DISCUSSION of "The implications of projected climate change for freshwater resources and their management"*

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

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To predict something is to measure its probability. The Science of Prediction or Stochastics is therefore defined as the science of measuring as exactly as possible the probabilities of events so that in our decisions and actions we can always choose or follow that which seems to be better, more satisfactory, safer and more considered. In this alone consists all the wisdom of the Philosopher and the prudence of the Statesman.
(Jakob Bernoulli, *Ars Conjectandi*, 1684–1689, published in 1713; quoted from von Collani, 2006)

INTRODUCTION

Kundzewicz *et al.* (2008; herein referred to as KEA) summarize the key findings of the chapter "*Freshwater resources and their management*" (Ch. 3) of the Fourth Assessment Report (AR4) of Working Group II of the Intergovernmental Panel on Climate Change (IPCC), in which they were the lead authors (Kundzewicz *et al.*, 2007). They provide an extremely useful summary, given the importance of the theme and the laborious preparation of the report. As the authors state, the multi-disciplinary and multi-national authorship of the report, and a large pool of experts involved in a three-stage review process, ensure that a wide variety of available information, opinions and hypotheses was assessed. Indeed, given the complexity of climate, our incomplete knowledge of and the contradictions in many aspects of climate change, the presentation of different opinions and hypotheses is perhaps more important to the achievement of a balanced and complete perspective than the summarization of information. Thus, our discussion paper aims at complementing KEA by emphasizing certain significant points, and offering some additional key references from the literature.

Given the political implications of IPCC, particularly with respect to potentially adverse consequences of greenhouse gas emissions, one may understand the article's focus (as with most IPCC texts) on negative impacts of projected climate change, especially catastrophic events. Yet we think that the necessary balance is provided seemingly as an afterthought by the last three sentences of the article, which note that: (1) the impacts of climate change, and the most effective ways of adapting to change, depend on local conditions; (2) climate change is superimposed onto other pressures on water resources; and (3) little can be said about the implications of climate change for the availability of safe water for the most vulnerable. Indeed, these concluding sentences illustrate the difficulties in predicting the future of water resources, the complexity of water resources problems, the numerous factors affecting them, and the dominance of local conditions.

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All three of these points delineate the high uncertainty associated with the assessment of future availability of water resources in a possibly changed climate. In fact, hydrological experience suggests that the uncertainty affecting water resources assessment is extremely relevant, even when the meteorological forcing is observed and not predicted. KEA appear to embrace the idea that this uncertainty is epistemic rather than structural, that is, it can be significantly reduced by increasing the complexity of models. Their concurrence is indicated by the title and the content of the section *Research Needs—Reducing vs Managing Uncertainty*. However, we believe that the structural character of uncertainty in climatic and freshwater behaviour may have been underrated, and the magnitude of uncertainty may have been underestimated by IPCC, as will be discussed below.

The general impression from KEA is that the hydrological and freshwater group of IPCC followed a unidirectional approach by assuming that the General Circulation Model (GCM) outputs provided a robust depiction of future climate and by trying to assess how this future climate would impact freshwater resources. In addition, such an approach seems to assume that future climatic change is the dominant factor influencing future water resources. However, future climate is but one of a number of important factors that affect water quantity and quality (e.g. changes in population, land use, environmental regulation, technology, water demand, etc.) and, as noted by Lins & Stakhiv (1998), climate may have much less effect on water and water management over decadal and longer time scales than these other factors. In our opinion a deeper, 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. In the following sections of the paper we discuss the relevant role played by uncertainty in the assessment of future water resources and show how climate research could benefit from a more effective dialogue with the hydrological community at least on some aspects where hydrological experience has been substantial.

CONCEPTUALIZATION AND UNCERTAINTY OF CLIMATE AND THE HYDROLOGICAL CYCLE

Climate is conventionally defined as the long-term average of weather (e.g. temperature, cloudiness, precipitation; US National Research Council, 2005). This definition emphasizes the statistical basis of the concept of climate as well as the atmospheric domain of its application. On the other hand, and in contrast to weather that can be adequately described solely on the basis of atmospheric processes, climate cannot be described unless additional (i.e. non-atmospheric) natural processes are taken into account. This is because at climatic time and space scales, the processes within the atmosphere are affected, *inter alia*, by ocean circulation, albedo, the chemical composition of the atmosphere, and vegetation patterns. Thus, the climate system includes, in addition to the atmosphere, the land, the oceans, the cryosphere (ice-covered regions of the world), and the terrestrial and marine biospheres, as depicted in Fig. 1 (from US National Research Council, 2005). Also, solar and volcanic activity are critical external agents of the climate system, whereas water is an internal key regulator. Considering the prevailing definitions of hydrology (e.g. Ad Hoc Panel on Hydrology, 1962; US Committee on Opportunities in the Hydrological Sciences, 1992; Dingman, 1994), which emphasize its involvement in the terrestrial, oceanic and atmospheric compartments, and the physical and chemical processes accompanying the movement of water, one may easily conclude that hydrology should have a key role in all components of the climate system and in their mutual interaction. In this respect, Fig. 1, is incomplete as it does not explicitly mention hydrological processes, or even evaporation. Yet such a key role for hydrological sciences is currently not adequately reflected in climate research.

The huge complexity of the climate system implies uncertainty and limitations in predictability. Examples demonstrating the limits of predictability are many, even if we focus on the separate components of the climate system and deal with short prediction time horizons. For

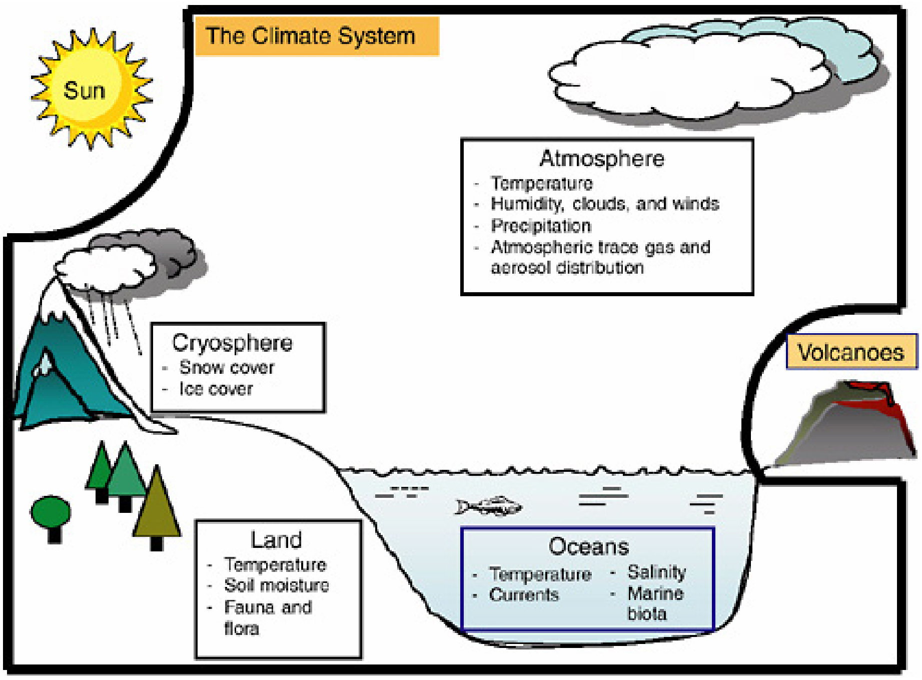

Fig. 1 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. [T]he Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (figure and caption from Figire 1-1 of US National Research Council, 2005; http://books.nap.edu/openbook.php?record_id=11175&page=12.)

instance, consider the cryosphere, for which, in June 2008, a number of organizations predicted that Arctic sea ice extent would be lower by the end of summer 2008 than it was in 2007, with some even speculating that the North Pole may be ice-free for the first time in history (Mehta, 2008). However, neither prediction has occurred. Also, despite climate modellers' emphasis on the cryosphere and their prediction that it will show the most dramatic effects of global warming, the reality is different from predictions in Antarctica, where the data indicate a slightly increasing trend of sea ice extent rather than the predicted reduction (data from the US National Snow and Ice Data Center, 2008). In addition to the huge internal complexity of the global climate system, we should consider the unpredictability of volcanic and solar activity which significantly affect climate, as well as technological and socio-economic conditions related to land-use change and the industrial consumption of hydrocarbons. Many experts opine that the economy cannot continue to be hydrocarbon-based. Furthermore, technological progress (e.g. in solar energy or hydrogen fusion) in long time horizons cannot be predicted. Finally, Hurst-Kolmogorov dynamics in climatic processes (see respective section below) is another factor that reduces predictability and emphasizes the structural character of uncertainty.

Uncertainty plays a significant role in the simulation of the hydrological cycle too. Numerous studies have proved the limitations of current hydrological models in providing a comprehensive picture of water resources availability, especially when groundwater plays a significant role. The above considerations motivate the doubt that hydrologists feel when dealing with predictions of water resources in the long term.

Within the context of the modelling of future climate and water resources availability, a potentially active contribution of the hydrological community relates to modelling philosophy and practice, and in particular to uncertainty assessment. It is current practice to assess the uncertainty of GCM predictions by using ensemble simulations. However, hydrologists well know that these techniques may be subjective and may capture only a fraction of the global uncertainty, especially in the presence of model structural uncertainty.

KEA indirectly point to the poor performance of GCMs with respect to hydrology when they state "*Precipitation, the principal input signal to freshwater systems, is not adequately simulated in present climate models*". In our opinion, what is feasible is the characterization (quantification) of future climatic uncertainty. The key to uncertainty characterization is provided by the data, rather than the models, which may underestimate uncertainty (Koutsoyiannis *et al.*, 2007).

We believe a deeper dialogue between climatologists and hydrologists would allow our communities to address better the problems related to uncertainty assessment and reduction when predicting the future availability of water resources. Predictions issued by climate models should be produced and evaluated coherently with the hydrologist's experience, given the importance of hydrological phenomena (mean hydrological regime, floods, droughts) in characterizing the climatic impacts and risks in an area.

THE IMPORTANCE OF DATA

Data are of primary importance within the hydrological community, which embraces the premise that hydrology (and geosciences) are by nature induction-based, rather than deduction-based and rely, therefore, to a greater extent on historical data as the key to the future (Koutsoyiannis *et al.*, 2009). KEA express a disbelief in the latter principle when they state: "*Traditionally, it has been conveniently assumed that the natural water resource base is constant, and hydrological design rules have been based on the assumption of stationary hydrology, tantamount to the principle that the past is the key to the future. Now, the validity of this principle is limited.*" On the other hand, they correctly state: "*Adequate data are crucial to understanding observed changes and to improve models*" and "*If only short hydrometric records are available, the full extent of natural variability can be understated and detection studies confounded.*"

We maintain that past data remain the key to the future for at least two reasons. The first is related to the indispensible utility of data in model building. Geophysical models, including climate and hydrological models, necessarily involve conceptualizations and parameterizations of the natural processes. Hence the need for data to calibrate models and also to validate them. The hydrological community is well aware of the importance of validation of models using a separate data set independent from that used in calibration (e.g. the split-sample technique, Klemeš, 1986). Validation is also necessary in uncertainty assessment (e.g. Montanari & Brath, 2004; Montanari, 2007). The IPCC models (i.e. GCMs reported by IPCC) were not subject to such validation (the term "validation" does not appear in IPCC AR4) and, therefore, the reliability of the outputs of these models, that have been used to assess the impacts on water resources, is not tested. Recent independent studies on the validation of IPCC models (Douglass *et al.*, 2008; Frank, 2008; Koutsoyiannis *et al.*, 2008a) indicate a rather poor performance, especially on long-term (climatic) scales. Solely using different unvalidated models to produce ensembles of climate predictions (or *projections*, in IPCC's vocabulary), as is current practice in IPCC reports, does not provide a scientific basis for uncertainty estimation. Rather, such a basis for estimating the likelihood of model outputs can be provided only by testing the model performance against observed data. This is established practice within the hydrological community and has been recently re-confirmed in discussions related to the generalized likelihood uncertainty estimation (e.g. Montanari, 2005; Stedinger *et al.*, 2008). It is very positive that similar ideas appear in recent climatic research publications. For example, Rougier (2007) indicates that in probabilistic inference for future climate using an ensemble of climate models, the conditioning of the probability density function on measured values of climatic variables is necessary.

The second utility of data is related to their crucial role in understanding past climatic and hydrological changes, which also provides an extremely useful guide in tracing possible futures. This is not to say that the future will mirror the past—this would be a misuse of the key role of the past for the future. The common assumption of static past climatic and hydrological systems is an incorrect interpretation of the data. *A fortiori*, a projection of an incorrect static perception of the past into the future, which in addition would imply neglect of the anthropogenic effects on the environment and water availability, would be tragic. In contrast, the understanding of the dynamic non-static character of past climate leads to correct use of the key to estimate future climatic uncertainty.

In order for past changes in climate, hydrology and water resources to be seen and understood, long observational time series are required. The longest available instrumental data set comes from hydrology and describes the annual maximum and minimum water levels of the Nile River (length >840 years). This instrumental record, along with additional documented information that extends for millennia, has taught us that a static climate and constant water resources conditions have never been the case in history (Koutsoyiannis & Georgakakos, 2006). Similar behaviour is seen in modern instrumental records, not only of the Nile (Koutsoyiannis *et al.*, 2008b), but also in almost all rivers with long records. It is, therefore, absolutely necessary to analyse past hydrological records, and recognition of this is the basis of a UNESCO Division of Water Sciences working group on identifying the relative roles of climatic variability and land cover change on floods and low flows as a function of spatial scale (Blöschl *et al.*, 2007).

Supplementary information on past changes is now being provided by scientific disciplines such as palaeoclimatology (e.g. Alley 2000, 2004; see also Fig. 3 to be discussed in the next section), palaeohydrology (e.g. Meko *et al.*, 2007), and historical hydrology (e.g. Brázdil & Kundzewicz, 2006). This information, produced from proxy reconstructions or documentary data, has less precision than instrumental observations and frequently relies on assumptions and procedures that can best be described as subjective. Thus, it may not provide solid grounds for formal statistical analyses and concrete results. It is, nevertheless, important in understanding and verifying natural behaviours and may be more useful as a key for the future than arbitrary scenarios and unvalidated model results. Significantly, one general conclusion from all sources of information of this type is the ever changing character of climatic and hydrological regimes at all time scales.

STOCHASTIC ASPECTS OF CLIMATE AND THE HURST-KOLMOGOROV BEHAVIOUR

The climatological community seems to subscribe generally to the deterministic paradigm, which is reflected in its confidence in the ability of GCMs to foretell the unknown future. In contrast, the research contributions of the hydrological community have been based on more pragmatic statistical and stochastic descriptions of natural processes, which reflect a different paradigm in both understanding and modelling natural processes. The fact that climate is not static is well founded in the climatological community (e.g. Rial *et al.*, 2004). The contribution of the hydrological community is its pioneering work on the stochastic representation and modelling of the non-static climate. The stochastic representation does not seek to reduce a phenomenon to a chain of cause-and-effect steps, thereby giving a full explanation of an eventual outcome (indeed, what would be the value of an explanation as to why the outcome of a dice throw was sixes?). Likewise, a stochastic representation does not seek to provide a single prediction for a future. Rather, it focuses on the quantification of future uncertainty. We show below how a stochastic representation of climate may provide an explanation for the presence of local trends as natural elements in climatic time series, which otherwise would be regarded as exceptional climate changes.

In a stochastic context, non-static climate is represented as Hurst-Kolmogorov (HK) behaviour and modelled as an HK stochastic process, after the English hydrologist H. E. Hurst (1951) who studied it in natural processes, and the Russian mathematician A. N. Kolmogorov (1940) who devised its stochastic representation as a mathematical tool for the research of turbulence (see also Shiryaev, 1989; Koutsoyiannis & Cohn, 2008). It is well known that the HK behaviour, mostly viewed as persistence or clustering of similar events in time, is relevant to (and virtually omnipresent in) all hydrological processes (e.g. Montanari *et al.*, 1997; Koutsoyiannis, 2002, 2003; Montanari, 2003). It is less well known that this behaviour exists within atmospheric processes and temperature in particular (e.g. Koscielny-Bunde, *et al.*, 1998; Koutsoyiannis, 2003;

Cohn & Lins, 2005 for instrumental temperature records; Koutsoyiannis, 2003; Rybski *et al.*, 2006; Koutsoyiannis & Montanari, 2007 for proxy temperature time series). As demonstrated below, temperature, due to its slow variation in time (but high variation in mean state and range of values on long time scales), exhibits HK behaviour even more prominently than rainfall and runoff. Therefore, HK behaviour is undoubtedly relevant to climate.

Hurst (1950) described the natural behaviour he discovered as follows: "*Although in random events groups of high or low values do occur, their tendency to occur in natural events is greater. This is the main difference between natural and random events*". Ignoring or neglecting the HK behaviour may lead to incorrect conclusions about the occurrence of statistically significant changes, or erroneous attribution thereof. Therefore, it is surprising that IPCC AR4, even in the chapters on *Paleoclimatology* (WG1, Ch. 6) and *Freshwater* (WG2, Ch. 3), does not contain any reference to Hurst. The only allusion to HK behaviour in AR4 appears in the last paragraph of Appendix 3.A (*Low-pass filters and linear trends*; WG1, Ch. 3) and indicates that the authors of the Appendix had no understanding of long-term persistence (i.e. HK behaviour) or of the substantial literature describing it. Indeed, the Appendix states "*... results depend on the statistical model used, and more complex models are not as transparent and often lack physical realism. Indeed, long-term persistence models (Cohn and Lins, 2005) have not been shown to provide a better fit to the data than simpler models.*" The assertions that long-term persistence models are "not as transparent" "lack physical realism" and "have not been shown to provide a better fit to the data" are not supported by the existing literature.

Prominent characteristics of HK behaviour are long and large excursions from average (Koutsoyiannis, 2002, 2003; Cohn & Lins, 2005). This is demonstrated in Fig. 2 for time scales of up to five years, based on global average lower tropospheric temperature, as estimated from satellite observations, and in Fig. 3 for time scales up to 8000 years based on a proxy series of temperature in Greenland, reconstructed from the GISP2 Ice Core. Both figures show the non-static, fluctuating behaviour of temperature.

In particular, Fig. 2 indicates a general increasing trend in global temperature during the last 30 years, but with a fluctuating (upward and downward) pattern (consistent with a HK climate).

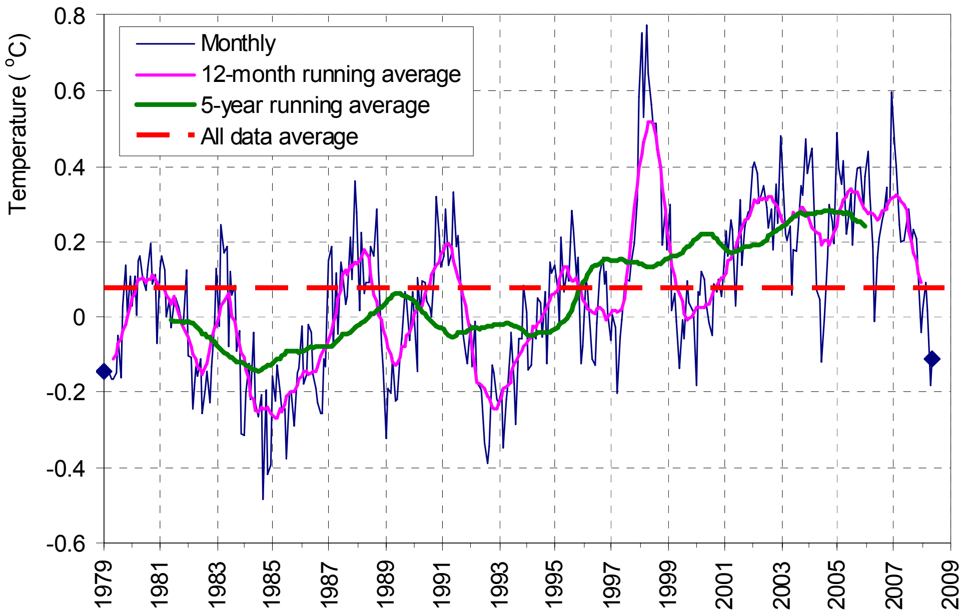

Fig. 2 Plot of the time series of global average of temperature of the lower troposphere (departures from 1979–1988 mean) as estimated from satellite observations (all available data; from http://vortex.nsstc.uah.edu/public/msu/t2lt/tltglhmam_5.2) showing the non-static, Hurst-Kolmogorov type, fluctuating behaviour of temperature (notice the equality of the most recent and initial observations).

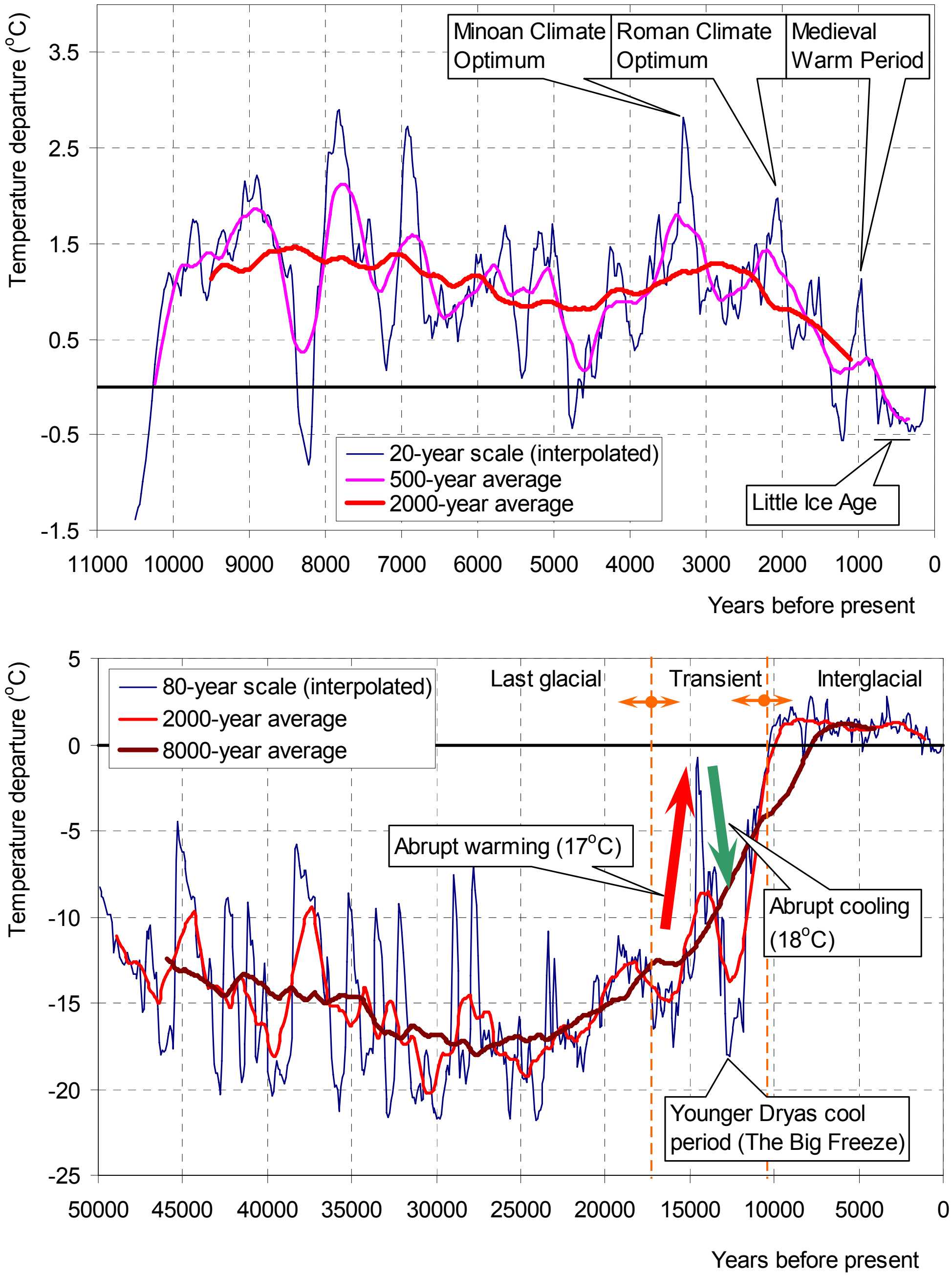

Fig. 3 Times series plot of the temperature in Greenland, as reconstructed from the GISP2 Ice Core (Alley 2000, 2004; temperature departures from the most recent value, which is –31.6°C; data from ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/gisp2_temp_accum_alley2000.txt): (a) during the Holocene (current interglacial period), with marking of the most prominent recent lows and highs; and (b) the entire record with marking of the most prominent abrupt warming and cooling episodes (in a transient period between the current interglacial and the last glacial period) that ended with the Younger Dryas cool period.

Figure 3(a) indicates large fluctuations of temperature during the Holocene period, with prominent minima (e.g. the recent Little Ice Age) and maxima (e.g. the Medieval Warm Period, the Roman Climate Optimum and the Minoan Climate Optimum, with temperatures that were likely higher than at present). Figure 3(b) extends back into the last glacial period and shows large fluctuations throughout. The most prominent fluctuation occurred in a relatively recent period, marked in Fig. 3(b) as "transient" (between the glacial and interglacial periods). Specifically, there was a rapid period of de-glaciation, leading to a temperature of about the current level, followed by a rapid period of re-glaciation with a temperature fall of 18°C, leading to what has been called the Younger Dryas cool period or the Big Freeze. Interestingly, it seems that this temperature fall was neither uniform throughout the year, as during the winter it may have fallen by 28°C (Broecker, 2006), nor throughout the globe, as it may not have extended to the Southern Hemisphere (Ackert, 2008). All these characteristics, along with the fact that the mechanisms that caused the Younger Dryas are not fully understood (Lowell & Kelly, 2008), indicate the high natural variability of climate over all temporal and spatial scales, and the high structural uncertainty of its evolution.

These are exactly the characteristics that are represented by the HK stochastic dynamics. Indeed, Figs 4 and 5, which depict the characteristic logarithmic plots of standard deviation *vs* time scale of aggregation, show that these time series are consistent with HK behaviour with a very high Hurst coefficient (about 0.94, where the upper limit is 1). Without considering the HK dynamics, the uncertainty is underestimated and even moderate changes are regarded as being significant. This is reflected, for instance, in KEA where the authors state "*By mid-century, annual average river runoff and water availability are projected to decrease by 10–30%*". Such percentage changes are typical of HK behaviour and no anthropogenic intervention is needed to produce them. On the contrary, climatic models produce future changes that are too weak in comparison with natural hydroclimatic variability (Koutsoyiannis *et al.*, 2007).

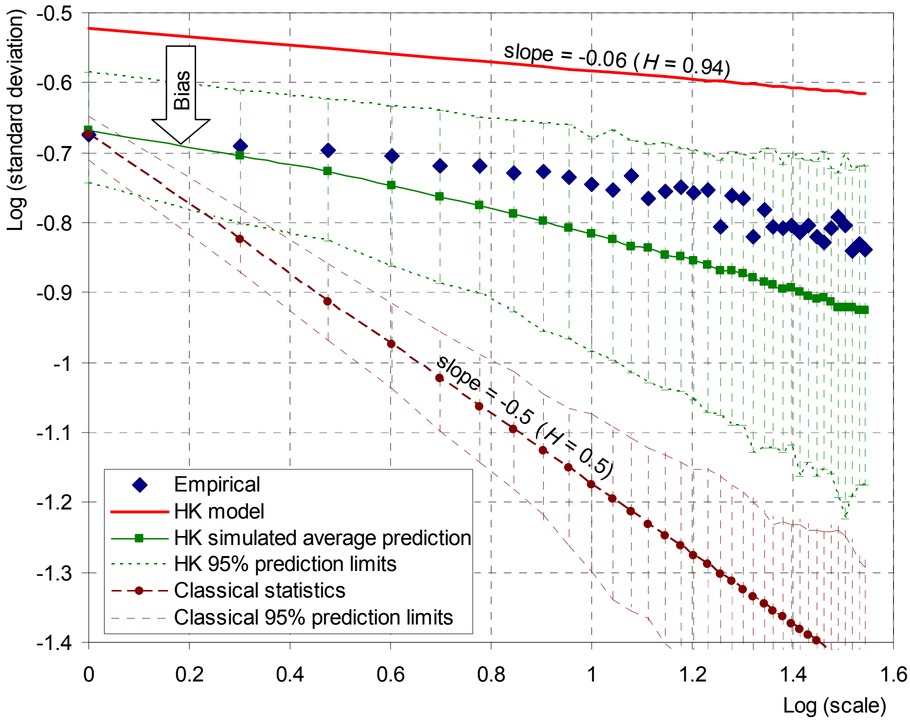

Fig. 4 Logarithmic plot of the standard deviation of the global lower tropospheric temperature (in °C, from Fig. 2) *vs* scale (in months) compared with simulation results (200 simulations with length equal to the historical series) using a HK stochastic process with Hurst coefficient H = 0.94, or a purely random process (H = 0.5). The plots demonstrate: (1) the consistency of the data with the HK model and their inconsistency with the classical model; (2) the dramatically-increased uncertainty (expressed by the standard deviation) of the HK model as compared to the classical model for increasing time scales; (3) the huge bias in the estimation of standard deviation if classical statistical estimation is used for the HK model (whereas such bias does not exist in the classical model); and (4) the wider band of prediction limits (as estimated by Monte Carlo simulations) in the HK case, again as compared to the classical case.

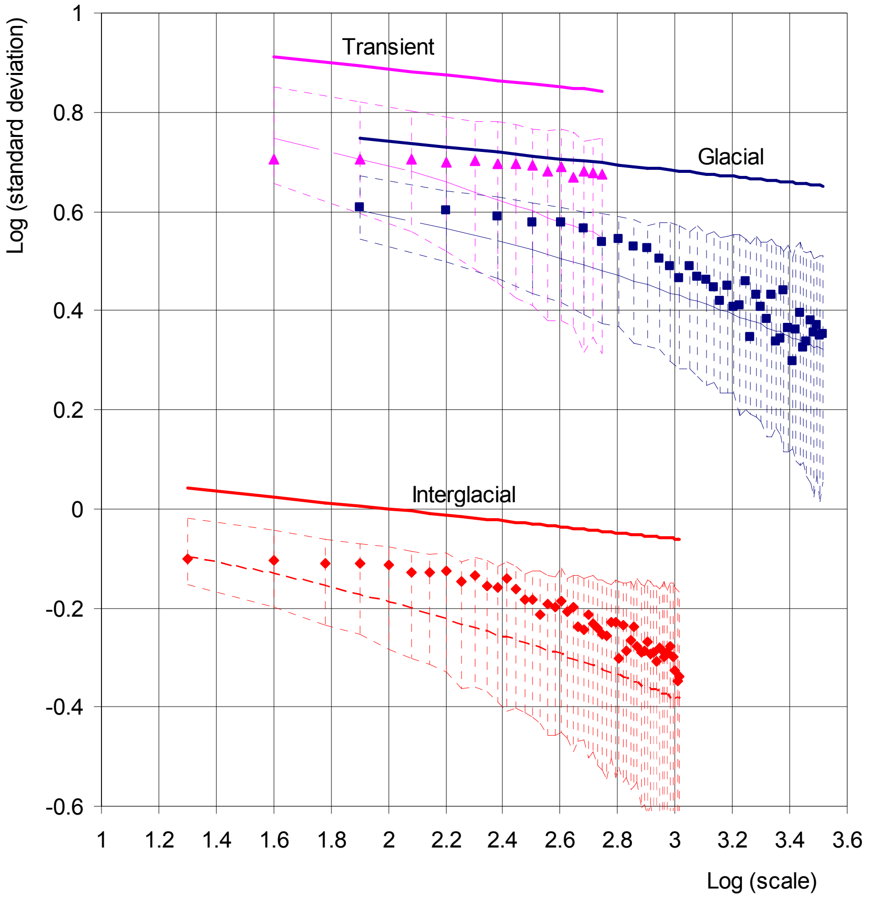

Fig. 5 Logarithmic plots of the standard deviation of the temperature in Greenland, as reconstructed from the GISP2 Ice Core (in °C, from Fig. 3) *vs* scale (in years) plotted separately for the glacial, transient and interglacial periods (points) and compared with simulation results (200 simulations with length equal to the historical series) using an HK stochastic process with Hurst coefficient $H = 0.94$ (same for all three cases; continuous lines). Simulation averages (dashed lines, which differ from the theoretical models due to large bias) and 95% prediction limits (dotted lines) are also plotted.

EXTREMES *vs* AVERAGES

If the uncertainty in predicting climatic averages is high, particularly given that climate dynamics are of HK type, the situation with extremes is even worse. In addition to the scaling in time which, in effect, is described by the HK model, there is also the scaling in state (across a variable's probability distribution), particularly the heavy distribution tails. Here again, the hydrological community has significant experience (e.g. Koutsoyiannis, 2004a,b, for maxima; Laaha & Blöschl, 2007, for minima; just to mention some recent examples). In this respect, we think that the results of multidecadal GCM predictions (e.g. in KEA: "*Some drainage basins are projected to experience increase in frequency of both floods and droughts*") could be affected by substantial uncertainty.

Given the importance of extremes in the public consciousness, as suggested by the extensive media coverage during extreme events, there is an urgent need for a more objective understanding of the characteristics of extreme events. The common assumption that meteorological and hydrological events have become more extreme and more frequent is affected by potential biases related to: (1) the media (where stories are biased toward devastating events because they are thought to be of greater interest to the public); (2) the politics (where climate alarmism can serve political, environmental, economic or other aims); and (3) the research community and its adaptation to research funding opportunities (where an uneventful climate can translate into diminishing financial support for research). Another issue giving rise to the perception (or misperception) that climatic hazards and extremes are increasing is the misinterpretation of the well-documented increase in damages associated with extreme events (e.g. floods) as being an increase in the severity of the events themselves. Studies have consistently demonstrated that the increase in damages associated with floods, for example, is directly related to the increasing development of flood-prone areas (Pielke & Downton, 2000). There is simply more property, and more highly-valued property at risk.

Although it has long been a cliché that *climate change will cause more floods and droughts*, a meaningful elucidation of the characteristics of such increased extremes has not been forthcoming. Nor has there been a detailed evaluation of how existing water resources planning and management principles and guidelines are inadequate or inappropriate in the face of climatic change. Actually, hydrologists are well used to adapting flood protection mechanisms and water resources management to changing conditions. The need to understand the strengths and weaknesses of existing water resources practices is requisite before any attempt is made to change inveterate, well-tested, and well-understood engineering practices because of potential climatic change. With respect to the question of how greenhouse-induced climatic change may affect streamflow in general, and flooding in particular, Lins & Cohn (2003) sought an answer using data and the published literature in terms of two issues: What is known about the sensitivity of various return-period floods and annual precipitation? What is the real significance of a given percentage change in precipitation on a flow quantile (e.g. Q_{100} *versus* Q_{mean})? They found that the observed elasticity (sensitivity) of streamflow to changes in precipitation indicates that the precipitation sensitivity of mean streamflow is much greater than that of flood flows. Their analysis also indicates that the greater the return period of the flood, the lower the precipitation sensitivity. They conclude that human-induced climatic change is more likely to produce changes in the mean state of hydrological regimes than in hydrological extremes. This result has significant implications for water resources planning and management, because the continued emphasis on greenhouse-induced increases in extremes, such as floods, may be misguided and detract from a more germane and necessary discussion of: (1) how to take advantage of opportunities posed by potential increases in mean discharge, and (2) how to prepare appropriately for the threats posed by potential decreases in mean discharge.

SEEKING THE REAL CAUSES OF PROBLEMS

A common argument in favour of the political orientation of the IPCC is that its aims are good for humanity and the natural environment and that reducing emissions of greenhouse gases will be beneficial for the planet, regardless of the ultimate validity of the IPCC model predictions. However, we believe that science is a process for the pursuit of truth and that fidelity to this system should not be affected by other aims. History shows that such distractions can be detrimental to science.

Problems and threats in water resources are both real and numerous. Relevant and already urgent problems are related to the unsustainable overexploitation of water resources (Falkenmark & Lannerstadt, 2005), the lack of an adequate water supply infrastructure in many parts of the world, pollution, and an increase in the population at risk to water hazards. Such problems are caused by an ever increasing population, consumerism, urbanization and agricultural expansion. Underpinning all of these causes is an energy system based on fossil fuels, which fully determines our economy and civilization. Given that the exploitation of fossil fuels is not sustainable by definition (they are non-renewable resources), our societal and economic future is predicated on ultimately finding a viable alternative source or sources of energy. We believe that our global society and scientific community is today dedicating much attention to a single by-product of the hydrocarbon-based economy, CO_2, and its potential consequences on climate, water, etc., while we fail to address the real causes of the above problems.

We believe that water quantity and quality problems, which are more prominent in drylands (e.g. Cudennec *et al.*, 2007), are primarily caused by increased irrigation demand, by related land-use changes and agricultural practices (including use of fertilizers and pesticides), by polluting streams and aquifers as a result of urban activities, and by perturbing the natural water balance through overexploitation of groundwater, resulting in a dramatic lowering of water tables and, in coastal areas, salt water intrusion.

CONCLUDING REMARKS

Climate is, unquestionably, an intrinsic part of human activities, biological and environmental functioning, and natural processes. It is well understood that climate is highly dynamic, and that the perception of a static climate has always been, in fact, a misperception. Importantly, the mechanisms driving the changes in climate are poorly understood and possibly beyond our ability to model adequately. Even if they can be adequately modelled, predictability is not a foregone conclusion. A more moderate target would be to model the uncertainty of future climate, which must necessarily be very wide. This target is pragmatic and calls for the recognition of the structural character of uncertainty in climatic research. Within this perspective, the hydrological community could play a more proactive role; one that differs significantly from the current role that essentially consists of taking GCM model outputs and trying to extrapolate their consequences on hydrological processes and into the subsequent state of water resources. The study of the regulating role of water and hydrological processes in climate, the recognition of the structural character of uncertainty, the understanding and modelling of the long-term variability of climatic processes in a stochastic context, with particular emphasis on the Hurst-Kolmogorov dynamics and the behaviour of extremes, are all important topics on which the hydrological community has broad experience and could further contribute in an interactive manner with the climatological community. The search for the real causes of extant water problems is another area of needed interaction, particularly to ensure that water resources planning and management professionals maintain their primary focus on the more influential factors affecting the availability of water.

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