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An analysis of the variation in hydrological conditions in the Korean peninsula due to global warming

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Abstract In this study, a mesoscale atmospheric/hydrological model (IRSHAM96) and a water balance model are applied to predict the possible changes in hydrological conditions (precipitation, air temperature, runoff, etc.) in the Geum River basin, Korea. From the simulation results for $1\times CO_2$ and $2\times CO_2$ conditions, it was found that the precipitation, soil moisture and runoff would decrease in spring, winter and autumn, but increase in summer due to the increase in CO_2. However, the air temperature and evapotranspiration amounts were found to increase in all seasons due to the increase in CO_2. As a result, it was predicted that the frequency of drought and flood occurrences in the Geum River basin would increase due to global warming.

Key words atmospheric/hydrological model (IRSHAM); CO_2; water balance model; Geum River, Korea

INTRODUCTION

Global warming has occurred since the industrial revolution and it has been getting worse recently. Even though the increase of greenhouse gases such as CO_2 is thought to be the main cause for global warming, its impact on the global climate has not been revealed clearly in a more quantitative manner. However, research using a general circulation model (GCM) has shown that the accumulation of greenhouse gases increases the global mean temperature, which in turn impacts the global water circulation pattern. These changes in global water circulation pattern result in abnormal and more frequent meteorological events, such as severe floods and droughts, which are now common around the world and are also referred to as an indirect proof of global warming. Thus, the Korean peninsula cannot be an exception and has experienced several hydrological extremes recently.

The objective of this research is to predict the hydrological environment changes in the Korean peninsula due to the global warming. A mesoscale atmospheric/

hydrological model (Integrated Regional Scale Hydrological–Atmospheric Model—IRSHAM96) is used to physically distribute the GCM simulation data into inner domains considering topography, land use and soil characteristics for the prediction of the possible changes in precipitation and temperature in the Korean peninsula. A conceptual water balance model is also used to analyse the changes in soil moisture, evapotranspiration and runoff in the Geum River basin, one of the four large river basins in the Korean peninsula.

THE CHANGES OF PRECIPITATION CHARACTERISTICS IN THE KOREAN PENINSULA

The change in annual precipitation pattern from 1954 to 1999 at 12 selected stations in the Korean peninsula can be seen in Fig. 1. Obviously, the annual precipitation does not show any particular trend of increase or decrease; however, the range between its maximum and minimum has been expanded greatly in recent years. It may also be seen that the extreme events of floods and droughts are repeated but irregularly in Korea.

This pattern of increase over recent years can also be found in the analysis of the frequency of occurrence of daily precipitation greater than 50 mm, which is believed to affect flood occurrences (Angel & Huff, 1997; Yoon *et al.*, 1999). For example, Yoon *et al.* (1999) showed that the annual precipitation amounts in flood years have a close correlation with the number of wet days with greater than 50 mm precipitation from the analysis of daily precipitation data in the Geum River basin in Korea. Angel & Huff (1997) also explained the trend of heavy rains using the same threshold level

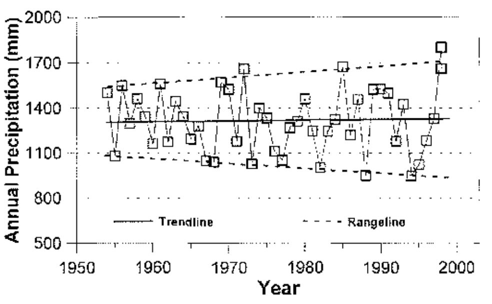

Fig. 1 The change in annual precipitation pattern in the Korean peninsula.

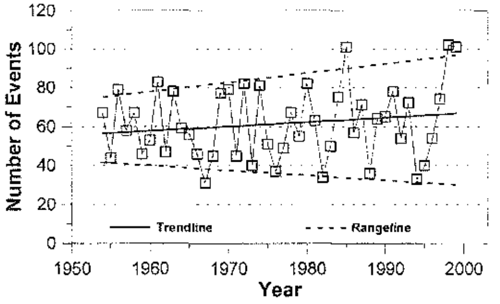

Fig. 2 Trend in the number of events with precipitation greater than 50 mm.

through the analysis of the number of daily precipitation events at 304 stations in the midwestern United States. Figure 2 shows that the number of events with greater than 50 mm precipitation increases during the 1980s–1990s compared to that during 1950s–1960s. Similar to Fig. 1, Fig. 2 has no obvious trend of increase and decrease in the number of wet days with greater than 50 mm precipitation, but its range of fluctuation becomes larger in recent years. It also shows that floods have occurred more frequently in recent years than in the past.

PREDICTION OF ANNUAL RUNOFF BY WATER BALANCE MODEL

The water balance equation can be written as:

$$\frac{dZ}{dt} = P - R - f(S) \cdot ET_p \tag{1}$$

where Z, P, R, S and ET_p are soil moisture, precipitation, runoff, soil moisture ratio and potential evapotranspiration, respectively, and f(S) is a function of the soil moisture ratio, S. The function f(S) is concerned with the vegetation of a basin and can be calculated as follows (Kaczmarek, 1990; Yates & Strzepek, 1998):

$$f(S) = \frac{5S - 2S^2}{3} \tag{2}$$

Runoff is a function of soil moisture ratio and precipitation (Rodriguez-Iturbe *et al.*, 1991):

$$R = \alpha \cdot S^{\beta} \cdot P \tag{3}$$

where α and β are parameters.

From equations (1)–(3), the water balance equation can be expressed as:

$$\frac{dZ}{dt} = (1 - \alpha \cdot S^{\beta})P - (\frac{5S - 2S^2}{3})ET_p \tag{4}$$

To apply water balance model to the Geum River basin, constant parameters α and β must be determined. In this research, monthly runoff and potential evapotranspiration data for 1981–1999 in the Daechung Dam basin (area: 4134.54 km^2), an upstream part of the Geum River basin, were used to calibrate and verify the parameters α and β.

As the runoff data are available since 1981, just after the Daechung Dam was completed in 1980, α and β were calibrated using the data collected during 1981–1990 and verified using the data collected during 1991–1999. By investigating the simulation result, α and β could be determined to be 0.67 and 0.55, respectively, and the water balance equation thus becomes:

$$\frac{dZ}{dt} = (1 - 0.67S^{0.55})P - (\frac{5S - 2S^2}{3})ET_p \tag{5}$$

The observed and simulated runoff values for the period of 1981–1999 are shown in Fig. 3(a) and (b) to compare the calibration and verification results, respectively.

(a)

(b)

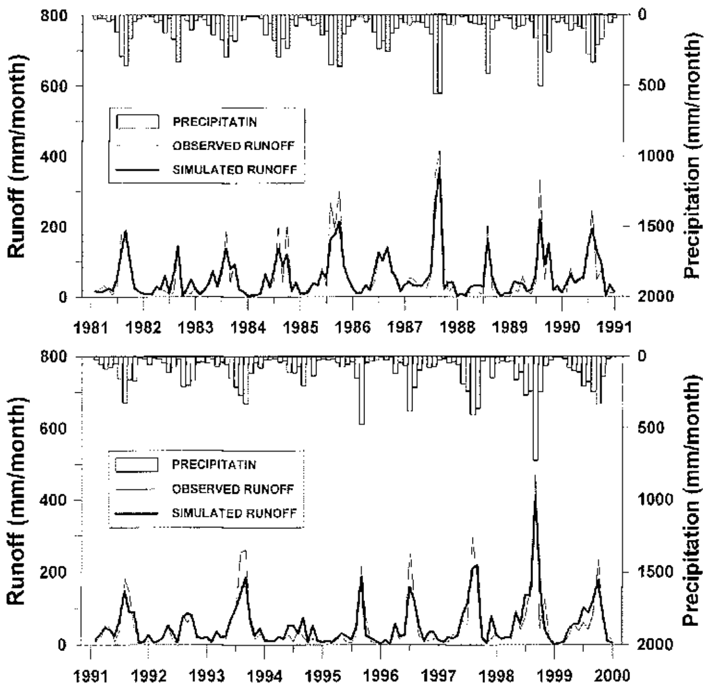

Fig. 3 Comparison between observed and simulated runoff (a) during 1981–1990, and (b) during 1991–1999 at Daechung Dam, for model calibration.

From Fig. 3(a) and (b), it was found that the water balance model expressed by equation (5) could well simulate the observed runoff in the Geum River basin.

PREDICTION BY HYDROLOGICAL–ATMOSPHERIC MODEL OF CHANGES IN ANNUAL PRECIPITATION DUE TO GLOBAL WARMING

Integrated Regional Scale Hydrological–Atmospheric Model (IRSHAM96)

The integrated regional-scale hydrological and atmospheric model (IRSHAM96) developed by Kavvas *et al.* (1995) is an integrated model of atmospheric and hydrological processes at regional scale which has been developed in order to translate the large-scale atmospheric conditions of critical climatic event to a region of 10^6 km^2. It is capable of providing quantitative information about air–soil temperature, surface water–soil moisture storage, wind velocity, relative humidity, precipitation, net solar radiation, evapotranspiration and infiltration rates, corresponding to critical scenarios of droughts and global climate change for studies of their water resources impacts and environmental consequences.

The IRSHAM96 consists of a mesoscale atmospheric model and regional-scale land surface hydrological model. The atmospheric model is a hydrostatic model that is based on the conservation equation of atmospheric dynamics, moisture and thermodynamics. It is coupled with the regional land surface hydrological model through an atmospheric boundary layer model. This model has been applied to Japan with spatial resolutions from 60×60 km^2 to 20×20 km^2 using Japan Meteorological Research Institute (MRI) GCM results (Kavvas *et al.*, 1995).

Results of model application

In the present study, IRSHAM96 is used to predict the changes of hydrological conditions in the Korean peninsula due to the change of global environment. To apply IRSHAM96 for the Korean peninsula, the data sets with 20×20 km^2 spatial resolutions were constructed for the topography, soil type, land use, vegetation type and snow cover.

As results of the MRI GCM simulation, several GCM data sets were produced and compiled into one compact data file consisting of: horizontal velocity in the longitudinal and latitudinal directions (U and V), air temperature (T), mixing ratio (Q) and geopotential height (Φ) which are in the σ-coordinate system of the MRI GCM. Then they were interpolated to the P-coordinate in the vertical direction at $P = 1000$, 900, 800, 700, 600, 500, 400, 300, 200 and 150 mb. The surface air temperature (T_s), the monthly mean ocean surface temperature (T_{sea}) and the monthly mean surface mixing ratio (Q_{sea}) were also computed. Using these MRI GCM data, a group of data sets, each containing one month of data for U, V, T, Q and Φ with 4° latitude × 5° longitude grids and 10 P levels in the vertical direction, and T_s, T_{sea} and Q_{sea} at 12-h intervals, were produced and used as input data for the model. Additionally, the data sets (precipita-

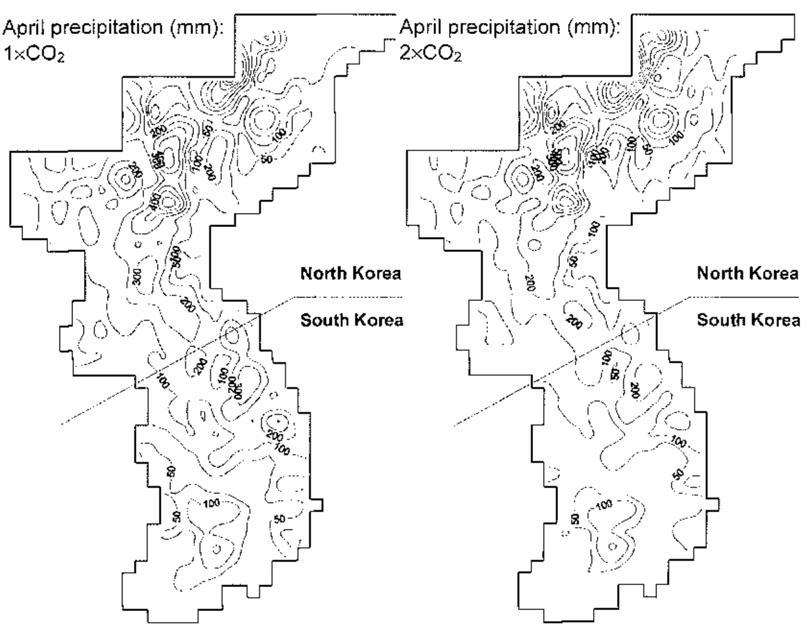

Fig. 4 Simulation results of precipitation in April for $1\times CO_2$ and $2\times CO_2$ conditions in the Korean peninsula.

tion, air temperature, runoff, etc.) during 1981–1999 in Geum River basin were used to predict the changes in hydrological conditions using the water balance model.

After data sets had been constructed for IRSHAM96, it was applied to the study of the impact of climate change on the hydrological conditions over the Korean peninsula. The change of hydrological conditions due to global warming varies with spatial locations and the time of year. For example, comparing the conditions of $1\times CO_2$ and $2\times CO_2$, the April precipitation is shown to decrease in South Korea within the range of 20–30 mm, but increase by about 30–40 mm in North Korea, as can be seen in Fig. 4. It was also found that the annual precipitation in the Korean peninsula has the tendency of decreasing, but the summer precipitation was shown to increase as a result of CO_2 increase.

Additionally, the conceptual water balance model was applied by utilizing simulation results of IRSHAM96 to analyse the changes in soil moisture, evapotranspiration and runoff in the Geum River basin. From the simulation results using the water balance model for $1\times CO_2$ and $2\times CO_2$ conditions, it has been found that the runoff decreases in spring, winter and autumn, but increases in summer due to CO_2 increase.

Therefore, it can be concluded that the frequency of drought and flood occurrence in the Geum River basin will increase under $2\times CO_2$ conditions.

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