Chapter 5

Inter-annual variability in the surface wind and wind stress curl
5.1. Introduction

North Indian Ocean is well known for the spectacular reversal of seasonally varying monsoon winds. During winter monsoon, i.e. from November onwards the winds blow away from the continent (northeasterlies) and during summer monsoon, the winds blow from the ocean towards the land (southwesterlies). South of 10°S the southeast trade winds persist throughout the year (Rao, 1976). They attain their seasonal maximum and most northward extent during the summer monsoon period. During the transition period between the monsoons i.e. during March/April and October, winds become westerlies in the equatorial Indian Ocean region. The zonal wind stress in the equatorial region is westerlies from March to October and largest during spring and fall that drive the equatorial spring and fall jets in the Indian Ocean (Wyrtki, 1973). The atlas by Hastenrath and Lamb (1979) gave a complete description of the atmospheric fields over this region.

The curl field also changes in response to wind stress reversal. During the summer monsoon, anti-cyclonic curl resides over most of the Arabian Sea and equatorial Indian Ocean north of 15°S. A sharp curl gradient was noticed in the southwesterlies of the Findlater Jet over the Arabian Sea (Findlater, 1971). Its maximum is over the central Arabian Sea. This reverses to become cyclonic during winter monsoon, whereas over the western Bay of Bengal, the curl is cyclonic in summer and anti-cyclonic in winter.

The climatological wind stress and curl of the wind stress (Hellerman and Rosenstein, 1983) showed maximum amplitude off the coast of Somalia. However, the curl changes its sign between the northeast and southwest monsoons. The region of negative wind stress curl extended over most of the Arabian Sea during the southwest monsoon. During the northeast monsoon, the surface flow exhibits two distinct jets, one in the Arabian Sea and the other in the Bay of Bengal. Even though the strongest winds are noticed over the western Arabian Sea, the region of maximum negative curl was reported over the southeastern Arabian Sea (Schott and McCreary, 2001).

Though a lot of studies have been carried out on the surface wind field and wind stress curl, their inter-annual variability particularly over the Indian region, have
not been studied much. In this chapter, the main emphasis is given on the inter-annual variability in the surface wind field and wind stress curl. Moreover, it has been reported that 1994 and 1997 are the years in which unusual climatic events, i.e. the Indian Ocean Dipole events (Saji et al., 1999) took place in the Indian Ocean. The variability in the surface wind field and wind stress curl associated with these events is also discussed here.

5.2. Data and Methodology

The study region extends from 25°S-25°N and 40°-120°E over the Indian Ocean. The monthly averaged wind at 10m levels is obtained from NCEP/NCAR Reanalysis corresponding to the period 1993-1997. The wind stress curl is also computed from the wind field as follows.

Wind stress is computed as

\[ \tau_x = \rho \, C_d \, U \times U_x \]  
\[ \tau_y = \rho \, C_d \, U \times U_y \]

where \( U = \sqrt{U_x^2 + U_y^2} \)

where \( C_d = 0.0013 \) and \( \rho = 1.2 \, \text{kgm}^{-3} \)

wind stress curl \( \equiv d\tau_y/dx - d\tau_x/dy \)

Curl values (Nm\(^{-3}\)) are either positive/cyclonic and negative/anti-cyclonic

5.3. Results and Discussion

5.3.1 Surface wind

Winds over the Indian Ocean reverse semi-annually associated with the monsoons. In this section, the surface winds (monthly averaged) over the Indian Ocean and their inter-annual variability are discussed during the period from 1993 to 1997 (Figs.5.1-5.5). During winter monsoon, (November to March) the winds are northeasterlies over the north Indian Ocean with maximum (>6-8 ms\(^{-1}\)) over the western Arabian Sea in January. The southwesterly winds are noticed from June to September over the North Indian Ocean with maximum magnitude (>10-12 ms\(^{-1}\)) over the western Arabian Sea and off the Somali coast during July. During the transition period between the monsoons i.e. March/April and October, winds are noticed to be
weak over the Arabian Sea and Bay of Bengal. In the equatorial region, wind direction changes from northeasterlies to westerlies (~2 ms\(^{-1}\)) during March/April and from southwesterlies to westerlies (~2-4 ms\(^{-1}\)) during October. While over the south Indian Ocean (SIO) southeasterly winds (or the southeast trades) prevail the whole year. During the winter monsoon (northern hemisphere) they are southerly (6-8 ms\(^{-1}\)) near the eastern Indian Ocean and turn to easterlies (~2-4 ms\(^{-1}\)) at about 60\(^{\circ}\)E and converge with the northeast monsoon winds crossing the equator near Madagascar.

During April, the southeasterlies from the south Indian Ocean and northeasterlies from the north Indian Ocean converge near the equatorial region west of 50\(^{\circ}\)E. The southeasterlies strengthen from April onwards and cross the equator during May to form the continuous summer monsoon current from June to September. Thus the southeast trade winds shift northwards and southwards with the season and have their maximum magnitude (> 8 ms\(^{-1}\)) during summer monsoon season. The figures (Figs.5.1-5.5), in general show the seasonal variability and inter-annual variability in the surface wind speed and direction for all the years.

It appears that during the years 1993, 1995 and 1996 (Figs.5.1, 5.3 & 5.4), wind pattern are similar while 1994 and 1997 are typical (Figs.5.2 & 5.5) and different from these years. The maximum magnitude of the northeasterlies and southeasterlies are observed over the Arabian Sea and their variability maximum is noticed over the Bay of Bengal. Over the equatorial region, during the transition period between the monsoons, the wind pattern shows large inter-annual variability.

The northeasterlies are observed to be relatively strong (6 ms\(^{-1}\)), extending over a wide area over the Bay of Bengal during January 1993, 1995 and 1996 (Figs.5.1, 5.3 & 5.4) compared to 1994 and 1997 (Figs.5.2 & 5.5). During 1993, it extends from 2\(^{\circ}\)-15\(^{\circ}\)N and 82\(^{\circ}\)-95\(^{\circ}\)E with a core magnitude of 8 ms\(^{-1}\). Similarly, during 1995 and 1996, the northeasterly winds (6ms\(^{-1}\)) extend from about 2\(^{\circ}\)-18\(^{\circ}\)N and 82\(^{\circ}\)-95\(^{\circ}\)E and 3\(^{\circ}\)-16\(^{\circ}\)N and 82\(^{\circ}\)-92\(^{\circ}\)E respectively. During 1994 and 1997, magnitude of the northeasterlies are weak (4 ms\(^{-1}\)) over the Bay of Bengal region. The southwesterlies over the Bay of Bengal, shows strong monsoon winds during July 1994 and 1997 and comparatively weaker winds during 1993, 1995 and 1996. During 1994 and 1997, the magnitude of the southwesterlies exceeds 8 ms\(^{-1}\) over the Bay of Bengal region between 5\(^{\circ}\)-20\(^{\circ}\)N. On the other hand, during 1993, the values are below 6 ms\(^{-1}\) but with a core speed of 8 ms\(^{-1}\) occur over northern Bay (around 15\(^{\circ}\)N) and south of Sri
Lanka (around 5°N). During 1995, the core magnitude of 8 ms⁻¹ is noticed over a small area in the northern Bay and south of Sri Lanka during July as observed from Fig.5.3 and even less during 1996, over south of Sri Lanka (around 5°N) only. During the transition period of October 1993, 1995 and 1996, strong southwesterlies (>2-4 ms⁻¹) are found over the southern and central Bay of Bengal compared to 1994 and 1997 (<2 ms⁻¹).

It is also interesting to note that the northeasterlies are slightly weak at the core during January 1994 (8 ms⁻¹ over a small area) and 1997 (6 ms⁻¹) over the western Arabian Sea compared to other years. In all other years, the northeasterlies of 8 ms⁻¹ at core extends over the western Arabian Sea northwards up to ~15°N.

Over the equatorial region the winds show semi-annual periodicity with westerlies occurring twice in a year during the transition period between monsoons. Over the western Indian Ocean during the winter monsoon period, the northeasterlies crosses the equator towards south to meet with the southeast trades over the southern Indian Ocean. They converge near the equator during April. During the transition period of March/April, a part of the northeasterlies turn first to northwesterlies and subsequently to westerlies, first noticed south of the equator and extending northwards. From May onwards, the southeast trade winds starts crossing the equator to form the southwest monsoon current. Again, during the transition period of October, the southwesterlies changes to westerlies over the equatorial region. The magnitude and direction of these westerlies over the equatorial region shows large inter-annual variability, with similar pattern observed during 1993, 1995 and 1996 (Figs.5.1, 5.3 &5.4) and different during 1994 and 1997 (Figs.5.2 &5.5).

During January 1993 (Fig.5.1), winds are observed to be very weak (< 2 ms⁻¹) south of equator up to 10°S (up to 15°S over the western Indian Ocean) and between 45°-85°E. By March, the northeasterlies changes to northwesterlies (> 2 ms⁻¹) near 57°E and to westerlies (> 2 ms⁻¹) east of 70°E and south of the equator to 10°S. The westerlies (> 2 ms⁻¹) strengthens during April between 5°N and 5°S over the central Indian Ocean. West of 70°E, winds are noticed to be weak (< 2 ms⁻¹) in the equatorial region and to ~10°S. The southeasterlies from the south Indian Ocean and northeasterlies from the north Indian Ocean converges near the equatorial region west of 50°E in April. By October, when the southwesterlies weakens over the Indian
Ocean, westerly winds (>4 ms\(^{-1}\)) are noticed over the central Indian Ocean between equator and 8°N. From November onwards northeasterlies appears over the Arabian Sea and Bay of Bengal, while in the equatorial region between 5°N to 5°S and 55° to 95°E westerly winds are noticed. The northeasterlies and southeasterlies from both hemispheres converge in the equatorial region west of 50°E in November. Equatorial westerly wind zone shifts southwards by December.

During 1995 (Fig.5.3), the magnitude and extent of northeasterlies over the western Indian Ocean (south of the equator) are more (> 2 ms\(^{-1}\)) during January compared to 1993 (Fig.5.1). The northeasterlies changes to northwesterlies and is strong (> 4 ms\(^{-1}\)) between 0°-12°S and west of 70°E. By March, the northeasterlies over the Arabian Sea weakens similar to that in 1993 and westerlies (> 2 ms\(^{-1}\)) are observed between 70°-100°E and 0°-5°S. The westerlies shift northward by April to extend east of 65°E over the equator, while between 55° and 65°E over the equatorial region, northwesterlies are also noticed. In April, the magnitude of the northeasterlies (2-4 ms\(^{-1}\)) over the Arabian Sea is found to be greater than other years. Westerlies are noticed between 0°-10°N and 60°-90°E (> 2-4 ms\(^{-1}\)), during October. They shift southwards by November and extend up to 100°E and weakens afterwards. In 1996, westerly winds (< 2 ms\(^{-1}\)) are noticed south of the equator during March but with northwesterlies (> 2 ms\(^{-1}\)) in the central equatorial region. In April, the northwesterlies and westerlies are stronger (2-4 ms\(^{-1}\)) than in all other years between 55° and 100°E in the equatorial region. But the northeasterlies are observed to be comparatively weaker over the western Arabian Sea in April. By October, again westerlies are also noticed to be stronger (4-6 ms\(^{-1}\)) between 0°-10°N and 60°-100°E, which weakens and shifts southwards by November/December.

The wind pattern during 1994 and 1997 (Figs.5.2 & 5.5), show slight differences from other years, more noticeable during the transition period between the monsoons. During March 1994, the northwesterlies over the western Indian Ocean and westerlies (< 2 ms\(^{-1}\)) over the central Indian Ocean appears weak. In April, the winds (< 2 ms\(^{-1}\)) are weak over the western equatorial Indian Ocean (between 50° and 70°E) and slight southwesterly winds are also noticed, in the usually westerly wind regime (between 70° and 100°E). Another noticeable observation is the southeasterlies (> 2-4 ms\(^{-1}\)) blowing alongshore of Sumatra from June to October, where otherwise winds are weak (<2 ms\(^{-1}\)). Similarly, westerly winds (<2 ms\(^{-1}\)) are noticed to be weak.
in the equatorial region during October also. Moreover, during this period also southeast trade winds from the southern Indian Ocean extends north of equator over the eastern Indian Ocean and west of Sumatra, where otherwise weak winds are noticed. These conditions are even more pronounced during 1997. In March, winds are easterlies over the Indian Ocean west of 80°E. Westerlies (2 ms\(^{-1}\)) are noticed during April between 70° and 90°E only and is very weak (< 2 ms\(^{-1}\)) west of 70°E. A southward flow is also observed over the western equatorial Indian Ocean. During October 1997, easterlies are also observed in the equatorial region. The winds over the eastern Indian Ocean and west of Sumatra are similar to 1994, with the southeasterlies from the south Indian Ocean extending north of the equator also from May/June to December, which is not observed in other years.

Over the South Indian Ocean, the southeast trades exist throughout the year extending northward during the northern summer and southward during northern winter. These winds are also noticed to have inter-annual variability in their magnitude and direction. During 1993, the trades are noticed south of 10°S (Fig.5.1) with a magnitude of 6 ms\(^{-1}\) (8 ms\(^{-1}\) to the core) in January over the eastern Indian Ocean and decreasing to 2-4 ms\(^{-1}\) over the western Indian Ocean. During this period, the northeasterlies from the north Indian Ocean and southeast trades converges over the Madagascar Island. Magnitude of the southeasterlies is noticed to decrease (4 ms\(^{-1}\)) during February over the eastern Indian Ocean and increases again by March. The southeast trades (6 ms\(^{-1}\)) over the western Indian Ocean extends towards the equatorial region in April. The cross equatorial flow increases from May (6-8 ms\(^{-1}\)) onwards, with maximum magnitude (8-10 ms\(^{-1}\)) over the western Indian Ocean during July. By August eastern region also attains a maximum of 8 ms\(^{-1}\). By October, these winds weakens and shifts southward.

The magnitude of the southeast trades is comparatively higher (>8 ms\(^{-1}\)) in February 1994 over the eastern Indian Ocean upto 80°E (Fig.5.2). This decreases in March (6 ms\(^{-1}\)) near the eastern Indian Ocean. The magnitude of the southeast trades over the western Indian Ocean is found to be small during April (4 ms\(^{-1}\)) and May (6 ms\(^{-1}\)) compared to 1993. Cross equatorial flow increases from May (6 ms\(^{-1}\)) onwards. The trade winds weaken (6 ms\(^{-1}\)) from September onwards. Another noticeable difference observed here is the southeasterlies (> 4-6 ms\(^{-1}\)) from the south eastern
Indian Ocean extending northwards across the equator over the Sumatra region from July onwards and are remains there till October/November.

During 1995 (Fig.5.3), magnitude of southeast trade winds (6 ms$^{-1}$) are comparatively smaller in January and extends from 110°E westwards upto 90°E in the south Indian Ocean. This extends to 60°E by February. Again, during April and May, the magnitude becomes less (4-6 ms$^{-1}$) over the south Indian Ocean and in June extends (6 ms$^{-1}$) only upto 70°E. The magnitude increases (8 ms$^{-1}$) during the monsoon months of July and August.

During 1996 January (Fig.5.4), the wind speed of 6-8 ms$^{-1}$ is noticed over the eastern Indian Ocean. By February, this speed decreases over the eastern Indian Ocean and increases over the western part. The trade winds extend more northwards by March with a core of 8 ms$^{-1}$ over the eastern Indian Ocean. During June and July the core maximum (8 ms$^{-1}$) shifts westwards (west of 90°E). Magnitude of the southeast trades weakens in September. By October again an increase in the magnitude (>8 ms$^{-1}$) of the trades are noticed west of 100°E.

During January and February 1997, the magnitude of southeast trades is found higher (>8 ms$^{-1}$) south of 17°S. In March the trades (>4 ms$^{-1}$) extends more northwards (north of 10°S). The summer monsoon flow, increases (>8 ms$^{-1}$) from June onwards. Here also similar to 1994, the southeast trades (>4-6 ms$^{-1}$) extends more northwards and is noticed west of Sumatra island, where otherwise the magnitude is comparatively small (< 2 ms$^{-1}$) during the summer monsoon. This southeasterlies remains over the eastern Indian Ocean north of the equator during October and November and their magnitude decreases and shifts slightly southwards by December.

Thus the wind pattern during 1993, 1995 and 1996 showed similar pattern and 1994 and 1997, different from these years. The westerlies over the equatorial region during the transition period between monsoons appeared weak (< 2 ms$^{-1}$) during 1994 and 1997 and even easterlies were noticed for 1997. Similarly another noticeable difference observed was the extension of southeast trades more northwards (north of equator) over the eastern Indian Ocean and over the Sumatra region from June/July to December during both 1994 and 1997. The variability in the monsoon winds was noticeable over the Bay also with weak northeasterlies (4 ms$^{-1}$) and strong
Figure 5.1 surface winds (ms$^{-1}$) for 1993
Figure 5.2 surface winds (ms$^{-1}$) for 1994
Figure 5.3 surface winds (ms\(^{-1}\)) for 1995
Fig. 5.4 surface winds (ms$^{-1}$) for 1996
Fig. 5.5 surface winds (ms$^{-1}$) for 1997
southerlies (>8 ms⁻¹) occurring during 1994 and 1997 compared to 1993, 1995 and 1996. During 1994 and 1997, El Nino has occurred over the Pacific Ocean. In addition Saji et al., (1999) has reported the occurrence of Indian Ocean Dipole (IOD) events in the Indian Ocean during these years. They have also reported the appearance of abnormally extended trade winds over the Sumatra region during IOD. Murtugudde et al. (2000) has also reported strong upwelling in the eastern Indian Ocean during 1997 and suggested that it was forced locally by alongshore winds and remotely by equatorial and coastal Kelvin waves. The surface winds analysed here also show typical patterns during 1994 and 1997 coinciding with the anomalous events in the Indian Ocean.

In the south Indian Ocean also winds showed anomalous behaviour during 1994 and 1997, when the southeast trades over the eastern Indian Ocean extended further northward in the eastern equatorial region (near the Sumatra region) from June/July onwards. These winds remained there till December although with slightly less magnitude.

5.3.2 Wind stress curl

The wind stress curl computed from the wind field shows the rotating effect of the wind, either cyclonic represented by positive values or anti-cyclonic circulation represented by negative values in the northern hemisphere. The curl fields (Figs.5.6-5.10) are also noticed to change in correspondence with the wind reversals, with large reversals observed with the seasons over the northern Indian Ocean. In this section, the curl corresponding to the north Indian Ocean only is discussed.

Generally over the north Indian Ocean, during the northeast monsoon period and till May, curl values (Figs.5.6-5.10) are noticed to be negative or anti-cyclonic over the western Bay (-0.02 x10⁻⁵ Nm⁻³) to the southern tip of India (-0.01 x10⁻⁵ Nm⁻³), around Sri Lanka (-0.015 x10⁻⁵ Nm⁻³) and also over the northwestern Arabian Sea (-0.025 x10⁻⁵ Nm⁻³). However, curl is positive over the offshore regions of the Somali coast (0.015 x10⁻⁵ Nm⁻³) and negative over the Somali coast during the same period. With the establishment of southwest monsoon winds, the curl also reverses its sign. The positive or cyclonic curl (0.015 x10⁻⁵ Nm⁻³) starts appearing first over the west coast and over the east coast of India during the pre-monsoon period itself. From May onwards, cyclonic curl (>0.015 x10⁻⁵ Nm⁻³) extends over the western Bay to the
southern tip of India and around Sri Lanka and also extends towards the central Bay. However, near the Somali region from June onwards, anti-cyclonic/negative curl is noticed (< -0.03 x10^{-5} \text{Nm}^{-3}) extending to the central Arabian Sea, with cyclonic curl west of it over the coast of Somali and extending to the Arabia coast and northern Arabian Sea. With the weakening of summer monsoon winds by September, both the curl values decreases. The intensity and extent of the curl (Figs.5.6-5.10), either positive or negative shows large variability in all the years indicating inter-annual variability. The prominent regions of positive and negative curl, which favour cyclonic and anti-cyclonic circulation over the region, are separately discussed here to explain their inter-annual variability in each case.

Around the tip of India, curl is negative (-0.005 x10^{-5} to -0.01 x10^{-5} \text{Nm}^{-3}) (Fig.5.6) during January 1993 (core around 8°N, 75°E). This value decreases with the progress of time, but the curl is still negative over regions offshore of the west coast of India. By May, positive curl (0.02 x10^{-5} \text{Nm}^{-3}) appears over this region, which prevails there till September/October. From December, again negative curl (-0.005 x10^{-5} \text{Nm}^{-3}) is noticed over the southern tip of India. In January 1994 (Fig.5.7), the region of negative curl (-0.005 x10^{-5}-0.015 x10^{-5} \text{Nm}^{-3}) is shifted a little southward (core around 5°N, 75°E). The negative wind curl again forms from November 1994 onwards, earlier than 1993. The years 1995 (-0.005 x10^{-5} to -0.01 x10^{-5} \text{Nm}^{-3}) and 1996 (-0.005 x10^{-5}-0.015 x10^{-5} \text{Nm}^{-3}) also, exhibits similar pattern (Figs.5.8 & 5.9) as that of 1993. While for 1997 (Fig.5.10) the negative curl (-0.005 x10^{-5} to -0.01 x10^{-5} \text{Nm}^{-3}) is noticed southward (~5°N and 75°E) similar to 1994 during January. Thus negative curl, which represents anti-cyclonic circulation over the region is found more southward during 1994 and 1997 compared to 1993, 1995 and 1996. The curl remains anti-cyclonic (negative) till March/April around the tip of India.

The positive curl for 1993-1997 over the southern tip of India during the southwest monsoon season also reveals similar patterns during 1993, 1995 and 1996 (Figs.5.6, 5.8 & 5.9). During these years, the positive curl (0.005-01 x10^{-5} \text{Nm}^{-3}) remains around the tip of India till October and November. While during 1994 and 1997 (Figs. 5.7 & 5.10), values are comparatively less during September and October (0.005 x10^{-5} \text{Nm}^{-3}) around the southern tip of India. It is also noticed here, that during 1994 and 1997 the negative curl start forming in November itself.
Curl is negative found over the northwestern Arabian Sea (off the Arabia coast) during the northeast monsoon and changes to positive with the onset of summer monsoon. The extent and core maximum of this negative/anti-cyclonic curl, also shows inter-annual variability (Figs.5.6-5.10). During 1993 (Fig.5.6), the core maximum (-0.025 x10^-5 Nm^3) is noticed around 15°N in January and curl is negative off the Arabia coast and over the northern Arabian Sea (70°). During February/March, the negative curl (-0.01 x10^-5 Nm^3) is seen extending from the northern Arabian Sea to the west coast of India. This negative curl changes by June to cyclonic/positive curl (0.015 x10^-5 Nm^3). From December, again negative curl forms over the Arabian coast. During January 1994 (Fig.5.7), the extent of the negative curl (-0.015 x10^-5 Nm^3) over the northern Arabian Sea is less and is upto 68°E only. During 1995 (Fig.5.8), the core maximum (-0.02 x10^-5 Nm^3) is seen over the Arabia coast region in January and comparatively weak values (-0.015 x10^-5 Nm^3) over the northern Arabian Sea during May. The maximum negative curl is noticed during January over the western Arabian Sea (-0.025 x10^-5 Nm^3) in 1996 (Fig.5.9). During 1997 (Fig.5.10), negative curl is noticed to be less (-0.02 x10^-5 Nm^3) in January. However, it is interesting to note that during 1995 and 1997, the negative curl (<-0.015x10^-5 Nm^3) over the northwestern Arabian Sea prevails during June also, while during 1993, 1994, and 1996 (Figs.5.6, 5.7 & 5.9), positive curl develops well over the region from June onwards. Thus the negative curl denoting anti-cyclonic circulation over the western Arabian Sea (off the coast of Arabia) shows typical patterns during the years 1995 and 1997.

From May/June onwards, curl becomes positive (>0.02 x10^-5 Nm^3) over the Somali coast and extending northwards over the Arabia coast and northern Arabian Sea while negative curl (-0.025 to -0.03 x10^-5 Nm^3) is noticed away from the shore (Somali) and extending to the central Arabian Sea (Figs.5.6-5.10). Both this values and its extent starts decreasing from August/September and changes sign by October/November. This condition reverses from November onwards. The extension of this curl and its value indicates large inter-annual variability over the Somali region and Arabian Sea. During 1993 (Fig.5.6), the negative curl values (<-0.025 x10^-5 Nm^3) extend from the equator to 12°N off the Somali coast during July with core maximum of -0.04 x10^-5 Nm^3. The values are negative (-0.02 x10^-5 to -0.025 x10^-5 Nm^3) over the Arabian Sea also up to 12°N. The magnitude of this curl starts decreasing from
August onwards and reverses by November. For 1994 (Fig.5.7), the curl values (-0.025 x10^5 Nm^-3) are similar to 1993 in June and extends more northwards during July (~15°N). During 1995 (Fig.5.8) and 1997 (Fig.5.10), the negative curl (-0.025 x10^5 Nm^-3) does not extend much northeastwards over the Arabian Sea in June, but extends up to 12°-15°N by July. During 1997, the negative curl was high (-0.025 x10^5 Nm^-3) in August also, over the central and eastern Arabian Sea compared to other years. During 1996 (Fig.5.9), the extension of this curl values over the central Arabian Sea during June is greater than 1995 (Fig.5.8) and 1997 (Fig.5.10), but less than 1993 and 1994 (Figs.5.6 &5.7), and remains till September. But the northward (~10°N) extent of the negative curl values (-0.025 x10^5 Nm^-3) is less during July 1996 compared to 1995 and 1997. Thus the negative/anti-cyclonic curl values over the offshore regions of Somali and over central Arabian Sea during the summer monsoon season favouring anti-cyclonic circulation exhibits large inter-annual variability.

Over the western Bay and extending almost over the entire Bay, the curl is negative (-0.02 x10^5 Nm^-3) during the northeast monsoon and positive (0.02 x10^5 Nm^-3) during the southwest monsoon (Figs.5.6-5.10). Negative curl is noticed from November onwards till April/May. During April and May both positive (over the coast line) and negative curl (in the offshore regions) is seen over the western Bay. From June, positive curl values intensifies over the coastline and is noticed till September/October. During 1993 (Fig.5.6), curl is negative (-0.02 x10^5 Nm^-3) over the western Bay and extending eastwards. From April/May, positive curl (0.02 x10^5 Nm^-3) is also noticed over the east coast with negative curl (-0.02 x10^5 Nm^-3) existing over the offshore regions. By June, curl is positive over the east coast of the India, extending over the western Bay till September. This prevails till August and dissipates afterwards. The negative curl during the northeast monsoon period (maximum in January) is higher (-0.02 x10^5 Nm^-3) over the western Bay during 1995 and 1996, with core maximum (-0.025 x10^5 Nm^-3) noticed over the northwestern Bay. During 1994 and 1997, the negative curl values are less (-0.015 x10^5 Nm^-3) over the western Bay during January.

Around Sri Lanka, the curl is positive (>0.02 x10^5 Nm^-3) from May onwards with a shift towards the northeast. Its maximum extension is noticed during July/August, northeastward from the Sri Lankan region towards the central Bay. This curl is noticed till October and November with decreased magnitude (<0.005 x10^5
During 1996 September, positive curl ($0.005 \times 10^{-5} \text{Nm}^3$) extends from the Sri Lanka region continuous across to the eastern Bay. During 1994 and 1997, the curl value weakens from September onwards. In all other years i.e. 1993, 1995 and 1996, the positive curl remains there even though with decreased magnitude ($0.005 \times 10^{-5} \text{Nm}^3$) till November/December.

Thus curl values are noticed here with large inter-annual variability during the period 1993-1997. The major areas of negative and positive curl representing anti-cyclonic and cyclonic circulation respectively have been identified and their inter-annual variability discussed. It was found that the negative curl over the southern tip of India remained there till March/April for all the years and is shifted more southwards during 1994 and 1997 compared to other years. The positive curl during the summer monsoon period around the tip of India also showed similar patterns during 1994 and 1997 and different from 1993, 1995 and 1996. During 1993 and 1995 and 1996, the positive values are noticed upto 15°-20°N along the west coast and remains over the southern tip of India even in October, while the curl values are comparatively less along the west coast and curl is negative from November onwards during 1994 and 1997. Negative curl values were less during January 1994 and 1997 over the western Bay compared to other years. Over the western Arabian Sea, negative curl was prevalent over the region during June 1995 and 1997 when positive curl appeared over this region during the same period for other years. In the offshore regions of Somalia, the negative curl from May/June onwards also showed large variability with 1993 and 1994 showing similar pattern in June. However, during 1996, the extension of the negative curl was higher than 1995 and 1997 but less than 1993 and 1994 in June. While the extension of the negative curl in August 1997 was higher than all other years. Over the Sri Lanka region curl value weakens earlier for 1994 and 1997 compared to other years. All these information about from this chapter has been utilized as further reference in the following chapters.
Fig. 5.6 Wind stress curl (x10^5 Nm^-2) during 1993
Fig. 5.7 Wind stress curl (x10^{-5} Nm^{-1}) during 1994
Fig. 5.8 Wind stress curl ($10^{-3}$ Nm$^2$) during 1995
Fig. 5.9 Wind stress curl ($x10^{-5} \text{Nm}^{-2}$) during 1996
Fig. 5.10 Wind stress curl ($x10^{-5} \text{Nm}^{-3}$) during 1997