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On the Relationship between Eurasian Snow Cover and Summer Rainfall in South Korea Part I: Statistical Analysis

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유라시아 적설 분포면적과 남한의 여름철 강수량과의 관계 1부: 통계적 분석

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요 약

한국 여름철 강수량은 동 아시아 몬순과 밀접하게 연관되어 있으며, 이 몬순은 대규모 적설 분포의 영향을 받는다. 이 논문은 남한의 여름철 강수량과 북반구, 유라시아 그리고 티벳 지역의 적설 분포면적과의 관계를 조사하였다. 적설 분포면적은 NSIDC의 위성 분석 자료를 사용 하였고, 남한의 강수량 자료는 12 관측지점에서 측정된 월 평균 강수량이다. 12 지점의 강수자료에 의한 요인분석 및 군집분석을 통하여 남한을 세 지역으로 구분하여 분석에 이용하였다.

연구 결과에 의하면 여름철 (6월 부터 9월) 강수량은 유라시아나 북반구의 전년도 10월 그리고 11월 적설 분포면적과 부의 상관을 보였다. 가장 높은 상관은 유라시아 전년도 10월 및 11월의 적설 분포면적과 여름철 강수량에서 나타난다 (r = -0.56). 한편, 전년도 10월 및 11월 대규모 적설 분포면적은 중서부 지역의 여름철 강수량보다 중동부 지역의 여름철 강수량과 훨씬 강한 부의 상관을 보인다.

Abstract

The rainfall of Korea during the summer season is closely related to the East Asian summer monsoon, which is in turn influenced by large-scale snow cover.

We investigated the correlation between previous season snow cover over the Northern Hemisphere, Eurasia and the Tibetan Plateau, and South Korean summer season rainfall. We used the Northern Hemisphere snow cover data obtained from the NSIDC (satellite data), and monthly precipitation data from 12 meteorological observatories in South Korea. We divided South Korea into three sectors such as middle-west sector, middle-east sector, and south sector according to the results of factor and cluster analysis of summer rainfall.

Results indicate that the summer rainfall (from July through September) is negatively correlated with the Eurasian (or the Northern Hemisphere) snow cover in the October or November of the previous year. In the case of the total summer rainfall over South Korean, the strongest negative relationship is found between the summer rainfall and the sum of preceding October and November Eurasian snow cover (r = -0.56). In general, the snow cover is most strongly correlated with the summer rainfall of the middle-east sector, and least strongly with that of the middle-west sector of South Korea.

1. Introduction

Snow cover interacts with the atmosphere on synoptic, regional or hemispheric scales (Davies, 1994). Snow cover over Eurasia plays an important role in modulating the strength of the East Asian monsoon (Hahn & Shukla, 1976; Dickson, 1984; Barnett *et al.*, 1989; Yasunari *et al.*, 1991). The results generally showed that more snow cover than normal in Eurasia and/or the Tibetan Plateau was linked with a delayed or weakened Indian summer monsoon. Barnett *et al.* (1989) suggested that this interaction might be part of a much larger effect of Eurasian snow cover on global climate dynamics. They also argued that greater snow cover (and its eventual melting and evaporation of the melted water) weakened the summer heating of the Asian land mass and, hence, the land/sea temperature contrast which drives the monsoon. A model-based study (Yasunari *et al.*, 1991) has shown that, during summer months, the snow-hydrological feedback can induce a weakening of the Asian summer monsoon to some extent. The weakened monsoon is characterised by higher sea level pressure over India, a weaker Somali jet, weaker lower tropospheric westerlies, and weaker upper tropospheric easterlies (Verneker *et al.*, 1995). The weak monsoon is also associated with the weaker secondary circulations. Verneker *et al.* (1995) also argued that the remote response to excessive Eurasian snow cover is to reduce the strength of trade winds in the eastern equatorial Pacific Ocean. Hahn and Shukla (1976) have discussed an apparent inverse relationship between Eurasian mean winter (December~March) snow cover extent and following warm season (June~September) Indian monsoon rainfall for the period 1967 to 1975. Dickson (1984) substantiated this relationship by the addition of five subsequent years of data if known deficiencies in satellite snow observations are accommodated.

Some observational studies have strongly suggested that the Eurasian snow cover plays an important role in producing anomalous conditions in the coupled ocean/atmosphere system of the equatorial Pacific (e.g., El Niño) by means of the Asian monsoon (Barnett, 1985; Yasunari, 1990).

A number of studies have investigated the relationship between South Korean summer rainfall and large-scale circulation patterns or sea surface temperature (Chun and Park, 1990; Lee, 1991; Lee, 1993; Park, 1996). Lee (1991) stated that anomalously large amounts of Changma rainfall over the South Korean peninsula are associated with a strengthened upper-level anticyclonic stream function over the Tibetan Plateau. Park (1996) suggested the early development of the upper level anticyclonic flow over East Asia is responsible for the absence of the middle latitude monsoon rainfall. However a possible relationship between South Korean summer rainfall and large-scale snow cover has not previously been studied.

In this paper we analyse the relationship between the snow cover of the Northern Hemisphere, Eurasia and the Tibetan Plateau and summer rainfall (June through September) in South Korea. The precipitation in South Korea is concentrated in the above 4 months, probably linked to the Asian summer monsoon (refer to Fig. 5).

2. Data

2.1 Snow cover in Northern Hemisphere, Eurasian and Tibetan Plateau

The snow cover data over the Northern Hemisphere were obtained from the national snow and ice data center (NSIDC, http://www-nidc.colorado.edu/NSIDC/). The snow data were derived from the NOAA satellites between January 1971 and August 1995, and were in the EASE-Grid (Equal Area SSM/I Earth Grid) format, with 721 columns and 721 rows. The "Equal Area" means that every pixel represents the same area, 628.38 km^2. The North Pole is aligned with the centre of the pixel at column 361, row 361 (Fig. 1).

In this paper, "Eurasia" is the area to the right of the thick line in Fig. 1 (rows from 0 to 290 by columns from 338 to 721; rows from 291 to 431 by columns from 361 to 721; and rows from 432 to 721 by columns from 338 to 721), and "Tibetan Plateau" represents the area denoted T.P. in Fig. 1 [co-ordinates (column and row) of the corners of this area are: (568, 416), (568,304), (617,429), (617,291)]. The Tibetan Plateau's region approximately covers longitudes between 75°E approximately and 105°E and latitudes between 27°N and 40°N.

We constructed a monthly data set using the day-weighted means of the weekly snow data. Fig. 2 shows the monthly time series of the snow cover of the Northern Hemisphere, Eurasia and the Tibetan Plateau. The monthly snow cover time series of the Northern Hemisphere and Eurasia show more regular patterns than that of the Tibetan Plateau, because their seasonal cycles are much stronger relative to residual variability.

Generally speaking, the snow data derived from satellites is more reliable when applied to the large-scale rather than the small scale. Dickson (1984) pointed out that the smaller scale snow cover is more difficult to measure accurately from satellites due to persistent mountain cloudiness. Part

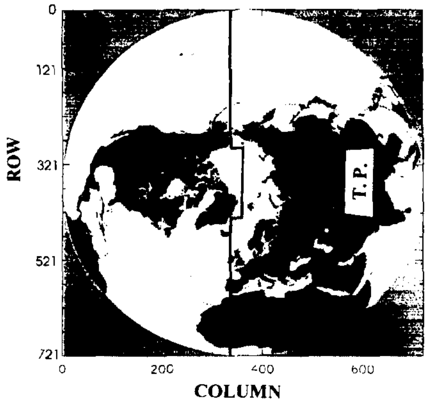

Fig. 1. Areas of Northern Hemisphere, Eurasia and the Tibetan Plateau (T.P.).

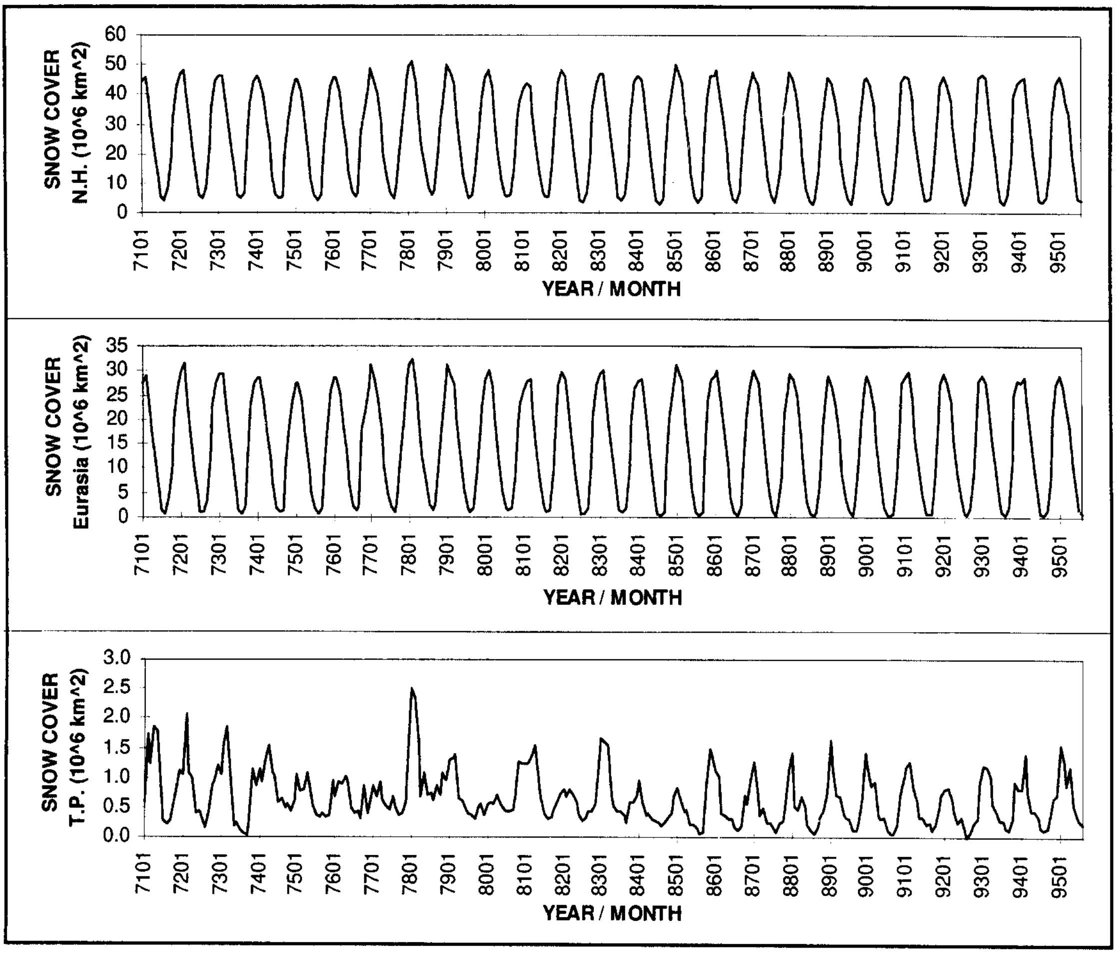

Fig. 2. Monthly snow cover time series of the Northern Hemisphere (N.H), Eurasia and the Tibetan Plateau (T.P.).

Table 1. The coefficents of linear correlation between snow covers in the Northern Hemisphere, Eurasia, and the Tibetan Plateau.

	JAN	FEB	MAR	APR	MAY	JUN	
NH : EU	0.94**	0.91**	0.92**	0.85**	0.93**	0.97**	
NH : TP	0.27	0.43*	0.14	0.31	0.47*	0.51**	
EU : TP	0.32	0.49*	0.12	0.30	0.51**	0.61**	
	JUL	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANNUAL**
NH : EU	0.92**	0.90**	0.97**	0.97**	0.94**	0.95**	1.00**
NH : TP	0.75**	0.73**	0.38	0.51*	0.45*	0.40*	0.72**
EU : TP	0.82**	0.89**	0.34	0.51*	0.44*	0.41*	0.72**

Where NH, EU, and TP mean the Northern Hemisphere, Eurasia, and the Tibetan Plateau, respectively.

* ; Correlation is significant at the 0.05 level (2-tailed). ** ; Correlation is significant at the 0.01 level (2-tailed).

of the irregularity in the record of Tibetan Plateau snow cover may be caused by the difficulty of measuring snow cover accurately from satellites due to persistent mountain cloudiness.

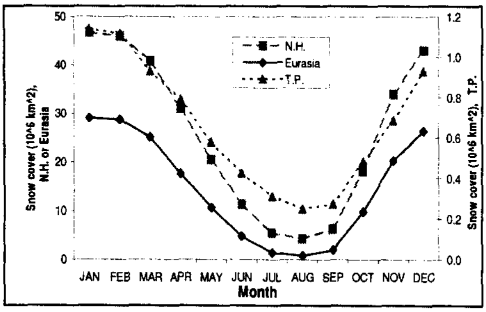

Fig. 3. Monthly mean Northern Hemisphere (N.H.), Eurasia and the Tibetan Plateau (T.P.) snow cover over 1971 to 1995.

The monthly correlations between the snow cover of Northern Hemisphere, that of Eurasia, and that of the Tibetan Plateau over 25 years are generally very high, except those between the snow cover of Northern Hemisphere (or Eurasia) and that of the Tibetan Plateau in January, March, April, and September (Table 1). The annual correlations are relatively high (Table 1).

Fig. 3 shows the mean monthly snow cover of the Northern Hemisphere, Eurasia and the Tibetan Plateau over 1971 to 1995. The snow cover of the Northern Hemisphere, Eurasia and the Tibetan Plateau show minimum values in August (4.3, 0.8, and 0.3 million km^2, respectively) and maximum values in January (46.8, 29.1, and 1.1 million km^2, respectively). The seasonal cycles show sharp increases from September until January, and then decrease rather more gradually until August.

In this paper we used the monthly snow cover time series for the Northern Hemisphere, Eurasia and the Tibetan Plateau from January 1971 to August 1995 in order to examine the relationship with summer rainfall in South Korea. We use the term "previous snow cover" to mean the extent of the snow cover from the previous October to May.

2.2 Summer season rainfall in South Korea

We used monthly precipitation data at 12 meteorological observatories in South Korea during the period January 1953 to December 1996. The stations are Kangnung (105), Seoul (108), Inchon (112), Chupungnyong (135), Pohang (138), Taegu (143), Chonju (146), Ulsan (152), Kwangju (156), Pusan (159), Mokpo (165), and Yosu (168). The numbers in parentheses are the respective station numbers and their locations are shown in Fig. 4.

Fig. 5. shows the mean monthly precipitation of the 12 stations in South Korea over 1953 to 1996 (a simple arithmetic average of the data from 12 stations).

The rainfall in South Korean is concentrated in the summer season (June through September). The summer rainfall yields 62% on average (range 43~76%) of the annual rainfall during the period 1953 to 1996. The standard deviation (SD) of the annual rainfall during the time was 222 mm, and the SD of the summer rainfall 174 mm. The summer rainfall shows large year-to-year variations and regional differences depending on observation sites. The observation at Seoul, for example, shows the largest rainfall during the summer season.

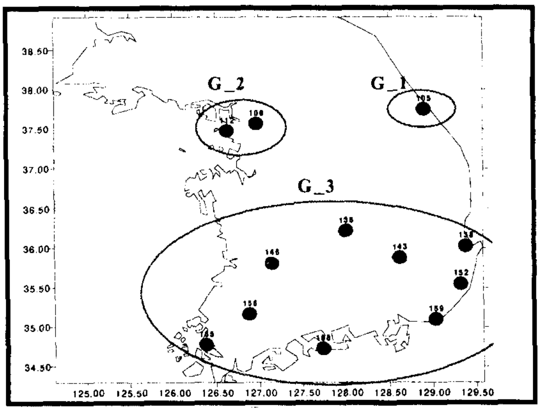

Fig. 4. Position of meteorological observatory stations and the border of three rainfall groups (G_1, G_2, and G_3) in South Korea.

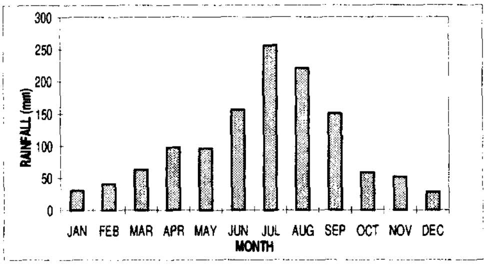

Fig. 5. Monthly mean precipitation rainfall of the 12 stations in South Korean (1953 to 1996).

Moon (1990) noted that the rainfall characteristics in South Korea exhibited regional differences according to the interaction between geographical characteristics and inflowing air patterns. We applied factor analysis (using principal component analysis) to the rainfall data of the 12 meteorological observatories. The analysis indicated that the stations should best be divided into three groups, explaining about 80% of the total variance. We also carried out hierarchical cluster analysis using the Pearson correlation measure to define three groups of stations. Table 2 shows the results of factor and cluster analysis. Based on the results in Table 2, we defined the following three

Table 2. Factor and cluster analyses of 12 meteorological observatories for the monthly rainfall in South Korea.

Rainfall (period)	Factor	Cum. % of variance	Group 1	Group 2	Group 3
June ('53~'96)	3	89.7	105	108,112	135,138,143,146,152,156,159,165,168
July ('53~'96)	3	80.3	135,146	105,108,112	138,143,152,156,159, 165,168
August ('53~'96)	3	76.6	105	108,112	135,138,143,146,152,156,159,165,168
September ('53~'96)	3	87.1	105	108,112	135,138,143,146,152,156,159,165,168
JJAS ('53~'96)	3	81.1	105	108,112	135,138,143,146,152,156,159,165,168

Numbers in the groups are the station numbers (refer to Fig. 4). JJAS means the total summer rainfall of June, July, August and September.

Table 3. Correlation coefficients between previous Northern Hemisphere snow cover (October to May) and summer rainfall in South Korea.

	Previous Northern Hemisphere snow cover								
	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	Annual Snow cover
Summer Rainfall, G_A	-0.41*	-0.43*	-0.11	0.01	0.21	0.29	-0.02	-0.02	0.01
〃 G_1	-0.60**	-0.46*	-0.24	-0.24	-0.08	0.04	-0.29	-0.16	-0.20
〃 G_2	-0.22	-0.15	0.08	-0.12	-0.22	-0.17	-0.18	-0.33	-0.24
〃 G_3	-0.36	-0.43*	-0.14	0.07	0.32	0.39	0.05	0.08	0.10

* ; Correlation is significant at the 0.05 level (2-tailed). ** ; Correlation is significant at the 0.01 level (2-tailed).

sectors for the summer rainfall, JJAS (Fig. 4):

G_1 (middle-east sector): one station [Kangnung (105)]

G_2 (middle-west sector): two stations [Seoul (108), Inchon (112)]

G_3 (south sector): nine stations [Chupungnyong (135), Pohang (138), Taegu (143), Chonju (146), Ulsan (152), Kwangju (156), Pusan (159), Mokpo (165), Yosu (168)]

We will also refer to the whole group, G_A representing G_1, G_2, and G_3. Generally speaking, the G_1 rainfall is more similar to G_2 rainfall rather than to G_3 rainfall.

3. The relationship between large-scale snow cover and summer rainfall in South Korea

We analysed the correlation between the previous snow cover of the Northern Hemisphere, Eurasia and the Tibetan Plateau, and summer rainfall in South Korea, with lead times of up to 8 months.

3.1 Relationship between Northern Hemisphere snow cover and summer rainfall in South Korea

The correlation coefficients (r) between previous snow cover of the NH and the summer mean rainfall in South Korea are shown in Table 3.

In the case of the whole groups in South Korea, there are negative relationships (significant at the 95% level) between the summer rainfall and the previous October or November snow cover (Table 3). In this case, the snow cover is much better correlated with the G_1 rainfall (r = -0.60** for the snow cover in October, r = -0.46* for the snow cover in November) than with the G_2 rainfall. The correlation coefficient for the G_3 sector is similar to that for the whole of South Korea (G_A).

Somewhat stronger relationships are found by combining months. In the case of the whole summer rainfall in South Korea, the strongest relationship is found with the sum of the snow cover from preceding October and November together (r = -0.50* ; not shown in the Table).

A decreasing trend of annual snow cover extent over the Northern Hemisphere during the past 20 years has been pointed out by Groisman *et al.* (1994). Using the NSIDC dataset, we confirmed this trend in annual Northern Hemisphere snow cover over the 1971 to 1994 period (r = -0.59** between snow cover and year), and identified a decrease in the sum of October and November snow cover as well (r = -0.21). It is interesting to note that, over the same period, both annual (r = 0.07) and summer (r = 0.18) rainfall in South Korea showed increasing trends; neither of which were statistically significant, however.

3.2 Relationship between snow cover in Eurasia and summer rainfall in South Korea

The correlation analysis has been repeated using the

Table 4. Correlation coefficients between previous snow cover in Eurasia (October to May) and summer rainfall in South Korea.

	Previous Eurasia snow cover								
	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	Annual Snow cover
Summer Rainfall, G_A	-0.41*	-0.54**	-0.20	0.03	0.19	0.27	0.10	-0.03	0.02
〃 G_1	-0.60**	-0.51*	-0.33	-0.26	-0.09	0.09	-0.10	-0.15	-0.16
〃 G_2	-0.24	-0.29	0.04	0.01	-0.15	-0.12	-0.03	-0.30	-0.14
〃 G_3	-0.37	-0.51*	-0.21	0.06	0.28	0.35	0.14	0.06	0.08

* ; Correlation is significant at the 0.05 level (2-tailed). ** ; Correlation is significant at the 0.01 level (2-tailed).

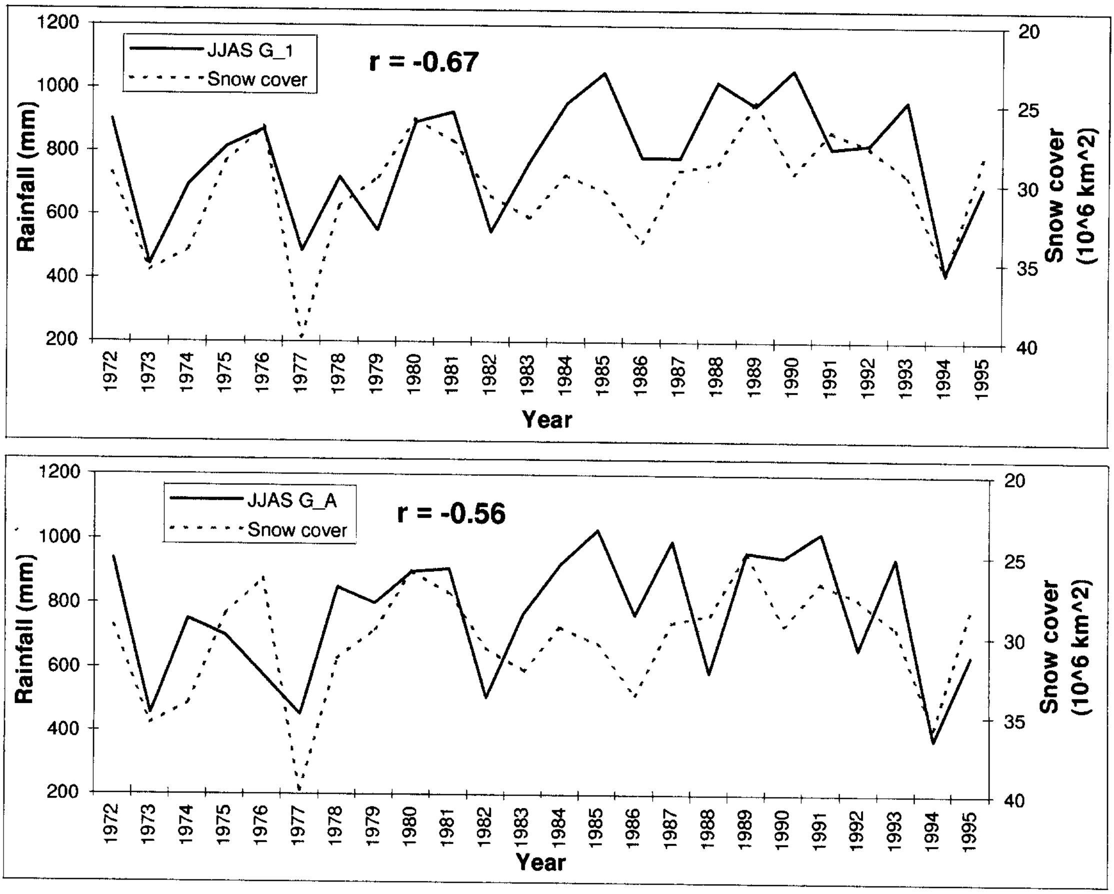

Fig. 6. Time series for the summer rainfall (JJAS G_1, JJAS G_A) and the sum of Eurasia snow cover from previous October and November (Snow cover). "JJAS G_1" denote the summer rainfall of the middle-east sector (G_1) and "JJAS G_A" the summer rainfall as a whole in South Korea (G_A).

snow cover over Eurasia, rather than the Northern Hemisphere, with results shown in Table 4.

In the case of South Korea as a whole, significant negative correlations are found between the summer rainfall and the snow cover in the previous October or November (Table 4). In this case as well, the snow cover is much better correlated with the G_1 rainfall (r = -0.60** in October, r = -0.51* in November) rather than the G_2 rainfall. The correlation coefficient for the G_3 region is similar to that of the whole South Korea (G_A). Once again, a combination of monthly values can improve the correlation. In the case of the G_A region, the strongest negative relationship is found between the summer rainfall and the sum of the snow cover from the preceding October and November (r = -0.56** ; not shown in the Table). On the other hand, in the case of the G_1 region the strongest correlation coefficient is -0.67**. Fig. 6 shows the time series of summer rainfall and the sum of the snow cover from the preceding October and November.

For China, Yang and Xu (1994) found that some sub-regions (defined on the basis of the observed characteristics of interannual rainfall variations) were negatively correlated with previous Eurasia snow cover, whereas other sub-regions were positively correlated. Considering China as a whole, they found a much weaker relationship with snow cover, due to the cancelling of the sub-regions with opposite responses. For South Korea this is not the case (Table 3). Eurasia snow cover from the preceding October to November correlates negatively with the summer rainfall of all sectors (i.e., G_1, G_2, G_3) as well as with the summer rainfall over whole South Korea (G_A). So, the Eurasia snow cover of the preceding October to November may be a useful predictor for whole South Korea summer rainfall as well as regional South Korea summer rainfall.

3.3 Relationship between Tibetan Plateau snow cover and summer rainfall in South Korea

A third correlation analysis was undertaken, using previous Tibetan Plateau snow cover as a potential predictor of South Korea summer rainfall. Only one correlation with apparent statistical significance is found, between G_1 rainfall and previous October snow cover (Table 5). Given the number of correlations tested (Table 5), one or two correlations with significance at the 0.05 level would be expected by mere chance; our results are not, therefore, field significant. These results are, perhaps, not surprising because of the above-mentioned difficulty in estimating smaller scale snow cover accurately from satellite observations (Dickson, 1984).

4. Summary and Discussion

We investigated the correlation between previous snow cover extent of the Northern Hemisphere, Eurasia or the Tibetan Plateau, and South Korea summer rainfall. We used the Northern Hemisphere snow cover data (1971 to 1995) obtained from NSIDC, and the monthly precipitation data (1953 to 1996) of 12 meteorological observatories in South Korea. South Korea was divided into three sectors according to the results of factor and cluster analysis of the South Korea summer rainfall.

Considering only the cases significant at the 95% confidence level, the results indicate that whole South Korea summer rainfall is negatively correlated with the Eurasia (and the Northern Hemisphere) snow cover in the previous October or November. In the case of the whole South Korea summer rainfall, the strongest relationship is found between the summer rainfall and the sum of Eurasia snow cover from the preceding October and November (r = -0.56). In general, the snow cover is most strongly

Table 5. Correlation coefficients between previous Tibetan Plateau snow cover (October to May) and summer rainfall in South Korea.

	Previous Tibetan Plateau snow cover								
	OCT.	NOV.	DEC.	JAN.	FEB.	MAR.	APR.	MAY	Annual snow cover
Summer Rainfall, G_A	-0.17	-0.05	0.15	0.22	0.07	-0.18	-0.08	-0.08	0.05
〃 G_1	-0.42*	-0.31	0.13	-0.01	-0.18	-0.37	0.05	0.09	-0.11
〃 G_2	-0.05	-0.01	0.33	0.16	0.11	-0.14	-0.05	-0.09	-0.07
〃 G_3	-0.15	-0.03	0.07	0.22	0.06	-0.13	-0.09	-0.08	0.09

* ; Correlation is significant at the 0.05 level (2-tailed).

correlated with the summer rainfall of the middle-east sector (G_1), and least strongly correlated with that of the middle-west sector (G_2) of South Korea. For instance, the correlation coefficients between the G_1 summer rainfall and the sum of Eurasia snow cover from the preceding October and November is -0.67.

On the other hand, statistically significant correlations are not found between the summer rainfall of the whole South Korea and the snow cover for just the Tibetan Plateau. This may be because the smaller scale snow cover is more difficult to measure accurately from satellites due to persistent mountain cloudiness (Dickson, 1984), or because it is the large-scale snow cover that exerts an influence on the summer monsoon.

We investigated the empirical correlation between the large-scale snow cover and South Korea summer rainfall, but made no attempt to study the mechanisms. The large-scale snow cover may be related to the strength of Tibetan Plateau High, which is itself associated with the Korea summer rainfall (Lee, 1991). This discussion needs further investigation to enable our better understanding about the relationship between the large-scale snow cover and the summer rainfall in South Korea.

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