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Connection between the South and East Asian Monsoons: Comparing Summer Monsoon Rainfall of Pakistan and South Korea

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Abstract: This study investigates the tele-connection of the southeast Asian monsoon systems by comparing the summer monsoon (June to September) rainfall variability between Pakistan and south Korea. The daily data sets (1981-2014) of rainfall of Pakistan and south Korea are utilized to explore the possible link. The data products of the National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) were also used for the understanding of the large-scale atmospheric environments. The patterns of summer monsoon rainfall on a daily basis between Pakistan and south Korea followed to each other throughout the year. Sub-seasonal differences of the summer monsoon revealed that July is the wettest month in both countries. The large-scale atmospheric environment of higher geopotential height revealed that the Tibetan high and the western north Pacific subtropical high are showing positive anomalies during positive phases over south Asia and east Asia, respectively. The anomalies of zonal wind are negative during positive phase and adverse in the negative phase between 20-40^{o}N. The reduced westerly is interpreted as the seasonal variation and moving of jet streams from the east Asian route. The Tibetan high, northwestern Pacific subtropical high and the east Asian jet stream have reliable and sufficient linkage between the Pakistan and south Korea summer monsoon system.

Keywords: Summer monsoon rainfall, southeast monsoon, monsoon tele-connection, Tibetan high, teleconnection.

Introduction

Rainfall in summer monsoon season is an important factor for a large section of the world's population. Extensive studies are being carried out to improve the understanding of monsoonal system. (Goswami et al. 1999; Sperber et al. 2001; Zhou et al. 2008; Zhou et al 2009; Yun et al. 2014). The monsoon climatology is characterized by annual reversal cycle of the prevailing winds (Ramage, 1971; Trenberth et al., 2000) and contrast between wet summer and dry winter (Shukla, 1975; Webster et al., 1998; Hussain and lee, 2014). Trenberth et al., (2000) concluded a persistent atmospheric large-scale overturning change in summer monsoon. This atmospheric overturning established as complex system of land-atmosphere-ocean (Krishnamurti and Bhalme, 1976; Goswami and Goswami, 1992; Wang and Ding, 2008).

The Asian monsoon system consists of the south Asian (or Indian monsoon) monsoon (SAM), the east Asian monsoon (EAM), and the western north Pacific monsoon (WNPM) systems (Wang et al., 2003; Rasul and Chaudhary, 2010). The monsoon system is strongly encompassed in the Indian region and the east Asia. These subsystems of monsoon are linked in response to the continental high-low pressure on seasonal basis by the contrast of sea-land distribution. These physical differences lead to noteworthy regime and internal feed-back systems of the both monsoonal regions (Kriplani et al. 2005; Wang et al. 2005). Asian summer rainfall shows an evidence of large-scale variability from intra-seasonal to interdecadal (Zveryaev and Aleksandrove, 2004). These regional summer monsoons are composed of various internal dynamics (Goswami et al., 1998; Singh et al., 2015) and atmospheric circulation system (Choi et al., 2014) strongly affects each other (Qian and Zhu, 2002).

Several studies have been explored teleconnections between the SAM (particularly Indian monsoon) and the EAM (particularly China monsoon) monsoon system. Hu et al. (2005) investigated a significant relationship between the south Asian monsoon and the northern during the ENSO. Kriplani and Kulkarni, (2001) studied teleconnections of summer monsoon rainfall of south and east Asia. Zveryaer and Alaksandrovea, (2004) investigate the variability in the summer monsoon rainfall of southeast Asia. Qian and Zhu, (2002) reported an interconnection of the south Asian and east Asian monsoon. Kim et al. (2002) investigated the teleconnections of summer rainfall between India and Korea and found a strong negative relationship. Choi et al. (2014) observed the propagation of strong westerly northward over south Asia and a substantial movement of wind from Pacific to east Asia in northward route.

Some classic studies for example, circulation anomalies at 850 hPa over Indian domain are linked with northward moving through line over east Asia. Yasunari (1986) and Kriplani et al. (1997a) studied the possible association between the mid-latitude circulation and summer rainfall in India and found strong links of 500 hPa geopotential height with summer monsoon rainfall. Kriplani and Singh (1993) also confirmed the strong association of summer rainfall of north China and India. However, the relationship mystery of the south and east Asian monsoon rainfall has still some gaps of understanding the links between SAM and EAM, particularly the monsoon cycle over Pakistan with east Asia region. The objective of current study is to investigate the tele-connections of south-east Asian monsoon, analyzing the summer monsoon rainfall variability of Pakistan and South Korea.

Materials and Methods

The daily rainfall data were analyzed for 36 meteorological stations in Pakistan and 61 meteorological stations in south Korea. The datasets of rainfall were obtained from Pakistan Meteorological Department and the Korea Meteorology Administration. The data sets consist on the summer monsoon season (June to September). The summer monsoon rainfall season in Pakistan is defined starting from June 1st to September 30th (Hussain and Lee, 2016) which is same as in India (Singh et al., 2014). Similarly, the season of summer monsoon in south Korea is also from June to September (Kim et al. 2002; Choi et al., 2014). The monsoon climatology of south and east Asia is from June to September (Krishnamuti and Bhame, 1976; Kripalani and Kulkarni, 2001). Figure 1 indicates monthly rainfall climatology of Pakistan and south Korea.

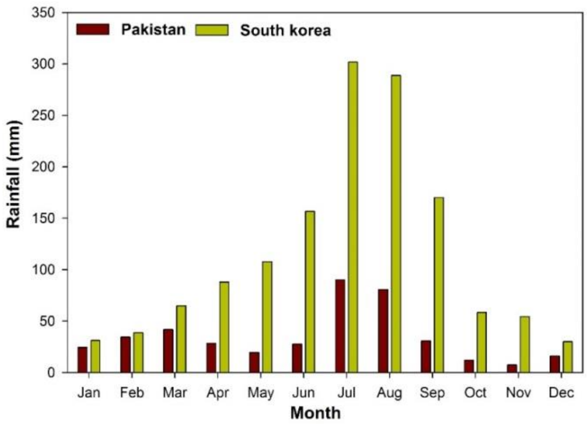

Fig. 1 Monthly rainfall climatology of Pakistan and south Korea.

The atmospheric reanalysis datasets of monthly means were archived from the National Center for Environmental Prediction/National Center for Atmospheric Research (Kalnay, et al., 1996). For further investigation, several reanalysis datasets were used including geopotential height (at 850hPa, 200hPa), zonal winds, and sea level pressure at 2.5° by 2.5° resolution. For all datasets, the period of investigation were adopted from 1981 to 2014. The domain of analysis is marked between 0-45°N latitude and 50 -150°E longitude, which cover the study area. The regions are selected considering the geography of the area and coherent rainfall systems.

To identify any possible relationship between rainfall climatology of Pakistan and South Korea, the statistical procedures comprising standard deviation, moving averages, trend analysis, standardization and Kendal *tau*-correlation techniques were applied. On the first step, summer monsoon rainfall anomalies of Pakistan and South Korea were calculated. When standardized summer monsoon rainfall anomalies standard deviation of the average rainfall were same for both countries in same year it considered as positive and negative rainfall years.

After the normalization procedure nine positive rainfall years (1984, 1989, 1990, 2003, 2006, 2007, 2010, 2011 and 2012) and four negative rainfall years (1982, 1986, 2001 and 2009) were chosen for composite analysis. The composite method (mean of the chosen years) were used to study the summer monsoon interlinks between the SAM and EAM. Discussions have been given considering the regions where the values of composite anomalies were significant more than 90% based on Student's *t*-test (Wilks, 1995). The composite analysis has been preferred (Harou et al., 2006; Singh et al., 2014; Saeed et al., 2011) because this technique has no assumptions regarding the linearity of association between two variables.

Results and Discussion

Local Rainfall of Pakistan and South Korea

Pakistan is located in south Asia between 24-37°N of latitude and 61-76°E of longitude. According to the diverse topology and altitude, Pakistan has a more continental type of climate than the other countries of south Asia. The spatial distribution of rainfall and its amplitude across Pakistan is controlled largely by the annual monsoon system and western disturbances (Hussain and Lee, 2009). About 56% rainfall of the country is associated with the summer monsoon during June to September (Hussain and Lee, 2014).

South Korea is located predominantly in temperate climate region with heavy rainfall especially in the summer season (Ho et al., 2003). This climatology of summer rainfall in Korea is immensely influenced by the far east Asian summer monsoonal system (Park et al., 2011). In Korea, more than 50% of the total annual rainfall is associated with the summer monsoon rainfall (Ho et al., 2003; Choi et al., 2010).

Statistical Analysis of Summer Monsoon Rainfall

Figure 2 shows the interannual variability of the JJAS for the period of 1981-2014 over Pakistan and south Korea. The horizontal lines denoted the temporal linear trends and the vertical bars showed summer monsoon annual rainfall. The 34 years average rainfall in

Pakistan 58mm and in south Korea 229mm are calculated during the JJAS. The coefficient variation (CV) suggested a high frequency of inter-annual variation of summer rainfall in Pakistan (26%) and south Korea (24.24%). Trend of summer monsoon rainfall revealed that the annual increase of rainfall is higher in south Korea than Pakistan. In regard of seasonal differences of the JJAS, July is noted as the wettest month over both countries during the summer season. Pakistan and South Korea received 37.25% and 33% rainfall during July respectively.

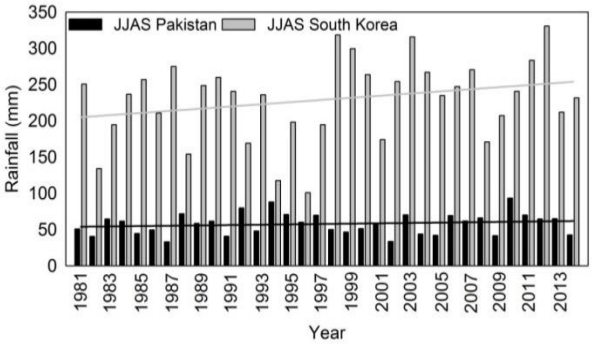

Fig. 2 Interannual summer monsoon rainfall variability over Pakistan and south Korea (1981-2014).

Figure 3 shows the daily variation of the summer monsoon rainfall for the period of 1981-2014 over the Pakistan and south Korea. In the months of July (August) with its average of highest rainfall as 173.2mm (134.1mm) and 625.62mm (601.11mm) over Pakistan and south Korea respectively. The moving average of 10-day presents the rainfall of JJAS by removing high-intensity. The average of 10-day rainfall revealed high rainfall during July and August in both countries. However, its amplitude is higher for south Korea. The daily rainfall datasets of both countries are significantly correlated (r = 0.443). Standardized values of the JJAS rainfall show variation of summer rainfall and relationship between Pakistan and south Korea.

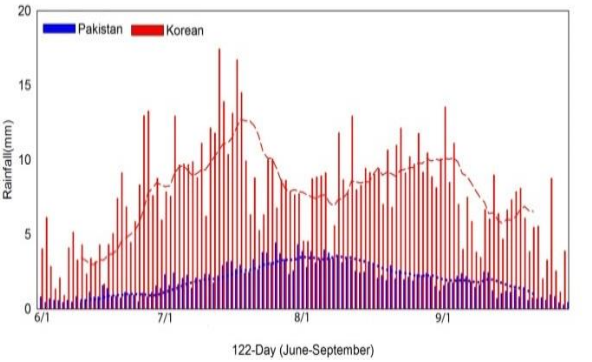

Fig. 3 Moving Average of daily summer rainfall between Pakistan and south Korea (1981-2014).

Composite Analysis of Large-Scale Environments

The figure 4(a) exhibit the geopotential height at 850 hPa during the positive phases of summer rainfall. The higher geopotential height is representative of the western Pacific subtropical high (WPSH), which dominates from east to west. This east-west direction of the WPSH is the main feature of the east Asian summer monsoon, which brings moisture (Zhou et al. 2009) over the land of China, Japan and the Korean Peninsula. The higher geopotential height observed in northwestern Pacific Ocean and lower geopotential height identified in the Indian peninsula and the Bay of Bengal are the main features of the east Asian monsoon and the south Asian monsoon climate respectively.

The geopotential height during the negative phases shows approximately contrary variation. The regions with high geopotential height during positive phases having low geopotential height during negative phases of summer rainfall. A low geopotential height become high over Bangladesh and the Bay of Bengal. Relatively positive anomalies of geopotential height can be noted over the Arabian sea, Pakistan and the western Ghats of the Indian peninsula during the negative phases. According to the examination of the geopotential height at 850hPa, it can be described that higher geopotential height has positive anomalies (intense monsoon) over the northwestern Pacific Ocean, Japan and the Korean peninsula and negative anomalies (low monsoon) over the Arabian sea and the Indian peninsula during the positive and negative phases of the summer monsoon rainfall respectively.

The formation of high and low geopotential height is opposite at upper level of 200hPa (Fig. 4c, d). The positive anomalies are dominated between 20^{o}N to 50^{o}N. This high geopotential height over south Asia is known as the Tibetan High (TH). A smaller zone of low geopotential height can be seen over the northern Pacific Ocean between 15^{o}N to 30^{o}N during the positive phases. The High is a significant element of the large-scale anticyclonic environment over the subtropical northern hemisphere (Zhou et al. 2009; Choi et al. 2014).

The map of negative anomalies of geopotential height depicts the low values from 25^{o}N to higher latitude toward the north (Fig. 4d). Particularly, the negative anomalies are low over Japan, the north eastern China and the Korean peninsula in east Asia and Pakistan and the western India in south Asia. This lower geopotential height at 200hPa over east Asia and South Asia indicate relationship (Choi et al. 2014) between two systems of the Asian monsoon. According to the examiner of the charts of the geopotential height, it can be concluded that the Tibetan high and the western north Pacific subtropical high show high anomalies during positive phases in South and east Asia respectively, which revealed opposite formation during negative phases. Thus, it is suggested that TH and WNPSH have significant effect on monsoon systems of Pakistan and south Korea.

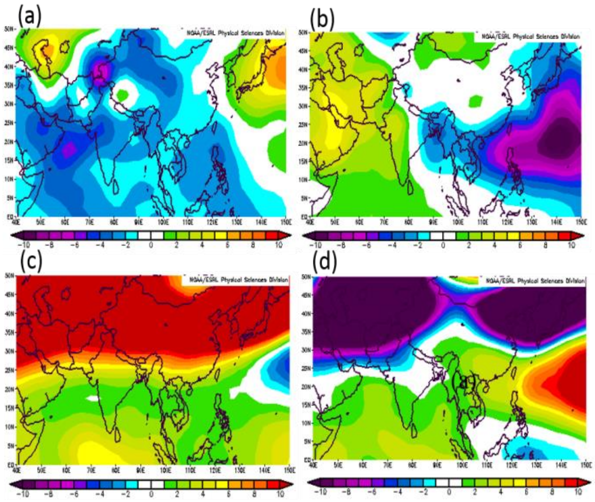

Fig. 4 Composite analysis of geopotential height (m) at 850 hPa (a. positive phases, b. negative phases) and geopotential height (m) at 200 hPa, (c. positive phases, d. negative phases) based on NCEP/NCAR reanalysis data.

Figure 5 (a, b) shows composite anomalies of zonal wind at 200hPa for positive and negative rainfall phases. The anomalies of zonal wind are negative during positive phase and adverse in the negative phase between 20-40°N. Shifting of the east Asian jet stream from lower latitude to higher latitude during positive phases of summer rainfall and opposite mechanism during negative phases should be investigated in this region.

Previous studies found that the east Asian jet stream is one of the significant components of east Asia summer monsoon (Choi et al. 2014). Figure 5 (c, d) shows composites of Sea Level Pressures (SLP) anomalies for positive and negative monsoon years. The thermal contrast is more pronounced for positive monsoon years with strong western north pacific sub-tropical high (WNPSH) and Asiatic low. On the other hand, negative monsoon years were characterized by weaker WNPSH having strong negative anomalies over the Pacific Ocean and positive anomalies over the land.

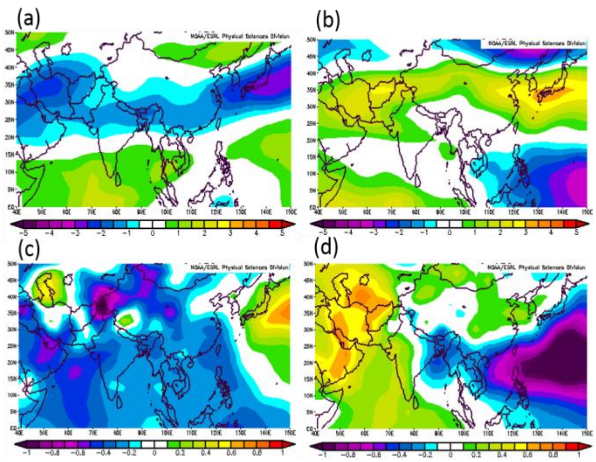

Fig. 5 Composite analysis of zonal wind (m/s), (a. positive phases, b. negative phases) and sea level pressure (hPa), (c. positive phases, d. negative phases) based on NCEP/NCAR reanalysis data.

Conclusion

The main objective of current study is to explore the possible links of summer monsoon rainfall over the region of south and east Asia and comparing summer monsoon rainfall in Pakistan and south Korea during the period of 1981-2014. The statistical procedures were adopted to find annual, seasonal and daily association between two countries. The composite analysis was applied to reanalysis datasets of geopotential height, sea level pressure, and zonal wind.

Large-scale atmospheric environments depicted that the reduced westerly is interpreted as the seasonal shift of the East Asian jet stream. The examination of atmospheric environments on the 200hPa heights suggest that the Tibetan high and the northward move of the subtropical upper-level jet exhibit connection between summer monsoon rainfall over Pakistan and South Korea. This study suggested that Tibetan high, northwestern Pacific subtropical high and the East Asian jet stream have role in the tele-connection between the monsoon systems of Pakistan and South Korea. The present study has not considered the intensification of underlying physical process of monsoon system. Therefore, an observational study is required to determine the physical mechanism of monsoon rainfall over the south and east Asia.

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