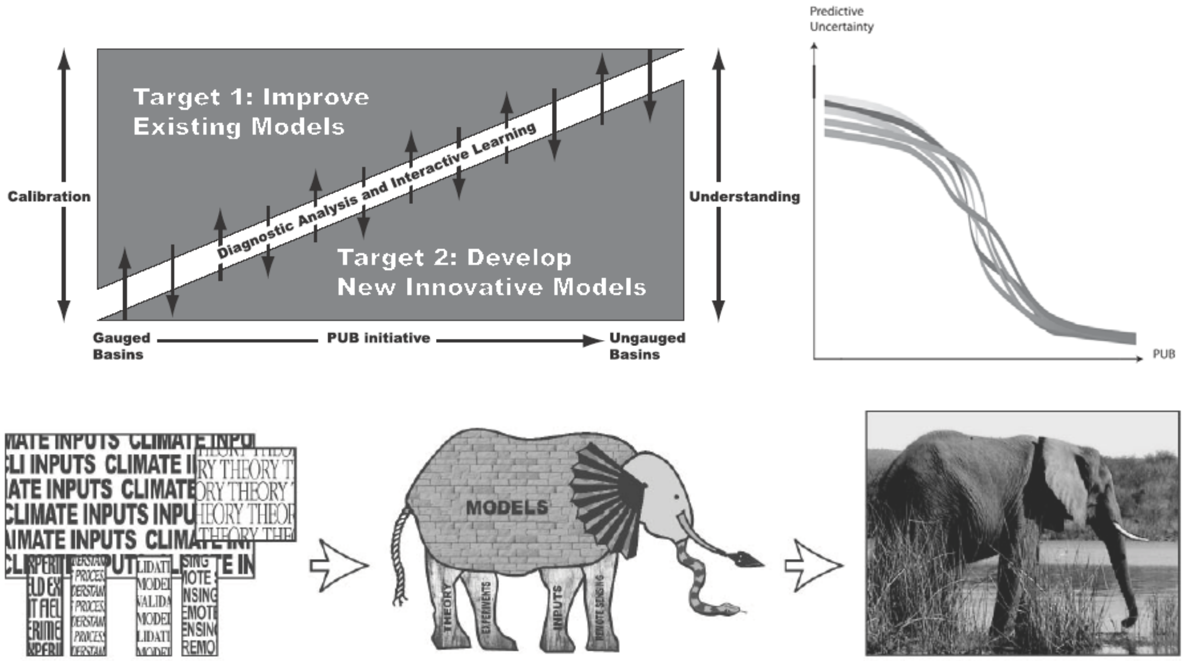


Figure 4:. Schematic of the anthropogenic vicious circle of the 20th century. Despite scapegoating climate change, major environmental problems are caused by overpopulation and overconsumption including increased urban, industrial and irrigation water consumption and energy production from fossil fuels to sustain increased food production needs and current lifestyle. Modern agricultural practices, urban agglomerations and industrial activities pollute water resources and, in turn, water pollution decreases availability of drinking water and increases energy needs for treatment (source: Koutsoyiannis, 2008).



From a cacophony of noises to a harmonious melody

Figure 5: Reproduction of three figures from Sivapalan et al. (2003) (with kind permission of IAHS Press) with the following original captions: (Upper left; original Fig. 3) Targeted research—towards paradigm change—from models based on calibration to models based on increased understanding. (Upper right; original Fig. 5) Convergence of a plurality of approaches towards the single objective of “reducing predictive uncertainty”, with a single-minded focus. (Lower; original Fig. 9) PUB will undoubtedly lead to a greater harmony of scientific activities, and increased prospects for real scientific breakthroughs.

Figure 6: Demonstration of the potential for deduction and induction in hydrological systems: (Left) A system of many water molecules. Despite random positions and momenta of molecules, fundamental macroscopic (statistical) quantities of a huge number of molecules can be easily produced using deduction (e.g., by maximizing entropy in an analytical manner), which is possible because the system (in gaseous or liquid state) consists of precisely identical molecules (or, in case of a mixture, of a few types of identical molecules). (Middle) Topographical relief and the vegetation pattern forming the background (boundary) of a surface hydrological system (part of the Acheloos River basin at Mesounta, Greece; image from Google Earth). All system components are unique (nothing is identical to each other) and, thus, pure deduction cannot be effective and should be replaced by induction, which requires data (measurements) to model the processes and estimate the parameters. Even the statistical description of the relief and vegetation is much more complex than pure randomness, due to the rich patterns at all scales, rather than a monotonous repetition of a (random) motto, thus pointing to the need of entropy maximization at multiple scales. (Right) Three-dimensional detail of a hydrological system (credit: Lessovaia et al., 2008). Different soil and rock fabrics, multiple scale porosity, irregular macropores, faults and cracks with their irregular patterns, combined with two phase flows, irregular wetting fronts, etc., form an even more complex system, for which pure deduction is impossible.

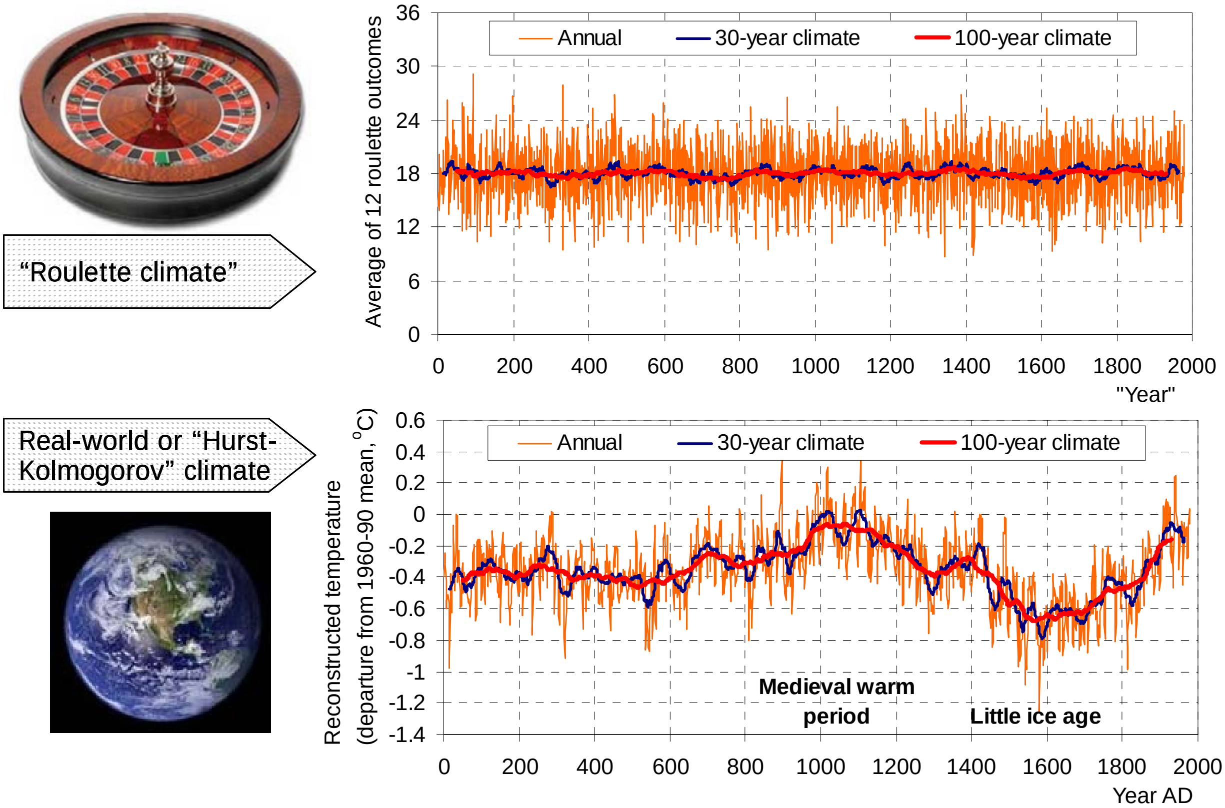


Figure 7: Demonstration of the differences between the classical statistical paradigm, represented by an ideal roulette wheel (random simulation), and a real world process, represented by a time series of the Northern Hemisphere temperature (assuming that it can be approximated by the proxy data from Moberg et al., 2005). The differences mainly involve the behaviour of local averages. The real-world processes exhibit long excursions from global mean (suggestive of multi-scale patterns as in the photos in Fig. 6), which characterise a Hurst-Kolmogorov behaviour (adapted from Koutsoyiannis and Cohn, 2008).