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HESS Opinions “Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability”

D. Koutsoyiannis[1], **C. Makropoulos**[1], **A. Langousis**[2], **S. Baki**[1], **A. Efstratiadis**[1], **A. Christofides**[1], **G. Karavokiros**[1], and **N. Mamassis**[1]

[1]Department of Water Resources and Environment, School of Civil Engineering, National Technical University of Athens, Greece
[2]Department of Civil and Environmental Engineering, MIT, Cambridge, Mass., USA

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Correspondence to: D. Koutsoyiannis (dk@itia.ntua.gr)

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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. There is a real risk of severe socioeconomic crisis in the not-too-distant future, unless energy saving and use of renewables become the norm. A framework for drastic change is needed, in which water plays a central role, due to its unique link to all forms of renewable energy, from production (hydro, wave) to storage (for time-varying wind and solar sources), to biofuel production (irrigation). The expanded role of water should be considered in parallel to usual roles in domestic, agricultural and industrial use. Hydrology, the science of water on Earth, must reinvent itself within this new paradigm and radically rethink its fundaments, 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, revealing the intrinsic character of uncertainty/entropy in nature, thus advancing towards a new understanding and modelling of physical processes, which is fundamental for the effective use of renewable energy and water resources.

1 Climate and climate research

Since 1990, major funds adding up to 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, the 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 and 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 of "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 in 2006 and 2007; thus, the warmest year in the last ten-year period is the first one (1998) (Fig. 1). This has been viewed by some as a sign that "global warming takes a break" (www.livescience.com/environment/060921_oceans_cooling.html). One should however 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*. Thus, the fact that the historical evolution of *temperature* at the *global* scale resists GCM predictions, may 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 and generally used them to predict future evolution of water resources availability as if they were credible (a recent investigation indicated that they are not credible 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 Nile) of the phenomenon named after him (also known as the Joseph effect, scaling behaviour, long-term persistence, long-range dependence, long memory), which is verified in most long geophysical data records (Koutsoyiannis and Montanari, 2007) and implies dramatically high variability and uncertainty into 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 statistical 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, favouring (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" does not guarantee a sustainable future for science and its impact on the society, because, even in scientific progress, sustainability presupposes diversity, rather than dominance of a single species, group, or idea. Falsification of current research trends is a likely possibility (cf. Miller, 2007) and history teaches that, sooner or later, myths collapse. A characteristic (and alarmingly relevant) example is the myth of “global cooling” that was prevailing in 1970s (Gwynne, 1975; Ponte, 1976) and whose collapse was followed by “global warming”.

2 Sustainability, energy and water

Sustainability has been a highly promoted principle in the last two decades (Brundtland and World Commission on Environment and Development, 1987) and significant efforts have been put to embed it into several aspects of natural resources management and environment preservation. For example, the number of recent papers indexed in Web of Science with the word “sustainability” in their topic amounts to about 12 000. However, 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. The very recent developments in terms of oil, i.e. the stagnancy of oil production since 2005, despite the increase of demand, and the almost ten-fold increase of the price in the last decade (Fig. 3), indicate the plausibility of the Peak Oil hypothesis (Hubbert, 1956, 1982; Grove, 1974; Kerr and Service, 2005; van der Veen, 2006). Recent opinions reviewed in *Science* (Kerr and 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 fuel (coal-to-oil, tar sands, etc.), and related extraction technology development, the fact that the fossil fuels era is coming to an end is inescapable and its implications on global economy and demography (Duncan, 2001, 2005–2006) may be profound. 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 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 (Vlachos and Braga, 2001), with increasing environmental impacts and consequences. 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. 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 in the long run. The role of science is to deal with the true cause of problems before a crisis appears, leading developments and providing society with the ability to react promptly 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 biofuels, are all based on solar energy. The amount of solar energy should not be underestimated (Crabtree and Lewis, 2007): solar energy reaching Earth in one hour only is equivalent to the current energy use for all human activities in one year (460 EJ=460×10^{18} J). 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 and Service, 2005; Lewis and Crabtree, 2005; Crabtree and Lewis, 2007) and their improvement continues at a growing pace.

Water is going to play a principal role in this future energy scene: it is the medium of hydroelectric energy generation but is also closely related to wind energy, photovoltaic energy and biofuel energy. As wind and solar energy are highly variable, dependent on atmospheric and climatic conditions, unpredictable and often unavailable at the time of demand, their exploitation should be necessarily combined with technologies for energy storage. In their state of the art review, Crabtree and Lewis (2007) classify the cost effective storage of electricity well beyond any present technology. Admittedly, electricity is easy to transport but difficult to store, while water is exactly the opposite. This 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.

3 Hydrology, uncertainty and risk

It follows therefore 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 expanded role of water should be considered in parallel to traditional roles, in drinking water, agricultural production and industrial use. 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 projections is largely 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” allowing for spatial variations (Abbott et al., 1986) 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 pure deterministic modelling still dominates. The relative myth has been "officially" formulated in the framework 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 (the beginning of the PUB initiative), 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.

This direction in hydrology 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 with better understanding of mechanisms that are regarded to follow a "sharp" causality. This general view fails to recognize the radical advances in physics and mathematics 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 purely 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; and (d) Gödel's incompleteness theorem in mathematical logic, which challenged the almightiness of deduction (inference by mathematical proof) thus paving the road to inductive inference. Several modern thinkers (Ravetz, 1986; Funtowicz and 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 hence to renewable resources

management. Lessons from the dynamical systems 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); and the incompleteness result could be used, at least as a metaphor, to understand the impossibility of hydrological modelling without data, and the appreciation of the necessity of induction, i.e. model calibration (Fig. 6).

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 the illusive idea of a predictable distant future. 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. Hydrology has never been divorced from probability theory, but 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 in 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 or scaling behaviour mentioned above, which seems to be consistent with the principle of maximum entropy (Koutsoyiannis, 2005b) and has been detected to be omnipresent in long time series of hydrological processes, is not represented by classical Markov-type models and is completely unaccounted for in classical statistics.

Therefore we claim that hydrology must reinvent itself within a new paradigm and radically rethink its fundaments, which are unjustifiably trapped in the deterministic myth of the 19th century and the illusive promise of uncertainty elimination. 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 with it, 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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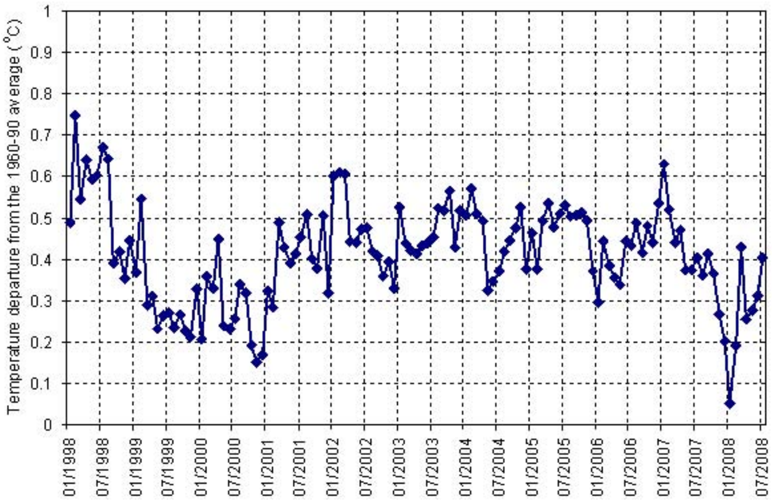


Fig. 1. Evolution of the global temperature in the last ten years (data from CRU; combined land and marine temperatures; www.cru.uea.ac.uk/cru/data/temperature/hadcrut3gl.txt).

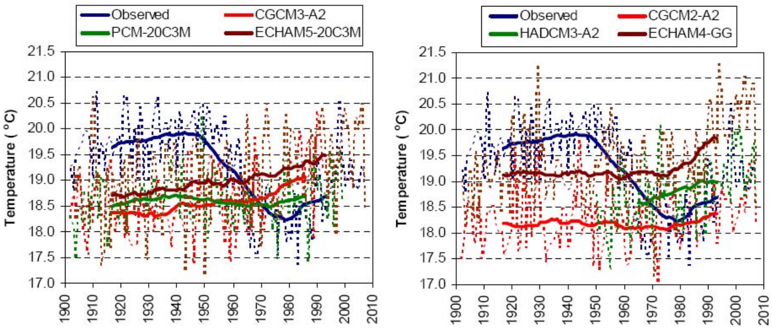


Fig. 2. Plots of observed and GCM modelled annual (doted lines) and 30-year moving average (continuous lines) temperature time series at Albany, USA (left AR4 models; right TAR models; reproduction of the original Fig. 5 from Koutsoyiannis et al., 2008, with kind permission of IAHS Press).

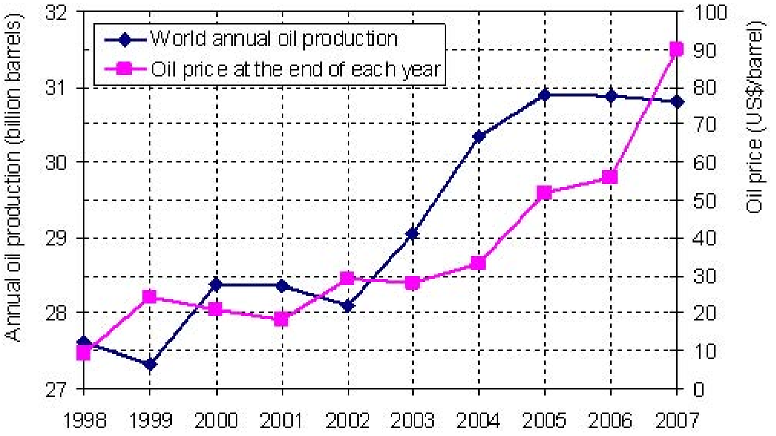


Fig. 3. Evolution of world annual oil production and oil price in the last ten years (data from www.eia.doe.gov/emeu/ipsr/ and tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm).

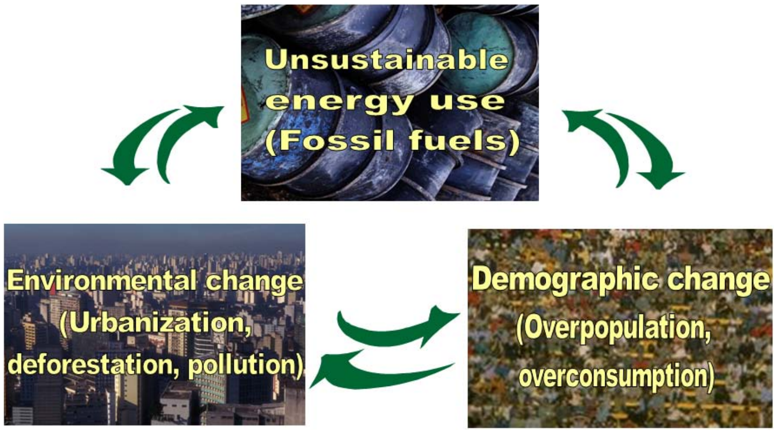
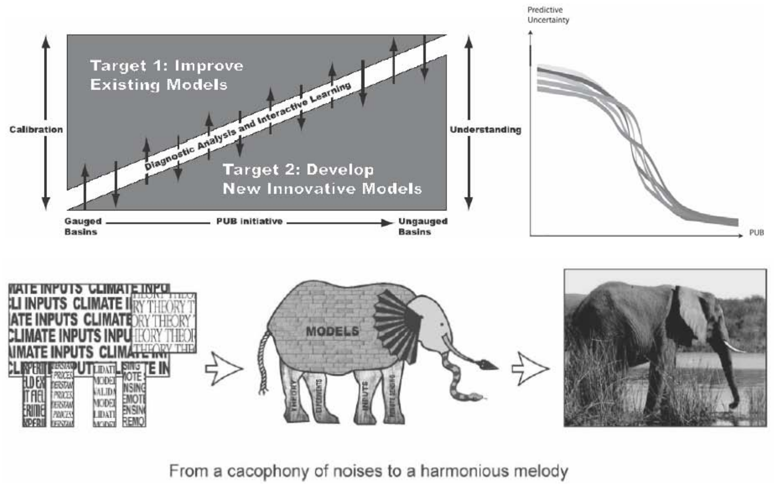


Fig. 4. Schematic of the anthropogenic vicious circle of the 20th century. Despite scapegoating climate change, major environmental problems are caused by overpopulation and overconsumption including increased urban, industrial and irrigation water consumption and energy production from fossil fuels 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

Fig. 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.

Fig. 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) A topographical relief and the vegetation 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 parameters. Even the statistical description of the relief and vegetation is much more complex than pure randomness, due to rich patterns on 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.

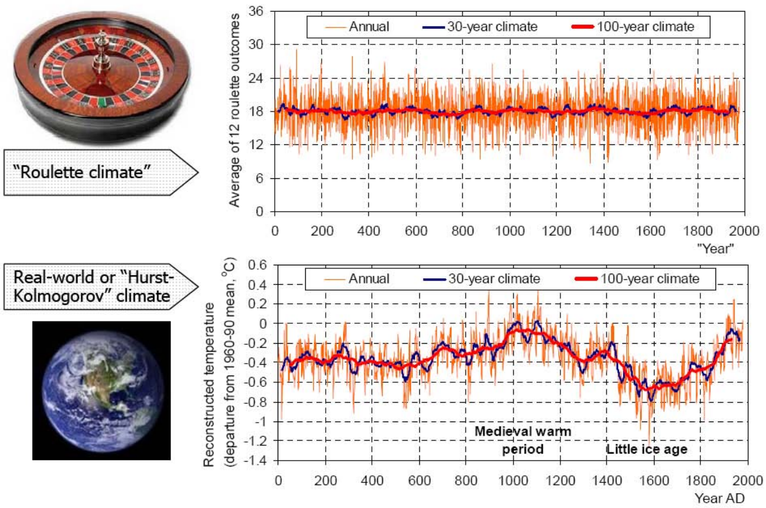


Fig. 7. Demonstration of the differences between the classical statistical paradigm, represented by an ideal roulette wheel (random simulation), and a real world process, represented by a time series of the Northern Hemisphere temperature (assuming that it can be approximated by the proxy data from Moberg 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).