Article ID: 1673-1719 (2009) Suppl.-0047-07

Research Advances in Impacts of Natural Climate Variability and Anthropogenic Climate Change on Streamflow

Liu Chunzhen

Water Resources Information Center, Ministry of Water Resources, Beijing 100053, China

Abstract: Based on the review of the successive four assessment reports of the IPCC WGII on climate change impacts on streamflow from 1990 to 2007, it is summarized that the first (FAR) and second (SAR) assessment reports were regarded as the first generation studies, featuring the impacts of mean climate change on streamflow and the adaptation, while the third (TAR) and forth (AR4) assessment reports as the second generation studies, emphasizing the impacts of anthropogenically and naturally forced climate changes on streamflow and the adaptation. The development process and existed problems of traditional assessing methodologies of the impacts of climate change on hydrology and water resources are analyzed. It is pointed out that the impacts of decadal and multi-decadal variabilities of climatic variables on streamflow can be identified in the traditional methodology of hydrological impact studies, but without consideration of daily, seasonal and interannual variabilities, which are related with changes in the frequency and intensity of extreme events. As the results, the negative impacts of climate warming on droughts, floods and water demand of irrigation might be underestimated. As for further studies, the paper comes to a conclusion suggesting the enhancement of the interdisciplinary study of hydrology and climatology in the next IPCC assessment report.

Key words: natural climate variability; anthropogenic climate change; streamflow; IPCC assessment report

Introduction

Four assessment reports have been released since 1988 when IPCC was established by the WMO and the UNEP. With the view of climate change impact on hydrology and water resources the four repots can be divided into two generations. The first (FAR) and second (SAR) assessment reports of the IPCC WGII can be regards as the first generation studies, which concentrated mainly on the impact and adaptation of the changes in mean climate [1−2] ; and the third (TAR) and forth (AR4) assessment report as the second generation studies. The TAR presented the importance of natural variability of streamflow, and paid more attention to the detection of the impact of natural climate changes on streamflow [3]. With development of climatology and climate models, the Fourth Assessment Report has attempted to separate the impact of natural climate variability from that of anthropogenic climate change on streamflow in terms of model simulation; and a statistical indicator of "signal-to-noise" ratio has been used to assess their respective contributions to the past observed and future projected runoff trends, indicating regions with anthropogenic climate change influence larger than nature climate variability influence, as well as the regions where the natural climate variability is still playing a major role [4]. This progress not only reflects the deepening of hydro-climate research, but also provides decision-makers and managers of water resource effective information on risk management of climate change. Since then, the study on adaptation to climate change has extended from adaptation to the impact of mean climate change to the impacts of anthropogenic and naturally forced climate changes, therefore it is of more application value.

However, the study of anthropogenic impacts on the natural climate variability is still in an early stage. The challenges for the study are that the time scale of climate

Received: October 22, 2008

Corresponding author: Liu Chunzhen, E-mail: liucz@mwr.gov.cn

change covers the full time spectrum of natural climate variability, from daily, seasonal, yearly, decadal to centurial and even millennial scale; and the anthropogenic impact on natural climate variability involves changes on all time-scales. So far, climate models could simulate the decadal and multi-decadal natural variabilities dominated by interactions between the ocean and atmosphere, but could not successfully simulate daily, seasonal, and interannual variabilities which are governed by the land surface condition, such as snow cover on the Tibetan Plateau; polar sea ice; land surface processes; soil temperature/humidity states and interactions among atmospheric chemical constituents–aerosols–clouds–radiation in addition to the ocean state. If climate models are not good enough in the spatio-temporal resolution and precision, it will be difficult to identify these refined changes of the natural variability and to finally resolve the important issues with great scientific and operational values.

In this paper, the mechanism and cause of natural climate variability are not involved for it is the business of climate science. Historical evolution of the studies on the impacts of natural climate variability and anthropogenic climate change on streamflow is reviewed and analyzed in an attempt to understand the current scientific level and gaps of the studies and research issues in hydrology needed to be further investigated.

1 Trends of hydrological time series related to climate change

In recent years, there are two points of view on the variation trend of hydrological time series. One of them considers the hydrological phenomena as a steady random process with fluctuations but without trends, and the mean value of long term hydrological variable is an unchanged constant; while another one holds that there exist trend variations in long term hydrological variables, their changes in recent 30 years are attributed to climate warming. Gain of long time series of observed climatic data in the global range and development of climate models in simulating climate and its variability promote the statistical analysis of the historical data and the numerical simulations. All of these reveal the natural climate variability from weeks to centuries and millennia interior the climate system. The oceans, as a slow varied climate component integrating high frequency weather variabilities and interacting with faster varied components, play important roles in climate changes on decadal and centurial time scales [5–6]. Thus the climate system itself is capable of producing long term scale internal variations of considerable magnitude on long term scale without any external influences. Progresses in climate science facilitate hydro-climate research. Since 1995 when the SAR was released, the study on the correlation between hydrological phenomena and low-frequency climate variability has started over the world, which has explored linkages between recognizable patterns of climate variability, particularly El Niño events, the North Atlantic Oscillations and Pacific Decadal Oscillation, and hydrological behavior, in an attempt to explain variation in hydrological characteristics over time. The studies for North America [7–8], South America [9–10], Australia [11], Europe [12], southern Africa [13] and Asia [14–15] have revealed that the variability not just from year to year, but also from decade to decade, although the patterns of variability vary considerably from region to region. The studies have also shown three important implications: first, the hydrological "baseline" cannot be assumed to be constant, even in the absence of climate changes forced by anthropogenic impacts, and future studies on the trend in hydrological time series should consider both the impacts of the natural multi-decadal climate variability and the anthropogenic climate change; second, an assessment of possible changes in the interannual and interdecadal variability of hydrological behavior induced by climate change must be based on accurate representations in climate models of patterns of low-frequency variability; third, the future variations of hydrological behavior can be predicted only if its cause is correctly understood.

In recent years, there are two aspects of trends study on hydrological consequences of global warming in the world. The first is to separate the natural climate variability from anthropogenic one in historical data of hydro-meteorological observations for a long term period. The second is to assess the contributions of natural and anthropogenic climate variabilities to future trend of streamflow under different scenarios projected by climate models. Owing to the limited simulation accuracy and uncertainties in current climate models, the study on the impact of future natural climate variability on streamflow is still in starting stage, and many scientific issues remain to be resolved.

2 Discriminating the natural climate variability from anthropogenic climate changes in observed hydro-climatic time series

Since 1995, many climatologists, by applying coupled ocean-atmosphere models, have simulated the contributions of natural and anthropogenic climate variabilities to the trend of historic long-term climate variable series. Hulme *et al*. [16] used results from recent global climate simulations and two environmental response models to consider systematically the effects of natural climate variability (30-year timescales) and future climate-change uncertainties on river runoff and agricultural potential in Europe. Taking the ratio of signal (anthropogenic climate change) to noise (natural climate variability) greater than two times of the standard deviation of natural climate variability as an indicator of significant climate change, he pointed out that, for some regions, the impacts of anthropogenic climate change by 2050 will be undetectable relative to those due to natural multi-decadal climate variability caused by the North Atlantic Oscillation. Based on numerous trend detection studies on variations in long term observed data, IPCC WGI in the TAR explicitly gave the definition of climate change detection: "the presence of this natural climate variability means that the detection and attribution of anthropogenic climate change is a statistical signal-in-noise problem, and detection is the process of demonstrating that an observed change is significantly different (in a statistical sense) from those can be explained by natural internal variability". In the 12th chapter of TAR, a global mean surface temperature ensembles of four simulations from 1985−2000 were represented with a coupled ocean-atmosphere climate model, and separated contributions of natural forcing (solar and volcanic activities) and anthropogenic forcing to simulated global mean surface temperature anomalies relative to the 1880 to 1920 mean from the instrumental record were also given. This kind of separation of natural and anthropogenic forcing effects from climate model simulation is more suitable to these phenomena or variables influenced mainly by temperature rising, but not to those influenced by precipitation. On the one hand, variability of precipitation is large, and it is not sensitive to the rising of greenhouse gas concentration; on the other hand, the confidence level in precipitation simulation is lower than that in temperature simulation by current climate models, and under the same emission scenario of greenhouse gases, different climate models may produce quite different rainfall and its spatial patterns. Therefore, it is difficult to separate the contributions of natural variability and anthropogenic forcing in long-term observed precipitation series by using climate model simulation. Recently, the detection and attribution of precipitation changes are completed in two steps: firstly, analyze the variation characteristics of long-term observed precipitation data and their significantly related phenomena or events; and then prove the relation between those phenomena or events and anthropogenic climate change by climate model simulation. For example, Fauchereau *et al*. [17] analyzed the natural variability and anthropogenic change in Southern African precipitation during the 20th century and found that the interannual variability has increased since the late 1960s, In particular, droughts become more intense and widespread. More significantly, teleconnection patterns associated with Southern African rainfall variability changed from regional scale before to near global scale after the 1970s, and an increased statistical association to the El Niño Southern Oscillation (ENSO) phenomenon was also observed. Numerical experiments with GCMs indicated that these changes in teleconnections could be related to the long-term variations in the sea surface temperature background, which are part of the observed global warming signal; and many statistical studies on the long term series of observed precipitation data also revealed significant increases in the interannual variability of precipitation and the frequency of extreme events and alternatively occurrence of droughts and floods after the 1970s [18−19].

Detection and attribution of a trend in a hydrological time series are much more difficult than those in a temperature series [20], because changes in runoff are affected not only by climate factors, but also by non-climate factors, such as increases in water use and water consumption resulted from population growth, economic development, and changes in land use and land cover. Their effects may outweigh any climatic trends. In some regions, variability over time in hydrological behavior is very high, and the variability induced by low-frequency climate rhythms must be corrected when looking for the trend of runoff variation. For example, the signal of the impact of anthropogenic climate change on natural runoff supplied by rainfall may be masked by the noise of large natural climate variability in precipitation or weak change in runoff. Radziejewski *et al*. [21] pointed out that statistical tests are not able to detect weak changes or changes which have not lasted long, but this cannot be interpreted as a demonstration of absence of a change. With the enhanced climate change, the changes of hydrological processes may be stronger and last longer, so that the likelihood of change detection may grow. In the IPCC TAR, there have been many studies on possible trends in hydrological data, trying to explain cause of runoff variation with precipitation and temperature changes in different climate zones of the world. These studies are of some meaning for assessing the vulnerability of river systems and its adaptation measures for certain regions to global climate changes, but they are unable to give the ratio of anthropogenic climate change in the trend of runoff variation. Unless all influencing factors have been considered, and their observed data are long enough, the contribution of anthropogenic forcing could not be recognized under a certain range of error by statistical analysis. But even so, it is still difficult to identify the contribution of natural and anthropogenic climate changes in the runoff trend. In the IPCC AR4, a concept called joint attribution has been introduced, which consists of two steps. Firstly, the statistical analyses demonstrate the observed changes in physical and biological systems, which are attributed to a given regional climate change, particularly temperature increase. Secondly, climate model simulation is used to illustrate that the observed regional climate changes are attributed to anthropogenic climate forcing. This method has been applied in detection of Arctic streamflow variation and river runoff fed by snow ice melting in the permafrost regions. Recently, a methodology combining climate model with response model has been developed to compare the observed trends with simulated results with or without anthropogenic climate change. Applying this method, Reichert *et al*. [22] and Wu *et al*. [23] have shown that the retreat of two glaciers in Switzerland and Norway cannot be explained by the natural variability of climate and the glacier mass balance. Applying several GCMs ensembles and the statistical technology, Milly *et al*. [24] simulated global patterns of trend in streamflow during 1900−1998, and pointed out that the anthropogenic climate forcing has influenced the global runoff pattern since 1970s and the climate forcing signal is relatively more significant in the northern part of Eurasia and in the high latitudes of the northwest part of North America.

3 Future trends of hydro-meteorological variables and the causes

Studies on the detection and attribution of the impacts of natural and anthropogenic climate variabilities on projected future hydro-meteorological variables are in an initial stage. The conventional methodology of climate change impact assessment used in the four IPCC assessment reports and its ability in identifying the natural and anthropogenic climate changes are introduced as follows:

(1) The FAR and SAR climate models were in the early stages of model development, their simulation abilities were limited. And there was a scarcity of suitable observational data, particularly long, reliable time-series. By the time of the SAR in 1995, considerable progress had been made in attempts to identify anthropogenic effect on climate. The first progress was that climate models were beginning to incorporate the possible climatic effects of human-induced changes in sulphate aerosols and stratospheric ozone. The second area of progress was in better defining the background variability of the climate system through multi-century model experiments where no change in forcing was assumed. These experiments provided important information about the possible characteristic of the internal components of natural climate variability. The third area of progress was in the application of pattern-based methods in an attempt to attribute some part of the observed climate changes to human activities, although these studies were still in their infancy at that time. Climate scenarios were taken as arbitrary changes in precipitation and temperature or based on equilibrium GCM experiments — doubling of current atmospheric CO_2 concentrations (approximately in 2030) without consideration of the increasing process of greenhouse gases; and hydrological models were driven by the mean climate change. During the Eighth Five-Year-Plan in China, the mean precipitation and temperature changes from 7 equilibrium GCMs simulations were used to modify the observed temperature and precipitation in the period 1961−1990. These modified long-term mean monthly values of precipitation and temperature were input into hydrological models, to simulate the impact of mean climate change on the annual runoff in 7 representative river basins in China. In order to consider climate fluctuation, the concept of guaranteed rate has been introduced: how much runoff would be changed if climate change occurred in the normal year (guaranteed rate of 50 percent), dry year (guaranteed rate of 75 percent) and exceptionally dry year (guaranteed rate of 95 percent). The study results show that although the impact of CO_2 concentration-doubling on annual runoff is small, and the percent change of runoff induced is in the range of 2%−12%; however, the small runoff reduction will produce serious water shortage in the Jing-Jin-Tang region [25] if it happened in the exceptional dry year. At that time, the interannual variation in runoff was considered unconsciously by applying the simple assumption method of “if-then”.

Along with the connection of greenhouse gas emission scenarios with socioeconomic development ways and population growth, as well as the advance in climate models, GCM’s simulations have developed from equilibrium to transient experiment and from single emission scenario to multiple scenarios. By employing a coupled ocean−

atmosphere model, Mitchell *et al*. [26] studied climate changes relative to the baseline scenario from 1990 to 2100 when the CO_2 concentration firstly increases by 1% per year, and then stabilizes at 550 mL/m^3 (ppmv) and 750 mL/m^3, respectively. They took the standard deviation of variables estimated from a long control run of the HadCM2 OAGCM as the "natural variability" and two times the standard deviation of natural variability as the criterion of the statistically significance of variable changes. Study results showed that annual temperature changes in five selected regions over the world are all significant under all three transient scenarios, but in some regions, changes in seasonal precipitation are smaller than two times the standard deviation of natural variability, even in 2085, therefore are not statistically significant. This may be due to the large natural variability of precipitation, which masked the anthropogenic climate change, or due to large errors in the precipitation simulations based on a single OAGCM.

(2) During the periods of TAR and AR4, studies on the impact of climate change on hydrology and water resources were mainly concentrated on the effect of interdecadal climate change and the comparison of the impacts of anthropogenic and natural climate changes on runoff. A representative work on this aspect is that Arnell [27] applied the SRES socioeconomic scenarios and six climate models to describe the effect of climate change on future global and regional water resources stresses. The study can be divided into following steps:

(i) Construct climatic scenarios. The climate scenarios for the 2020s (2010−2039), 2050s (2040−2069) and 2080s (2070−2099) were constructed from six climate model runs under the SRES emission scenarios, which characterize the change in the 30-year mean climate relative to the modeled one over 1961−1990.

(ii) Construct the climate scenarios for hydrological model. An anthropogenically perturbed climate series field was created by overlaying the observed global 0.5°×0.5° baseline climatology in 1961−1990 with values of climate change at the resolution of 100 km ×100 km output from the GCMs [28].

(iii) Run a macro-scale hydrological model at the resolution of 0.5°×0.5° latitude/longitude to simulate the runoff variations (%) in the 2020s (2010−2039), 2050s (2040−2069) and 2080s (2070−2099) relative to the period 1961−1990 under different emissions scenarios. The changes in 30-year mean runoff reflect the impact of multi-decadal climate variability.

(iv) Assess the effect of decadal climate variability on runoff. The above mentioned three steps were repeated with the control experiments without greenhouse gases emission, to calculate the 30-year average annual runoff, and its standard deviation influenced by the natural multi-decadal climate variability. Finally a figure was given to show the simulated percentage changes in average annual runoff in the 2050s relative to the period 1961−1990, across the world, under the A2 emissions scenario by six climate models; and the areas, where the anthropogenic climate changes were significant (climate change signal greater than two times the standard deviation of natural multi-decadal variability in the control experiment) were marked.

It is worthy to emphasize that hydrological models can't be driven directly by the absolute value of precipitation output from climate models, due to substantial differences between the observed values of precipitation and those computed by climate models. Time series of observed precipitation values from 1961−1990 are needed to be adjusted with the computed change in precipitation to produce the scenarios for hydrological impact study. Otherwise the simulated biases in precipitation will produce disorderliness variations in runoff. The methodology means that although the climate model is unable to simulate the absolute value of precipitation correctly, the biases in climate modeling can be supposed to be similar for current and future time horizons, so the impacts of the error in climate modeling of the GCMs will be minimized. And the methodology also provides a simple downsclaling procedure.

In Arnell's study [27], the impact of decadal climate variability on runoff was remained, but the impact of interannual or even short time scale variations obviously can not be involved. Even climate models are able to correctly simulate the natural interannual variations and anthropogenic change, they are only reflected in the 30-year mean climate and hydrology. Because the impact of increasing greenhouse gas concentration on the interannual or even shorter time scale variability of climate variables, particularly on daily precipitation is not taken into account in hydrological impact studies, this will lead to an underestimation of future floods, droughts and maximum irrigation water requirements.

Recently the mean of multi-model ensembles [29], or the mean simulation of the same climate model with slightly different boundary conditions has been applied to study runoff variations at global or river basin scales in order to minimize the uncertainties of precipitation in climate model simulation [30−31].

4 Suggestions on future research in climate change impact on hydrology and its assessment

Based on the facts of the significant natural variabilities on interannual to decadal time-scales of all components of the hydrological cycle and the increased interannual variations of climate in recent years, it can be foreseen that the next IPCC assessment report of climate change impact on hydrology will be done along combination of anthropogenic forcing with natural climate variability in future. The final approach to resolve this issue is to develop a coupled land surface−ocean−atmosphere regional climate model with high resolution in time and space. Before it is done in practice, the one way off-line methodology and coupled model simulation will be coexisted in studying climate change impact on hydrology. However the multi-discipline infiltration between hydrology and climatology is an inexorable trend. The following is recommended for future Eleventh-Five-Year-Plan period research in climate change impact on hydrology.

(1) Incorporate statistical significant test and climate model to study the detection and attribution of the trends in long time series of observed hydro-climatic data and their spatial patterns on catchment/regional scales in order to answer whether it was caused by natural variability, anthropogenic climate change or the combination of the both.

(2) Incorporate the off-line methodology and the coupled model simulation to study the impact of natural variability and anthropogenic climate change on future runoff variations on regional and watershed's scales.

(3) Use the one way off-line methodology and the hydrological model to study the response of hydrological variables to the anthropogenic forcing on watershed scale, and incorporate the climate model simulation and the statistical detection methodology to study the impact extent of natural climate variability on runoff.

(4) Ensemble simulations have been applied to reduce noise in estimates of the time-dependent response. Multi-climate model ensembles are mainly focused on the large spatial pattern of trends in hydrological variables in future. It is necessary to validate the simulated runoff from climate model by off-line research.

5 Conclusions

(1) The climate system involves multi-scale variabilities from daily, seasonal, year, interannual, decadal to centurial and millennial scales. The effect of anthropogenic forcing on the full spectrum of climate variability will change the timing and spatial probability pattern of hydrological extreme events, and probability patterns over/lower climate average as well. All of these will exert critical impact on floods-droughts disaster prevention; water resources risk management and agriculture production.

(2) Recently, the off-line method, in which observed baseline climatology from 1961−1990 at a spatial resolution of $0.5^\circ \times 0.5^\circ$ is adjusted with the computed change in climate variables from GCMs, is applied in many impact studies to create higher-resolution perturbed climate scenarios for hydrological models. In this kind of impact study, the multi-decadal variability caused by anthropogenic climate change can be detected, but the impacts of daily, seasonal, yearly and interannual variabilities on runoff are unable to be considered, which leads to an underestimation of climate change impact on extreme events. The final approach to resolve this issue is to develop a coupled land surface−ocean−atmosphere regional climate model with high resolution in time and space and to raise its simulation precise on precipitation and runoff as well.

(3) Nowadays, in the field of climate change impact study on runoff, there is still coexistence of off-line method and climate model simulation.

(4) Incorporating physical models and the statistical technology to study the detection and attribution of the impacts of natural climate variability and anthropogenic climate change on the trends of observed and projected hydro-climate variables could be one of the cores of impact, adaptation and vulnerability assessment in the fifth IPCC report.

References

[1] IPCC. Climate Change 1990: The IPCC Impacts Assessment. Canberra, Australia: Australian Government Publishing Service, 1990

[2] IPCC. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 1996

[3] IPCC. Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2001

[4] IPCC. Climate Change 2007: Impacts, Adaptation, and

Vulnerability. Contribution of Working Group II to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2007

[5] IPCC. Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 1996

[6] IPCC. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press, 2001

[7] Vogel R M, Bell C J, Fennessey N M. Climate, streamflow and water supply in the northeastern United States. Journal of Hydrology, 1997, 198: 42−68

[8] Piechota T C, Dracup J A, Fovell R G. Western US streamflow and atmospheric circulation patterns during El Niño/ Southern Oscillation. Journal of Hydrology, 1997, 201: 249−271

[9] Marengo J A. Variations and change in South American streamflow. Climatic Change, 1995, 31: 99−117

[10] Compagnucci R H, Vargas W M. Interannual variability of the Cuyo river's streamflow in the Argentinian Andean mountains and ENSO events. Journal of Climatology, 1998, 18: 1593−1609

[11] Chiew F H S, Piechota T C, Dracup J A, *et al*. El Niño Southern Oscillation and Australian rainfall, streamflow and drought-links and potential for forecasting. Journal of Hydrology, 1998, 204: 138−149

[12] Shorthouse C, Arnell N W. Spatial and temporal variability in European river flows and the North Atlantic Oscillation. International Association of Hydrological Science, 1997, 246: 77−85

[13] Schulze R E. Impacts of global climate change in a hydrologically vulnerable region: challenges to South African hydrologists. Progress in Physical Geography, 1997, 21: 113−136

[14] Jiang T, Zhang Q, Ming D M, *et al*. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470−2003). Quaternary International, 2006, 144 (1): 29−37

[15] Zhang Q, Xu C, Jiang T, *et al*. Possible influence of ENSO on annual maximum streamflow of the Yangtze River, China. Journal of Hydrology, 2007, 333: 256−274

[16] Hulme M, Barrow E M, Arnell N W, *et al.* Relative impacts of human-induces climate change and natural climate variability. Nature, 1999, 397: 688−691

[17] Fauchereau N, Trzaska S, Rouault M, *et al*. Rainfall variability and changes in Southern Africa during the 20th century in the global warming. Natural Harzards, 2003, 29: 139−154

[18] Trenberth K E, Dai A G, Rasmussen R M, *et al.* The changing character of precipitation. Bulletin of the American Meteorological Society, 2003, 84: 1205−1217

[19] Zhai P M. Climate change and meteorological disasters. Science and Technology Review, 2004, 193 (7): 11−14

[20] Liu Chunzhen. Advances in study of climate change impact on river runoff trend. Advance in Earth Sciences. 2007, 22: 777−783 (in Chinese)

[21] Redziejewski M, Kundzewicz Z W. Detactability of changes in hydrological records. Hydrological Sciences Journal, 2004, 49: 39−51

[22] Reichert B K, Bengtsson L, Oerlemans J. Recent glacier retreat exceeds internal variability. Journal of Climate, 2002, 15: 3069−3081

[23] Wu P, Wood R, Stott P. Human influence on increasing Arctic river discharges. Geophysical Research Letters, 2005, 32 (2): L02703

[24] Milly P C D, Dunne K A, Vecchia A V. Global pattern of trends in streamflow and water availability in a changing climate. Nature, 2005, 438: 347−350

[25] Liu Chunzhen. Possible impact of climate change on hydrology and water resources in China. Advances in Water Science,1997, 8 (3): 220−225 (in Chinese)

[26] Mitchell J F B, Johns T C, Ingramm W J, *et al*. The effect of stabilizing atmospheric carbon dioxide concentrations on global and regional climate change. Geophysical Research Letters, 2000, 27, 18: 2977−2980

[27] Arnell N W. Climate change and global water resources: SRES emissions and socio-economic scenarios. Global Environmental Change, 2003, 14: 31−53

[28] New M, Hulme M, Jones P D. Representing twentieth century space-time climate variability. Part 1: development of a 1961−1990 mean monthly terrestrial climatology. Journal of Climate, 1999, 12: 829−856

[29] Murphy J M, Sexton D M H, Barnett D N, *et al*. Quantification of modeling uncertainties in a large ensemble of climate change simulation. Nature, 2004, 430: 768−772

[30] Palmer T N, Raisanen J. Quantifying the risk of extreme seasonal precipitation events in a changing climate. Nature, 2002, 415: 512−514

[31] Jasper K, Calanca P, Gyalistras D, *et al.* Differential impacts of climate change on the hydrology of two alpine rivers. Climate Research, 2004, 26: 113−125