1.1 General features of southern hemisphere

Southern hemisphere is the segment of Earth that has more water bodies than landmass. About 80.9% of the southern hemisphere is covered by water, including South Pacific, South Atlantic, Indian Ocean, Tasmania Sea and Weddell Sea, while the land comprises only 19.1%. The continents in this hemisphere are Antarctica, southern part of Africa, South America and Australia (fig 1.1). Only 10% of the total world population lives in Southern hemisphere. This hemisphere is distinct with different varieties of flora and fauna. Amazon and Madagascar are areas located in southern hemisphere are rich in biodiversity than any part of the world. The Austral hemisphere shows diversity in many aspects that is well reflected in the climate and weather over this region. The coldest continent in the world is in this hemisphere, which receives less than five centimeters of precipitation annually. The cold winter season begins in June and persists till August and summer period is from December to February.

Based on climate, Austral hemisphere is divided in to different regions. Tropic is the area between equator and Tropic of Capricorn, this area has warm temperature and precipitation. Temperate zone is in between Tropic of Capricorn and Antarctic Circle at 66.5° S. The area has high precipitation, cold winters and warm summers. South of the temperate zone is the Antarctic Circle, the area covered by cold Antarctic land mass and are colder.
than the Arctic. Quite amazingly, it is found that this cold Antarctica has warm period that occurred about 15.7 million years ago and lasted for a few thousand years.

Southern hemisphere identity is entirely different from the northern hemisphere in many aspects. The climate in the southern hemisphere does not vary like the northern hemisphere. This is due to the vast Ocean in this hemisphere, which heats and cools slowly as a result the effect of climate perturbation is not intense like in boreal hemisphere, where land-sea contrast is substantially high. Another noticeable thing is the deflection of an object caused by Coriolis force. The object moving away to the Antarctic Circle is deflected to the left. In southern hemisphere, clockwise rotation is related to low-pressure centre where it is anticlockwise in northern hemisphere.
The differences between the southern hemisphere (SH) and northern hemisphere (NH) are also observed in the stratosphere, where they differ in the dynamics, chemistry and radiation properties. Due to the low temperature in the southern polar cap region, the winter-time SH polar vortex is much stronger and is long lasting than its boreal counterpart. The austral winter-time stratospheric polar vortex appears a month earlier in autumn than its NH counterpart, and the vortex persists longer into the spring than the NH. The break-up of polar vortex is mainly through the planetary waves which deposit its momentum and energy to the stratosphere and thereby weaken the polar vortex, but the wave activity is less in southern hemisphere due to the absence of strong generating mechanism like in northern hemisphere.

Southern hemisphere has its own unique identity with respect to northern hemisphere that can be noticed in the climatology of wind and temperature pattern. During winter (July), the southern hemisphere troposphere and stratosphere are dominated by westerly winds (see fig 1.2). The westerly

![Figure 1.2. Zonal wind structure for a) July and b) January of Southern hemisphere (adapted from SPARC)](image)
wind maxima in the upper troposphere level is 5m/s weaker and is 2-3° latitude nearer the equator than NH. Towards the polar region, the winter westerlies are quite stronger than the NH. The distribution of wind pattern in the two hemispheres is different during summer. During summer (January), the tropical easterlies in the middle and upper troposphere are weaker in SH while the westerlies in the subtropics are stronger than NH.

The summer hemisphere has cold tropopause and warm stratopause region. The mesopause region is extremely cold in summer hemisphere. During winter, the midlatitude troposphere is warm and the polar region is extremely at very low temperature. During winter, Antarctic temperature are quite lower compare to Arctic winter. The winter polar vortex is quite stronger in SH than in NH. Southern hemisphere polar vortex is less disturbed compare to NH, so the event known as Sudden Stratospheric Warming (SSW) is also less intense in SH

**1.2 Major events in the southern hemisphere**

Southern hemisphere is in the focus of attention due to its peculiar feature like Antarctic Ozone hole and Sudden Stratospheric Warming (SSW). These feature alter the existing dynamical and chemical behaviour in the Austral hemisphere and are important in global climate.

**1.2.1 Sudden Stratospheric Warming**

Sudden Stratospheric Warming is one of the dramatic phenomenon occurring in the stratosphere of high latitude. During cold winter, temperature in the stratosphere suddenly raised upto 70° C within a week,
and on certain occasions the zonal wind change its direction from westerlies to easterlies. The anomalous temperature variation without overturning of zonal wind is known as Minor warming while the temperature perturbations with phase change of zonal wind is termed as Major Warming. Minor warmings are observed in Southern hemisphere during winter. But the Major warming event is unusual in the Southern hemisphere because the winter vortex is stronger and also due to the absence of large Planetary waves, in this part of Earth.

Due to the presence of strong vortex, Austral hemisphere is noted for minor warming, where temperature increases but the zonal wind does not change its direction. But on September 2002, the southern hemisphere experienced a major warming which was unusual for this hemisphere for a long period. The change in polar vortex occurred in a dramatic manner. On September 20 (fig 1.3), the polar vortex get elongated, and it got weakened in following

![Figure 1.3. Polar vortex breakup on September 2002 (adapted from SPARC)](image)
dates. The vortex split in to two on September 25 and resulted in the intrusion of warm air to the South Pole. After the split the vortices are weakened rapidly on September 30. It is noted that the zonal wave number 2 reached the peak when the polar vortex split in to two. The major warming also resulted in the split of ozone hole into two.

1.2.2 Antarctic Ozone Hole

Another important phenomenon that brought the southern hemisphere in focus during 1970 is due to the discovery of ozone hole. Antarctic ozone hole refers to the seasonal (spring) depletion of stratospheric ozone in a large area over Antarctica (Farman et al., 1985; Solomon, 1999; Staehelin et al., 2001). This discovery guide the world to rethink in the use of ozone-depleting substances (ODS). The seasonal thinning of ozone layer is shown in figure 1.4. Intense thinning of ozone layer occurs due to the emission of man-made halocarbon to the atmosphere and this chemical is transported to high and midlatitude of lower stratosphere. In the extreme lower temperature they find substrate in cold clouds and was dormant in winter.

Figure 1.4. Seasonal thinning of ozone layer above Antarctic (adapted from NASA)
During spring the ice melt and the ozone destroying molecule get released and break apart the molecular bonds in UV radiation-absorbing ozone. As a result highly destructive rays penetrate to the lower atmosphere thereby affecting the living species. This event is noted mainly in Antarctica region in spring (September-October) due to the extreme low temperature, forming polar stratospheric clouds that will provide substrate to the ozone depleting compounds.

1.3 Southern Annular Mode

Southern Annular Mode is the normalised difference in the zonal mean sea-level pressure between mid and high latitudes. The sea level pressure pattern associated with SAM is a nearly annular pattern with a large low pressure anomaly centered on the south pole and high pressure anomalies at mid-latitudes and it is the principle mode of variability in Southern hemisphere (Thompson and Wallace, 2000; Visbeck and Hall, 2004). Southern Annular Mode is also known as Antarctic Oscillation (Gong and Wang, 1999) or Southern hemisphere Annular Mode (SHAM).

During the positive phase of SAM, pressure is lower than normal in high latitude and higher than normal in midlatitude. The strong westerlies undergo changes during the positive and negative phase of this high latitude mode and thereby affect the Oceanic circulation (Hall and Visbeck, 2002; Oke and England, 2004). The westerlies are stronger than normal over the southern oceans in the positive phase and weaker than normal during its negative phase. Pattern of the pressure variations associated with the positive phase of the SAM is depicted in figure 1.5.
In recent decades, SAM is showing positive trend (Marshall, 2003), and it is predicted that the upward trend will persist in future decades (Cai et al., 2003; Kushner et al., 2001). The positive trend of this high latitude mode is as a result of stratospheric ozone depletion and emission of greenhouse gas (Hartmann et al., 2000; Thompson and Solomon, 2002; Gillett and Thompson, 2003; Marshall et al., 2004).

1.3.1 Effect of SAM on other meteorological parameters

On interannual timescales southern annular mode (SAM) contributes a significant proportion of SH mid-latitude circulation variability (Hartmann...
The southern annular mode is linked with variability of many parameters of northern and southern hemisphere. It has been noticed that the SH cyclone track undergo north-south migration during the alternative phase of SAM (Kidson and Sinclair, 1996). Model studies predict that the southern Ocean takes lesser amount of carbon dioxide during the positive phase of SAM (Lenton and Matear, 2007).

Extensive study has carried out by several scientists to understand the effect of SAM. One such study explored the impact of this extratropical mode on surface wind, sea surface temperature and chlorophyll concentration in the Southern Ocean. The study concludes that the enhanced westerlies during positive phase affect the Ekman transport and the SST anomalies. They even noted that the chlorophyll concentration is significantly correlated with phase of SAM (Lovenduski and Grube, 2005). Temperatures also get modified due to this mode, significant temperature anomalies are observed in Australia due to the effect of Southern Annular Mode (Hendon et al., 2007).

Sea ice content over the Antarctic region has varied due to the impact of SAM, during its positive phase decrease in ice area in the Weddell Sea and Antarctic peninsula and increase in the Ross and Amundsen Sea is reported (Lefebvre and Goosse, 2005). This oscillation play enhanced role in the intraseasonal oscillation over tropic to extratropics of the Southern and Northern hemisphere (Carvalho et al., 2004). This mode is known to influence the rainfall over many regions. The effect of SAM on Australian monsoon is observed for a period from 1958 – 2002 and it has been noted that the SAM has in-phase relationship with north Australia and has inverse
relationship with southern Australia. There is significant association between winter and spring rainfall over South America (Silvestri and Vera, 2003) and SAM, due to the impact of this mode, significant reduction in rainfall is observed in southwest Western Australia (Li et al., 2005). An inverse relationship between SAM and winter rainfall over South Africa is identified (Reason and Rauault, 2005).

**1.3.2 Impact of SAM on northern hemisphere**

It is well explicit that the Southern Annular Mode has high influence in the temperature, circulation and rainfall properties of southern hemisphere. But the question arises whether this mode can account for the northern hemisphere variability. It is reported that, this high latitude mode accounts for 10% of global variance (Trenberth et al., 2005), several studies also has connected the boreal hemisphere variability with extra tropical phenomenon of SH. It is observed that the global monthly variability has linked with SAM that is seen active in all months compared to the oscillation in northern counterpart, known as North Annular Mode. North Annualar Mode is the leading mode of variability in northern hemisphere which has strong teleconncetion with many Oceanic and atmospheric properties. The NAO modulates the tropical circulation during its phase change.

Summer rainfall over Yangtze river shows significant positive correlation with the boreal phase of SAM (Nan and Li, 2003). Positive polarity of SAM favours weakening of East Asian Summer Monsoon and westward expansion of western subtropical high. Further the variability play a key role in modulating the vertical velocity, specific humidity and water vapour flux and thereby precipitation. Winter monsoon over China has exhibited relation
with this high latitude mode. During the positive phase of SAM in Autumn, anomalous change occur in Hadley cell associated with SST anomaly and influence the lower troposphere over China and weaken the monsoon pattern existing there (Zhiwei et al., 2009).

1.4 Climate change in southern hemisphere

Change in the mean state of variables for a decade or longer due to anthropogenic origin or natural forcing is termed as climate change. This climate change has noticed in the 20th century in many atmospheric and oceanic parameters. Compared to northern hemisphere the variation in southern hemisphere ocean is more intense in the second half of the 20th century. Several model and observation studies have suggested the climate change is will evident in the Southern ocean during recent decades (Arbic and Owens, 2001; Wong et al., 2001; Wainer et al., 2004; Sprintall, 2008).

Not only oceanic properties have varied in SH, the impact is well evident in troposphere and in stratosphere. Anomalous variation is observed in Antarctic tropopause due to phase change in SAM (Santer et al., 2003). It has been reported that the midlatitudes of SH is warmer than the equator while high latitude and Antarctic have cooled in recent decades (Parkinson 2006; Chapman and Walsh 2007). Strengthening of westerlies and its contraction towards South Pole is also observed (Marshall, 2007).

Stratosphere over Antarctica region has showing anomalous variation. The stratospheric anomalies are observed seriously by researchers due to its downward propagation to the troposphere and its known influence to circulation pattern and thereby playing prominent role in changing the
climate. The lower Antartican stratospheric region has shown large trend during 1979–2007 period due to ozone changes (Randel et al., 2009). Intense variation in temperature properties is observed in many southern hemispheric variables since 1970. Sea ice had experienced a rapid decrease during the 1970s, followed by a slow gain, indicating higher variability in the Antarctic sea ice during recent decades (Parkinson, 2006). Southern Annular mode had shown significant upward trend since 1970. This trend is related to anthropogenic activities due to CO₂ and change in ozone concentration (Sexton, 2001; Miller et al., 2006; Cai and Cowan, 2007). It is reported that the increases of greenhouse gases and ozone layer changes in future decade may have adverse consequence in Antarctic region by melting of sea ice (Shindell and Schmidt, 2004).

1.5 Meridional circulation in southern hemisphere

The meridional circulation is a response to the differences in insolation between low and high latitudes resulting in the transfer of energy. During the seasonal march of Sun the centre of convergence and divergence migrate to its respective hemisphere (fig 1.6). Meridional circulation in the southern hemisphere has three cells. viz., Hadley Ferrel and Polar cell. The annual mean tropical Hadley cell in the southern hemisphere is stronger than its counterpart in the northern hemisphere. During the solstice period, the area of rising and subsidence change according to the shift of mean position of Sun. Hadley cell has ascending in the equatorial region and sinking motion near 30⁰ S. During Austral summer, the ascending motion of the Hadley cell occurs south of the equator and it subside to the south of 30⁰ S. In winter the ascending branch is to the north of equator while subsidence occur to the
equatorward of 30° S. The change in Hadley circulation also shifts the mean position of other cells. The southern hemisphere winter Hadley cell is stronger than the northern hemispheric cell. During the equinoctial transition period Austral hemispheric cell are double intense than the boreal cell. The differences in the thermal properties give rise to region local Hadley circulation which is well evident in the Pacific and also during the summer monsoon period over India.

The Ferrel cell extend from 30° S to 60° S which is thermally an indirect cell, due to rising motion in the cold area and subsidence over the warm region. Another cell that exist in the Austral hemisphere is the Polar cell. The Polar cell extend from 60° S to polar region, this cell bring cold air equatorward. Both the Ferrel and Polar cells change their mean position, and are generally
weak in intensity throughout the year. Recently, changes are observed in the Hadley cell circulation that has influenced the existing circulation pattern and modulated the rainfall characteristics to a great extent.

In addition to this meridional circulation, the southern hemisphere has another meridional circulation known as Brewer Dobson Circulation (BDC). This BDC consists of three parts (fig 1.7), rising motion from troposphere to stratosphere in the tropical region, secondly, poleward transport in the stratosphere and the third part is the descending motion in the midlatitude and polar stratospheric region. The midlatitude sinking part transport back in to the troposphere while the poleward descending air accumulates in the

Figure 1.7: Schematic representation of Brewer Dobson Circulation (adapted from Frankfurt University)
lower stratosphere. The BDC transport is weak in the SH due to the strong polar vortex and lack of planetary scale wave activities.

1.6 Walker Circulation

The pressure and temperature difference in the western and eastern tropical Pacific result in the Walker circulation. The warm west Pacific and cool east Pacific creates pressure gradient with flow from east to west along surface and west to east in upper atmosphere completing the Walker circulation. The convergence in the western Pacific is associated with rainfall and the divergent in the east Pacific causes dry weather. The circulation undergoes changes and lead to the evolution of La Nina in its strong phase and El Nino in its weak phase (fig 1.8). During El Nino, low level convergence is shifted to the east Pacific and the divergence occur in the west Pacific region. During La Nina, the low level convergence occurs in the west Pacific and divergence is
observed along the east Pacific. On the basis of Indo-Pacific sea level pressure it is concluded that the Walker circulation is undergoing a weakening trend and the models also have supported this observational finding. This weakening trend has modulated the thermal and circulation properties of tropical Pacific Ocean (Vecchi et al., 2006).

1.7 Asian summer monsoon

One of the large scale and complex circulation pattern is the Asian summer monsoon. This monsoon is one of the major system that decides the dry and wet spells of rainfall over the most populated regions. This monsoon mechanism arises due to the heat difference between continent and Ocean, Coriolis force by rotation of earth, moisture transport, and meridional temperature gradient and also due to various other phenomenon. One of the fundamental cause of monsoon cycle is the cross-equatorial pressure gradient due to the differential heating (Webster, 1987). During the northern summer, winds flow from the southern hemisphere, transporting moisture and thereby accelerating the precipitation amount over the south Asian region (fig. 1.9).

Figure 1.9: Summer circulation near the equatorial region (adapted from http://www.ncclimate.ncsu.edu/secc_edu/images/monsoon.gif)
The Asian summer monsoon can be divided into two, the South Asian (Indian monsoon) and the East Asian monsoon system. Both of them are independent but interact each other through transfer of energy exchange, oscillation and moisture transport (Zhu et al., 1986). It is independent because the East Asian monsoon is not an extension of Indian monsoon. Study has shown that the Asian summer monsoon can include the western north Pacific region. Thus the Asian-Pacific monsoon can be subdivided into Indian Summer Monsoon (ISM), the western North Pacific summer monsoon (WNPSM) and the East Asian summer monsoon (EASM) which is schematically depicted in figure 1.10. The ISM and WNPSM are tropical monsoons in which the low level wind change its direction from easterlies to westerlies, and the EASM is a subtropical system where wind change its direction from northerlies to southerlies (Wang and Lin 2002).

Figure 1.10. Schematic representation of Asian summer monsoon (adapted from Wang and Lin, 2002)

Onset phase of Asian monsoon is complex because it is regional dependent. Ding (2004) has split the monsoon onset dates into four stages. During the first stage the earliest onset occur during late in April and in May in the
central Indo-China peninsula but some times it may be in southern or western part of peninsula. On stage 2 (mid to late May), the monsoon advance northward to the Bay of Bengal region. During stage 3 (June), the monsoon onset begins on Indian region and also in the East Asian region. On stage 4, it will reach to the north China and the Korean peninsula that occurs during July. Fluctuation is noticed in the Asian summer monsoon, it basically arises due to meridional temperature gradient (Yanai et al., 1992; Meehl, 1994; Li and Yanai, 1996; Wu and Zhang, 1998).

1.8 Indian summer monsoon

One of the strongest monsoon system in northern hemisphere is the Indian summer monsoon (ISM). This system brings copious rainfall all over India during June to September. Around 80% (Selvaraju, 2003) of the annual rainfall occurs during southwest monsoon period. This system starts with cross equatorial flow and wind blowing southwest direction associated with heavy rainfall all over India (fig 1.11). The migration of Indian monsoon

![Figure 1.11. Pressure and wind pattern during Indian summer monsoon (adapted from http://www.cdc.noaa.gov/Composites/Day/)](image)
system depends on the synoptic scale features. The western and central India receives more than 90% of annual precipitation, on the other hand the southern and northwestern India receives 50 – 70% of their annual rainfall during ISM period. The fluctuation in the monsoon system affects the production of agriculture and thereby it can alter the economic balance of India.

The failure of monsoon brings famine, while strong monsoon leads to flood. The delay in monsoon onset adversely affects the agriculture sector. Extreme precipitations do occur in India that also lead to economic and human loss. During summer monsoon, heavy rainfall occurs in the west coast of peninsula where the rainfall is related to the orography and over the northeastern region. High rainfall is also observed around 20° N, which is considered as core monsoon zone because the variation of ISM rainfall are highly correlated with variation of rainfall over this zone (Sikka and Gadgil, 1980). Rainfall over Indian region during the summer monsoon mostly occurs in association with development of convective systems and its propagation to the subcontinent. There are certain features that control the amount and spatial distribution of rainfall (fig. 1.12).

One among the parameter that control the rainfall pattern is the Low Level Jet (LLJ) at 850 hPa level (also known as Somali jet stream), this flow are vital in the distribution and intensity of rainfall by carrying moisture to the subcontinent. The flow pattern passing through India at 100 hPa level near 13.5° N is also important in the distribution of rainfall. This upper level flow is the Tropical Easterly Jet (TEJ) stream that runs from Vietnam to the west.
coast of Africa. The movement of this jet is associated with active and break spell of rainfall.

Another component of monsoon circulation is the monsoon trough extending from heat low over Pakistan to head Bay of Bengal. Monsoon trough is an east west oriented semi-permanent feature that maintain the precipitation activity in India. The trough in its normal position accounts for well-organized rainfall where its undulation to north results in break condition over India, during that period Himalayan foothills experience heavy rainfall. At the same time, the monsoon low and depression embedded in trough enhances the rainfall. Dislocation of the monsoon trough can be identified with the presence of blocking high over the Caspian Sea and also through the meridional flow in upper troposphere of northeastern hemisphere.
Monsoon low and depressions developing in the Bay also contributes to the summer rainfall. The monsoon low and depression travel westward causing heavy rainfall in India. The formation of this system shifts during different months. Earlier advancement of southwest monsoon is favoured by the formation of low or depression in June. In July, they are formed north of 18° N in the northwest Bay while in September it from in southward of central Bay. Usually two depressions form each of the monsoon seasons.

Tibetan anticyclone, which is seen in middle and upper troposphere during summer monsoon period, has a strong hand in controlling precipitation. The shift of anticyclone to south adversely affects the Indian monsoon. The anticyclone also moves towards west from its climatological position and affects the monsoon properties. Presence of Mid-Tropospheric Cyclones (MTC) in the northern parts of west coast of India also influences the deep convection during monsoon.

1.8.1 Onset characteristics of Indian monsoon

Monsoon onset over India expected to begin in early June over the southwest India. The onset is dependent on the changes in the circulation features of the lower and upper troposphere (Pearce and Mohanty 1984, Ananthakrishnan et al., 1983, Joseph et al., 1994). The primary driver of the Indian monsoon is the pressure gradient between southern (Mascarene high) and northern hemisphere (heat low over Pakistan). Li and Yanai (1996) has concluded that the reversal of land–sea thermal contrast and large temperature increase over the Tibetan Plateau in May–June help for ISM onset. Goswami et al. (2006) suggested ISM onset index based on the reversal of the large-scale meridional temperature gradient in the upper
troposphere. Strengthening of low-level wind over the low-latitude Indian region has been noticed to be a good indicator of the ISM onset (Taniguchi and Koike, 2006; Joseph et al., 2006). During the monsoon onset time a band of deep convection in the east-west direction passes through the southern tip of India (Sikka and Gadgil, 1980). After the onset of monsoon, moisture transport get well organized with cross equatorial flow in the western part of equatorial Indian Ocean thereby inducing rainfall mechanism in India.

1.8.2 Mean rainfall during summer months

The temporal and spatial distribution of rainfall during June to September has large scale variability which is evident from the subdivisional rainfall over India. This arises due to the fluctuation in synoptic scale activities. It is better to understand the monthly mean of rainfall distribution during each month. During June heavy rainfall greater 15 mm/day occurs in the west coast (fig. 1.13) and in the northeast regions. Rainfall less than 5mm/day

Figure 1.13. Mean rainfall (mm/day) over India during June

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occurs in the southeast coast of India. Precipitation of about 2-4 mm/day occurs to the north of 20° N. In July, the precipitation enhances all over India. During this month widespread rainfall occurs all over India (fig 1.14). In the southwest coastal station and northeast India rainfall about 28mm/day is observed. About 10 mm/day of rainfall is seen around 20° N. The enhanced precipitation during July is well evident along southwest coast, northeast regions, north India and along 20° N of India.
The precipitation during August seems to increase near 20° N than July precipitation by about 2mm (fig 1.15). Along the southwest coast in between 10° N to 21° N rainfall exceed to about 24mm/day. Precipitation greater the 12mm/day occurs in many parts of northeast India. Precipitation less than 2 mm/day is observed along northwest and southeast India.

As the monsoon recedes in the month of September the intensity of rainfall decrease which is evident in all over India. Most of the central, and south India shows precipitation less than 15 mm/day (fig 1.16). There are areas of northeast India were precipitation greater than 15 mm/day is observed. Northwest India shows precipitation less that 2 mm/day during the monsoon retrieval period.

Figure 1.16. Mean rainfall (mm/day) over India during September
1.8.3 Interannual and Intraseasonal variability of Indian Summer Monsoon

Indian monsoon shows variability in both interannual and intraseasonal timescales. Interannual variability refers to unevenness within years, while intraseasonal is the variability within season. These changes are important to understand the scale of precipitation and its distribution over Indian domain.

1.8.3.1 Interannual Variability (IAV)

The year to year variation has high potential impact in the Indian economy. Interannual variability of the tropical climate is partially governed by internally generated low frequency (LF) oscillations in addition to being forced by slowly varying sea surface temperature, soil moisture, sea ice etc. Non-Linear interaction between high frequency oscillation, non-linear interaction of intraseasonal oscillation, interaction between flow pattern and topography lead to the generation of low frequency variability. Several studies were carried out to find the mechanism of the IAV of Indian summer monsoon. Extensive study of seasonal mean Indian rainfall had shown that the rainfall is sensitive to small changes in the initial condition rather than the slowly varying boundary condition (Brankovic and Palmer, 1997; Palmer and Anderson, 1994).

Several research work also supported that the interannual variability of Indian monsoon is controlled by internal dynamics (Goswami 1998; Hazrallah and Sadourny, 1995; Stern and Miyakoda, 1995). But these studies do not provide strong evidence of the origin of this internally generated mechanism. Studies with an atmospheric system models, (Goswami, 1997)
has observed that change in the intra seasonal oscillation by the annual cycle could give rise to an internal quasi-biennial oscillation in the tropical atmosphere and influence the IAV of the Indian monsoon. The interannual variability in monsoon rainfall could cause severe droughts and floods (Kripalani et al., 2003) and will adversely affect the agriculture production. This seems that IAV of Indian summer monsoon is chaotic and complex.

1.8.3.2 Intra seasonal Variability (ISV)

Rainfall over Indian region varies in shorter time scales. The fluctuation in rainfall is associated with periodicities like 3-7 days, 10-20 days and 30-60 days. Monsoon trough undulations result in 3-7 day oscillation where the monsoon low/depression or the westward moving waves are associated with 10-20 days. The higher period of oscillation in the ISV is the 30-60 day known as Madden-Julian Oscillations (Madden and Julian, 1971). The Madden-Julian Oscillation propagates eastward slowly through warm centers of Indian and Pacific Oceans and help in the organised convection. These oscillations result in active and break spells of summer monsoon over Indian region. Rainfall is sporadic for several days during the peak monsoon months of July–August, have been called breaks in the monsoon by the Indian meteorologists for several decades (Krishnamurti and Bhalme, 1976; Sikka, 1980). This Intra seasonal variability is important in the evolution and character of Indian monsoon (Lau and Waliser, 2005, Zhang, 2005; Waliser, 2006). Several research works has carried out to understand the intraseasonal variability of Indian monsoon.
During active and break periods, the circulation and precipitation pattern have high variability. The northward migration of trough causes dry spell of rainfall like condition (Blanford, 1886). The intra seasonal variability is high during the peak monsoon months (July and August). The active-weak spells in rainfall are associated with fluctuations in the intensity of the continental tropical convergence zone (Sikka and Gadgil, 1980).

1.8.4 Extreme in monsoon rainfall events

Indian summer monsoon has experienced heavy rainfall during summer monsoon season. These extreme precipitation events destroy the production of agriculture and cause human loss. Several investigations have carried out to understand the summer monsoon rainfall extremity. It is noted that during a period from 1901 to 1980, significant increase occur in the extremes in the west coast north of 12°N and over certain locations of eastern part of Western Ghat where southern peninsula and lower reaches of Ganges exhibit a decreasing trend. Goswami et al. (2006) have analysed the extremes and reported that the frequency and magnitude of extremes has intensified for period from 1951 – 2003 at the same time the trend of moderate events decreased. Recent observation of Indian Meteorological Department has reported that there is decreasing trend of wet days in most part of the country and also added that the flood risk also has increased.

1.8.5 Strong and weak monsoon characteristics

Prolonged active and break condition in monsoon leads to strong and weak monsoon. The active and break situations are observed mainly in July and August. During this period rainfall over Indian region is well spread.
Maximum amount of precipitation occurs in month of July and August, but the amount of precipitation varies in strong and weak monsoon years. In association with the varying precipitation large scale circulation and SST also changes. One of the important parameter that affects the strength of Indian monsoon is the low level flow at 850 hPa (Somali jet stream). The composite difference of weak minus strong condition is depicted in figure 1.17. From the figure it is evident that during weak monsoon condition anomalous easterlies flow occur in the south Indian region. Anomalous cyclonic circulation is also observed along the northwest coast of India.

The western Pacific and tropical Indian Oceans are the warmest water in the global ocean. This warm pool is sensitive to slight variations which will affect the atmospheric convection and thereby changes the precipitation pattern.
existing there. The sea surface temperature during the composite difference of weak minus strong monsoon years shows slight cooling in the western Arabian Sea. During weak monsoon years, the equatorial Indian Ocean and Bay of Bengal region experiences warming (fig 1.18). The warming is intense in the southern hemisphere (area near Mascarene high). Along 100° E and to

![Figure 1.18. Composite of SST difference in July-August for weak minus strong monsoon.](image)

the south of 10° S cooling occurs while to the north of 10° S warming intensifies during weak monsoon. In addition to this features, weak monsoon result in large scale subsidence over Indian domain with equatorial enhancement of rising motion (fig 1.19). Anomalous ascending motion also occurs near 27° N with descending motion near 30° N. During weak monsoon condition the moisture transport through the monsoon area also get reduced. These changes will adversely affect the precipitation amount during July-August.
1.9 Teleconnection of Indian summer monsoon

Teleconnection is the link between weather changes of different regions of world. The global scale interaction of various parameters with El Nino and Annular modes is one of the best examples of teleconnection. Indian summer has teleconnection with various parameters. Prediction of Indian monsoon depends upon the variability of nearby features. One among them is the El Nino, which plays major role in the success or failure of Indian summer monsoon. El Nino the tropical disturbance of Pacific region is associated with lower than normal rainfall due to the positive pressure anomalies over Indian region (Maity and Kumar, 2006; Rasmusson and Carpenter, 1983).

During El Nino, the Walker circulation gets altered with subsidence over Indian region. Warm phase of ENSO result in anomalous descending motion over Indian sub-continent while ascending motion is enhanced in near equatorial region (Krishnamurthy and Goswami, 2000). Another parameter that affect the Indian summer monsoon is the Pacific Decadal Oscillation (PDO), warm phase of this oscillation contribute to decrease in Indian summer monsoon rainfall index.
Teleconnection of Indian summer monsoon is not only confined to Pacific region but the link is also observed with Atlantic region. Atlantic Ocean weakens the monsoon circulation over India (Wang et al., 2009). Several studies have reported the existence of correlation between subtropical Atlantic sea surface temperature and Indian monsoon (Yadav, 2008; Rajeevan and Sridhar, 2008).

The snow over the different region exhibits relationship with Indian summer monsoon. The winter snow cover western Eurasia shows negative correlation with Indian summer rainfall (Bhanzai and Shukla, 1999) while the snow melt over western Himalayas is conducive for Indian monsoon rainfall (Kripalani et al., 2003). The study has further concluded that the snow melt influence the cross-equatorial flow and the heat low over northwest India.

The extra tropical oscillation known as North Atlantic Oscillation (NAO), the mass difference between mid and high latitude of northern hemisphere also play significant relation in controlling the summer precipitation over India and the relation are more effective over the sub-divisional rainfall (Kakade and Dugam, 2006). The midlatitude and ISM relation is also studied in detail, it is hypothesised that the easterly vertical shear and moist dynamic instability is related to the eastward propagation of wave train originating in Atlantic region (Ding and Wang, 2007). The pressure fields of other region also influence the ISM on intraseasonal time scales.

Fabio et al. 2003 has shown that the precipitation during June – July - August over India correlates negatively with sea level pressure field over the eastern
Mediterranean. Another influential factor to Indian summer monsoon is the Tibetan anticyclone, the temperature anomalies in the northeastern region is a useful predictor of rainfall along the monsoon trough region (Bansood et al., 2003). The southern hemispheric variation is interrelated to the summer monsoon. It is shown that the low temperature over Australia can enhance evaporation rate over the eastern tropical Indian Ocean and can induce rainfall over western India (Lee and Koh, 2012).

Relationship of Indian monsoon various parameters have altered their relationship during recent decades, in this context the search for other parameter is of great interest. Extensive work has carried out to understand the extra tropical influence on Indian summer monsoon. One such relation has accounted by the Atlantic Multidecadal Oscillation (AMO). The AMO oscillation result in the negative anomalies in Eurasia during late summer and autumn, results in early withdrawal and persistent decrease of summer monsoon rainfall. Strong North Atlantic Oscillation (NAO) also produces similar anomalies in Eurasia (Goswami et al., 2006) and thereby affects summer monsoon. At the same time it is observed that the April NAOI index is significantly related to Indian monsoon (Kakade and Dugam, 2000). During strong NAO anomalies the outgoing longwave radiation anomaly are positive and suppress the convection (Dugam, 2008) and it is concluded that the NAO index can be used as a predictor for summer monsoon. Southern hemisphere polar region has shown connection with Indian monsoon through the Antarctic sea ice content (Prabhu et al., 2009). Southeast Indian Ocean is linked with the variability of monsoon rainfall, which is a precursor of Indian summer monsoon.
1.10 Objectives of the study

The primary aim of the present doctoral thesis is to understand the variability in southern hemisphere and its relation to tropical climate. Primarily, the study focuses to find the period of climate shift in the troposphere and stratosphere of southern hemisphere. An attempt is made to understand the magnitude of temperature change in the troposphere and stratosphere of southern hemisphere after the well documented climate shift. The spatial and temporal variation of temperature is observed for specific vertical levels. Radiosonde observations are also used to understand the period and magnitude of climate shift.

Recent trends and extreme variability of meteorological parameters in southern stratosphere is another objective of the present study. The frequency of extremity is noticed to understand the magnitude of anomalous change in different stratospheric levels. Percentage dispersion of mean temperature at specific levels has been studied to understand the variability in different months. In addition to this, the El Nino teleconnection to stratosphere is observed to find the relation of troposphere perturbation to the stratospheric temperature. For the above analysis, different Nino indices are used to find the variability.

Second objective of the study is to understand the Southern Annular mode impact on the tropical circulations. The tropical circulation pattern includes Hadley and Walker circulation. Velocity Potential is used to find the area of divergence and convergence. In addition to Hadley and Walker circulations variability associated with SAM, the climatology of these circulations after
the climate shift period has been analysed. Interannual variation of Hadley cell is studied to understand the year-to-year change in circulation.

The teleconnection of summer monsoon over India with the Southern extratropical oscillation is the third objective of the present study. The study also focuses on the predictability of monsoon with Southern Annular Mode. Variability in rainfall, sea surface temperature, moisture transport and vertical velocity is investigated to find the teleconnection of SAM to Indian summer monsoon. The influence of SAM on India summer monsoon is analysed using June and July-August indices. Further the study concentrate on the influence of North Atlantic Oscillation on the SAM-Monsoon relationship. Simultaneous effect of SAM and NAO are studied to understand the variability in various monsoon parameters like precipitation, sea surface temperature and moisture transport. By keeping the constant phase of North Atlantic Oscillation, the effect of June SAM to the Indian monsoon has been studied.

1.11 Justification of the Thesis work

The present study mainly concentrates on the change of southern hemisphere climate. Compared to northern hemisphere, the variability in the Southern hemisphere has not studied in detail. Moreover, it is interest to note the variation after the well documented climate shift. Recently it is known that the stratosphere is also a driver of climate change, so the anomalies and abrupt variation in the stratosphere is also a matter of concern. Moreover the finding of El Nino teleconnection to the stratosphere is important thing to be analysed. In addition to this, the present study focus
on the influence of Southern Annular Mode in changing the large scale patterns like Hadley, Walker and Monsoon circulations.

As it is known that the Indian summer monsoon circulation arise due to differential heating of Mascarene high (located in Southern hemisphere) and heat low in the northwest Indian region. Both observational and modeling studies have reported the importance of cross equatorial flow over Indian Ocean and moisture flux from both Indian Ocean and Arabian Sea regions in Indian monsoon rainfall (Saha, 1974; Pisharoty, 1976; Washington et al., 1977; Cadet and Reverdin, 1981).

In this context it is important to analyse whether the Southern extra tropical mode can influence Indian summer monsoon, in the light of weakening relationship of monsoon and El Nino, and also with various other parameters. Further, the association of NAO to SAM-Monsoon link also boost the potential predictability of summer monsoon parameters. The SAM related work has not studied well by the scientific community, so the present study will help in better understanding the tropical variation associated with southern extra tropical mode.