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Precipitation Change in Korea due to Atmospheric CO_2 Increase

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ABSTRACT : A precipitation change scenario in Korea due to atmospheric CO_2 doubling has been provided with a mixed method (Robinson and Finkelstein, 1991) based on the simulated precipitation data by three GCM (CCC, UI, and GFDL GCM) experiments. Through the analysis the precipitation change by atmospheric CO_2 doubling can be summarized as follows: Korea may have more precipitation as much as 25 mm/yr during spring season and more than 50 mm/yr during summer and autumn, respectively. In the contrary Korea may have less rainfall as much as 13 mm/yr during winter. In terms of percentage with respect to current climatological value of precipitation Korea may have more rain as much as 10%, 13% and 24%, respectively, for spring, summer and autumn than current climate. However, Korea may have less precipitation during winter than current climatological average.

1. Introduction

The concentration of greenhouse gases in the atmosphere has been gradually increased since the industrial revolution of the seventeen century due to heavy use of the fossil fuels (Trend, 1991). Recently many climatologists reported that the atmospheric CO_2 concentration will be double its pre-industrial revolution value in near future, if the current increasing trend of CO_2 does not slow down. Meanwhile, the explosive increase of human population keeps pushing to develop the forest area in the industrial countries located at the mid-latitudes mostly. Such a continuous development has been expanded to not only the tropical rainforest region but also the Tundra in Siberia already. The development of forest takes away the chance of removing the atmospheric CO_2 through the solidification of the plants. In other words, we may accelerate the increase of CO_2 in the atmosphere by the massive use of fossil fuel in one hand and by putting a restriction on solidification of the carbon cycle in another hand (Pastor and Post, 1986).

In 1990 about 300 leading scientists of the world in climate change problem warned that the increase of atmospheric CO_2 may intensify the greenhouse effect, which is occurred by the relatively

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transparent characteristics of greenhouse gases in the atmosphere for the solar radiation but opaque for the longwave radiation from the earth's surface. They concerned about the global warming resulting from the intensification of greenhouse effect. They also reported that it may bring significant risks on the human life itself in addition to the global warming such as the frequent occurrence of extreme weather phenomena, the change of precipitation pattern and the rising of sea-level (WMO/UNEP, 1990). In particular, the expected global warming is not a slow and periodic natural variation but a rapid anthropogenic change. The fact that it is not periodic but directional and very fast compared to the past change of greenhouse gases concentration in the atmosphere is sufficient enough to bring awareness to us. Bruce(1994) reported that the property loss by natural disaster during the last ten years became quadruple since 1960s. Also, he insisted that this trend will be growing more rapidly.

The shrink of forest area resulting from the economic development and the increase of buildings and pavements resulting from the urbanization may allow additional chance of severe flooding. For example, the run-off at Ontario, southern Canada has been increased about 10~43% of its traditional value by urbanization in this region (Organization for Economic Cooperation and Development, 1986). Recently many climate change studies noted the possibility of severe floods and droughts in near future than present based on the simulation of general circulation model (GCM) for the situation of greenhouse gases increase (Rind, 1993; Rowntree, 1993). In other words, it is expected more frequent floods in the wet regions, while more severe droughts in the relatively dry regions (Meehl, 1993). This is another dangerous factor on human life in addition to the growing risk due to the natural disaster caused from the competitive economical development in the world.

One of the ways to easy the global warming is to reduce the concentration of CO_2 in the atmosphere. It might be achieved through reduction of fossil fuel usage and expanding the forest area to remove the atmospheric CO_2 by plants. None of them, however, can be achieved easily and effectively. As Pearce (1991) reported, these are hardly considered as effective solutions of the global warming because the depress of fossil fuel usage may bring an economic depression and the reforestation at the developed area will take a significant time to plant to grow.

Now, it is about time to set up a conserving plan against the potential global warming by industry itself. In particular, this plan should be prepared in consideration of several possible scenarios on the climate change to minimize the impacts of global warming on both social and economic situation. The global warming has been known as one of the most rapid transition to the earth's ecosystem in the earth's history. Also it affects not only on our current economic activities but also on the future of human life. The main objective of this study is to prepare a necessary information to assist to provide a reasonable confrontation plan against the potential precipitation change in Korea.

2. Climate Simulation with GCM

GCM as well as many other numerical models have been developed and enhanced for the better simulation of the global climate based on the physical laws. In particular, GCM is known as the only and the most effective tool to provide essential informations of climate change at this moment, because it provides relatively objective numerical data of the past as well as the future climate in consideration of necessary numerous interactions among important physical processes in the climate system. Thus, GCM is a combined tool consist of many numerical schemes to represent the climate system based on scientific laws, however, it still includes several not physically-based numerical techniques from either empirical studies or experiences due to the limits of our knowledge on the nature and/or compute hardware and software. Actually most of contemporary GCMs do not have enough spatial resolution due to the technical restriction. Thus, GCM involves many mathematical characterizations so-called parameterization to represent the relatively small scale atmospheric phenomena compared to the size of GCM grid. The parameterizations in the GCM are kept to be enhanced for better simulation of climate because many important variables in the GCM are directly related to the mathematical representations.

The hydrosphere is one of the most important components in the climate system. The earth known as aqua-planet in the solar system is distinguished from other planets by the existence of water. With such important existence of water in the earth, most contemporary GCMs are still limited to represent many necessary interactions of clouds and ocean which play key roles in the water cycle of the earth. This is the major reason why the precise prediction of future climate is not easy. For example, Cess et al. (1990) reported that there is some similarity among the GCM simulations of climate without clouds, however, a big difference has been observed with clouds. As mentioned above, GCMs involve a number of parameterizations to describe many physical phenomena in the climate system. The difference in the GCM simulations even with the same boundary conditions may be caused from the fact that several parameterizations in GCM are still based on the unproved assumptions and/or hypotheses. Another possible explanation of difference among the GCM simulations will be the coarse spatial resolution of GCM to resolve small scale physical processes in detail. For example, the GCM experiment for either the $2 \times CO_2$ climate or gradual increase of CO_2 in the atmosphere may provide somewhat reasonable information on the large-scale precipitation pattern change, however, it may hardly present the characteristics of local atmospheric phenomena, such as the precipitation system in the Alps or Africa Plateau (Hulme, 1992).

Another difficulty in the climate change study is that the signal of climate change due to the increase of CO_2 is not clear enough to be distinguished from other signals at this moment. In the case of weaker signal of changes in surface air temperature and precipitation than that of natural variations or the interannual variation, it becomes very hard to detect the signal of climate change due to the increase of atmospheric CO_2. Even though GCMs still have many aspects to be improved as mentioned above, GCMs provide many reasonable informations of the major climatic variables, such as geographical distribution of temperature and precipitation, seasonal distribution of surface air temperature, large-scale sea-level pressure pattern and its annual variation, three-dimensional wind fields, the Jet stream at the lower stratosphere and associated storm tracks, etc. (IPCC, 1990).

3. Simulated Climate Change for the case of $2 \times CO_2$

Oh (1993) and Oh et al. (1994) reported the potential precipitation change in Korea based on the GCM simulations for the climate of $2 \times CO_2$. The GCMs used by Oh (1993) and Oh et al. (1994) are CCC (Canadian Climatic Center) GCM (Boer et al., 1992), UI (University of Illinois) GCM (Schlesinger and Zhao, 1989), and GFDL (Geophysical Fluid Dynamics Laboratory) GCM (Manabe et al., 1991). The dynamical and physical characteristics of these GCMs are summarized in Table 1. Basically, GCMs have similar physical processes and boundary conditions. But the CCC and UI GCM are considered the diurnal variation of solar radiation, while the GFDL GCM does not. Another distinguishable difference can be found in the treatment of ocean. The GFDL GCM is coupled with the three-dimensional dynamic ocean model, but CCC and UI GCM have a simple mixed layer ocean only.

Table 1. General Characteristics of Three Climate Models used on the CO_2 Doubling Experiment

Parameter	Models		
	CCC	GFDL	UI
Horizontal spatial resolution (lat. by lon.)	T32	4.5 by 7.5	4 by 5
Vertical resolution (no. of layers)	10	9	2
Geography of land/ocean distribution	Reallistic	Reallistic	Reallistic
Topography	Reallistic	Reallistic	Reallistic
Solar radiation	Seasonal and diurnal cycles	Seasonally varing, not diurnal	Seasonla and diurnal
Cloud distribution in troposphere: computed or specified	Computed	Computed	Computed
Aspects of sea-surface temperature(SST) calculation	Computed SST based on surface energy budget and specified ocean heat transport and mixed-layer heat capacity	Ocean temp. change computed by OGCM	Computed oceanic mixed-layer temperature and SST
Surface albedo over snow-free land	Depend on local vegetation	Prescribed geographically	
Normal Atmospheric CO_2 concentration used for $1 \times CO_2$ control run	330 ppmv	330 ppmv	330 ppmv
Basis of soil moisture budget calculations	Bucket method	Bucket method: one layer of soil: only one specified soil field capacity	
Number of cloud layers permittted	9	Clouds are allowed from in each layer	Clouds are allowed from in each layer
Type of ocean model: depth of mixed layer	Mixed-layer ocean model: constant 50m depth of mixed layer	OGCM	Mixed-layer ocean model: constant 50m depth of mixed layer
Horizontal oceanic heat transport?	No	Yes	No
Oceanic heat exchange between mixed-layer and deeper layer of ocean?	No	Yes	No

The precipitation might be generated through the micro-physical processes in the clouds, however, the progress of the micro-physical processes is highly related to the large-scale atmospheric circulation together with regional characteristics. Considering that our interest is not in the each event of regional precipitation but its climatological value in this study, we have to review the regional precipitation pattern with a global perspective.

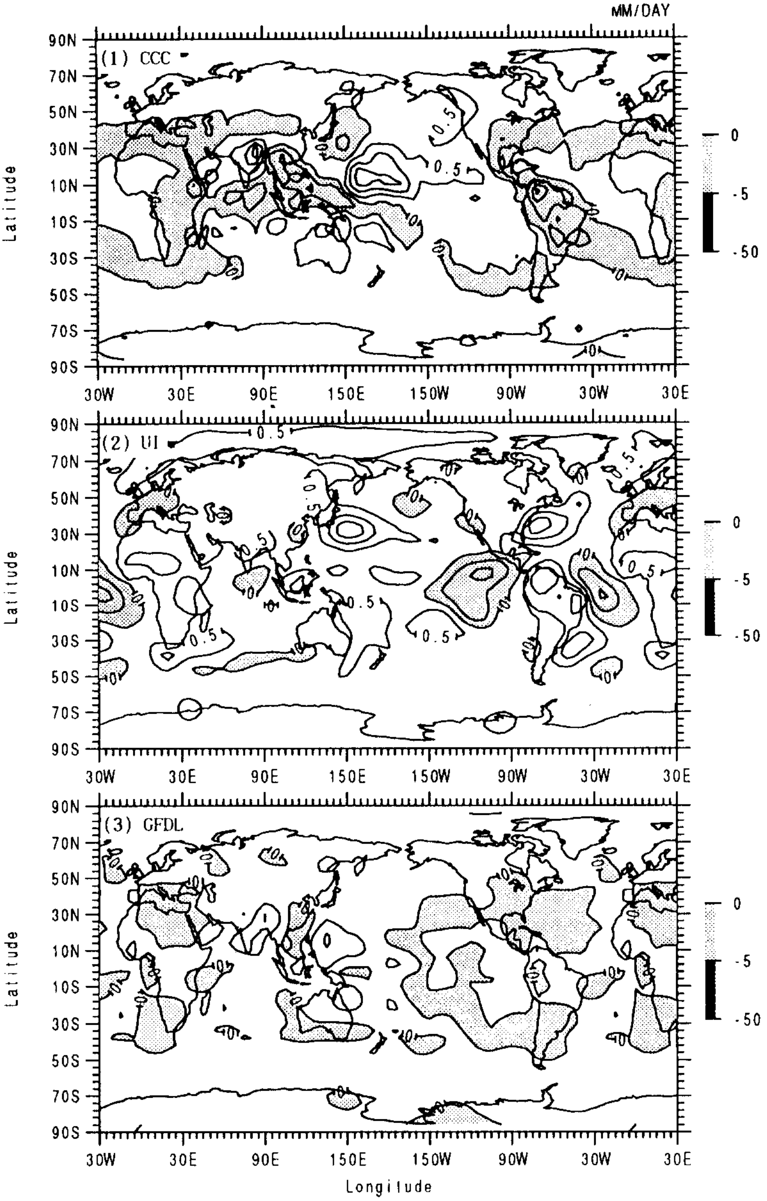


Fig. 1. Precipitation Change by GCMs with Atmospheric CO_2 Doubling: (a) CCC GCM, (b) UI GCM, and (c) GFDL GCM (Contour interval: 0.5 mm/day)

As a summary of Oh et al. (1994),, Fig. 1(a) presents the precipitation change by the CCC GCM due to the doubling of atmospheric CO_2, while Fig. 1(b) and Fig. 1(c) present, respectively, that by the UI and GFDL GCM. Over all sense the simulated precipitation has increased about 4–12% in terms of global average by doubling the CO_2 concentration in the atmosphere. In northeast Asia it reaches to about 5–21% by the UI and GFDL GCM, while it is not significant at all in the CCC GCM.

The general pattern of precipitation change due to the doubling of CO_2 is that the precipitation has increased in most current wet regions. But, it has diminished in the region of large-scale convergence in the Indian Ocean, Kuroshio, and southern Pacific significantly. The increase of simulated precipitation by the UI GCM is much larger than that by the CCC GCM in many regions. In particular, it has significantly increased at the mid-latitude ocean area in the east of major continents. But it diminished at the tropical Pacific and Atlantic. In the GFDL GCM simulation the precipitation has increased at the India-Tibetan region and tropical western Pacific particularly, while it has decreased somewhat in southeast China, Vietnam, northern and central America and the regions of surrounding the Mediterranean Sea including southern Europe and northern Africa.

In general perspective, the precipitation has been enhanced at the region near the Korean peninsula due to the doubling of atmospheric CO_2 concentration. Briefly the precipitation has diminished at southern China, Mongolia and mid-latitude wastern Pacific including Japan in the simulation of the CCC GCM. In the UI GCM simulation case it has increased significantly at the region of mid-latitude wastern Pacific including Korea and Japan, while it has diminished in the central and southern China. A similar change has been found at near the Korean peninsula in the GFDL GCM simulation.

As summarized above, all GCM simulations considered in this study show that the precipitation will increase globally with the doubling of CO_2, however, they present somewhat different pattern in the regional precipitation changes. The difference among the GCM simulations may caused from somewhat different dynamical and physical representations each other among GCMs as summarized in Table 1.

4. Empirical Relationship between the Large-scale Pattern and Regional Scale of Precipitation

The GCM simulation data is not dense enough to provide necessary informations on the regional climate change due to their relative coarse horizontal resolution (see Fig. 2). There are numerous efforts to overcome this coarse resolution of GCMs. The easiest way among them will be a direct interpolation method from the large-scale data to the detail regional scale simply. But Grotch and Mccormack (1991) pointed this simple interpolation method may mislead us to provide a meaningful regional climate informations. Recently Willey et al. (1990) suggested a linear regression method with a concept of linkage between the regional variable and the large-scale variable to provide a detail regional climate change information from the GCM simulation based on the assumption that the linear linkage is not changed all the time. They demonstrated the usefulness of this regression method to get a regional climate change information from the GCM data with the use of observations, such as monthly-mean surface air temperature, precipitation, sea-level pressure and geopotential height of 700 hPa. To obtain the future precipitation change in Korea from the GCM data the mixed method is used as shown in Fig. 3. The mixed method is one of the popular methods to provide the regional climate change scenario as reviewed by Robinson and Finkelstein (1991).

With the assumption of existence of a certain relationship between the precipitation data at the stations in Korea and that at the large-scale of GCM grids, the linear relationship has been obtained as follows (for details see Oh et al., 1994):

$$P_j^{(t)} = \sum_{i=1}^{I} a_{ij} R_i^{(t)} + \varepsilon_j^{(t)}, \; i=1, \cdots\cdots, 9; \; j=1, \cdots\cdots, 85 \qquad (1)$$

where P_j is the values of precipitation at each station in Korea as shown in Fig. 2. The subscript j represents each station marked 1 to 85, while i presents the GCM grid point surrounding the Korea. Here, we considered only nine GCM grid points as shown in Fig. 4. R is the precipitation values at the GCM grid points, a is a transfer matrix of linear regression between the regional precipitation (P) and large-scale precipitation (R). Also, ε is an error and superscript t represents a function of time.

As presented at Appendix in detail, we may obtain a relation between R and P in terms of standard deviation σ and correlation γ to minimize the sum of square of the error in Eq. (1) as follows:

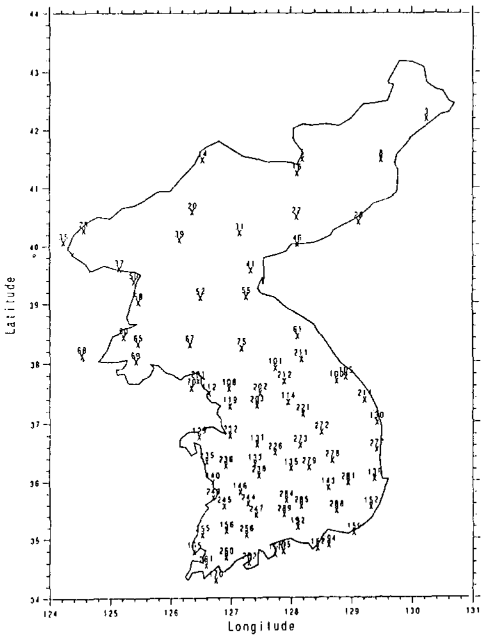


Fig. 2. Location of Rain Gauge Stations in Korea with Their Station Numbers

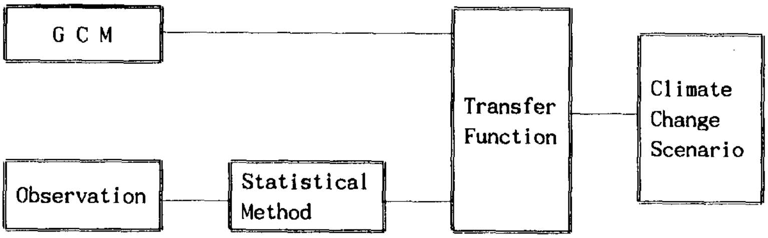


Fig. 3. Combined Scheme for Scenario Development (from Robinson Finkelstein, 1991)

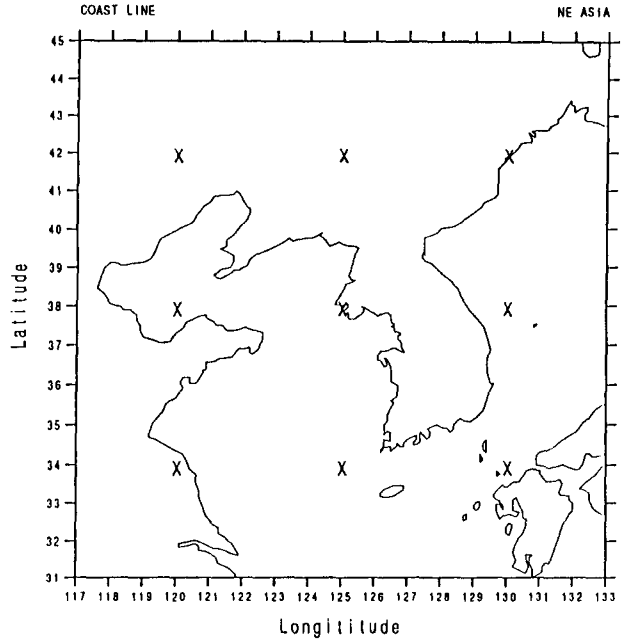


Fig. 4. Typical Location of GCM Precipitation Data Points Marked by x's near Korea

$$\sum_{i=1}^{I} \alpha_i \sigma_i \gamma_{ik} \sigma_k + \lambda \overline{R_k} = \alpha_j \gamma_{jk} \sigma_k,\ i=1, \cdots\cdots, 9;\ k=1, \cdots\cdots, 9, \tag{2}$$

and

$$\sum_{i=1}^{I} \alpha_{ij} \overline{R_i} = \overline{P_j} \tag{3}$$

where (—) presents time average, *j* and *k* are present one of GCM grid point, respectively. λ can be any variable. And,

$$\sigma_i \gamma_{ik} \sigma_k = \overline{R_i' R_k'} \tag{4}$$

and

$$\sigma_j \gamma_{jk} \sigma_k = \overline{P_j R_k'} \tag{5}$$

In Eqs. (4) and (5), $\overline{R_i R_k'}$ is covariance between the precipitation values at the GCM grid points, while $\overline{P_j R_k'}$ is covariance between the precipitation value at the GCM grid point and that at regional station. Thus, we may estimate $\overline{P}_j$ from $\overline{R}_i$, if the transfer matrix, a_{ij} is known. The transfer matrix a can be obtained from the linear equation (3) with the GCM grid values, R, and regional precipitation values, P. Also, we may estimate the regional precipitation of $2 \times CO_2$ case from the GCM simulation with the assumption of that the transfer matrix is hardly changed. It may be justified by a strong local geographical impact on the regional precipitation pattern.

The used precipitation data of observation and simulation are the observation at 85 stations in Korea during the ten years from 1983 to 1992 and the last ten year integration of the current climate ($1 \times CO_2$) by the CCC, UI and GFDL GCM. Here, the simulated data does not mean any particular ten years but represent climatology.

One more thing to be pointed is that the transfer matrix may represent regional characteristics so that it may have both temporal and spatial pattern. However, the temporal pattern is not considered in this study because the consideration of temporal pattern is not robust with the quality of GCM precipitation simulation at this moment. Since the transfer matrix is meaningful for the climatological sense only, the consideration of temporal variation of transfer matrix may result in the loss of objectiveness under such a circumstance. The precise statistical analysis will be more meaningful when the simulated precipitation data becomes more credible through the current enhancement of the physical processes in the many GCMs.

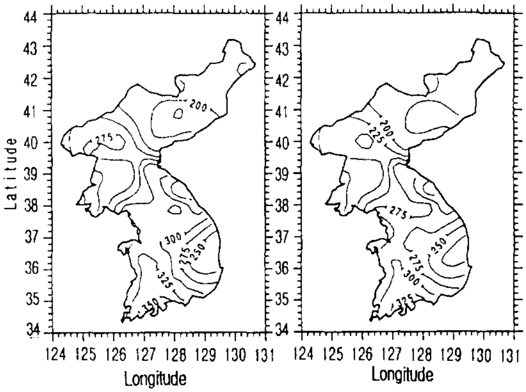
5. Regional Precipitation Change due to the Doubling of CO_2

The precipitation change in Korea for the case of $2 \times CO_2$ has been reported by Oh et al. (1994) in detail. It has been estimated from the GCM simulation with the transfer matrix obtained by the observed precipitation data and the GCM simulation for current climate as presented in section 4. The result can be summarized as follows: First, the precipitation in Korea has increased with the doubling of CO_2 in the atmosphere generally (CCC GCM, UI GCM). It is similar to the global mean response. But the increase of simulated precipitation with the GFDL GCM is only 2%, while it reaches as much as 13~15% with the CCC and UI GCM. Second, the summer (June, July and August) precipitation increases as much as 15% and 26% with the CCC GCM and UI GCM, respectively. Differently from the CCC and UI GCM simulations, it decreases about 20~30% in the GFDL GCM simulation. Third, the change of the winter (December, January and February) precipitation is opposite to the other season's precipitation so that it diminished as much as 25~30% in the CCC GCM simulation, while it is not significant in national average in the UI GCM simulation even though the regional changes are in a wide range of −4∼40% variation. However, it records as much as 4∼12% increase in the GFDL GCM simulation.

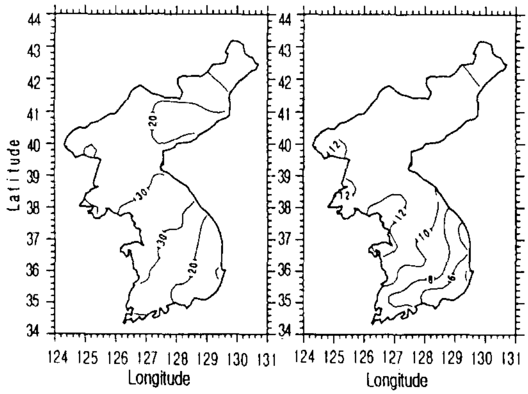
This differences among the estimation of precipitation change in Korea due to the doubling of the atmospheric CO_2 concentration may be mainly caused from both the subjective methodology to obtain the transfer matrix and the existence of some differences in the treatment of dynamical and physical processes in GCMs as mentioned above. However, it may be still fare enough to estimate the precipitation change in consideration of current our knowledge and skill level on the climate prediction at this moment.

Figs. 5∼8 have been provided from the average of GCM simulation results, even though this average does not mean real climatology by two facts: One is the limited number of GCM simulations used in this study. Another is the systematic error in GCMs to simulate the climate as presented at section 2. It is still uncertain that the source, sign and magnitude of systematic errors in the GCM simulation.

In Figs. 5∼8 the panel (a) and (b) show, respectively, the precipitation of $2\times CO_2$ and $1\times CO_2$, for spring, summer, autumn and winter. And the panel (c) and (d) present the change of precipita-

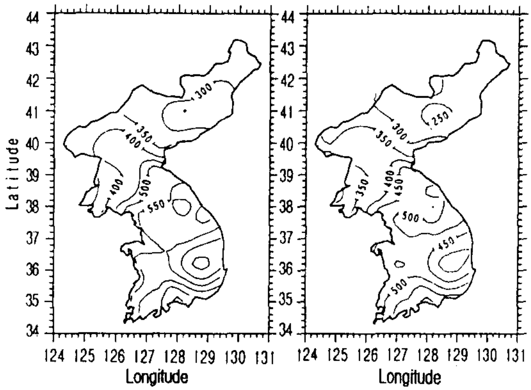


(a) GCM Mean ($2\times CO_2$) (b) GCM Mean ($1\times CO_2$)



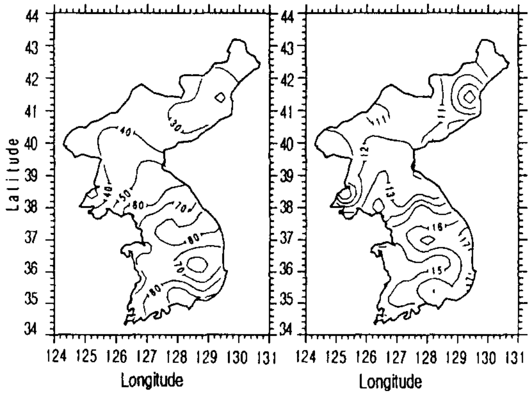
(c) Difference (mm/yr) (d) Difference (%)

Fig. 5. Regional Spring Precipitation Estimated from Three GCM's Precipitation Data



(a) GCM Mean ($2 \times CO_2$)

(b) GCM Mean ($1 \times CO_2$)



(c) Difference (mm/yr)

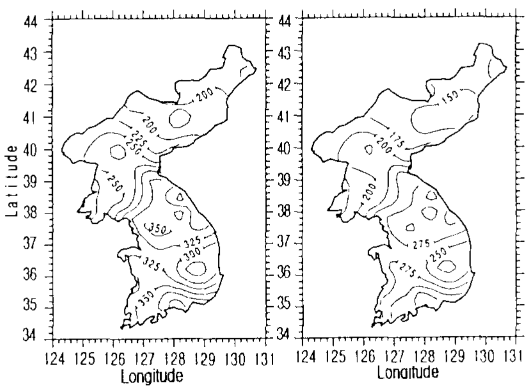
(d) Difference (%)

Fig. 6. Regional Summer Precipitation Estimated from Three GCM's Precipitation Data.

tion due to the doubling of CO_2 in the atmosphere in unit of mm/yr and percentage respect to current precipitation rates, respectively.

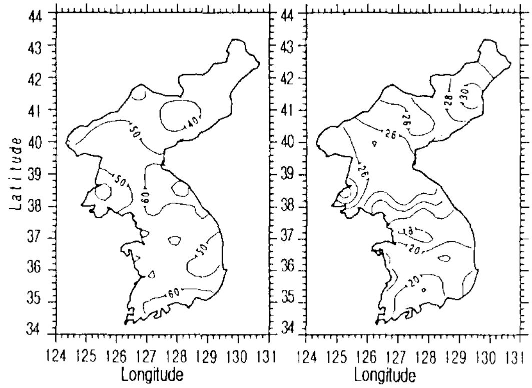
As shown in Fig. 5 the spring (March, April and May) precipitation has increased about 24 mm/yr in the national average by doubling of CO_2. It reaches to more than 30 mm/yr in the central region in Korea, while it is less than 20 mm/yr in both Youngnam province located in the southeast part of Korea and Hamkyoung-Do province located in the northeast part. It is about 10% precipitation increase in the national average respect to the current precipitation rates due to the doubling of CO_2. In terms of percentage the precipitation increase exceeds 10% in the most region of Korea except the coastal region of Youngnam province. The precipitation increase records more than 12% at the Pyoungan-Do, Hwanghae-Do and some west coastal region of Kyoungki-Do located in the western central part of Korea.

Fig. 6 presents the summer case. The increase of national averaged summer precipitation reaches to more than 50 mm/yr by doubling of atmospheric CO_2 as shown in Fig. 6(c). It reaches to more than 80 mm/yr at the southern coastal region and central region, while it is smallest as much as 60 mm/yr at the Kyoungsangbuk-Do centered at the Taegu City. The precipitation increase in the



(a) GCM Mean (2 × CO_2)

(b) GCM Mean (1 × CO_2)



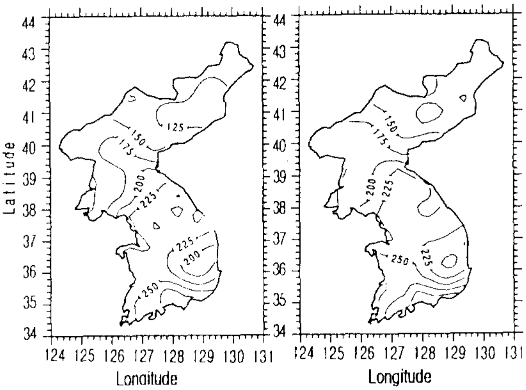
(c) Difference (mm/yr)

(d) Difference (%)

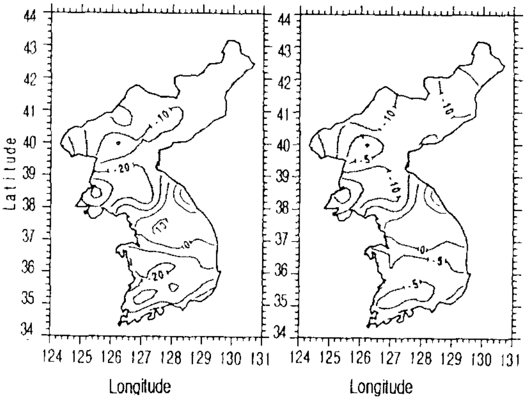
Fig. 7. Regional Autumn Precipitation Estimated from Three GCM's Precipitation Data

northern Korea is somewhat less than that in the southern Korea. And it becomes more significant northward. In terms of percentage respect to current precipitation rates the national averaged precipitation increases as much as 13%. The largest increase appears in the east coastal region of Youngnam region and the precipitation increase reaches to more than 15% in the most south coastal region. In the northern Korea it is more than 10% except the limited part of Hamkyoung-Do Province.

Fig. 7 presents the autumn case (September October and November). The precipitation has increased about 50 mm/yr. The increase of precipitation records more than 60 mm/yr at the southern coastal regions, while it is somewhat less than the national average at the northeast region (Hamkyoung-Do). In terms of percentage, however, the precipitation increase at the Hamkyoung-Do reaches to 26% and it is the highest value in Korea. The main reason of this large change in the Hamkyoung-Do is just due to the small annual precipitation in this region, which is only about 700 mm/yr. This area is the driest region in Korea with a record of about 200 mm/yr below the national average. In general, the precipitation has increased only 20% in the southern Korea, while it is more than 25% in the northern Korea.



(a) GCM Mean ($2 \times CO_2$) (b) GCM Mean ($1 \times CO_2$)



(c) Difference (mm/yr) (d) Difference (%)

Fig. 7. Regional Winter Precipitation Estimated from Three GCM's Precipitation Data

Differently from other seasons the precipitation has diminished during winter season in most Korea except the some part of central province including Kangwon-Do (Fig. 8). In average, Korea has about 13 mm/yr less precipitation than the current climate value. It is equivalent to about 7% decrease respect to that the amount of the winter precipitation which is about 200 mm. A similar precipitation change pattern has been observed with the largest decrease at the Hwanghae-Do and southern coastal region in terms of either precipitation amount or percentage.

6. Discussion

The most important thing associated with the global climate change might be the consideration of the regional precipitation pattern change. As presented in Table 2 the floods and droughts are the primary factor of human life losses by the natural disaster during the last 25 years from 1967 to 1991. Obviously the CO_2 increase may not be the only reason of this precipitation pattern change. Other potential causes on the precipitation pattern change in Korea can be selected as follows: First, it can be a result of natural variation. There are alway floods in some place on the earth and

Table 2. Total number of people affected by type of natural disater for the period of 1967 to 1991 (Obasi, 1994)

Disaster Type	Event Number	Number affected	Number killed
Floods	1,358	1,057,193,110	304,870
Droughts	430	1,426,239,250	1,333,728
Cyclones, Hurricanes, Typhoons	894	149,835,879	896,063
Storms	819	68,122,680	54,500
Cold Surges & Heat Waves	133	71,000	4,926
High Winds	Unknown	2,960	13,904

droughts in other places or heat wave here and cold serge there without any particular reasons. The precipitation is one of them changed always all the time. Second, it may be caused from the El Niño events occurred at the tropical Pacific region – one third of the whole tropics – and related variation of mesoscale circulation. The perturbation of mesoscale circulation related the variation of tropical SST spreads into the remote region. Typically the El Niño events occur once per every 3–7 years, however, recently it shows a trend to come more frequently. The recent frequent occurrence of extreme weather events may be related to the shortening of El Niño period. The climate of Korea can be also modulated by the strength of El Niño/La Niña because Korea is belong to the region under influence of El Niño and La Niña events.

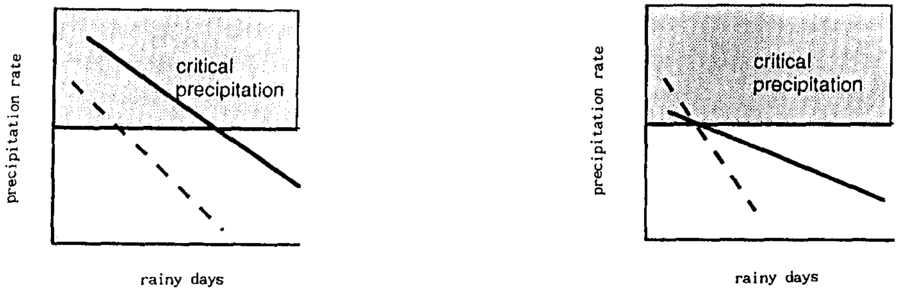
The CO_2 increase is the most anxious cause of precipitation pattern variation we faced among the above causes. Differently from other causes it is anthropogenic and not periodic. Nevertheless the precipitation is one of the most important climatic variables affecting the human life and industrial activities, our knowledge on the variation of precipitation is quite limited. The first rain gauge was invented about 550 years ago (Kim, 1990). It means the importance of precipitation has been recognized since a long time ago. However, the precipitation monitoring system is still limited only on the land. Because the ocean covers 70% of the earth's surface, the precipitation of many regions is still estimated from the statistical analysis instated of the actual measurement (Jaeger, 1976; Legates and Willmott, 1990). As a result of estimation the global daily precipitation varies in the wide range from 2.6 mm/yr to 3.15 mm/yr depending on the analysis method of the data (Jaeger and Kellogg, 1983; Korzoun, 1978). Recently the remote sensing technique has been developed to replace the estimation of the precipitation over the ocean (Arkin and Ardanuy, 1989). However, it is still study stage due to the limitation of our technology at this moment.

7. Conclusion and Suggestion

The precipitation has increased more than 25 mm/yr and 50 mm/yr during spring and summer/autumn in Korea, respectively, due to the increase of atmospheric CO_2 doubling. It is equivalent to 10%, 13 % and 24% increase of precipitation during spring, summer, and autumn respected to the current climate respectively. To obtain the precipitation change in Korea it has been assumed that the relationship between the large-scale precipitation pattern and the regional scale precipitation pattern may not be changed regardless of CO_2 doubling. Even though the relationship is not changed with time, the estimated regional precipitation change pattern is not the same from season to season because the geographical distribution of the GCM precipitation, which is a key factor to decide the regional precipitation, is different in seasons.

One important thing we have to note on this study is that the precipitation change is not obtained with a precise and objective numerical model but calculated indirectly with the coarse GCM grid point values. In other words, the precipitation change may depend on the methodology of estimation. This is one of the things to be required to improve urgently. The enhancement of hardware to simulate the climate system will provide an opportunity to estimate the regional climate directly within near future.

Finally, it is worth to be noted that the precipitation is not a contiguous weather event but a temporal event occurred in the limited area within relative short time in preparation of the precipitation change scenario with the increase of atmospheric CO_2. Accordingly, an important thing to be considered in the scenario is the occurrence of the heavy rainfall events together with a monthly rainfall amount as shown in Fig. 9. It might be more important in some industrial activities than the monthly rainfall value itself. The future scenario of precipitation change accompanied with climate change should be provided including not only a precise statistical analysis but also an information on the change of the heavy precipitation occurrence over the critical precipitation rate.



(a) Case of Increased Precipitation and Extreme Rainfall

(b) Case of Increased Precipitation and Reduced Extreme Rainfall

Fig. 9. Schematic Diagrams for Mean Precipitation and Extreme Rainfall Change Scenario (The dashed and solid line represent, respectively, current and future distribution of precipitation. The shaded area represents a critical precipitation range.)

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APPENDIX : Calculation of Regional Precipitation from the GCM Data

The estimation of regional precipitation from the GCM data is obtained based on the assumption of existence of a linear relation between the precipitation of each station in Korea ($j=1, \cdots\cdots, 85$) and the large-scale GCM data as shown in Eq. (1). In Eq. (1) both P and R are the function of time and represented with a superscription of t. Averaging Eq. (1) respect to time we may obtain two equations of mean and perturbation as follows:

$$\overline{P}_j=\sum_{i=1}^{I} a_{ij}\overline{R}_i+\overline{\varepsilon}_j, \tag{6}$$

and

$$P'_j=\sum_{i=1}^{I} a_{ij} R'_i+\varepsilon'_j. \tag{7}$$

Here, the over-bar represents time-mean and $\overline{\varepsilon}_i$ is the systematic error occurred with this method, and ε'_i is a random error, which is an additional error of each time to its time-mean systematic error. In Eqs. (6) and (7) it is assume that the transfer matrix a is not changed with time and P and R have been known already.

In Eqs. (6) and (7) a becomes any function without restriction. Accordingly, it has been assume to fix the transfer matrix a between regional precipitation and GCM data that the selected a should satisfy two conditions: One restriction is to minimize the absolute value of ε'_i. Another restriction is to satisfy $\overline{\varepsilon}_i=0$. To do that following attempts have been applied. To find out the case of minimum $|\varepsilon'_i|$ it has been squared and averaged with respect to time as follows:

$$\overline{\varepsilon'^2_j}=\overline{(P'_j-\sum_{i}^{I}a_iR'_i)^2} \tag{8}$$

Then above two restrictions can be converted to a single restriction by introducing a new variable F as:

$$F_j=\overline{\varepsilon'^2_j}-2\lambda\overline{\varepsilon}_j \tag{9}$$

Using Eqs. (6) and (8) we may rewrite Eq. (9) as follows:

$$F_j=\overline{(P'_j-\sum_{i}^{I}a_{ij}R'_i)^2}-2\lambda(\overline{P}_j-\sum_{i}^{I}a_{ij}\overline{R}_i) \tag{10}$$

Thus, the restrictions are switched to minimize F_j. Here, λ is any variable and F_j is a function of $(a_{1j}, a_{2j}, \cdots\cdots, a_{Ij}; \lambda)$. If F_j is minimum,

$$\frac{\partial F_j}{\partial a_{kj}}=0, \tag{11}$$

and

$$\frac{\partial F_j}{\partial \lambda}=0. \tag{12}$$

Using Eq. (10) we may rearrange Eqs. (11) and (12) as

$$2\overline{(P'_j-\sum_i^I a_{ij}R'_i)(-\sum_i^I \delta_{ik}\overline{R'_i})}-2\lambda(-\sum_i^I \delta_{ik}\overline{R_i})=0, \tag{13}$$

and

$$-2(\overline{P_i}-\sum_i^I a_{ij}\overline{R_i})=0, \tag{14}$$

where δ_{ik} is a Kronecker-delta defined as,

$$\delta_{ik}=\begin{cases}1, & \text{if } i=k\\ 0, & \text{otherwise}\end{cases} \tag{15}$$

With the use of this definition Eqs. (13) and (14) can bere written as:

$$\sum_i^I \mathrm{a}_{ij}\overline{\mathrm{R}_i'\mathrm{R}_k'}+\lambda\overline{\mathrm{R}_k}=\overline{\mathrm{P}_j'\mathrm{R}_i'}, \tag{16}$$

and

$$\sum_i^I \mathrm{a}_{ij}\overline{\mathrm{R}_i}=\overline{\mathrm{P}_j}, \ \mathrm{i}=1, \cdots\cdots, 9. \tag{17}$$

Here $\overline{R_i'R_k'}$ is the covariance between GCM precipitation and $\overline{P_i'R_k'}$ is the covariance between regional precipitation and GCM data. With standard deviation at each station σ and correlation γ we may obtain Eqs. (4) and (5). In Eqs. (4) and (5)

$$\sigma_i=\sqrt{\frac{1}{N-1}\sum_n^N(R_i^n-\overline{R_i})^2}\text{, } N=\textit{total number}, \tag{18}$$

and

$$\gamma_{ik}=\frac{\overline{(R_i-\bar{R}_i)(R_k-\bar{R}_k)}}{\sqrt{(R_i-\bar{R}_i)^2(R_k-\bar{R}_k)^2}}=\frac{\overline{R_iR_k}}{\sigma_i\sigma_k} \tag{19}$$

Then Eq. (16) can be written as:

$$\sum_i^I a_{ij}\sigma_i\gamma_{ik}\sigma_k+\lambda\overline{R_k}=\sigma_j\gamma_{jk}\sigma_k \tag{20}$$

Then Eq. (17) is identical to Eq. (3). Therefore, we may calculate the regional precipitation ($\overline{P_j}$) from the GCM precipitation data ($\overline{R_i}$), if the transfer matrix a is known.