4.1 Introduction

4.1.1 Currents, Gyres and Eddies

The ocean is a huge body of water and is constantly in motion. Different propagating features such as currents, gyres and eddies at the ocean surface and beneath, play a crucial role in physically shaping the coast and the bottom surface of the ocean through transporting and mixing energy, chemicals, and other biological materials within and among ocean basins. These features have greater importance in global and regional ocean circulations. The flow of ocean is known as current. Currents may be referred basing on the forcing mechanism, as either wind driven or thermohaline and are steered by Earth’s rotation as well as the continental shelf and ocean bottom topography. The ocean surface circulation of the world’s oceans is mostly wind driven. Because of the influence of wind in creating currents, there is a relationship between this oceanic circulation and the general circulation of the atmosphere. A seasonal current is one which changes in speed or direction due to seasonal winds. Speed may vary somewhat with the seasonal winds. This is particularly noticeable in the Indian Ocean and along the South China coast, where currents are influenced to a marked degree by the monsoons. Thermohaline currents are driven by differences in heat and salt and are associated with the sinking of dense water at high latitudes. At any given depth, the density of water varies with salinity, temperature, and pressure.

An ocean gyre is a large system of circular ocean currents formed by global wind patterns and forces created by Earth’s rotation. Three forces are responsible for the circulation of a gyre: Global wind patterns, Earth’s rotation, and Earth’s landmasses. Wind drags on the ocean surface, causing water to move in the direction of the wind. The Earth’s rotation deflects, or changes the direction of the ocean currents. This deflection is a part of the coriolis effect. The coriolis effect shifts surface currents by angles of about 45 degrees. From Figure 4.1 it is clear that, in
the Northern Hemisphere, ocean currents are turned to the right, in a clockwise motion. In the Southern Hemisphere, ocean currents are deflected to the left, in a counter clockwise motion. Earth’s continents and other landmasses (such as islands) also influence the formation of ocean gyres. The massive South Pacific gyre, for instance, covers hundreds of kilometers of open ocean (Figure 4.1). It is bounded only by the continents of Australia and South America, as well as the Equator and powerful Antarctic Circumpolar Current (ACC). In contrast, the northern Indian Ocean gyre is the smallest oceanic gyre and its extent is determined largely by landmasses. The Equator forms its southern boundary, but it is bounded elsewhere by the Horn of Africa, Sri Lanka and the Indian subcontinent, and the Indonesian archipelago. Gyres are comprised of ocean currents that link up as they follow the coastlines of the Earth’s continents. Each gyre has a powerful western boundary current and a weaker eastern boundary current. Figure 4.1 shows the different currents and their direction of propagation and also the formation of gyres over the entire globe.

![Figure 4.1 Global ocean surface currents and gyres.](image)

An **eddy** is a circular current of water that is cut off from the main current, or a small, spinning current. These are common in the ocean, and range in diameter from
centimeters to hundreds of kilometers. The small scale eddies may last for a matter of seconds, while the larger ones may persist for months to years. Eddies which are between 10 and 500 km in diameter, and persist for periods of days to months are known as meso-scale eddies. There are warm-core eddies and cold-core eddies (Figure 4.2). The cold-core eddies are known as cyclonic eddies and the warm-core eddies are known as anticyclonic eddies. The coriolis effect causes cold-core eddies to rotate counter clockwise and warm-core eddies to rotate clockwise in the Northern Hemisphere, while in the Southern Hemisphere cold-core eddies rotate clockwise and warm-core eddies rotate counter clockwise. Warm-core eddies trap and transport a variety of different kinds of animals within them. Cold-core eddies carry greater biomass, but less diversity of species. Cold-core eddies trap nutrient-rich water and transport both nutrients and plankton.

**Figure 4.2** Cyclonic and anticyclonic eddies

### 4.1.2 Planetary Wave

**Kelvin waves** have long been known to fluid dynamicists interested in the atmosphere. They were first identified by William Thomson (Lord Kelvin) in the nineteenth century. Broadly speaking, Kelvin waves are large-scale waves whose structure "traps"
them so that they propagate along a physical boundary such as a mountain range in the atmosphere or a coastline in the ocean. In the tropics, each hemisphere can act as the barrier for a Kelvin wave in the opposite atmosphere, resulting in "equatorially-trapped" Kelvin waves. Kelvin waves are thought to be important for initiation of the El Niño Southern Oscillation (ENSO) phenomenon. A feature of a Kelvin wave is that it is non-dispersive, i.e., the phase speed of the wave crests is equal to the group speed of the wave energy for all frequencies. This means that it retains its shape as it moves in along the shore direction over time.

Coastal Kelvin Waves balance the coriolis force against a topographic boundary (i.e., Coastline). They always propagate with the shoreline on the right in the Northern and the left in the Southern Hemisphere. A Coastal Kelvin wave moving northward along the coast is deflected to the right, but the coast prevents the wave from turning right and instead causes water to pile up on the coast. The pile of water creates a pressure gradient directed offshore and a geostrophic current directed northward. Kelvin wave amplitude is negligible at a distance offshore given by the Rossby radius of deformation. For mid-latitude Kelvin waves travelling on the ocean surface is about 200 km. For mid-latitude Kelvin waves travelling in the thermocline is about 25 km. Because of this rapid decay, Coastal Kelvin waves appear to be trapped close to the coast. Equatorial Kelvin waves are a special type of Kelvin waves that balance the coriolis force in the Northern Hemisphere against its Southern Hemisphere counterpart. This waves always propagates eastward and only exist on the equator. Equatorial Kelvin waves propagating in the thermocline have wave speeds slow enough to give a Rossby radius of deformation that is on the order of 250 km and thus they appear to be trapped close to the equator. Rossby waves move along the thermocline, that is, the boundary between the warm upper layer of the ocean and the cold deeper part of the
ocean. Rossby waves are large scale waves within an ocean basin. They have a low amplitude, on the order of centimeters (at the surface) to meters (at the thermocline), compared to a very long wavelength, on the order of hundreds of kilometers. They may take months to cross an ocean basin. They gain momentum from wind stress at the ocean surface layer and are thought to communicate climatic changes due to variability in forcing, due to both the wind and buoyancy.

4.1.3 Indian Ocean in this context

Indian Ocean is the smallest among the major oceans and it is least understood because of its complexities associated with the seasonal reversal of winds. The winds over the region reverse the direction two times in a year, generally blowing from southwest during May-September and from northeast during November-February. During, transition period i.e. March-April and October, the winds are weak [Hellermann and Rosenstein, 1983]. During summer monsoon (May-September) the winds are much stronger than the winter monsoon (November-February). These seasonally reversing monsoon winds over the North Indian Ocean force a seasonally reversing circulation in the upper ocean. The North Indian Ocean (NIO) is divided into two basins.

- the Arabian Sea
- the Bay of Bengal

The north-western part of the Indian Ocean is known as the Arabian Sea and its coastal boundaries constitute the Indian coastal belt, Pakistan, Oman, Yemen and Somalia. The north-eastern part of the Indian Ocean is known as Bay of Bengal (BoB) completely separated from the Arabian Sea by the Indian sub-continent and is in contact with the equator along the eastern boundary. BoB, the north-eastern arm of the Indian Ocean is a semi-enclosed basin which experiences the monsoon winds and
associated seasonal reversing circulation. In the northern part of the Bay, mighty rivers from Indian subcontinent discharge vast amount of fresh waters, this is highly contributing to the water characteristics and stratification. Wyrtki [1971] presented preliminary information of the BoB waters. Arabian Sea is characterized by vigorous changes of the Somali Current at its western margin [Schott and McCreary, 2001] with the influence of seasonal cycle of the monsoon circulation, but in interior of the Arabian Sea the monsoon related circulation variability is generally small.

**Figure 4.3** Currents over Indian Ocean during summer monsoon

The currents that are found in the NIO are in between equator and approximately 10° N. These currents flow between the BoB and the Arabian Sea because of seasonal reversal of winds. During summer monsoon the currents flow eastward and are called Summer Monsoon Currents (SMC) and in winter monsoon the Winter Monsoon Currents (WMC) flow westward and are shown in Figures 4.3 and 4.4 respectively. These currents undergo transition in the months of March-April and October. These currents transport water masses between the two highly dissimilar arms of the NIO, the BoB and the Arabian Sea. The coastal currents over the NIO draw a significant attention from last decade which include the currents along the east coast of India, called the East India Coastal Current (EICC) [Shetye et al., 1991; Shetye et al.,
1993; Shetye et al., 1996; Shankar et al., 1996; McCreary et al., 1993; McCreary et al., 2001], the currents along the west coast of India, called the West India Coastal Current (WICC) [Shetye et al., 1990; Shetye et al., 1991; McCreary et al., 1993; Stramma et al., 1996; Shankar and Shetye, 1997; Shetye and Gouveia, 1998], and in the currents along the Arabian Sea coast of Oman [McCreary et al., 1993; Flagg and Kim, 1998; Shetye and Gouveia, 1998; Shi et al., 2000; Schott and McCreary, 2001]. The Somali Current flows southward off Somalia, crossing the equator in winter and is supplied by inflow through the passage between Socotra and the African continent in the north as well as out of the Arabian Sea from the east [Schott and Fischer, 2000].

Figure 4.4 Currents over Indian Ocean during winter monsoon

Apart from these currents, the most significant features that are observed over the NIO are the planetary waves, gyres and eddies. The most prominent circulation feature is the Great Whirl (GW), which develops seasonally approximately nearer to northern Somalia after the onset of the summer monsoon and may last well into the transition period and even continue underneath the developing surface circulation of the winter monsoon. Bruce et al. [1994] observed the elevation of the sea surface in January near the tip of India as the Lakshadweep High (LH), an anticyclonic gyre that
develops off the southwest coast of India just north of the Lakshadweep’s. The westward translation of the LH by January, with a subsequent dissipation in mid-basin is found. The LH is replaced by a region of low sea level, called the Lakshadweep Low (LL) during the summer monsoon.

Large scale forcing associated with the wind reversal during monsoons leads to the propagation of Kelvin waves along the equator [Yu et al., 1991; Potemra et al., 1991]. During monsoon winds, Kelvin waves in the Indian Ocean originate off the coast of Somali and the eastern Africa. These waves propagate along the equatorial wave guide, crossing the Indian Ocean and finally reach the west coast of Sumatra. After reaching the eastern boundary of the BoB, the Kelvin waves get reflected in the form of Rossby waves which propagate westwards and remaining split into two waves one propagate south along the Sumatra coast into the Indonesian through flow and the other wave propagate around the perimeter of the BoB reaches the southern tip of India and radiate Rossby waves into the interior Arabian Sea as they propagate northwards along the west coast of India [Moore and Philander, 1977; Yu et al., 1991; Shankar and Shetye, 1997; Shenoi et al., 1999]. During the northeast monsoon the coastally trapped Kelvin waves are believed to play a significant role in the transport of low saline waters from the BoB to the Arabian Sea which eventually facilitates the building up of mini warm pool in the Lakshadweep area [Shenoi et al., 1999]. These waves also contribute substantially in the generation and propagation of Somali eddies in the Arabian Sea and the western boundary current in the BoB [Potemra et al., 1991; McCreary et al., 1996; Shankar et al., 1996; Subrahmanyan et al., 2001]. During the monsoon transitions the equatorial Indian Ocean experiences strong westerlies and results in the generation of eastward flowing strong equatorial jets [Wyrtki, 1973; Han et al., 1999].
The generation of downwelling Kelvin waves during the monsoon transition [McCreary et al., 1993, 1994; Vinayachandran et al., 1996, 1998; Shankar et al., 2002], the upwelling Kelvin waves during monsoon periods in the upper ocean and their propagation across the equator and the coastally trapped Kelvin waves are strongly associated with westerlies at the equatorial region over the Indian Ocean. An upwelling Kelvin wave is associated with a large negative Sea Surface Height Anomaly (SSHA), while the downwelling Kelvin wave with that of large positive SSHA in the equatorial wave guide and along the coast. Further, the negative SSHA coincides with the cyclonic circulation and the positive SSHA coincides with the anticyclonic circulation. Rao et al. [2010] studied the annual cycle of SSHA in the Indian Ocean and described the variability of SSHA in association with the two sets of upwelling Kelvin waves (January – March and July – September) and two sets of downwelling Kelvin waves (April – August and September – December).

Numerical studies [Lighthill et al., 1969, Jensen et al., 1990, McCreary et al., 1993] also clearly demonstrated that planetary waves may play an important role in the generation and propagation of the Somali eddies in the Arabian Sea, the western boundary current EICC in the BoB [Potemra et al., 1991, McCreary et al., 1996, Shankar et al., 1996] and other surface circulation features. It is very difficult to identify the generation and propagation of Kelvin waves and the radiation of the Rossby waves generated by these Kelvin waves using in-situ observations [Perigaud and Delecluse, 1992; Prasanna Kumar and Unnikrishnan, 1995; Unnikrishnan et al., 1997]. Hydrographic observations are very limited and hence it is very difficult to understand the generation and propagation of the planetary waves, year by year changes in propagation strength and period depending on the monsoons [Luyten and
The recent developments in satellite remote sensing provided a wealth of information on the world’s ocean. Satellite altimetry provides a quantitative observational capability, which samples in space and time consistent with the space-time variability characteristics of the dynamical phenomena over oceans. Hence, satellite altimetry offers a suitable approach in enabling observations of the elevation and depression of sea surface height associated with some propagating features over global and regional areas at regular time intervals. Compared to in-situ observations, the recent advances in altimeters become a powerful tool in estimating SSH with high spatial and temporal resolutions which can produce sea surface circulations and meso-scale features with good accuracy. This can be ably met by a recent altimeter called SARAL/AltiKa. The present study determines the variability of SSHA over the BoB and the Arabian Sea during 2013-2015 using SARAL/AltiKa observations. The data is processed and the period of analysis is discussed in the following section. Section 4.3 gives the detailed description of the method that is adopted for the present analysis and the results are discussed in the last section.

4.2 Data processing and period of analysis

The Indian Space Agency, Indian Space Research Organisation (ISRO) and French Space Agency Centre National d'Etudes Spatiales (CNES), jointly conducted the SARAL/AltiKa (hereafter referred as AltiKa) mission for studying ocean surface topography from space. It was launched on 25th February 2013 from Sriharikota, India. The satellite orbits at an altitude of 810 km above the Earth at an inclination of 98.54°. AltiKa altimetry with its 35 day repeat cycle and high accuracy gives an opportunity to study the long waves in the ocean using sea level variations. The predefined range accuracy of AltiKa GDR SSH data is 4.3 cm [Bhowmick et al., 2015]. The 35 day
repeat AltiKa altimeter SSHA data extracted from the geophysical data records (GDR-T) patch-2 is available on Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) website generated by CNES ftp://avisofrp.cnes.fr/AVISO/pub/AltiKa/gdr-t and ISRO, India through Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC: http://www.mosdac.gov.in). SSH values (GDR-T) are extracted in the Indian Ocean between 40° E – 100° E and 15° S – 30° N, covering the BoB, the southeastern tropical Indian Ocean and the Arabian Sea. This analysis includes from cycle 1 to cycle 19, pass number 795, and the period March 14, 2013 to December 31, 2014. The geophysical corrections are applied following the AltiKa product Handbook. Different model and algorithms that are used to remove the effects of ocean tides, and the single frequency ionospheric correction at Ka-band is used for reducing the range delay of the microwave signal. All the corrections are applied to the AltiKa altimeter data and then, SSHA data available at 35 day interval is reprocessed/regridded at 0.1° x 0.1° (latitude x longitude) grid for the study of different propagating features over the present study region. The climatology of the region is presented by monthly averages of SSH for the years 2013 and 2014.

Data Unification and Altimeter Combination System (DUACS) process merged data from all altimeter missions: HY-2A, AltiKa, Cryosat-2, OSTM/Jason-2, Jason-1, TOPEX/POSEIDON (T/P), ENVISAT, GFO, ERS-1&2. The DUACS 2014 global products are directly computed on a Cartesian 1/4° x 1/4° spatial resolution. The gridded data is available in near-real time and in delayed time over global coverage and regional products are also computed as well. The gridded data of Sea Level Anomaly (SLA) is provided at http://www.aviso.altimetry.fr/. The data product is prepared from all the present active altimeters such as Jason-2, HY-2, Cryosat-2 including AltiKa.
4.3 Method of Analysis

The variability of SSHA over the NIO using AltiKa data during the period 2013-2014 is used to examine the meso-scale and planetary wave process in the monsoon response of the Indian Ocean by analysing the records of AltiKa with respect to the gridded product. The SSHA from T/P data is utilized to study the characteristics of the propagating waves in the Indian Ocean [Basu et al., 2000; Gopalan et al., 2000; Subrahmanyam et al., 2001; Brandt et al., 2002]. Kumar et al., [1993] described the seasonal and inter-annual sea surface height variations using T/P altimeter data. The SSHA data were gridded on to regular 0.5° x 0.5° bins by Gaussian interpolation with a search radius of 200 km [Cipollini et al., 1997]. The propagation of Kelvin and Rossby waves in the BoB was discussed by Benny and Mizuno, [2000]. The monthly gridded SSHA data were prepared on 1° x 1° grid by means of Gaussian interpolation using a full-width half maximum (FWHM) of 150 km and a search radius of 200 km [Subrahmanyam et al., 2000]. The altimeter data, which are corrected for geophysical, tidal, sea state bias and instrument effects as well as for orbit errors, are part of the T/P SLA products provided by CNES/NASA (AVISO, 1998). The processed along track-data were interpolated by objective analysis to a 1° x 1° grid [Peter Brandt et al., 2002]. Benny Peter et al., [2012] obtained the maps of SLA by merging JASON/T/P and European Remote Sensing Satellites ERS/ENVISAT data using optimum interpolation. Maps were produced every seven days since 1992 August with a resolution of 1/3° in both latitude and longitude. The spatial and temporal variations of sea level anomalies in the BoB are understood using Empirical Orthogonal Functional (EOF) analysis.

The seasonal monsoon winds over the equator trigger the formation of Kelvin and Rossby waves that control the propagation of energy across the ocean. These
waves are useful to define the ocean surface circulation and currents in the NIO and also play an important role in the formation and propagation of Somali eddies. These eddies are the major carriers of heat in the ocean. To study the nature of the propagating waves, SSHA from AltiKa is retrieved. Initially AltiKa SSHA is computed by correcting the geophysical effects, instrumental errors and path delays in the atmosphere. The daily data of SSHA that is extracted, is reprocessed into monthly data and then it is gridded into 0.1° x 0.1° by means of scattered interpolation technique using MATLAB. This gridded data of SSHA from AltiKa is useful for observing the propagating meso-scale features over the Indian Ocean. The SSHA distribution throughout the years 2013 and 2014 are used to illustrate typical seasonal behaviour as well. The analysis of the propagating features are discussed separately as

1) The equatorial region and the planetary waves.

2) The circulation and formation of eddies and gyres over the Indian Ocean.

3) The behaviour of the EICC within the BoB.

Finally the plots from AltiKa monthly gridded SSHA are compared with the plots from the merged SLA data product.

### 4.4 Results and Discussions

The eddies and the propagating Kelvin and Rossby waves are the major features that influence the Indian Ocean circulation. Here, the main focus is on the various eddies and the planetary waves over the NIO and the inter-annual variability over the period 2013 and 2014. Figures 4.5 to 4.17 present the monthly mean SSHAs in the Indian Ocean for the years 2013 and 2014. These figures illustrate many propagating features which include the Planetary Waves, LH, LL, the Anticyclonic high off the southwest coast of Arabia, the Cyclonic and Anticyclonic eddies in the Somali basin and the
western BoB, and the Cyclonic Sri Lanka Dome. Figures 4.16 and 4.17 show the merged and AltiKa SSHA plots that are used for the comparison of propagating features and also to identify the difference if any.

### 4.4.1 Planetary Waves at Equator

Over the equatorial region the wind direction changes abruptly during the months of April and May. Large scale forcing associated with this wind reversal leads to the propagation of Kelvin waves along the equator \([\text{Yu et al.}, 1991; \text{Potemra et al.}, 1991]\). The downwelling Kelvin waves along the equator during the monsoon transition period are associated with large positive SSHA values. In April 2013, the equatorial SSHA slopes down from the west to the east, where the SSHA near the Somali region is in the range of 5 cm– 12 cm and 5 cm – 7 cm near the Sumatra coast (Figure 4.5a). But in April 2014, the SSHA is in the range of 5 cm – 10 cm near the Sumatra coast (Figure 4.5c). In May 2013 (2014), the SSHA increases to 28 cm (20 cm) at Sumatra coast clearly indicates the eastward propagation of Kelvin wave which deepens the thermocline and raises the sea surface heights slightly (Figure 4.5b & 4.5d). \textit{Subrahmanyan et al.}, [2000] had reported that, in April 1993, the equatorial SSH slopes down from the west (about 0.04 m in the Somali region) to the east where contours of - 0.04 m are found near the Sumatra coast. By May, the SSH off Sumatra has risen to 0.04 m.

As these waves reach the eastern boundary of the BoB, they get reflected back in the form of Rossby waves and some of its energy propagate along the coast as two coastally-trapped Kelvin waves, one northward and the other southward \([\text{Potemra et al.}, 1991]\). The Kelvin waves that propagate eastward are slightly weak in 2014 compared to 2013. This may be due to less monsoon winds that generate weak equatorial Kelvin waves. In some years the monsoon winds are not adequate to
generate a strong equatorial Kelvin wave in April. In weak monsoon years, the signal that propagates eastward may be very much weaker or later than normal [Subrahmanyam et al., 2000]. As the equatorial Kelvin waves are weak, the Kelvin waves near the Sumatra region are also weak. Hence, the SSHA values are low during May 2014, compared to 2013. This indicates that, 2013 is a strong monsoon year relative to 2014.

**Figure 4.5** SSHA (cm) during (a) April 2013 (b) May 2013 (c) April 2014 (d) May 2014.

During the month of January 2014, the upwelling equatorial Kelvin waves are due to the negative SSHAs present during the northeast monsoon (December – January) by the strong northeasterly winds along the equator (Figure 4.6b). These are the upwelling Kelvin waves along the equator during the winter monsoon and are
associated with negative SSHA. The small negative values those are present around the eastern perimeter of the Bay moves northward and covers along the coast finally reaches the east coast of India during March – April, where it may play an important role in defining the EICC.

![Figure 4.6 SSHA (cm) during (a) December 2013 (b) January 2014 (c) February 2014 (d) March 2014](image)

Along the west coast of India, small positive SSHA are present in January 2014 (Figure 4.6b). These positive SSHAs start moving northward as a coastal Kelvin wave along the west coast and also appear to move westward as a Rossby waves into the interior of the Arabian Sea. The westward propagation from the west coast of India
started during January 2014 and is further reinforced by the month of March 2014 and finally reaches the west coast as Rossby waves (Figure 4.6d). These Rossby waves may trigger the Somali Currents [Lighthill et al., 1969; McCreary et al., 1993] and its meandering after the onset of the strong southwesterlies.

4.4.2 Arabian anticyclonic high

In the north-western Arabian Sea, it is observed that SSHA gradually increases from January onwards to May/June. The positive SSHA during this period is known as Arabian anticyclonic high. This pattern is clearly observed during March to June and covers many parts of the Arabian coast up to 65° E. The northeast monsoon winds favour the downwelling in this area and persist up to May and causes anticyclonic high over the Arabian Sea [Hareesh Kumar and Sanill, 2004]. The positive SSHA starts dissipating by the onset of summer monsoon in June.

As the data of AltiKa from January – March is not available, the plots of SSHA during this period is not shown in the present analysis. In April, May and June the SSHA positive values increase up to 25 cm – 30 cm and greater than 10 cm are noticed in several parts of the western Arabian Sea (5° N – 20° N) (Figures 4.7a to 4.7c). The positive SSHAs are started forming in the month of January 2014 at the western part of the Arabian Sea and completely covered the entire Arabian Sea in the month of June (Figures 4.8a to 4.8f). The anticyclonic highs noticed during 2014 over the Arabian Sea are little bit small compared to 2013. During summer monsoon starting from June, these positive anomalies start dissipating and are replaced by negative values in both the years.
Figure 4.7 SSHA plot showing Arabian anticyclonic high, 2013 (a) April (b) May (c) June

Figure 4.8 SSHA plot showing Arabian anticyclonic high, 2014 (a) January (b) February (c) March (d) April (e) May (f) June

4.4.3 Cyclonic and Anticyclonic Eddies at south-west coast of India

The anticyclonic circulating features in the eastern Arabian Sea are noticed during the north-east monsoon season. The positive SSHA during this season extends up to April/May. This anticyclonic circulating feature at the south-west coast of India is known as Lakshadweep High (LH). The positive SSHA values slowly disappear and are replaced by negative SSHA values in May and extend throughout the summer.
monsoon season. The negative SSHA that are noticed between May/June and October are the cyclonic circulating features and are known as Lakshadweep (LL). These features start moving westward is a consequence of radiation of Rossby waves from the coastally trapped Kelvin waves as they propagate northward along the west coast of India [Shenoi et al., 1999].

**Figure 4.9** SSHA plot showing LH (a) November 2013 (b) December 2013 (c) January 2014 (d) February 2014 (e) March 2014 (f) April 2014

The formation of LH in November at the eastern Arabian Sea is clearly shown in Figure 4.9a. The arrival of downwelling Kelvin waves off the south west coast of India during November also favours the formation of positive SSHA. An intermediate anticyclonic eddy with positive SSHA (15 cm – 25 cm) is observed in 2014 January (Figure 4.9c) near the eastern Arabian Sea between 6° N – 10°N, 70° E – 80° E in the Lakshadweep or Lakshadweep Islands, which is named as the LH, propagate westwards during February (Figure 4.9d) and finally reaches the Somali coast in March.
During the westward propagation the LH eddy split into two anticyclonic eddies with low SSHA values in between them. The positive SSHAs remains in the western coast of India till May and during southwest monsoon the entire pattern in the east coast of Arabia changes to cyclonic for at least four months i.e., from June to September and the generation of SSHAs during 2013 and 2014 are presented in Figures 4.10 and 4.11.

During southwest monsoon season (June to September) the negative SSHA values are observed off the southwest coast of India. The appearance of negative anomaly in the Lakshadweep region is known as LL. This cyclonic eddy starts moving westward from southern tip of India to the west coast of Arabian Sea. This westward propagation of negative SSHA is strongly associated with the radiation of Rossby waves from the coastal Kelvin waves [Shankar and Shetye, 1997]. After southwest monsoon, it is noticed that the LL starts dissipating and is replaced by the positive SSHAs in the month of November which are associated to LH. Subrahmanyam et al., [2000] had observed the LH that is generated during December, 1995, is located at position 5° N – 10° N, 70° E – 74° E. The T/P altimetric observations indicate that the LH is composed of multiple eddies.

From the present analysis, the formation of LL shows different patterns during 2013 and 2014 (Figures 4.10 and 4.11). The negative SSHA (0 to -5 cm) appears off the west coast of India during June 2013, while in 2014 the SSHA varies from -5 cm to -10 cm. But the cyclonic low is well developed in August 2013 with intensity of -25cm, and in 2014, the mature cyclonic low is noticed in the month of September with intensity is in the range of -10 cm to -15 cm. It is noticed that the low sea level values extend northwards along the east coast of Arabian Sea throughout the southwest monsoon season. The cyclonic low propagates westward from southwest coast of India
in the month of September and reaches the western Arabian Sea. In the Year 2013, during westward propagation the negative SSHA varies from -5 cm to -12 cm while in the year 2014 the range varies from -5 cm to -27 cm. During September 2013, the LL is developed in between 4° N – 12° N and 72° E – 80° E and in 2014, it is observed in between 7° N – 12° N and 75° E – 80° E occupying much lesser area compared to the year 2013. After LL completely separates from the southwest coast of India the negative SSHA reaches to Somali coast in the month of December 2013 and 2014. From the Figures 4.9 to 4.11 it is observed that both the cyclonic and anticyclonic features propagate westwards and are strongly associated with the Rossby waves [Shankar and Shetye, 1997].

Observations of AltiKa altimeter reveal that the appearance of this LH and LL varies with the strength (active/weak) of the monsoon, month by month and also the magnitude of SSHA during the west ward propagation of both these cyclonic and anticyclonic features is also different. It is also observed that the range of SSHA in the Arabian Sea during the westward movement of LH is 5 cm – 20 cm in the year 2014, whereas, in the year 2013 the positive SSHA varies from 5 cm – 25 cm. Hence the inter-annual variability of SSHA during 2013 and 2014 is clearly observed from this analysis.

4.4.4 Somali Eddies

As discussed in the section 4.4.1, the radiated Rossby waves from the west coast of India during January reach the Somali coast by March/April has the possibility of triggering the Somali current and their meandering before the onset of summer monsoon. And also the southwest winds during the summer monsoon (June-September) forces the formation of strong anticyclonic circulation near the Somali region. Hence, eddies near the Somali region are together named as Somali eddies. The Kelvin and
Rossby waves also play an important role in the formation and propagation of the Somali eddies [McCreary et al., 1993]. The global circulation features at the western Arabian Sea is due to the formation of Southern Gyre (SG) in the month of June and the Great Whirl (GW) during the onset of summer monsoon. Another eddy formed at the end of September at the north of Somali known as Socotra Eddy (SE). The negative SSHA south of Somali is formed in the month of May known as cold wedge and moves northwards as the time progresses. Schott et al., [1990] had reported the formation of this feature prior to the formation of SG and GW. To the east of this cold wedge, an anticyclonic eddy starts forming in the month of May.

From the present analysis it is noticed that, in 2013 and 2014, the Somali currents become strong with the coastal parallel winds and move northward forming a series of eddies along the western edge of the Arabian Sea. The Somali current leaves the coast at about 6° N – 7° N in 2013 and 5° N – 6° N in 2014 and appears as an anticyclonic eddy in between 3° N – 9° N in June 2013 and 4° N – 8° N in June 2014 (Figures 4.10a and 4.11a). This is the so-called SG. The diameter of eddies are of about 500 km – 600 km with SSHA of 10 cm – 20 cm in 2013 and 200 km – 300 km with 10 cm – 15 km in 2014 (Figure 4.10a and 4.11a). Another eddy appears in the July month, often called Great Whirl (GW), is split into a two gyre system, and formed between 7° N – 12° N and 54° E – 60° E in 2013 while in 2014, July the GW is formed with moderate intensity in between 8° N – 11° N and 55° E – 58° E (Figure 4.10b and 4.11b). Subrahmanyam and Robinson [2000] had revealed that, the Somali current leaves the coast at about 3° N – 4° N, turns offshore at about 10° N and appears as a large anticyclonic eddy centered at ~ 5° N, 55° E in the month of June 1993 and in July 2013, the GW is found in between 9° N – 10° N, 56° E – 60° E with a diameter of about 600 km. Their observations also revealed that, during August 1993, the GW
splits into a two-gyre system between $8^\circ$ N – $10^\circ$ N, $58^\circ$ E – $64^\circ$ E. Socotra Eddy was also found between $10^\circ$ N – $12^\circ$ N, $55^\circ$ E – $58^\circ$ E in the late August.

Figure 4.10 SSHA plot during southwest monsoon (a) June 2013 (b) July 2013 (c) August 2013 (d) September 2013

Multiple Arabian anticyclonic highs are present at the western part of Arabian Sea in the month of June 2014 and these highs slowly disappear in July and August. In August 2013, a well developed GW is displayed with maximum intensity at $8^\circ$ N – $15^\circ$ N, $57^\circ$ E – $60^\circ$ E and also another warm core eddy known as SE is also clearly observed to the west of GW with a diameter of about 400 km (Figure 4.10c). The SE is
small in size compared to SG or GW. In August 2014, it is clear that the SG is well developed and the GW is elongated eastward and present in between 8° N – 14° N and 59° E – 64° E (Figure 4.11c). It seems that the SG remains in the same place and the eddies GW and SE coalesce to form a single eddy which moves westward in between 8° N – 14° N, 50° E – 58° E in 2013, Where as in 2014, the GW moves westward and combine with SG form a single large eddy in between 7° N – 12° N, 50° E – 58° E.

![SSHA plot during southwest monsoon](image)

**Figure 4.11** SSHA plot during southwest monsoon (a) June 2014 (b) July 2014 (c) August 2014 (d) September 2014

The negative SSHA near the Somali coast is observed in the month June 2013, called as clod wedge (Figure 4.10a). To the east of this cold wedge, the formation of
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SG is observed. But in 2014 June, the SG is weak compared to 2013, because the larger cold wedge (more negative SSHA area) weakens the formation of SG in the year 2014 June (Figure 4.11a). In 2013, all the Somali eddies are evident where as in 2014, only SG and weak GW appear in August and merges in to a single eddy system in September. It is noted that, weak Somali eddies are generated during 2014, because of large negative SSHA is covered towards the east in the month of June. Hence, the 2013 is a strong monsoon year compared to 2014. During January 2014, cyclonic eddies with a diameter of about 350 km is formed between 3° N – 9° N, 49° E – 55° E in the same place where the SG is in the SW monsoon (Figure 4.6b). However, the number of eddies, the area covered by the eddies and their dimension vary from year to year i.e., 2013 and 2014.

4.4.5 Eddies over BoB

In the western region of BoB, an anticyclonic gyre exists from February to July and a cyclonic gyre in the rest of the year [Culter and Swallow, 1984; Subrahmanyam, 1999]. Several eddies are formed in the western BoB due to the reversal of current directions. These currents are known as EICC which reverses direction twice a year, moving poleward from February to September and equatorward from October to January [Shetye et al., 1993]. Two anticyclonic eddies are identified at two different locations over the BoB, one eddy is generated in between the months of January and May in the northern BoB and second eddy is at the east of Sri Lanka formed between the months of October and May. The northern anticyclonic eddy moves southward while the Sri Lankan eddy moves north westward. During January a cyclonic eddy is noticed in between these two anticyclonic highs. Vinayachandran and Yamagata [1998] had reported that there exist an another cyclonic eddy at the east of Sri Lanka during southwest monsoon and this low sea level is known as Sri Lanka Dome (SD). As the
time progresses the SD moves north westwards and undergoes dissipation in the month of September.

It is noticed that both the anticyclonic eddies are identified in the month of January 2014 near the east coast of India (Figure 4.12a). As AltiKa data is not available from January to March 2013, the SSHA plots of these months are not estimated. During the months of April and May 2013, these anticyclonic eddies exhibit maximum dimension whereas, in May 2014 these eddies are comparatively small in size but intense at the centre with 30 cm SSHA. Three anticyclonic eddies are noticed near the east coast of India in April 2013, one in the northern Bay with a diameter of 300 km, second one is at the east of Sri Lanka with a diameter of 500 km, in between these two a large anticyclonic high eddy is formed (Figure 4.13a). In 2014, two anticyclonic eddies are noticed in the same region one month late i.e., in May 2014, one in the northern Bay with diameter of 200 km and another at the east of Sri Lanka with a diameter of 400 km (Figure 4.13e).

The SSHA from AltiKa during January, 2014 shows a weak anticyclonic gyre near the eastern side of Sri Lanka, between 6° N – 10° N, 83° E – 90° E (Figure 4.12a) and stars moving close to the Sri Lanka coast in the months of February and March (Figures 4.12b and 4.12c). Along the east coast of India the poleward current starts roughly at about 15° N. This is another gyre attached to the east coast of India between 15° N– 20° N, 83° – 91° E. The poleward current of a seasonal subtropical gyre is the EICC which form in January. A strong anticyclonic gyre was observed by Subrahmanyam et al., [2000] near the eastern side of Sri Lanka, between 8° N –12° N, and 82° E – 87° E with a diameter of about 400 km using T/P SSHA during January, 1993.
In April 2013, the anticyclonic eddies appears in between 16° N – 19° N and 82° E – 87° E (Figure 4.13a). In May, all the three eddies merged into a single elongated eddy centered at 13° N, 85° E with a diameter of 700 km (Figure 4.13b). This eddy splits again into two small eddies of 100 km diameter in June and weaken...
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thereafter (Figure 4.13c). From Figure 4.12, in between these two anticyclonic highs, a cyclonic low is noticed with -5 to -15 cm SSHA in the month of January 2014, and disappears in the month of April 2014 (Figure 4.13d). Another cyclonic eddy called SD noticed near the east of Sri Lanka in both the years.

**Figure 4.14** SSHA plot (a) August 2013 (b) October 2013 (c) November 2013 (d) December 2013.

The cyclonic low (negative SSHA) started in the month of May 2013 and in 2014 the negative SSHA clearly exists in the month of June in both the years and it is called as SD. During 2013, this dome attains its maximum dimension in the month of August with diameter of 600 km and it is noticed in between 7° N – 12° N and 82° E – 85° E (Figure 4.14a). In 2014, the dome attains to be well developed in the region of 11° N – 13° N and 84° E – 88° E. This negative SSHA moves north westward and
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weakens as the time progresses upto October. Again this low sea level cyclonic eddies in the BoB merged together to form a single large cyclonic low in December 2013 (Figure 4.14d), and November in 2014 (Figure 4.15c).

**Figure 4.15** SSHA plots (a) August 2014 (b) October 2014 (c) November 2014 (d) December 2014.

4.4.6 Comparison with merged data

The monthly gridded plots that are processed for the present study are compared with DUACS delayed time merged (level 4) product. To observe the differences and similarities between AltiKa and merged product, January, February and March 2014, SSHA maps are compared and the corresponding plots are shown in Figures 4.17. Figure 4.16 illustrates the SSHA maps of merged data product during the period of
January to March 2013. As AltiKa data is not available at the beginning of 2013, these plots are used for the present analysis.

**Figure 4.16** Merged SSHA plot (a) January 2013 (b) February 2013 (c) March 2013

**Figure 4.17** AltiKa SSHA plot (a) January 2014 (b) February 2014 (c) March 2014 and merged SSHA data plot (d) January 2014 (e) February 2014 (f) March 2014.

From the Figures 4.16 and 4.17, it is clear that the formation of anticyclonic eddies at the western BoB in the year 2013 and 2014, January. In the month of January 2013, the positive SSHAs (0.05 to 0.12) are present near the Sumatra coast at equatorial
region and along the eastern part of the BoB (Figure 4.16a – 4.16c). While in the year 2014 January, from the merged data low SSHA (upwelling Kelvin waves) values are present along the equatorial region which are moving from east to west (Figure 4.17d) and it is also evident from the AltiKa data from Figure 4.17a – 4.17c. From Figures 4.17a to 4.17f, it is noticed that the formation of EICC over the western Bay, the LH off the southwest coast of India as well as the negative SSHA over the entire eastern boundary shows a good match between merged and AltiKa values. AltiKa SSHA plots follow the same pattern with the corresponding merged data plots and hence, AltiKa data is consistent with respect to merged product. However, it is observed that the AltiKa SSHA values are slightly underestimated relative to merged product over the entire range i.e., 30 cm to -30 cm.
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