Shift in the summer rainfall over the Yangtze River valley in the late 1970s

Dao-Yi Gong
School of Earth and Environmental Sciences (BK21), Seoul National University, Korea

Key Laboratory of Environmental Change and Natural Disaster, IRS, Beijing Normal University, China

Chang-Hoi Ho
School of Earth and Environmental Sciences, Seoul National University, Korea

Received 6 December 2001; revised 25 February 2002; accepted 6 March 2002; published 25 May 2002.

[1] The summer rainfall over the middle-lower valley of the Yangtze River and over the whole eastern China experienced a notable regime shift in about 1979. This change is consistent with a simultaneous jump-like change in the 500 hPa geopotential height (Φ500) over the northern Pacific. The rainfall over the Yangtze River valley is closely related to the Φ500 averaged over the area 20°–25°N, 125°–140°E, with a correlation coefficient of 0.66 for the period 1958–1999. Since 1980, the subtropical northwestern Pacific high (SNPH) has enlarged, intensified, and extended southwestward. The changes in the SNPH are strongly associated with the variations of the sea surface temperatures (SSTs) of the eastern tropical Pacific and tropical Indian Ocean. The anomalies of these SSTs, responsible primarily for the shift of the summer rainfall over the Yangtze River through the changes in SNPH, precede the Φ500 signals with different leading times. *INDEX TERMS:* 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 4215 Oceanography: General: Climate and interannual variability (3309); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620)

1. Introduction

[2] The middle-lower valley of the Yangtze River (Changjiang River) has experienced frequent floods during the recent years. In the 1990s, for example, severe floods occurred in 1991, 1996, 1998, and 1999. These floods, especially the extremely destructive flood of 1998, caused tremendous damage to the lives and properties in the region. During the past decades, substantial effort has been devoted to the understanding of the characteristics and causes of the floods [e.g., *Ye et al.*, 1992]. Recently, more and more research interest has been focused on the occurrence frequency of severe floods, the prediction of extreme rainfall conditions, and the decadal variability of the floods [e.g., *Huang*, 2001]. Nevertheless, while previous studies have provided accumulated evidence that is helpful for understanding many aspects of rainfall variability, a better understanding of the mechanisms that are responsible for the floods is still an important research subject. In this study, we will document the interdecadal variability of the summer rainfall over the Yangtze River valley, analyze the related changes in the atmospheric circulation, and investigate the physical mechanism for the variability of the rainfall. We analyze the monthly rainfall from a data set archived by the National Climate Center of China. The data covers the period 1951–1999 and includes the information of 160 stations. In particular, we choose 32 stations that are located in the middle-lower Yangtze River valley (see Figure 1).

[3] We also analyze the monthly 500 hPa geopotential height (Φ500) from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kalnay et al.*, 1996]. Sea surface temperature(SST) data is from the data sets of *Kaplan et al.* [1998] and the NOAA Climate Prediction Center (CPC).

2. Summer Rainfall Shift in 1979

[4] Figure 2 shows the time series of the summer rainfall over the Yangtze River valley, in anomalies with respect to 1961–1990. A striking feature is the strong year-to-year fluctuations. In particular, the extreme events in 1954, 1969, 1980, 1998, and 1999 exhibit large positive rainfall anomalies. It is interesting to note that in addition to the strong interannual variability, there exist several periods when abundant or insufficient rainfall persists for several years. Result from analysis using a 9-point low-pass filter indicates that there are apparent long-term variations (figure not shown) and the transition year is around 1979. There is a remarkable difference between the periods before and after the transition year. The rainfall during 1957–1979 is relatively low, but afterward it increases steadily. The average rainfall is 452.3 mm (28.3 mm less than normal) for the period 1957–1979, but 544.5 mm (63.9 mm above normal) for 1980–1999. The 1980s and 1990s are the two wettest decades during the past 50 years.

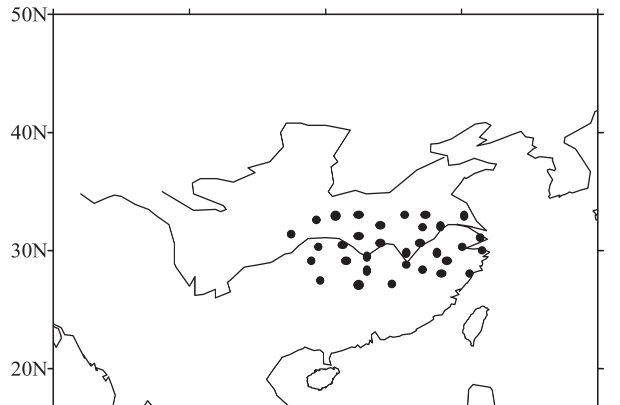

Figure 1. Map of the target region and stations. The thirty-two black dots indicate the stations with rainfall data available for 1951–1999.

0094-8276/02/2001GL014523$05.00

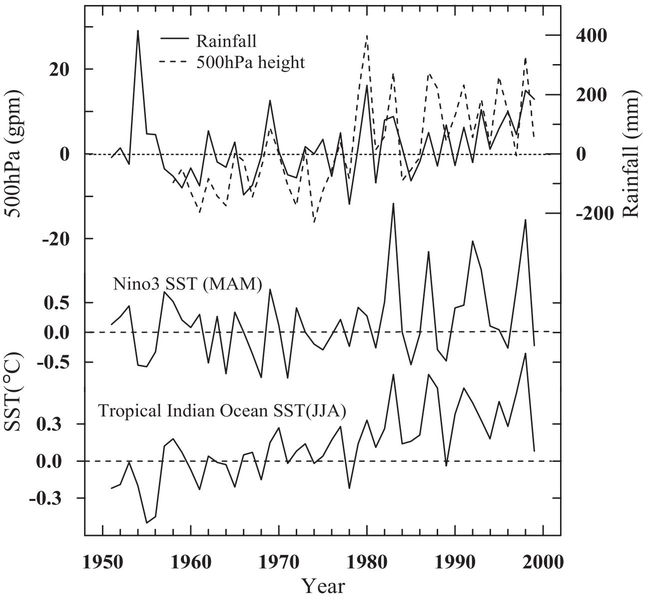

Figure 2. Time series of the mean rainfall over the Yangtze River valley and the regional mean 500 hPa geopotential height over 20°–25°N, 125°–140°E (uppermost curves), Niño3 SST (middle curve), and tropical Indian Ocean SST in 7.5°S–7.5°N, 65°–100°E (lowermost curve). The rainfall, geopotential height, and Indian Ocean SST are for summer and the Niño3 SST is for spring. For each curve, the deviation from the climatology is plotted.

Result from t-test shows that the decadal change between the two periods is statistically significant (t = 3.4) at the 99% confidence level (also see Table 1).

[5] Figure 3 shows the summer rainfall anomalies over the entire eastern China for the periods of 1957–1979 and 1980–1999. It is observed that the decadal change in the rainfall over the Yangtze River valley is concurrently consistent with the large-scale rainfall pattern shift in eastern China. The most striking features are the two coherent zonal bands of precipitation anomalies with opposite signs over most of the eastern China. One zone spans from 105°E to 120°E along the Yangtze River. Over the northern China, large precipitation anomalies with opposite signs are also observed. During the period 1980–1999, there is excessive rainfall over the Yangtze River valley but dry anomalies over the northern China. During the period 1957–1979, however, the pattern is comparable but rainfall anomalies switch signs: wet anomalies span over the northern China and dry condition predominates over the Yangtze River valley. This pattern is found to be a predominant mode of the summer rainfall in China [*Yang and Xue*, 1994]. *Nitta and Hu* [1996] analyzed the spatial and temporal variations of the summer rainfall in China and found that the first empirical orthogonal function (EOF) mode accounts for 11.45% of the total interannual variance. This primary mode shows a large signal of seesaw between the middle-lower valley of the Yangtze River and the region north of it (see their Figure 2a). The time coefficients of their first EOF mode also show a jump-like change around 1979 (see their Figure 3a). All these results indicate that the decadal change of the summer rainfall over the Yangtze River valley in the late 1970s is not a local phenomenon, but connected to the large-scale rainfall regime shift. *Shen and Lau* [1995] showed that the biennial signal is strong over the Yangtze River valley and has a similar pattern to the interdecadal change. The occurrence of the similar spatial distribution of different time scales may be due to the interplay between them or due to different mechanisms.

Table 1. Results from *t*-tests For the Summer Rainfall, 500 hPa Geopotential Height (20°–25°N, 125°–140°E), Spring Niño3 SST, and Indian Ocean SST (7.5°S–7.5°N, 65°–100°E)

	1957–79	1980–99	*t*-value
500 hPa anomaly	−4.9 gpm[a]	8.9 gpm	5.4[c]
Rainfall anomaly	−28.3 mm	63.9 mm	3.4[c]
AMA Niño3 SST	0.01°C	0.42°C	2.1[b]
JJA Indian Ocean SST	0.04°C	0.37°C	5.5[c]

[a] for 1958–99.
[b] Significant at 95%.
[c] Significant at 99%.

3. Associated Changes in 500 hPa Height

[6] The summer precipitation over the Yangtze River valley is controlled by a variety of factors, from surface boundary forcing to atmospheric teleconnections. Figure 4 shows the simultaneous correlation between the summer rainfall over the Yangtze River valley and Φ500. Two positive centers are located in the central Asian continent and the western Pacific, and a negative center appears over Korea and Japan. The high in the region from the South China Sea to 150°E along 20°N and the low over Korea and Japan lead to wet anomalies over the Yangtze River valley. This pattern implies a strengthening of the subtropical northwestern Pacific high (SNPH). Associated with this change, the northward warm and moist flow along the western edge of the high intensifies. At the same time, the stronger anticyclone pattern in the central continent and the adjacent cyclone pattern over Korea and

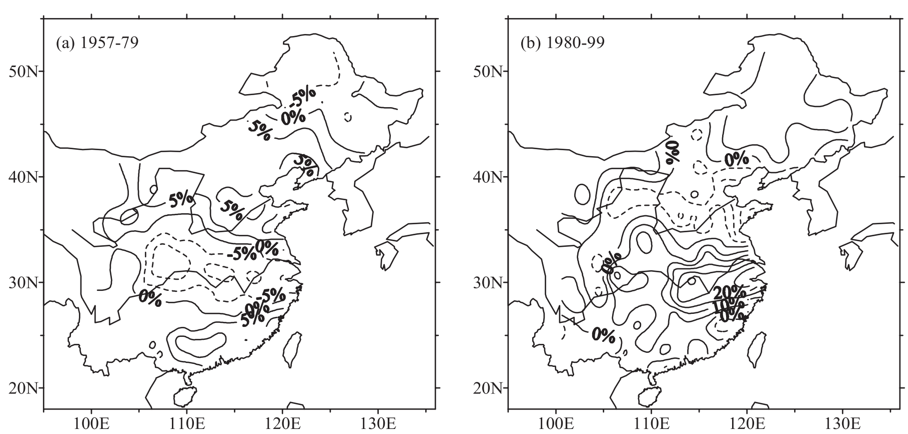

Figure 3. Summer rainfall anomalies (in percent) during (a) 1957–1979 and (b) 1980–1999 with respect to 1961–1990. The contour interval is 5%.

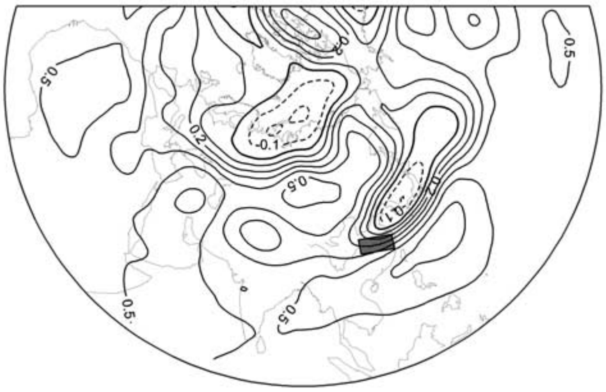

Figure 4. Correlation between summer rainfall and 500 hPa geopotential height for the 1958–1999. The Yangtze River valley is shaded. The 95% and 99% confidence levels are 0.30 and 0.39, respectively. Contour interval is 0.1.

Japan bring more cold air southward. All of these changes contribute to strong moisture convergence and thus excessive precipitation along the middle-lower valley of the Yangtze River.

[7] The anticyclone over the subtropical western Pacific is of particular interest, because this circulation feature has been identified as one of the key features of the Asian summer monsoon that affects the floods and droughts in China [*Huang and Yan*, 1999; *Lau et al.*, 2000]. The summer rainfall is strongly correlated with the Φ500 over the region from the northwestern Pacific to the South China Sea. The strongest correlation appears in the east of 120°E. The mean Φ500 averaged over the domain 125°–140°E, 20°–25°N shows a significant positive correlation with the rainfall over the Yangtze River valley and a relatively weaker negative correlation with the rainfall over northern China.

[8] The strong relationship between the summer rainfall and Φ500 anomaly is evident in Figure 2. The two curves strongly correlate to each other, with a coefficient of 0.66 for the period 1958–1999, significant at the 99.9% confidence level. It is very interesting to note that the geopotential height also shows a jump-like change around 1979. The mean difference between the two periods (1957–1979 and 1980–1999) is significant at the 99% confidence level (see Table 1). This is well consistent with the feature of rainfall variability.

[9] The variation of Φ500 over the western Pacific apparently reflects the activity of the SNPH, which is an important atmospheric circulation system. When the SNPH becomes stronger and shifts toward the equator, the rain band is situated along the Yangtze River and causes floods. Since the region 20°–25°N, 125–140°E is near the western flank of SNPH, the rain band is sensitive to the location and intensity of the high. We measure the SNPH by the contour lines for 5870 gpm. As shown in Figure 5, there is a remarkable difference in the position and extent of the high between the two periods. Since 1980, the SNPH has enlarged, strengthened, and extended southwestward. This change gives rise to anticyclonic circulation anomaly over the region from the South China Sea to western Pacific and thus results in prevailing southerlies over southern China. In summary, the wet anomalies over the Yangtze River valley since 1980 are closely related to the intensification and southwestward shift of the SNPH.

4. Relationship to SSTs

[10] The time series of the regional SSTs in the northwestern Pacific does not show a significant change between the two periods analyzed above. Thus, we focus on the variability of the SSTs of other regions. Previous studies [*Huang and Wu*, 1989; *Dai and Wigley*, 2000] have indicated that there is an evident relationship between the summer rainfall over the Yangtze River and tropical Pacific SST on interannual time scales. Wet anomalies usually appear in the southern China during El Niño episodes. *Hu* [1997] and *Chang et al.* [2000] investigated the possible linkage of the interdecadal variability of the summer rainfall over East Asia to the global and tropical Pacific SST. The primary modes of rainfall are usually connected to the El Niño-like mode in global SSTs. Interestingly, the corresponding principal components show an evident shift in the late 1970s [*Lau and Weng*, 1999, 2001; *Weng et al.*, 1999].

[11] The SNPH plays an important role in connecting SST forcing to rainfall anomaly. *Angell* [1981] demonstrated that during high SST conditions the subtropical high in the Northern Hemisphere strengthens and its center moves southward. Atmospheric circulation in the middle to low latitudes responds to SST forcing with a lag time of one to two seasons [*Gong and Wang*, 1999]. To better understand the time lag aspect of the connection, the correlation coefficients between the Niño SSTs and the western Pacific Φ500 are computed. The summer height correlates simultaneously with the Niño3 SST at 0.21 (not significant), with the previous spring-winter SST at 0.56, and with the previous fall and summer SST at 0.53 and 0.36, respectively. Here, the SST data of *Kaplan et al.* [1998] is used. The values are only slightly different when the CPC Niño3 SST is used, as shown in Table 2. Generally, the relationship is best when the SST leads by one to two seasons. A comparison of the spring Niño3 SST and the SNPH (Figure 2) indicates that they are consistent not only in the means but also in their variabilities. The SST shows a weak variability prior to 1979 but very strong year-to-year variation afterward. These features are evident in the western Pacific Φ500. Associated with the changes in SST, the western boundary of the SNPH also displays a consistent change, with weak variability appearing during 1957–1999 and much strong variability during 1980–1999.

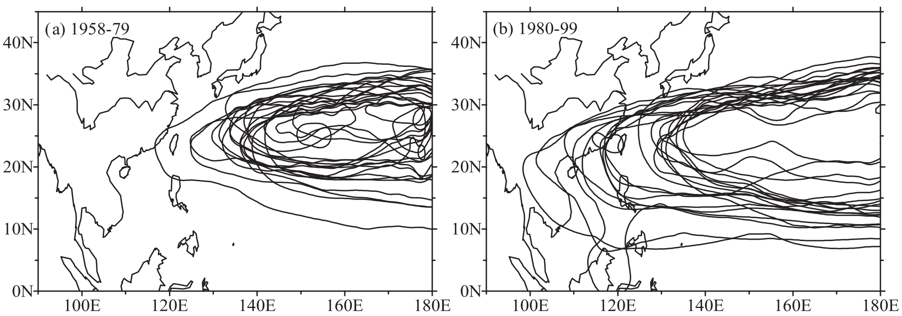

Figure 5. Contour lines for 5870 gpm for each summer during (a) 1958–1979 and (b) 1980–1999.

Table 2. Correlation Between SSTs and 500 hPa Height (20°–25°N, 125°–140°E), with Different SST Leading Season(s)

	Season(s) of SST leading Φ500					
	5	4	3	2	1	0
Niñol + 2	0.13	0.23	0.47	0.56	0.44	0.27
Niño3	0.19	0.32	0.52	0.51	0.50	0.15
Niño3.4	0.20	0.35	0.48	0.48	0.51	0.08
Niño4	0.33	0.49	0.49	0.52	0.48	0.30
IND SST	0.27	0.32	0.53	0.67	0.76	0.77

Data Period is 1958–1999. IND SST is for the region 7.5°S–7.5°N, 65°–100°E.

[12] It is interesting to note that there are even stronger correlations between Φ500 and the tropical Indian Ocean SST. After removing the linear trends, the correlation of the residual Indian Ocean and Φ500 timeseries is 0.62. That means the portion accounted for by interannual variability is 65%. This is much lower than that for Niño 3 SST (82%). Compared to Niño 3 SST, much of covariance is clearly due to the decadal component. The jump-like change in the tropical Indian Ocean SST is most striking in the late 1970s (see Figure 2 and Tables 1 and 2). Although the relationship between the Indian Ocean SST and summer Φ500 is also strong when the Indian Ocean leads by one to two seasons, the simultaneous relationship is the strongest. This is different from the case for Niño SSTs, as discussed above.

[13] Some other studies indicated that interdecadal climate regime shift over the Pacific occurred in mid-1970's. For example, *Graham et al.* [1994] indicated the transition had occurred in 1976; *Trenberth and Hurrell* [1994] also indicated the interdecadal change in mid-1970's; and *Wang* [1995] used 1977 as transition year. These slightly different results may be due to some reasons. First, the results are sensitive to the record length used for analysis. Second, sea level pressure, SST, etc., may show the different aspects of the climate system, thus, the changes in them are not necessary to be exactly the same. We have checked the different possible transition years (from 1976 to 1979) for each index as listed in Table 1. Results also confirm that all of the highest *t* values occur in around 1979.

5. Conclusion

[14] A significant change occurred to the summer rainfall over the Yangtze River valley in about 1979. This change is consistent with the shift of large-scale rainfall pattern over East Asia. The rainfall shift is related primarily to the concurrent changes in the subtropical northwestern Pacific high. Since 1980, the SNPH has enlarged, intensified, and shifted southwestward. This change gives rise to an anti-cyclonic circulation anomaly over the region from the South China Sea to western Pacific and thus causes wet anomalies over the Yangtze River valley. The SNPH responds significantly to the tropical eastern Pacific SST with a lag of one-two seasons and simultaneously to the tropical Indian Ocean SST. The changes in the SSTs are mainly responsible for the interdecadal variability of the summer rainfall over the Yangtze River through their influence on the SNPH. The strong teleconnection between the SSTs and the rainfall should provide helpful information for understanding the recent climate regime shift and for improving the prediction of the long-term variations of the Chinese summer rainfall.

[15] **Acknowledgments.** This work is supported by BK21 and KOSEF Science Research Center Program. The first author is supported by a NKDPFBS project under grant G1998040900. The authors appreciate the insightful comments and helpful suggestions from the two anonymous reviewers. The authors also thank Dr. J.-J. Baik at the Seoul National University for reading carefully an early version of this paper.

References

Angell, J. K., Comparison of variation in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific, *Mon. Wea. Rev.*, *109*, 230–243, 1981.

Chang, C. P., Y. S. Zhang, and T. Li, Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part I: Roles of the subtropical ridge, *J. Climate*, *13*, 4310–4325, 2000.

Dai, A., and T. M. L. Wigley, Global patterns of ENSO-induced precipitation, *Geophy. Res. Lett.*, *27*, 1283–1286, 2000.

Gong, D. Y., and S. W. Wang, The response of global subtropical highs to the equatorial eastern Pacific SST anomaly, *Acta Oceanologica Sinica*, *18*, 203–214, 1999.

Graham, N. E., T. P. Barnett, R. Wilde, M. Ponater, and S. Schubert, On the roles of tropical and midlatitude SSTs in forcing interannual to interdecadal variability in the winter northern hemisphere circulation, *J. Climate*, *7*, 1416–1448, 1994.

Hu, Z. Z., Interdecadal variability of summer climate over East Asia and its association with 500 hPa height and global sea surface temperature, *J. Geophys. Res.*, *102*, 19,403–19,412, 1997.

Huang, R. H., Decadal variability of the summer monsoon rainfall in East Asia and its association with the SST anomalies in the tropical Pacific, *CLIVAR-Exchanges*, *6*, 7–8, 2001.

Huang, G., and Z. W. Yan, The East Asian summer monsoon circulation anomaly index and its interannual variations, *Chinese Sci. Bull.*, *44*, 1325–1329, 1999.

Huang, R. H., and Y. F. Wu, The influence of ENSO on the summer climate change in China and its mechanism, *Adv. Atmos. Sci.*, *6*, 21–33, 1989.

Kalnay, E., and M. Kanamitsu, et al., The NCEP/NCAR 40-year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471, 1996.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856–1991, *J. Geophys. Res.*, *103*, 18,567–18,589, 1998.

Lau, K. M., and H. Weng, Interannual, decadal-interdecadal and global warming signals in sea surface temperature during 1955–97, *J. Climate*, *12*, 1257–1267, 1999.

Lau, K. M., and H. Weng, Coherent modes of global SST and summer rainfall over China: An assessment of the regional impacts of the 1997–98 El Niño, *J. Climate*, *14*, 1294–1308, 2001.

Lau, K. M., K. M. Kim, and S. Yang, Dynamical and boundary forcing characteristics of regional components of the Asian summer monsoon, *J. Climate*, *13*, 2461–2482, 2000.

Nitta, T., and Z. Z. Hu, Summer climate variability in China and its association with 500 hPa height and tropical convection, *J. Meteor. Soc. Japan*, *74*, 425–445, 1996.

Shen, S. H., and K. M. Lau, Biennial oscillation associated with the East Asian summer monsoon and tropical sea surface temperature, *J. Meteor. Soc. Japan*, *73*, 105–124, 1995.

Trenberth, K. E., and J. W. Hurrell, Decadal atmosphere-ocean variations in the Pacific, *Cli. Dyn.*, *9*, 303–319, 1994.

Wang, B., Interdecadal changes in El Niño onset in the last four decades, *J. Climate*, *8*, 267–285, 1995.

Weng, H. Y., K. M. Lau, and Y. K. Xue, Multi-scale summer rainfall variabiity over China and its long-term link to global sea surface temperature variability, *J. Meteor. Soc. Japan*, *77*, 845–857, 1999.

Yang, S., and L. Xue, Linkage between Eurasian snow cover and regional Chinese rainfall, *Int. J. Climatol.*, *14*, 739–750, 1994.

Ye, D., and et al., Regularities and causes of the droughts and floods in the Yangtze River and Yellow River valleys, Shandong Science and Technology Press, Jinan, China, pp. 387, 1992 (in Chinese).

D.-Y. Gong, Institute of Resources Science, Beijing Normal University, China; School of Earth and Environmental Sciences (BK21), Seoul National University, 151-742, Korea. (gdy@pku.edu.cn)

C.-H. Ho, School of Earth and Environmental Sciences, Seoul National University, 151-742, Korea. (hoch@cpl.snu.ac.kr)