REPLY to "Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research"

Water and climate projections

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So far as the laws of mathematics refer to reality, they are not certain. And so far as they are certain, they do not refer to reality.
(Albert Einstein, quoted in Newman, 1956)

As the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.
(Zadeh, 1965)

INTRODUCTION

We thank Koutsoyiannis *et al*. (2009) for their interest in our paper, Kundzewicz *et al*. (2008). However, the discussion essay by Koutsoyiannis *et al*. (2009), being considerably longer than our short communication, covers a much broader ground, extending far beyond our modest aim of providing a compact interpretation of the findings from the water chapter of the IPCC Fourth Assessment Report (AR4) (Kundzewicz *et al*., 2007), focusing on projections for the future.

In fact, in most of their contribution, Koutsoyiannis *et al.* (2009) do not really discuss the contents of our paper (Kundzewicz *et al*., 2008). Rather, they devote ample room to explicit discussion of climate change matters, from a healthy-doubt/skeptic stance. In particular, they criticize the IPCC assessment process and the scientific methods of the climate change research community, but their criticisms are often based on a misleading conflation of the science with media hype, as well as a faulty understanding of both the process and methods. This aspect of their paper is unfortunate, because it conveys a distorted picture of the state of the science and the contribution of collaborations between hydrologists and other members of the science community to understanding the linkages between climate change and water resources.

Despite its divisive tone, the Koutsoyiannis *et al*. (2009) paper makes a number of valid points that are fully consistent with material to be found in Kundzewicz *et al*. (2007, 2008). In several instances, we can broadly agree with the discussers (though the devil is often in the details). For example, they note that water resources around the world are subject to many stresses related to "unsustainable overexploitation". The significance of such stresses for the ability of human communities and natural systems to cope with the impacts of climate change is a point that is articulated forcefully in both Kundzewicz *et al*. (2007, 2008) documents. In addition, both they and we seek better integration of climate and hydrological modelling, and express the longing for better observational data. Many arguments of Koutsoyiannis *et al*. (2009) are common sense and have been indeed recognized in climate and climate impact modelling. In some cases we have a different opinion and find it necessary to react. This reply thus seeks to clarify areas of both agreement and disagreement.

CLIMATE *vs* WATER SCIENTISTS

One of our principal areas of disagreement is with the way the discussers write about the IPCC (Intergovernmental Panel on Climate Change), even though one of them was, in fact, a Coordinating Lead Author of the hydrology and water resources chapter in an earlier IPCC assessment (Shiklomanov & Lins, 1990). The discussers suggest that the IPCC aims at reducing greenhouse gas emissions, "*regardless of the ultimate validity of the IPCC model predictions*". Their statement that the IPCC is politically-oriented conveys an insinuation of intentional bias. Such a charge cannot be supported by the evidence. The fact that the first letter of the acronym IPCC stands for "Intergovernmental" reflects the reality that the 192 national governments who are signatories to the UN Framework Convention on Climate Change have established this process for conducting impartial and fully-vetted reviews of the literature pertaining to all aspects of climate change science. While that indicates a certain policy dimension, it is ludicrous to suppose that all of those governments would seek to bias results in the same direction. In fact, the open and transparent process by which the governments review all IPCC assessment documents serves as an important check on any source of bias. The IPCC process is an international effort to seek, where possible, agreement between all the countries involved, in the constructive spirit of consensus building. In its activities, the IPCC follows the mantra: to be policy-relevant but not policy-prescriptive. The IPCC neither conducts nor funds scientific research (even if some nations may consider IPCC assessments in the research-funding process). What the IPCC does is to "*assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation*" (www.ipcc.ch/about/index.htm). The authors of Kundzewicz *et al*. (2008), along with many hundreds of other scientists involved in the process, perceive their work for IPCC as a kind of honorary, and unpaid, community service. It is a sacrifice, but also a reason for satisfaction and pride. The paper we have produced does not represent all the personal opinions or views of the authors, but it certainly reflects a common opinion and view of the groups and the reviewers that have participated during the process.

The authors of the IPCC AR4 water chapter (Kundzewicz *et al*., 2007) and of the paper subject to discussion (Kundzewicz *et al*., 2008) are a multi-national group of bona-fide scientists without any political agenda. Striving for objectivity, we critically assessed thousands of recent publications on different freshwater-related aspects of the climate change impacts, of adaptation and vulnerabilities and proposed a prioritization of the findings with respect to their importance, likelihood and confidence. The results of our assessment, in the form of draft material, were subject to a very intense, three-stage, scientific review process involving a large pool (hundreds) of international experts so that a wide variety of available information, opinions and hypotheses was represented. The mature drafts were sent to governments of all countries, seeking their opinions, which were taken into consideration. Among the government reviewers (national scientists nominated by governments) of the IPCC AR4 water chapter was at least one of the co-authors of Koutsoyiannis *et al*. (2009). The IPCC AR water chapter contains a sober assessment of available peer-reviewed material. A moderating effect of the involvement of governments in the process can be noted. Positive impacts of climate change were included, even if the negative ones were found to outweigh them.

The non-scientific allegations by Koutsoyiannis *et al*. (2009) jumble the research, politics and media communities into the same category, conveying a distorted and inaccurate impression that IPCC authors seek to satisfy the interests of funding agencies by providing a collection of alarmist stories. We are aware of the numerous over-interpretations on the part of some journalists, with hysterical newspaper headlines, such as: "our planet is dying and we, people, are guilty" or "only 13 years remain to save the planet", but such exaggerated statements have nothing to do with the IPCC; all the material in the IPCC chapter is based on published, peer-reviewed material.

We fully agree with Koutsoyiannis *et al*. (2009) that "*science is a process for the pursuit of truth and that fidelity to this system should not be affected by other aims*". For two decades, the IPCC process has contributed intensively (even if indirectly, because it has not funded research) to improvement of the understanding and development of climate change science and climate change impact science. By reviewing the material related to climate change and freshwater, Kundzewicz *et al*. (2007, 2008) tried to make a step towards better understanding and interpretation.

Koutsoyiannis *et al*. (2009) expressed the opinion that "*bidirectional interaction between the experiences of the climatological and hydrological communities should be sought, thereby ensuring that the overall results are consistent with established principles and practices in the water resources community*", and further stated that the "*key role for hydrological sciences is currently not adequately reflected in climate research*". Even though interdisciplinary cooperation between hydrologists and climate scientists certainly shows room for improvement (like any other interdisciplinary cooperation), there is no doubt that climate scientists have recently made considerable progress in understanding the essential role of water at the land surface for climate projections. The land-surface schemes of climate models have advanced considerably. Furthermore, climate scientists now better understand the requirements of hydrologists with respect to climate data and climate change information. Several research programmes/projects in different countries (and notably international projects within the framework programmes of the European Union, e.g. WATCH and ADAM in the Sixth EU Framework Programme) focus on truly multidisciplinary cooperation of scientists (in climatology, hydrology, economics and other social sciences) to advance adaptation of water resources management to climate change.

DATA ARE ESSENTIAL

By no means did Kundzewicz *et al*. (2008) deny the value of data. We explicitly stated: "*Progress in understanding is conditioned by adequate availability of observation data, which calls for enhancement of monitoring endeavours worldwide, addressing the challenges posed by projected climate change to freshwater resources and reversing the tendency of shrinking observation networks*". The lack of information is notorious, and critical, in particular in developing countries, and in some topical areas, such as water quality: "*Adequate data are crucial to understanding observed changes and to improving models, which can be used for future projections. If only short hydrometric records are available, the full extent of natural variability can be understated and detection studies confounded. Data on water use, water quality, groundwater, sediment transport and water-related systems (e.g. aquatic ecosystems) are even less available*." (Kundzewicz *et al*., 2008).

Kundzewicz *et al.* (2007, 2008) stated that, traditionally, it has been conveniently assumed that the natural water resource base is constant, and hydrological design rules have been based on the assumptions of stationary hydrology, tantamount to the principle that the (recent) past is the key to the future. This assumption is not correct. The term "key" can be understood literally—the key that was used to open a door in the past cannot open the door now. The lock has changed and the key simply does not work. The normal (up to now) practice of using the stationary statistics of observed discharge (and other) data for the design of storage reservoirs, flood protection or water supply systems with longer lifetimes is no longer adequate, given the strong recent nonstationarity of climate (cf. Milly *et al.*, 2008).

The iconic data set of direct observations of atmospheric CO_2 concentrations collected for over 50 years now at Mauna Loa (Fig. 1), and many other data sets, leave no doubt that gases responsible for warming (so-called greenhouse gases) are becoming more abundant in the atmosphere.

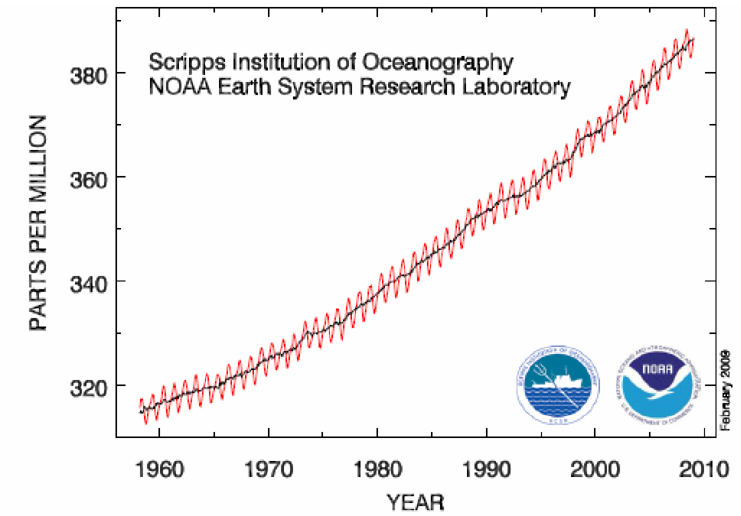


Fig. 1 Atmospheric concentration of carbon dioxide at Mauna Loa Observatory (Hawaii, USA). http://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2_data_mlo.pdf.

ARE MODELS TRUSTWORTHY?

There is no such thing as "IPCC models", and by using such shorthand to describe collectively the models included in the IPCC assessment reports (i.e. possibly all existing climate models), Koutsoyiannis *et al.* (2009) mislead the readership. Rather, the IPCC provides a comparative assessment of future climate projections and historical climate simulations by the major, independent climate modelling efforts around the world.

Koutsoyiannis *et al.* (2008, 2009) showed that the current generation of climate models reproduced aspects of past climate (at the local scale) poorly, and concluded that "predictions" based on these models are therefore unreliable. There are two flaws with this argument. First, climate models are not designed to reproduce accurately local variations in climate from year to year; they are designed to simulate broad features of the climate system and its variability. They will not reproduce exactly observed past variability if they are not guided with accurate, time-varying boundary conditions (such as time series of observed sea-surface temperatures), or if they do not represent exactly all the processes influencing year-to-year variability. Climate models which are driven with realistic sets of variable boundary conditions, such as observed sea-surface temperatures, are much more able to reproduce observed patterns of climatic variability (Hurrell *et al.*, 2006). The second flaw, however, is more fundamental. Climate models are not used to make predictions of the future; they are used to make plausible projections of possible futures, based on assumptions about, for example, future emissions patterns. There is therefore a fundamental difference between a weather forecast and a projection of possible future climate change. Projections can be plausible, even if the models used to make them do not reproduce exactly all features of past variability, so long as the models produce broadly realistic representations of climate. It is because climate models do not make predictions of future climate that impacts (and adaptation) assessments should be based on a range of climate projections (and this is why Kundzewicz *et al*., 2007, show results from several climate models and, when describing results from individual model runs, identify the model used).

General circulation models (GCMs), i.e. the principal tool for making projections into the future, are designed to give a broad, large-scale view of the evolution of global climate in response to changes in both natural and anthropogenic forcing variables. Limited computing resources require that they be run at coarse spatial resolution. Thus, it is well-known that they are not able to reproduce the fine-scale features of local climates, such as the effects of mountains on the location of precipitation. They are nonetheless useful in simulating the broad-scale features of possible futures, corresponding to assumed socio-economic scenarios (driving greenhouse gas emissions and carbon dioxide sequestration).

The ability of climate models to simulate past climate fluctuations is limited by the availability of data on volcanic activity, solar output and other natural sources of variability, but there has been considerable progress in palaeoclimatology that is unlocking the secrets of the past fluctuations in Greenland's climate, as shown in Fig. 3 of Koutsoyiannis *et al*. (2009). These fluctuations were not purely random—they had causes, which ongoing research is helping to explain (Hegerl *et al*., 2007a). As phrased by Karl & Trenberth (2003): "*global climate models ... are fully coupled, mathematical, computer-based models of the physics, chemistry, and biology of the atmosphere, land surface, oceans, and cryosphere and their interactions with each other and with the sun and other influences (such as volcanic eruptions)*." Karl & Trenberth (2003) suggest that "*through clever use of palaeoclimate data, our ability to reconstruct past forcing should improve, but it is unlikely to provide the regional detail necessary that comes from long-term direct measurements*."

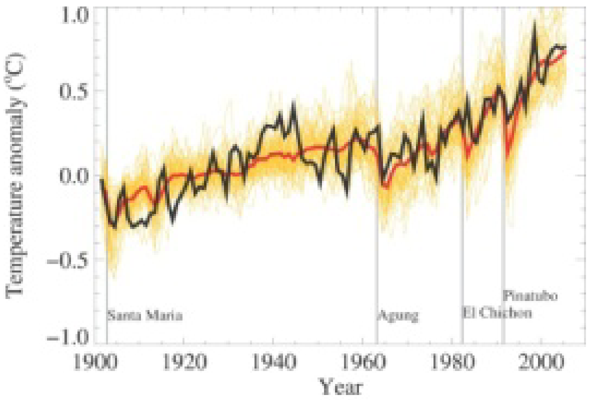
Climate has varied naturally many times in the past, but today's circumstances are unique because of human influence on the composition of the atmosphere (via increased emission and reduced sequestration of greenhouse gases) during the "Anthropocene", cf. Crutzen & Stoermer (2000). As a result of anthropogenic interference with the climate system, current climate anomalies are likely to exceed the bounds of natural variability. The climate research community knows full well that important natural sources of climate variability, such as volcanic eruptions, are not predictable. The climate of the future will be determined by both natural sources of variability and human-caused sources of change, such as the build-up of greenhouse gases in the atmosphere. They also know that natural variability means that we will likely see periods of cooling despite the underlying warming trend.

The hydrological models referred to in the IPCC reports have been validated (e.g. WaterGAP, see Döll *et al*., 2003). However, it is well known in hydrology that even a model that can simulate river discharge during the validation period quite well may still do it for the wrong reasons, and may not adequately simulate other variables such as evapotranspiration or groundwater recharge.

Despite the contrary claims of Koutsoyiannis *et al*. (2009), the climate models used to make projections have also been extensively validated, as described in the material on "Model evaluation" in Chapter 8 of the Working Group I AR4 Report (Randall *et al*., 2007). Climate models are much more complex than hydrological models, and many more output variables have to be validated concurrently. So, it would be rather arrogant to imply that climate modellers should learn from hydrological modellers about validation.

Figure 2 (from Hegerl *et al*., 2007b, after Stott *et al*., 2006) illustrates the climate change attribution, and the skill of global climate models, at the global scale. It compares global mean surface temperature anomalies relative to the control period (1901–1950), from observations and from AOGCM (Atmosphere–Ocean General Circulation Model) simulations forced with: (a) both

(a)



(b)

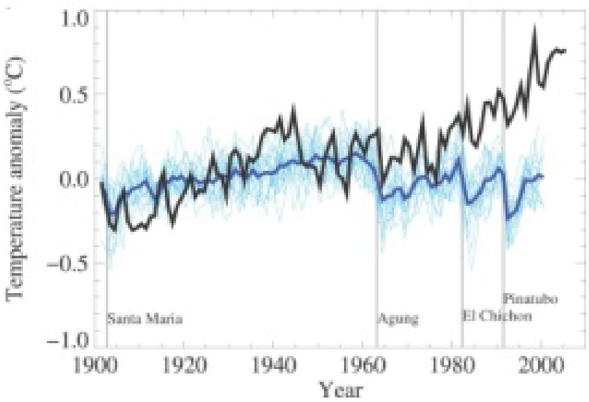


Fig. 2 Comparison between global mean surface temperature anomalies (°C) relative to the period 1901–1950, from observations (black) and AOGCM simulations forced with: (a) both anthropogenic and natural forcings, and (b) natural forcing only. Thick red and blue curves represent multi-model ensemble means, while individual model simulations are shown as thin yellow and blue curves. Source: Hegerl *et al*. (2007b), after Stott *et al*. (2006).

anthropogenic (increasing greenhouse gas emission and decreasing sequestration) and natural forcing (such as solar irradiance, volcanic eruptions), and (b) natural forcing only. Observed data are the Hadley Centre/Climatic Research Unit gridded surface temperature data set (HadCRUT3; see Brohan *et al*., 2006), While the model results in Fig. 2(a) are from 58 simulations produced by 14 models with both anthropogenic and natural forcings, and in Fig. 2(b) are from 19 simulations produced by five models with natural forcing only. The multi-model ensemble means are shown as a thick (red or blue) curve and individual simulations are shown as thin (yellow or blue) curves. Vertical grey lines indicate the timing of major volcanic events. Running models fed by natural forcing only, one cannot mimic the global warming observed since the 1950s. In fact, in response to natural forcing, the global temperature should not increase, but rather slightly decrease (Fig. 2(b)). However, if the models are fed by both natural and anthropogenic forcings, the temporal changes of global temperature are broadly mimicked (Fig. 2(a)). One can rightly state that there is still no perfect fit, but basic properties of the time series of temperature in the last 50 years or so are reconstructed reasonably well. Before 1950, the accuracy of the estimation of the global mean temperature from observations is not as good as in recent decades, and this also contributes to the discrepancy between modelled and observed values.

Koutsoyiannis *et al*. (2009) focus their attention on the principal climatic variable—temperature—which is represented in four out of five of their figures. Temperature is not a hydrological variable and was not dealt with in Kundzewicz *et al*. (2008). However, there is no doubt that, since temperature drives the hydrological cycle, interpretation of its variability and change is indeed of utmost importance to hydrological sciences.

We question the way that Koutsoyiannis *et al*. (2009) use some of these figures. For example, their Figure 2 conveys a misleading picture of global temperature trends by displaying only a short time-series plot of satellite-based estimates of lower-tropospheric temperature anomalies, ending with a low reading for 2008. The authors state that: "*... the most recent observations (2008) are very close to those at the beginning of the observational period (1979)*." This statement neglects the fact that satellites are only one form of observation, and that different estimation methods suggest different trends. A clearer long-term picture is provided by the instrumental surface temperature record, which indicates that, while calendar year 2008 was the coolest year since 2000, it was the ninth warmest year in the period of instrumental measurements, which extends back to 1880 (GISS, 2009).

Figure 3 of Koutsoyiannis *et al*. (2009) displays the well-documented record of dramatic temperature fluctuations recorded in Greenland ice cores, but their discussion leaves readers with the misguided impression that global climate is so highly variable by nature that we have little hope of understanding its evolution.

Contrary to allegations by Koutsoyiannis *et al*. (2009), Kundzewicz *et al*. (2008) do not assume that the GCM outputs provide a robust depiction of future climate. We stated that precipitation is not adequately simulated in present climate models, so that quantitative projections in river flow at the basin scale, relevant to water management, remain largely uncertain. We are aware of the existence of substantial uncertainty stemming from multiple sources, but the toolbox of projection-makers is modest.

Most essential hydrological cycles, which are considered to be relevant for the climate system, are included in the current climate models. The interactions between land and atmosphere are represented, including the detailed radiation budget and bio-geochemical processes, which are generally neglected in conventional hydrological models. The dependence of climate model output on soil moisture has been studied. Snow processes are also included, even if in a less complicated form than in dedicated "hydrological models" with an emphasis on snowmelt. However, the radiation budget, including the effect of aerosol deposition on the snow surface, compaction of snow-pack, and snow interception, is represented.

Poor seasonal weather forecasts are not surprising. Similarly unsurprising is the failure of the ungrounded forecasts for a possible record-low Arctic ice range in 2008, rightly ridiculed by Koutsoyiannis *et al*. (2009). Initial conditions play a dominant role for seasonal predictions of the climate system. However, the global warming simulations used for making long-term climate projections (Kundzewicz *et al*., 2007, 2008), i.e. for estimating the expected state of the weather several decades in the future, do not attempt to predict whether a specific summer, e.g. in 2099, will be wet or dry in a grid cell of interest, but try to predict changes in the statistics of climate variables.

It is not surprising that some areas of the world have experienced a long-term trend during the 20th century, the sign of which does not agree with the projected trend towards the end of the 21st century. Actually, there are places where the observed changes of annual precipitation during the latter half of the 20th century are in the opposite direction to those projected for the second half of the 21st century, and this has clear implications for river runoff. In glacierized basins, melting glaciers augment river flow, as compared to the control-period data with stable glaciers, but when the glaciers disappear, glacier-based augmentation of river runoff will cease to exist.

Koutsoyiannis *et al*. (2009) stated that Kundzewicz *et al*. (2008) "*appear to embrace the idea that ... uncertainty ... can be significantly reduced by increasing the complexity of models*." This is a wrong conclusion. We have no doubt that an increase in model complexity does not necessarily reduce uncertainty. As is well known in hydrology, complex models with many parameters may give a very good fit in the calibration stage, but may completely fail in the validation stage. However, improved data and improved understanding of the phenomena form a healthy basis for the reduction of uncertainty—"better" models need not be more complex.

Complexity at the micro-scale may turn into simplicity at the macro-scale. The process of transformation of precipitation into river runoff is complex and strongly nonlinear at the point scale. However, it may be approximated by a simple, linear, model (such as the IUH) at larger spatial scales.

Kundzewicz *et al.* (2008) do not imply that climate change will be the dominant factor influencing future water resources everywhere and at all time scales. What we declared is that the "*climate change is one of the multiple stressors for future water resources management*" (Kundzewicz *et al.*, 2007). We stated that "*These climate-driven hydrological changes will combine with other pressures on water resources, such as population growth, land-use change (e.g. urbanization, especially in coastal areas; deforestation), changes in life styles increasing water demand and environmental pollution, to challenge water management in the 21st century*." Which factors dominate will depend on the future changes of these drivers, the hydrological indicators considered, as well as on the location.

HURST FRAMEWORK—ONE SIZE FITS ALL?

Koutsoyiannis *et al.* (2009) present the Hurst phenomenon as an ignored revelation, whose broader use can revolutionize climate science and the science of climate impacts, and can solve many hydrological and water resources problems. The Hurst phenomenon (i.e. occurrence of a high value of the Hurst coefficient, $H > 0.5$) can indicate the possibility of long-term persistence and possible clustering in the data. The Hurst method is typically perceived as a statistical procedure and the Hurst phenomenon can arise from a variety of physical processes. Nowadays, there are various methodologies that may help incorporate additional information (e.g. the physical, process-relevant information and expert knowledge) into the modelling scheme, which help to incorporate useful physical ingredients into modelling rather than relying on purely time-series models, without physical backing.

Some authors of the discussed paper (Kundzewicz *et al.*, 2008) have worked on the Hurst phenomenon, and one of them received a doctorate for a work related to the Hurst effect (Şen, 1974). One possible approach could be the following: the Hurst approach represents long-term persistence, while short-term variability can be modelled by short-memory stochastic processes (Şen, 1974, 1979). It is well known that temperature series have long-term persistence and, therefore, they can be represented by the Hurst phenomenon (Şen, 1974). But the dominating component in the time series of future global temperature is expected to be the increasing greenhouse effect (via the rising atmospheric concentration of greenhouse gases).

However, using only statistical/stochastic approaches to characterize variations in some phenomena over time, we restrict our abilities and ignore knowledge of the processes and drivers of change. We know that the atmospheric concentrations of greenhouse gases are rising, thus strengthening the greenhouse effect. We also know that every major volcanic eruption yields a (short-lasting) global cooling. Further, we know, in statistical terms, the effect of ENSO phase on the global temperature and several regional variables.

The Hurst approach is a fine tool to explain the temporal variability of a time series of global mean temperature or annual precipitation at a point or a grid cell. However, by its nature, the approach is not capable of projecting future variations, as it does not incorporate understanding of the physical processes driving a time series. It does not account for the future change of essential system drivers (population, socio-economics, emissions, land use). There is a determinism hidden amidst strong and irregular variability, in addition to the Hurst approach, which is useful for representing the random part.

The empirical and statistical Hurst approach is not a one-size-fits-all solution, a magic cure for all maladies. But certainly, it is a useful addition to dynamic modelling including physical principles (mass, energy and momentum conservation).

Possibly, Koutsoyiannis *et al.* (2009) are right when they suggest including the idea of persistence in future IPCC assessments, especially when evaluating some adaptation options, e.g. searching for an optimal size of a reservoir. Conceptually, it is possible to construct statistically-based methodologies that can be used to help inform adaptation decisions, which do incorporate persistence; if such methods were developed and published, they would be reviewed in subsequent IPCC assessments.

CONCLUDING REMARKS

Koutsoyiannis *et al*. (2009) claim that climate is not changing due to human activities (climate is "naturally trendy": Cohn & Lins, 2005), and that climate models do not provide a credible basis for assessing possible future impacts. The first assertion is not supported by the evidence (as thoroughly reviewed by the IPCC (Hegerl *et al.*, 2007b), and we have demonstrated here that the second claim is also false. Climate models are not used to make predictions, but are used to make plausible projections of possible future change. The challenge for water management is to use this information on possible futures to help make adaptation decisions.

Koutsoyiannis *et al*. (2009) imply that the climate system is unpredictable, and so one should not waste time on hopeless projections. However, instead of accepting this stance and giving up the very idea of predictability, one can be more constructive and look into every major change in the observed time series of global temperature and try to explain it, trying to strengthen the interpretation of the deterministic behaviour of the time series of climate variables. We will never know the future of climate because human behaviour, and therefore greenhouse gas emissions, cannot be predicted. Nevertheless, scenarios of the future which present plausible futures of climate are necessary for supporting present-day decisions with respect to mitigation of and adaptation to climate change, e.g. in the water sector.

Water resources practitioners are used to dealing with the variability of water quantity and quality parameters, and they design reservoirs, irrigation schemes, water quality control structures and operating policies with uncertainty in mind. Researchers know how to predict the variability of the quantity and quality of water resources with models that use temperature and precipitation data as basic inputs. Their first challenge is to provide practitioners with quick-and-dirty estimates of an uncertainty increase due to climate change, based on the pragmatic use of available information and models. The second challenge is to improve the models. Dialogue is taking place between climate and water scientists, and between practitioners and researchers, and should be enhanced, in order to agree on priorities: firstly with respect to determining practical design parameters with available models and information; and secondly with respect to research for improving system understanding and model performance.

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