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Future change of world water resources under SRES climate warming scenarios: A multi-model analysis

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Abstract Projections of the changes in water resources due to climate warming are critical for assessing the potential impacts of climate warming on human and natural systems. We analyse the potential changes in world water resources at annual and monthly scales by multi-model analysis using an ensemble of six General Circulation Models (GCMs), that forecast the future climate change based on a number of climate warming scenarios, which are presented in the Special Report on Emission Scenatios, (SRES). The discrepancies among GCMs are large; in some regions the change predicted by different GCMs are completely opposite. We screened the regions with high forecast consistency among the GCMs and categorized them into increasing, no change, and decreasing in annual runoff change through the multi-model analysis. Further detailed analyses on the monthly change are conducted in seven selected typical basins, which represent the different regions in annual change directions. The characteristics and possible causes for the changes in different basins are also discussed.

Key words future water resources change; global warming; IPCC; monthly; multi-model analysis; SRES

INTRODUCTION

There are an estimated 2 billion people currently living in severely water stressed basins worldwide (Oki & Kanae, 2006). This number will probably increase in the coming decades due to climate warming and socioeconomic development (Arnell, 2004; Oki & Kanae, 2006; Shen *et al.*, 2007). One of the most concerning issues regarding to climate warming is how the world water resources will be affected, where the water resources will have evident change, and what the possible consequences are.

In many cases, river discharge (or runoff) is considered the most available renewable freshwater resource. Scientists translate the general circulation model (GCM) outputs to river runoff (or discharge) to evaluate future water resources availability. However, the GCM forecasted runoff change is largely dependent on the model dynamics and parameterization; for example, one model predicts a region will possibly become wetter, but another model may give completely reverse forecasts. Hence, it is necessary to transfer more plausible information by using multi-model analysis. Recently, several attempts using multi-model ensemble analysis technologies were reported to reduce the model-specific uncertainty in global hydrological research (Dirmeyer *et al.*, 2006; Nohara *et al.*, 2006; Tebalti *et al.*, 2006).

There is common recognition that global warming due to accelerating concentrations of greenhouse gases in the atmosphere is likely to have significant effects on the hydrological cycle and water resources (Houghton *et al*., 1996; IPCC, 2001). However, comprehensive analyses on the change in renewable freshwater resources availability under the scenario families described in the Special Report on Emission Scenarios (SRES) are still needed, particularly at the finer temporal scale. In this study, we will analyse the potential change of future world-water resources in annual and monthly scales using the outputs of six GCM models simulated for SRES climate warming scenarios A1b, A2, and B1.

METHODOLOGY

SRES scenarios and climate data

SRES scenarios The Special Report on Emission Scenarios (SRES), released by the Intergovernmental Panel on Climate Change (IPCC) for the Fourth Assessment Report (AR4) on global warming, comprises four scenario families; one family (A1) has three marker scenarios (A1b, A1FI, and A1T), and the others have one each (Nakicenovic & Swart, 2000). These scenarios set various predictions on changes in population, economic growth, technology transfer, energy consumption, and greenhouse gas (GHG) emissions into the atmosphere. Climatologists forecast climate warming using GCMs based on the GHG emissions under each scenario.

In general, the A1 scenarios describe a future world of very rapid economic growth and global population that peaks in 2050 and declines thereafter, as well as the rapid introduction of new and more efficient technologies under rapid globalization (Nakicenovic & Swart, 2000). Major underlying themes are convergent among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. A1b assumes a balanced energy adoption between fossil fuels and other energy sources to drive the expanding economy.

The A2 scenario describes a very heterogeneous world with low levels of integration. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in a continuously increasing global population.

The B1 scenario describes a convergent world, with almost the same global population as in the A1 scenario, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

Climate data In this study, the simulation results for three SRES scenarios, A1b, A2, and B1, by six GCM models from different organizations of the world, are employed to analyse the changes in freshwater resources availability due to climate warming. All of the GCM outputs are provided by the Program for Climate Model Diagnosis and Intercomparison (PCMDI). Due to a lack of the outputs for SRES B2

Table 1 Descriptions of climate forecasting data used for water resources analysis.

Model's name	Short name	Organization	Original resolution
Current (1986–1995)			
GSWP2-B1	GSWP2	GEWEX/GSWP2	1° × 1°
Future (2000–2100)			
GISS-ER	GISS	NASA/Goddard Institute for Space Studies, USA	5.0 × 4.0
MIROC3.2-Med	MIROC	CCSR/NIES, Japan	T42L20
MPI-ECHAM5	ECHAM	Max Planck Institute for Meteorology, Germany	T63L31
MRI-CGCM2.3.2a	CGCM	Meteorological Research Institute, Japan	T42L30
NCAR-CCSM3.0	CCSM	National Center for Atmospheric Research, USA	T85L26
UKMO-HadCM3	HadCM	Hadley Centre for Climate Prediction and Research, MetOffice, UK	2.5 × 3.75L19

scenario in PCMDI's data archive, we could not assess the water resources situation change for that scenario.

Table 1 shows the detailed information of the six GCM models. The original various spatial resolutions of the models outputs, i.e. total runoff, were interpolated linearly to global grid cells in 1.0-degree resolution.

The six GCMs' outputs for runoff are employed for estimating the future potential change in water resources supply. To do this, we averaged the 30-year GCM predictions at each time slice to minimize the inter-annual variability. The average of 1970–1999 was used for the present time slice, 2010–2039 for the 2020s, 2040–2069 for the 2050s, and 2060–2089 for the 2070s, respectively. Then, the differences of annual and monthly runoff at 1.0-degree grids in the 2020s, 2050s, and 2070s via the present time slice simulated by each GCM are treated as the change of water resources due to global warming. For the present distribution of water resource availability, we employ the runoff data set of the Global Soil Wetness Project 2 (GSWP2, for details see Dirmeyer *et al*., 2006; Hanasaki *et al*, 2007) data set.

Multi-model analysis the changes in water resources

We used six GCMs' outputs analysing the global-water resources change to minimize the model-specific uncertainty due to single GCM's dynamics and parameterization. Through multi-model analysis we can enhance our confidence on the regions/basins with consistency to change directions of water supply among different GCMs, and investigate the detailed seasonal (monthly) changes in the typical basins with consistency in annual runoff increasing, decreasing, or no change.

The method of multi-model analysis included the following steps. First, we calculated the basic statistical parameters of each grid, such as ensemble mean, standard deviation, and coefficient of variation (Cv) of the 30-year mean runoff with bias correction by GSWP2 data set in future time slices of the six ensemble members. Then the grid-scale variability of runoff among the six GCMs was evaluated using Cv for screening the grids significant or insignificant in the forecasted consistency of runoff amount simulated by the six GCMs. In other words, if the Cv of one grid is larger than a threshold value, the future runoff simulated by the six models at that grid will be insignificant or of low confidence in forecasted consistency, and *vice versa*. The threshold value is set as 0.1. Finally, we calculated the rate of change for the ensemble mean of future runoff against the current runoff at each grid; then, we classified the globe into four categories as: increase with high confidence, decrease with high confidence, no-change with high confidence, and change amplitude/direction uncertain. The classification criterion is 5% change against the current runoff. If increase (or decrease) in runoff is more than 5%, the grid is then classified as increase (or decrease) with high confidence; if the change in runoff is less than 5%, the grid is then classified as no-change with high confidence or subtle change. The change amplitude/direction uncertain regions are not classified.

In order to investigate how the water resource will possibly be changed intra-annually in the regions where the predictions among GCMs are highly convergent or divergent, we calculated the runoff change of some typical basins at monthly scale due to climate warming. Seven basins were selected for further investigation. These included the Yenisey and Parana, which represent basins with a high consistency in runoff increasing among the six GCMs; the Mississippi, which represents basins with a high consistency in subtle runoff change; the Garonne and Euphrates and Tigris, which represent basins with a high consistency in decreasing runoff; and the Amazon and Yellow River, which represent basins with a high inconsistency in the change in direction and/or amplitude of runoff.

RESULTS

Change in annual available freshwater resources

Figure 1 shows the changes in availability of global freshwater resource for the three SRES scenarios in different regions and for the world. On a global scale, the annual water availability will probably increase due to climate warming, which would enhance the hydrological cycle and increase precipitation and runoff. However, the change in amplitude varies, largely depending on the model. NCAR-CCSM3 shows the highest increase of total runoff due to climate warming; while MRI-CGCM2-3-2a forecasts the lowest runoff and slow rate of increase in total runoff. On a global scale, the difference of the change in annual global runoff among the models results range from 7 to 11%, depending on the climate scenario, which accounts for around 3000 to 5000 km^3 year of the terrestrial discharge.

At the regional scale, however, the change trends of water resource forecasted by the six GCMs show large divergence (Fig. 1). All the six models predict water resources in Northern America and CIS (Commonwealth of Independent States) will likely increase and the increasing range among the GCMs is about 5–10%. However, for the other regions, some models predict the water resource will increase, while other models predict a decreasing trend (Fig. 1), particularly in Latin America, the Middle East and Africa. Most models see water resources availability is likely to decrease in

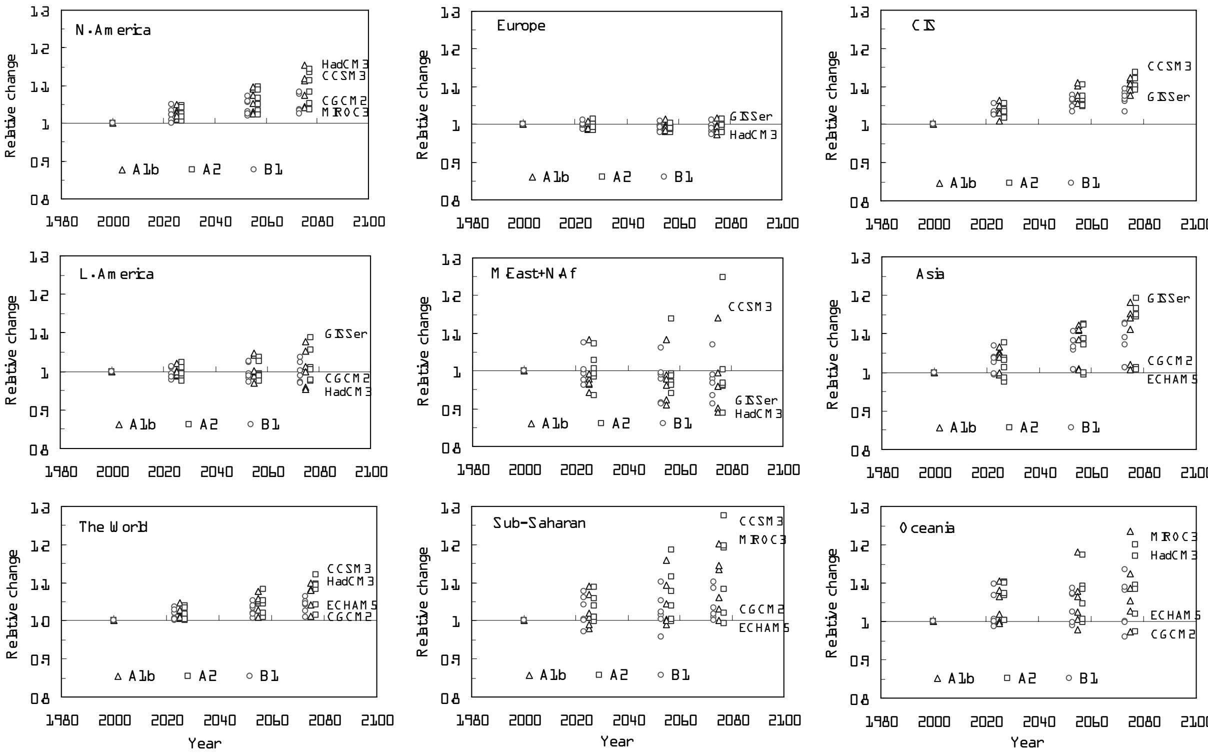

Fig. 1 Projected water resources changes in 8 regions and the world by the six GCMs. The names of the models giving highest and lowest projections are marked next to the points of 2070s.

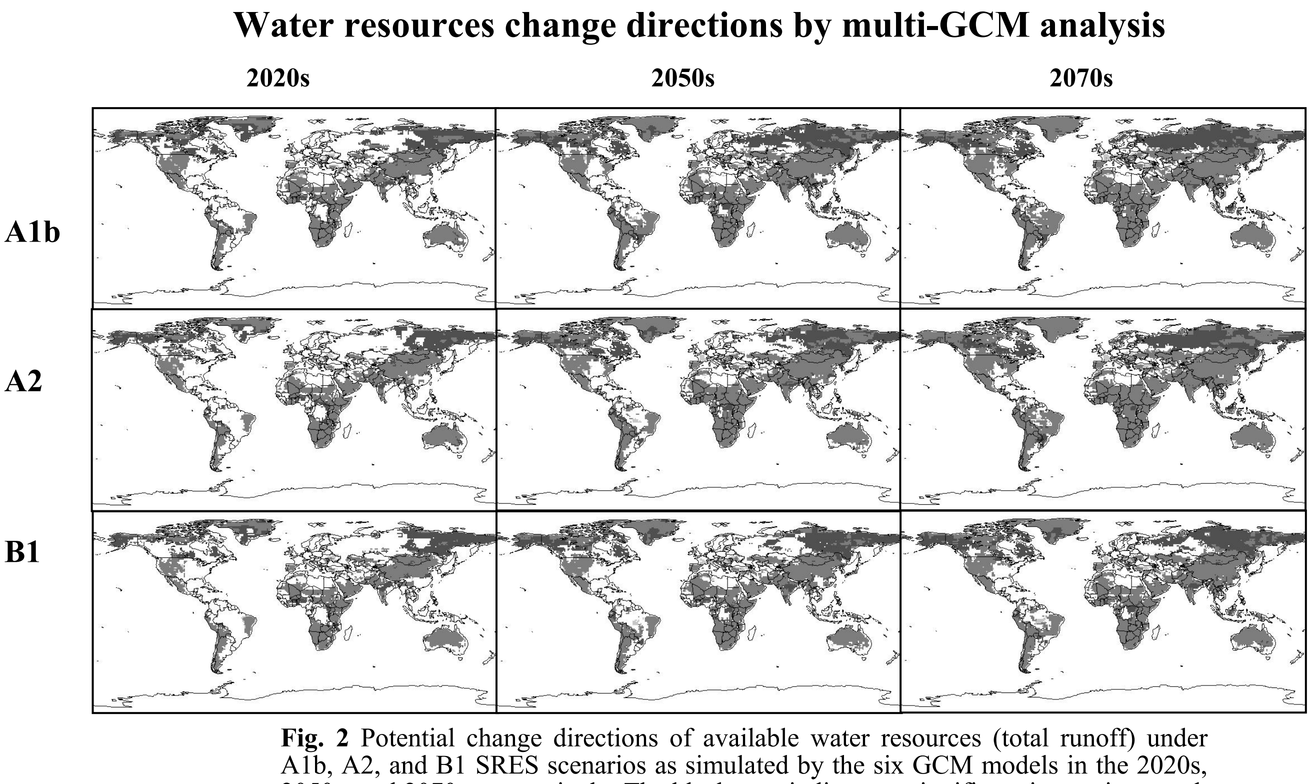

Fig. 2 Potential change directions of available water resources (total runoff) under A1b, A2, and B1 SRES scenarios as simulated by the six GCM models in the 2020s, 2050s, and 2070s, respectively. The black area indicates a significant increasing trend, light grey for significant decreasing trend, and white for subtle change. The areas with dark grey show large uncertainty in change directions among the different GCMs.

Europe; while, in Asia, Oceania, and Sub-Saharan Africa most models forecast water resources will be likely to increase. The model names of the GCM, which give maximum or minimum forecast in each region, are also labelled.

Figure 2 shows the spatial distributions of water resource change direction at grid scale for the three SRES scenarios in the 2020s, 2050s, and 2070s, respectively. Most areas with significant increasing trends are located in the boreal regions, central Africa, India, South-China, and Indonesia. The eastern USA, most of Europe, and some part of South America show subtle change in annual runoff in the 2020s and 2050s. The European countries near the Mediterranean Sea will probably become drier in future years compared to the present. There are large areas in semiarid to arid regions (e.g. North China, central Asia, Middle East, the Sahel, East and South Africa, western USA, and inland Australia) that show higher uncertainty in the change directions, i.e. the different model can give completely different change directions.

Changes of monthly runoff in selected basins

We can screen the regions with high convergence or divergence in water-resource change through multi-model analysis, and enhance our confidence on the change direction, or even amplitude/quantity of annual water resource in the regions with highly forecasted consistency among different GCMs. However, in most cases, more detailed information on the change in water–resource system due to climate warming are expected, because the influence of such changes are always more important for the local area at finer spatial or temporal scales.

Figure 3 shows the monthly runoff changes of the selected six basins between the 2050s and the present situation for A1b, A2, and B1 scenarios. It is implied in Fig. 3 that although there are large forecasted consistencies among the GCMs on an annual basis, the discrepancy among different GCMs is still large in some months. For example, the forecasts among the six GCMs in the Yenisey River basin show large consistencies in annual runoff change that will probably increase in the future (Fig. 2), but the forecasted change in spring months (March and April) still remains a large range among different models (Fig. 3). Similar phenomena can be seen in the other selected basins (Fig. 3). This suggests that the different GCMs describe different pictures of the future water resources.

However, the multi-model ensemble can still help sketch the future potential intra-annual changes in water resource of the basins. In the Yenisey River basin, the runoff in spring months is likely to increase due to earlier snowmelt, which is expected as a consequence of global warming. It means the snow melting peak is likely to be earlier than at present, and as a result the runoff in late spring (April and May) will decrease (Fig. 3). There is evidence that the runoff in autumn (September and October) is also increasing. Note that different scenarios show the evident difference in the amplitude and timing of the changes. The largest increase or decrease in A2 and B1 scenarios occur in April and May, showing about one month later than A1b scenario. B1 shows the smallest change. This is probably caused by the higher temperature increasing in the A1b scenario due to higher greenhouse gases emission. On the other hand, the changes in monthly runoff in Parana occur in the summer months, suggesting the increase might be caused by the increase of precipitation in summer.

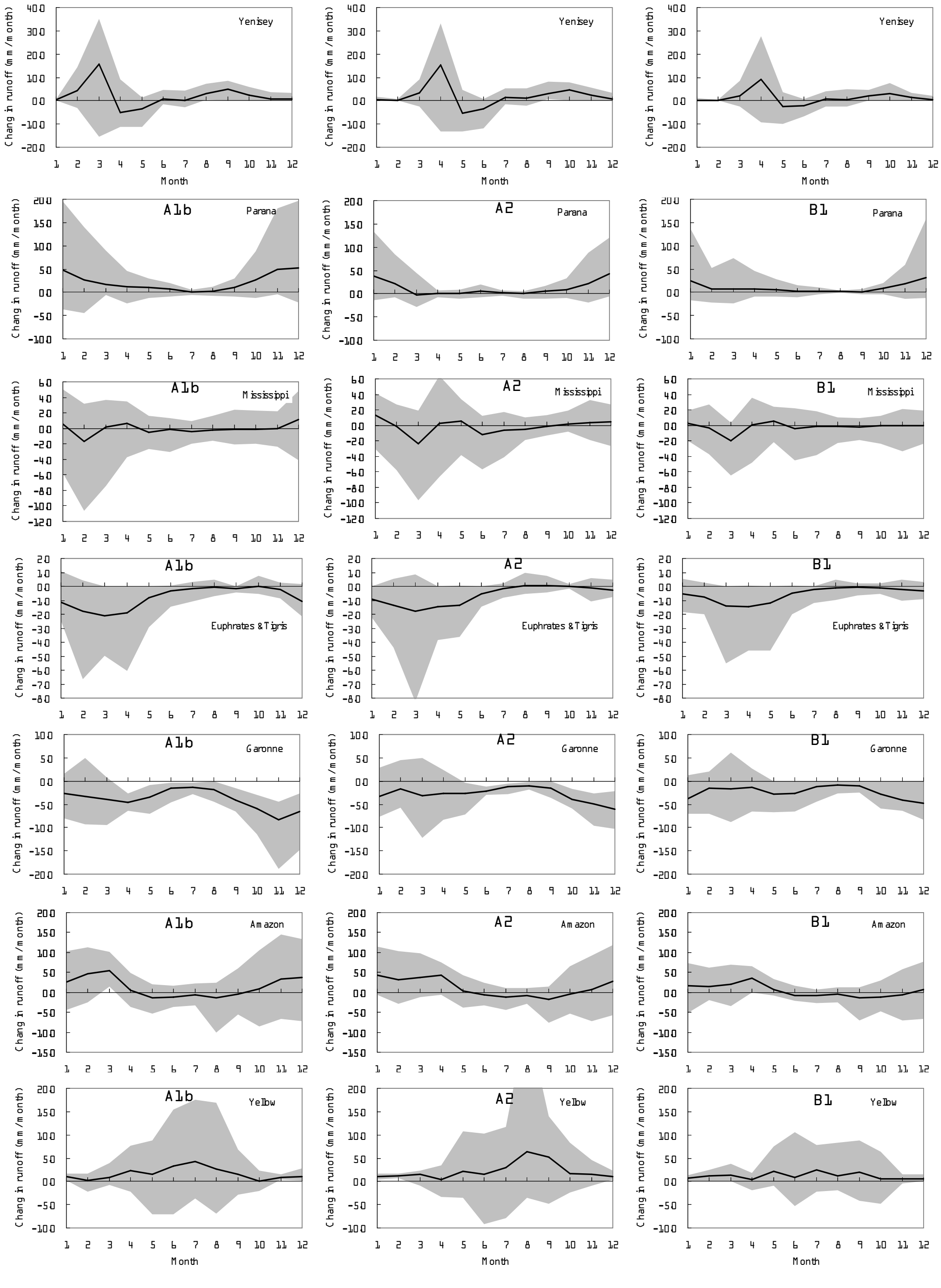

Fig. 3 Multi-model averaged changes in monthly runoff of the selected basins between 2050s and the present for SRES A1b, A2, and B1 scenarios. The solid line shows multi-model averaged change, and the shaded area shows the range among the different GCMs.

The simulated changes in the Mississippi River basin, where the annual runoff is forecasted to subtly change, primarily occur in the spring months, but the changes detected by the ensemble mean of the six GCMs are very subtle.

For the rivers with runoff decreasing annually, such as the Garonne, Euphrates and Tigris, the multi-model ensemble illustrates that the water resource probably decreases through nearly all months, but the decrease in winter months, or rainy season, seems more significant in these Mediterranean climate basins (Fig. 3).

In the Amazon and Yellow river basins, where the annual runoff change is very different among the six GCMs, the forecast shows a large range of the change in monthly runoff among the different models, especially for the rainy season. But the range among GCMs in the dry season, i.e. June–July in the Amazon and winter months in the Yellow basin, is very small, illustrating a higher consistency of the forecasts of the different GCMs in dry months in these basins.

DISCUSSION AND CONCLUSIONS

General circulation model and global hydrological modelling skills have become more advanced in the last decade. Additionally, there has been great progress made in computer science and technology. However, the variability among GCMs in some regions is still large due to their different dynamics and parameterization. For example, there is large variability in predicted precipitation or runoff among different GCM models, even though they all show a similar changing trend. On the other hand, an analysis of monthly changes in runoff in the regions with high consistency among different GCMs shows there still are large discrepancies in the amplitude of change.

It is clearly illustrated that the cause of the increase in runoff due to climate warming are different between the arctic river basins (e.g. Yenisey) and the basins in mid-latitudes (e.g. Parana). The increase in runoff of the Yenisey basin occurs primarily in spring and autumn months due to an increase in snow melting and precipitation. However, the increase in the Parana River basin primarily occurs in the summer months, implying that the increase in precipitation might be the major reason.

River basins with decreasing annual runoff are detected in the regions surrounding the Mediterranean Sea. The decrease in water resources occurs in the winter months or in the rainy season, indicating the decrease in winter precipitation will greatly affect the water resource change in such regions.

Another difference is found among the different scenarios. A1b shows the largest change amplitude because of its intensive emission of greenhouse gases, while B1 shows the smallest change due to its least emission of greenhouse gases among the SRES scenario families. Moreover, the timing of the largest change occurring is also different among the scenarios.

The effects of climate warming on the entire water-resource system are beyond the scope of study here. However, the impacts of climate change on patterns of precipitation, flood and drought frequency, crop-water requirement scheme, extreme events, and so on, always manifests at finer scales, including temporally at intra-seasonal or daily and spatially at sub-basin, grid, or sub-grid scales. Future investigations must address these aspects at finer scales to better understand the effects on the water-resource system and how human society could be better prepared for these changes.

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