Chapter 6

Signature of extratropical influence on the summer monsoon over India

6.1 Introduction

The spatial and temporal disparities of summer monsoon rainfall over India influence its economy and agriculture to a great extent. The variability in precipitation in turn depends on the circulation pattern and SST anomalies associated with it (Shukla, 1975; Rao and Goswami, 1988; Yamazaki, 1988; Clarke et al., 2000). Occurrence of monsoon variability due to the global variation of phenomenon like El Nino - Southern Oscillation (ENSO), Quasi Biennial Oscillation (QBO) and Indian Ocean Dipole (IOD) are also well documented (Webster et al., 1999; Ashok et al., 2001; Claud et al., 2007).

El Nino - Southern Oscillation is one of the dominant modes that influences the Indian monsoon rainfall (Shukla and Paolino, 1983; Rasmusson and Carpenter, 1982; Webster and Yang, 1992). But recently, weakening relationship of ENSO with Indian summer monsoon is reported (Kumar et al., 1999; Sudipta et al., 2004). In addition, the relationship between IOD and Darwin pressure index seems to be reduced due to the decrease in the IOD occurrence (Swadhin and Yamagata, 2003), which is one of the index influencing the Indian monsoon. It has been reported that the southwest monsoon flow over Indian region decreased due to the altered relation of ocean and atmosphere (Ramesh et al., 2009). Even the monsoon and
Tropospheric Biennial Oscillation (TBO) relation has changed after 1976 (Pillai and Mohankumar, 2009). These recently altered relationships of Indian monsoon with various parameters may sometimes excite other dominant mode of variability that can influence the precipitation pattern.

Studies have shown plausible relationship of monsoon with high latitude variability. This relationship is established through the linkage of Indian monsoon with North Atlantic Oscillation (NAO). It is reported that, there exist significant relation of monsoon with the boreal winter and spring-time NAO (Dugam et al., 1997). Indian Ocean warming has related with the changes of polar vortex in northern and southern hemisphere (Shuanglin, 2009), which act as an element for the monsoon (Shukla and Misra, 1977; Joseph and Pillai, 1984).

In southern hemisphere also there exist a flip-flop mass distribution between middle and high latitude, known as Southern Annular Mode (Gong and Wang, 1999). The influence of dominant mode of extratropical variability, called as Southern Annular Mode (SAM), on the moisture transport, sea surface temperature (SST) and regional rainfall are well documented (Boer et al., 2001; Rao et al., 2003; Screen et al., 2009). The seasonal impact of Antarctica variability is noticed upto the tropical northern belt (Reason and Rouault, 2005; Gillet et al., 2006). Further study shows that precipitation anomalies in southern and northern Australia are associated with SAM (Belinda et al., 2007). Decrease in precipitation due to SAM anomalies over the northern hemisphere is detailed through the monsoon over China (Nan and Li, 2003; Zhiwei et al., 2009), revealing that the leading mode influences in a wider sense. This indicates that SAM can influence both northern and southern
hemispheric monsoon patterns. But the relation of these modes (southern and northern) to Indian monsoon is not yet well studied. Since the Asian summer monsoon circulation originates in the oceanic region of southern hemisphere, it is interesting to search for a possible association between SAM and summer monsoon over Indian subcontinent.

The main objective of this study is to investigate whether there exist any possible link between Southern Annular Mode (SAM) and Indian Summer Monsoon Rainfall (ISMR). Precipitation changes were considered to understand the possible link between SAM and ISMR. The circulation changes, SST anomalies and moisture properties associated with variability of SAM were analysed during boreal summer.

6.2 Data and Methodology

For the present study, gridded rainfall data ($1^\circ \times 1^\circ$) procured from Indian Meteorological Department (Rajeevan et al., 2006), updated for a period of 58 years extending from 1951 – 2008 is considered. The updated Southern Annular Mode Index (SAMI) is used for the same period from 1951 – 2008 (Nan and Li, 2003). The SAMI of Nan and Li (2003) is used because it shows better negative correlation in the zonal-mean sea level pressure anomalies between $40^\circ$ S and $70^\circ$ S than that between $40^\circ$ S and $65^\circ$ S, developed by Gong and Wang (1999).

Southern Annular Mode Index is the difference of normalized monthly zonal mean sea level pressure between middle and high latitudes. High and low SAMI years are taken above and below one standard deviation in order to understand the variability of Indian summer monsoon during June
(correspond to the onset phase) and July-August (represents the wide spread rainfall period). Correlation analysis of SAMI and ISMR has been carried out for a period from 1951 – 2008. Composite difference of high – low SAMI years is also used to establish the linkage between SAMI and ISMR. Difference of weak minus strong rainfall is computed for below/above one standard deviation.

Sea surface temperature (SST) data obtained from National Oceanic and Atmospheric Administration/National Climate Data Center (NOAA/NCDC) Extended Reconstructed Sea surface temperature version 3b (ERSST. v3b) for a period from 1951 – 2008 (Smith and Reynolds, 2004), has been utilised in this study to understand the difference during high and low SAMI period.

For the analysis of circulation anomalies associated with the high and low SAMI index, we used monthly re-analysis data of NCEP/NCAR (Kalnay et al. 1996). The SAMI high/low related variation on circulation pattern of wind, specific humidity and moisture transport is studied. The profile of vertical velocity (w) is used to understand the variation in ascending and descending area during monsoon season.

The horizontal flow of moisture (\(qu\)) in kg m\(^{-1}\) s\(^{-1}\) from surface to 300 hPa level is calculated, using the equation

\[
qu = \left(\frac{1}{g}\right) \int_{300}^{ps} q u dp\]
Where $q$ is the specific humidity, $u$ is the zonal component of wind field, $P_s$ is the pressure at the surface (1000 hPa) and $dp$ is the pressure difference between the layers.

6.3 Results

Southwest summer monsoon over the Indian sub-continent is generally expected to begin around early June and cease by the end of September. Thar desert and the adjoining areas of the northern and central Indian subcontinent heats up considerably during the hot summer season causing a low pressure area over the north and central parts of India. To fill up the low-pressure zone, the moisture laden winds from the Indian Ocean dash into the sub-continent. The monsoon current for the Indian subcontinent is basically a product of southeast trade winds originating from a high pressure mass centered over the South Indian Oceanic region, therefore the SAM may have an influence on the Indian summer monsoon.

6.3.1 Association between June SAM index and the onset phase of Monsoon

In the present study, the possibilities of in-phase relationship between SAM index and monsoon onset period are studied. For this, onset phase of the monsoon during the month of June over the Indian region is correlated with June SAM index. The study further extends to interpret SAM index associated variability on the monsoon parameters. A correlation study has been made using the June SAM index with rainfall data at each grid point over the Indian region during the month of June to study the relationship between SAM and early phase of monsoon over the Indian subcontinent.
Linear correlation between June SAM index and ISMR during the onset phase of monsoon (June) for the period 1951-2008 is shown in figure 6.1. Significant positive correlation is observed in the Indo-Gangetic plain. The area of significant positive correlation between the rainfall during the onset phase and the difference of SAM index locates in the region of monsoon trough to the north of 20° N. Large areas of significant positive correlation are noticed between the belt of 24° N and 34° N. Though, negative relations are observed over the extreme southwest and southeast coast, north and north east of India, the relations seems to be insignificant.

Figure 6.1. Correlation between the June SAMI and June precipitation in India for the period 1951-2008. The positive (negative) correlation coefficients that are significant at the 95% confidence level are dotted.
Since, significant relation is observed between June rainfall and June SAMI, the effect of SAMI on ISMR is analysed using other parameters that affect the monsoon. For this, zonal wind pattern at 850 hPa level during the June is utilised.

One of the important parameters that affect the widespread rainfall during Indian summer monsoon season is the low level jet stream, which transports moisture from Arabian Sea to the mainland. The zonal wind begins as southeast trades far in southern hemisphere, migrate to northern hemisphere during boreal summer. After crossing the equator, it blows as southwesterly due to Coriolis force and provides moisture to Indian subcontinent; thereby intensifies the monsoon activity. The zonal wind difference during June corresponding to high and low SAMI is shown in figure 6.2. During high SAMI, the zonal wind strength increases from south of

![Figure 6.2. Composite difference of the wind at 850 (ΔV_{850}) hPa between high and low SAMI years during the month of June.](image)
the equator, and further enhancement is observed along north of $12^\circ$ N over the Indian mainland and nearby regions. Strong anomalous cyclonic flow occurs around $20^\circ$ N and $85^\circ$ E over the monsoon trough region, while weak anticyclonic flow occurs over the southernmost region, centered over west of Srilanka.

Zonal wind pattern shows anomalous variation over India and nearby regions. Moreover enhancement of westerly flow and anomalous cyclonic flow occurs near the area of observed positive (significant) correlation (see figure 6.1) that may influence the precipitation pattern existing there. So the study has further focused over this area ($25^\circ$ N - $30^\circ$ N; $75^\circ$ E - $85^\circ$ E), where significant positive relations are observed. Vertical velocity and specific humidity over the specified area is analysed to find whether ascending motion and increase in moisture are observed during high SAMI period. These changes have effect on the intensification of rainfall over this region. Figure 6.3 shows area averaged vertical velocity ($25^\circ$ N - $30^\circ$ N; $75^\circ$ E - $85^\circ$ E) of June during the composite of high and low June SAMI. Both high and low

![Figure 6.3](image)

Figure 6.3. Composites of the June vertical velocity (in $10^{-3}$ Pa s$^{-1}$) high (dotted line) and low SAMI (dark dotted line) years, where high/low SAMI is represented as HSAMI/ LSAMI.
SAMI show increase in ascending motion in the troposphere extending from 1000 hPa to 850 hPa over the domain. Above this level, the magnitude of ascending motion decreases to the upper tropospheric level. During high SAMI period, ascending motion enhances in the troposphere compared to that during the period of low SAMI years. The increase of ascending motion during high SAMI years is stronger in the lower troposphere up to 850 hPa than low SAMI period. Though the vertical motion is enhanced during high SAMI, the difference between the high and low SAMI decreases as it extends towards upper troposphere.

Variability of moisture over the particular region is analysed using specific humidity. Figure 6.4 shows area averaged specific humidity (25°N - 30°N; 75°E - 85°E) of June during the composite difference of high and low June
SAMI. Compared to low SAM index, it is evident that high SAM index leads to an increase in specific humidity in the troposphere extending from 1000 hPa to 500 hPa. The difference of specific humidity between high and low SAMI is larger in the lower troposphere, and it gradually reduced towards the upper tropospheric region. In the lower troposphere level, an enhancement of 5-8% of specific humidity is noted during high SAMI period. It can infer that increase in humidity as well as the enhancement of upward vertical velocity induces precipitation over the specific region during the period of high June SAMI years.

6.3.2 SAMI relation to widespread rainfall period (July-August)

During July-August, precipitation occurs over most parts of India. Prevailing synoptic conditions have strong undulations during this time. So we consider June and July-August SAMI in order to understand the variability of monsoon features during July-August period. The in-phase and lead-lag relationship is analysed to find whether there exist any predictive skill over the precipitation and circulation pattern over Indian region due to southern high latitude circulation (SAMI).

6.3.2.1 Correlation between SAMI and July-August rainfall

Figure 6.5a shows correlation between June Southern Annular Mode index and the July-August Indian summer monsoon rainfall for the period 1951-2008. June SAM index is negatively correlated over most of the areas of Indian region. Areas of significant negative relations are observed in between the belt of 18°N and 27°N, an out of phase relation occurs over the
northernmost region, and also over the southwest sector of India. Significant positive correlations are noticed over the northeast of India.

Figure 6.5b shows the correlation between July-August SAM index and the July-August Indian summer monsoon rainfall for the period 1951 - 2008. Significant negative relations are observed in north Indian region and positive relations are observed to the northeast India. Negative relations are observed over the eastern part of central India along 84° E and along southwest coast of India, but the relations are insignificant. From figures 6.5 a & b, it is well evident that the rainfall of July-August is significantly more correlated with June SAMI than July-August SAMI.

![Figure 6.5](image)

**Figure 6.5.** Correlation between the July-August precipitation for the period 1951-2008 and a) June SAMI and b) July–August SAMI. The positive (negative) correlation coefficients that are significant at 95% confidence level are dotted. The contour interval is 0.1.
6.3.2.2 Composite difference of June SAMI and July-August rainfall

Even though the correlations are not so high, the spatial structure shows a negative relation over most of the area, particularly in the southwest coast of India, where rainfall is maximum during these months. So, this study explore the difference of July-August ISMR corresponding to high and low June SAMI above/below 1.5 sigma level. In addition to that, weak minus strong ISMR for July-August is also plotted to find the magnitude and spatial similarity between them.

Figure 6.6a shows the difference of weak minus strong monsoon rainfall during July-August. During weak monsoon period, negative anomalies are strong in the southwest coastal regions, the regions along 81° E and the extreme north of India, where positive anomalies are noticed in the northeast India. The difference of July-August rainfall corresponding to high and low June SAMI is shown in figure 6.6b. During high June SAMI, rainfall anomalies are negative over the southwest coastal regions, south central India along 81° E and 22° N and in the northern most regions of India. The magnitude of negative anomalies is stronger in between 8° N and 20° N along the southwest coast, and along the area near 22° N and 81° E. Strong positive anomalies occur over northeast India and at the same time weak positive anomalies take place over some areas of southeast India.

During weak monsoon conditions, precipitation reduces along southwest coastal regions and at the same time heavy rainfall occurs in northeast regions. High SAMI period also shows similar characteristics of a weak monsoon conditions with negative anomalies over the west coast and positive anomalies over the northeast regions. The spatial distribution of
anomalies is similar in figures 6.6a and 6.6b, which is shown in the patched area along the southwest sector, north, northeast region and area around 22° N. At the same time, there is difference in the magnitude of anomalies over the specified region. It seems that high June SAMI results in decrease of rainfall along the areas of southwest coast, central and northern India, while precipitation enhances in northeast India.

Figure 6.6. Composite difference of the July-August rainfall (mm/day) a) between weak minus strong monsoon and b) corresponding to the difference of high and low SAMI years during June.
6.3.2.3 June SAMI linked variability on monsoon parameters

From the above results, it is evident that June SAMI has strong relation with Indian rainfall during July-August. As a result, Indian summer monsoon variability due to high minus low Southern Annular Mode has been studied in detail for the parameters like SST, wind, moisture transport and vertical velocity corresponding to the difference of June SAMI is during July-August. Indian Ocean SST is one of the major elements that affect the Indian monsoon (Webster et al., 1998; Yamazakhi, 1988). So the variation of SST associated with SAM is an important parameter considered for the analysis. Moreover, the gradient between the SST in south Indian Ocean and Indian landmass is an important feature for the development of monsoon system. The composite difference of averaged July-August SST corresponding to strong minus weak June SAM index is shown in figure 6.7. Increase in SST is observed during high SAMI to the south of $25^\circ$S and also over the areas of

![Figure 6.7. Composite difference of July-August SST between the high and low SAMI years during June.](image)
equatorial region (east of $60^\circ$ E) and the Bay of Bengal region. At the same time, during high SAMI, SST slightly decreases in the Arabian Sea and to the west of $60^\circ$ E around equatorial region and area located near $10^\circ$ S and $85^\circ$ E.

The magnitude of warming is intense near $30^\circ$ S, while cooling of $0.1^\circ$ C is observed over the Arabian Sea around $20^\circ$ N. This gradient of SST is favourable for the development of a weak monsoon condition during high SAMI. Moreover, the pattern also induces a weak monsoon circulation and thereby moisture transport. Circulation pattern also indicates the elements of strong monsoon. The major flow at 850 hPa level determines the strength of monsoon and associated rainfall.

The composite difference of averaged July-August vector wind at 850 hPa corresponding to high minus low of June SAMI index is shown in figure 6.8. During high SAMI, zonal wind at 1.5 km shows enhanced southerly flow.

![Figure 6.8. Composite difference of July-August wind at 850 hPa between high and low June SAMI years.](image)
towards equator between $50^\circ$ E and $65^\circ$ E. Anomalous easterly flow occurs over south India and northeasterly along the west coast of India, accompanied by enhanced northerly flow along $20^\circ$ N and $60^\circ$ E. Strong anomalous anticyclonic flow is observed in central India during high SAMI. Though the magnitude of variation is less, the flow pattern is disturbed in the southwest coastal regions of India, which results in anomalous variation in precipitation pattern over south India.

The variation in ascending and descending motion is examined using vertical velocity. The height–latitude profile of composite difference of vertical velocity during July-August corresponding to high minus low June SAM index is shown in figure 6.9. During high SAMI, enhanced ascending motion occurs from equator to $10^\circ$ N, where the increase in magnitude is high over the upper troposphere. While anomalous descending enhances in between $10^\circ$ N and $25^\circ$ N, the magnitude of variations are large in between 500 hPa and 300 hPa. At the same time, ascending motion enhances in the latitudinal belt between $25^\circ$ N and $35^\circ$ N during high SAMI. From the figure 6.9, it is evident

![Figure 6.9. Composite difference of July-August vertical velocity (in 10^{-3} Pa s^{-1}) averaged over 65-95^\circ E, between the high and low June SAMI years.](image)
that ascending motion enhances nearby equatorial region, but descending motion enhances in south India during the expected heavy rainfall period. Change in zonal moisture transport over south India due to June SAMI is also evaluated.

During monsoon, the transport of moisture through southern area is critical for precipitation. Moisture transport during July-August corresponding to high and low June SAM index is shown in figure 6.10. During high SAMI, moisture transport decreases to the west of 65° E in between the belt of equator and 20° N. The transport of moisture increases to the south of 6° N along the east of 65° E, while to the north of 6° N, moisture transport decreases. Anomalous decrease is observed near Somalian coast and over the east coast of the Arabian Sea (around 13° N) extending to the Bay region. In the near equatorial region, moisture transport seems to be increased, the region of maximum intensity is noticed along 85° E. The decrease in moisture transport during high SAMI period along the Indian domain also results in reduction of precipitation.

![Figure 6.10. Composite difference of July-August moisture transport (kg m⁻¹ s⁻¹) corresponding to high and low June SAMI years.](image-url)
From the above analysis, we observed that the variability of June SAM index influences the summer rainfall over India during onset and widespread rainfall period. Anomalous pattern similar to weak monsoon condition is observed during high June SAM index. In order to understand the interannual variability of SAM index during June, time series is plotted for a period from 1951 to 2008. During 1950 to 1980, positive trend of June SAM index is observed (see fig 6.11). The index showed abrupt positive departure for a couple of years during late 1970’s. From early 1980 onwards SAMI showed a negative slope till mid-1990. Thereafter, a gradual increase of positive trend is observed in June SAM index.

6.4 Discussion

The study reveals that, Southern Annular Mode (SAM) influences the Indian rainfall, and the parameters associated with it during the summer monsoon
period. When June SAMI is correlated with June ISMR, positive relations are observed over northcentral India. During positive phase of SAMI, enhanced westerly flow and anomalous cyclone occurs at 850 hPa level in the near regions of positively correlated area. At the same time anomalous anticyclone is observed over the extreme part of south India. During June, average rainfall of about 98.34 mm occurs in the positively correlated area (25° N - 30° N; 75° E - 85° E). During high SAM years, the specific humidity slightly increases in troposphere from 1000 hPa to the 500 hPa. The magnitudes of humidity variation between high and low SAM years are stronger in lower troposphere. At the same time, vertical velocity also shows enhanced ascending motion over this region. This reveals that ascending motion is enhanced and the atmosphere is fed by high moisture content over this region during positive phase of SAM, so precipitation may enhance over the region.

During July–August, monsoon has active and break spells of rainfall, where break situation affects the low level flow and also the moisture transport (Joseph and Sijikumar, 2004), thereby affecting the precipitation anomalies. Increase in break spell, during July-August over Indian region, and decreasing low level flow along with reduced moisture transport is documented (Ramesh et al., 2009). This makes clear that the properties of monsoon have changed during recent decades, and pose a question whether any other relationship is also influencing Indian summer monsoon during this season. So the in phase and lead-lag relation between Indian monsoon and SAMI seems to be a possible link.
To understand the predictive potential of SAM, we correlated June and July-August SAMI with July-August rainfall. The relation shows that the June SAMI has significant relation compared to July-August rainfall. Correlation between the June SAMI and rainfall over India during July-August shows significant negative correlation over most of the areas except in the northeast region of India. The southwest sector of India where the maximum rainfall occurs during summer monsoon due to orographic ascent, observed significant negative relation during high SAM years. During high SAMI years, the precipitation over Indian region shows pattern similar to weak monsoon rainfall. This is well evident in the southwest sector of India, where negative anomalies observes during the composite analysis of high SAMI.

During high SAM years, SST warming is observed over tropical regions of southern hemisphere and at the same time cooling over western sector of Arabian region. This can alter the horizontal temperature gradient that prevails during good monsoon, which in turn modifies the monsoon flow and moisture transport. Warming of SST is also noticed in the Bay of Bengal region. It is reported that, the western Arabian Sea cooling may cause reduction in rainfall (Shukla, 1975). While, changing relationship of Indian ocean with monsoon has already been noticed after the climate shift (Clarke et al., 2000).

The low level flow at 850 hPa (Somali jet stream) over South India seems to weaken slightly during high June SAM index. The flow pattern over southwest coastal regions which seems to be changed will possibly affect the precipitation in west coastal regions of India Anomalous anticyclone is also observed over central India. The present analysis shows a reduced moisture
flow in between equator and 20° N during high SAMI, indicating lack of moisture during peak monsoon period. Vertical velocity shows enhanced ascending motion over the equatorial region but increased descending motion over south India. It can conclude that the positive phase of southern extratropical phenomenon during June is not conducive for monsoon of July-August.

From the study, it is clear that SAM induct strong association to Indian monsoon. When June SAMI has positive polarity, it results in enhanced precipitation during June over northcentral India and moreover the circulation and moisture is also favourable for the increase in precipitation over that area. At the same time, high SAMI during June is not conducive for the precipitation over most parts of India during July–August, which is also evident from the anomalous circulation, moisture transport and vertical velocity. Simultaneously precipitation increases in the northeast regions of India during the positive phase of SAM. Sea surface temperature (SST) also favours a weak thermal gradient between northern and southern hemisphere, which will adversely affect the monsoon circulation, and thereby moisture transport. During this time, anomalous variations in the zonal flow at 850 is also noticed (Rao et al., 2004; Sathiyamoorthy, 2005; Joseph and Simon, 2005), these flows are important feature of monsoon.

Strong positive phase of SAM is seen during recent decades. The increasing trend of SAM is already reported during the second half of the 20th century (Gong and Wang, 1999; Kidson, 1999; Marshall, 2003; Miller et al., 2006). Moreover, SAM variation seems to be reinforced by anthropogenic force and ozone changes (Arblaster and Meehl, 2005). Another interesting thing is that,
the North Annular Mode and ENSO has combined affect over Indian Summer Monsoon (Dugam, 2006). But, studies also shown that the long-recognised negative correlation between Indian monsoon rainfall and ENSO has weakened rapidly during recent decades (Sudipta et al., 2004). So, we summarise, SAM is affecting Indian monsoon and circulation to a wider sense. The observational evidence perceived in the present study reveal that SAM has a strong linkage with the circulation and precipitation pattern of the Indian summer monsoon.

6.5 Conclusion

Southern Annular Mode shows indication of link with Indian monsoon during summer monsoon period. But the relation of June SAM is distinct with June and July-August rainfall. During June, high SAMI enhances the June rainfall over northcentral India. The circulation and moisture also provides an enhancement of rainfall over this region. The correlation between June and July-August SAMI with rainfall of July-August shows that the correlation is significantly high with June SAMI than July-August SAMI. During July-August, rainfall seems to be decreased in most of the regions due to the impact of high June SAMI except in northeast India where significant increase in precipitation is observed, which is similar to weak monsoon rainfall observed during high SAMI. The SST, circulation and moisture properties demonstrate a situation of weak monsoon condition. Anomalous variation in the low level flow and reduced moisture transport occur during high SAMI may affect the monsoon. Positive phase of June SAMI is observed in recent decades, suppresses active rainfall spells over southwest India, where the summer monsoon starts has its first spell and has strong spell during
monsoon period. June SAMI is useful to quantify the variability of parameter associated with summer monsoon and to some extend for the prediction of the widespread rainfall over the country during the July-August. Concisely, the Southern Annular Mode seems to be associated with the rainfall variability and distribution of Indian monsoon.