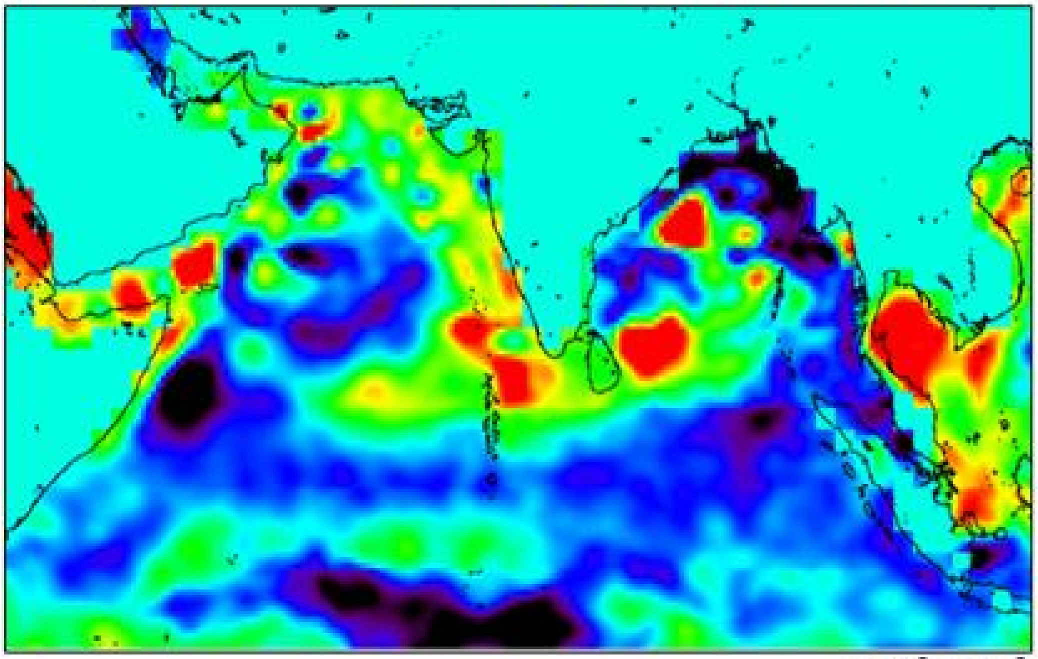
Eddy Kinetic Energy
of the North Indian Ocean



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15	**Abstract:** Eddy Kinetic energy of the north Indian Ocean is the representative field of ocean dynamic in the region. The data acquired from AVISO and PO.DAAC sites of girded fields of SSHA. The flow filed derived form SSHA in x and y direction as u and v components of geostrophic current used in the kinetic energy estimation. However a directional filter adopted in the present case is found to provide similar results. The results are presented as monthly distribution fields from 1993 to 2011 providing the state of regional dynamics in the north Indian Ocean. Key Words: Altimeter, Eddy, Kinetic energy, Indian Ocean					

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Executive Summary

Eddy Kinetic Energy (EKE) of the north Indian Ocean is of significance to regional changes in the weather and climate. The energy fields derived from the ocean currents are estimated to explain state of the sea with time. Conventionally they are estimated from hydrographic data converted to dynamic height through density as a function of temperature and salinity estimated at the sea. Otherwise estimated energy fields from current meters provide localized observation in kinetic energy form their derivatives of velocity fields. Such observations are difficult to map, but alternatively computed from satellite observations with sensors like altimeters make useful information to identify areas of highly dynamic environment in the ocean and seas. The present study provides monthly EKE maps for the north Indian Ocean. These are estimated from the SSHA fields after due conversion to geostrophic currents decomposed to their respective meridianal and longitudinal components squared and square-rooted of their sum. The results are similar to several of such estimates made indicating the eddy fields, fronts and boundary of ocean water masses.

Acknowledgements

The work is carried out as a part of Ocean Science Group activity to generate science products for the Earth and Climate Science Area activities. The encouragement and support extended by Dr. V.K. Dadhwal, Director, NRSC; Dr. C B S Dutt, DD, ECSA, and Mr. K. H Rao, Group Head, Ocean Science Group is acknowledged. The MSLA data was from AVISO website and EKE products generated in the process for NICES (National Institute for Climate and Earth Sciences) data base creation at the NRSC, Hyderabad.

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1. Introduction

The Eddy Kinetic Energy (EKE) mapped for the ocean environment represents dynamic state of the sea. They represent boundaries of water masses as fronts and currents. These areas are significantly important for vertical mixing. They explain upwelling and sinking processes at the sea and transfer of chemical constituents known as nutrients and trace elements for higher biological productivity in the surface waters. Besides, the maps show the areas of mass accumulation and energy dispersion at the sea. Conventionally, such fields are difficult to prepare with observational data collected through hydrographic studies or by deploying current meters. Satellite remote sensing provides a scope. Maps representing boundaries of dynamical state are prepared with ocean colour information, thermal and sea surface height variations derived from satellite data. Ocean colour and thermal mapping carried out with passive sensing with the Sun as a source is limited to clear weather condition. While Sea Surface Height Anomaly maps are acquired through non-imaging active microwave sensors known as satellite altimeters. These are equivalent to dynamic height estimated form hydrographic data of field observations. The field observations are sparse and limited to few observations in inaccessible areas for physical observation. In this context, satellite data provides observations at regular intervals. Thus, this provides a scope to derive information on ocean dynamics at regular intervals. SSHA is one such product that represent ocean dynamics through EKE estimation. The data are available from Topex /Poseidon, ERS-1/2 and Envisat and Jason-1 and 2, and Hy-2. Recently, SARAL AltiKa with Ka band sensor launched from India on 25 February 2013 in collaboration with the CNES, France. This will provide SSHA with better accuracies. Presently, the SSHA field of the Indian Ocean region was considered for Eddy Kinetic Energy estimations restricting to the north Indian Ocean. Monthly field of EKE are mapped along with the SSHA are presented in this document. The maps show overview of the eddy fields in the region and their frontal boundaries. The seasonal and inter annual variation in the dynamics with reference to monsoon change can be examined discriminating areas of strong flow. The seasonal changes in boundary current and equatorial flows in the region are also identified from the maps. Thus, the monthly maps of EKE provide a precursor to Indian Ocean dynamic studies.

The scope of the products leads to understand eddy variability, their persistence and change in the strength of the boundary features associated with them. The velocity components are minimum at the centre of eddies and magnitude increases away from the centre. The eddy field mostly represented as elevated and depressed areas for anti-cyclonic and cyclonic flow in the northern hemisphere and vice versa in the southern hemisphere. Upwelling areas are associated with anti-clockwise flow in northern hemisphere represented as holes or depressions in the ocean surface. The elevated areas are associated with anti-clockwise flow in the northern hemisphere and reverses in the southern hemisphere. The frontal boundaries are areas of convergence and divergence and associated with the regions of sinking and upwelling, respectively. The areas are important in providing information on suspended sediment accumulation and dispersion, air sea fluxes, congregation areas marine fisheries and thus influence the socio-economic changes.

2. Objectives

The monthly EKE helps in identification of frontal boundaries and eddies of the north Indian Ocean. Hydrographic data used involves acquisition of temperature and salinity profiles and converted to its density. This isr used in making of a vertical density profile of the water column. Thee relative fields of density with reference to a level of no motion help in estimation of dynamic height. The flow fields are established with reference to change in dynamic height. The change in flow field is used in the estimation of kinetic energy. In the case of satellite based altimeter observations, EKE is estimated from Sea Surface Height (SSH) and height anomalies (SSHA) derived from altitude and range information with due corrections from ionosphere, atmosphere, water vapor and surface bias at the sea. Beside tide from different sources such as pole tide, earth tide, and ocean tide to improve correction in the estimation of height information. The derived information on height are often referred to geoid to estimate dynamic height at the sea, while mean sea surface is used in estimation of mean sea level anomaly (MSLA) or SSHA. Mostly dynamic height is used in the estimation of geostropic component of flow field leading to eddy parameter retrieval. The variance field of geostrophic velocity component represents one of the parameter, the Eddy Kinetic Energy that represents dynamic state of the ocean environment. This finds its utility in exchange of gas components at the air-sea interface, exchange of momentum, transfer of heat energy and mass between surface and deep layers and, between tropics and polar regions. The products also help in defining and identifying areas of high productivity and availability of high nutrient concentration around the cold core eddy environment, while the warm core areas are associated with moisture flux to atmosphere, heat potential enhancement to build cyclone and low pressure events which introduces instability to the atmosphere and brings rainfall.

The present objective of EKE estimation is to provide views of eddy developing areas and understating of their seasonal variability. The SSHA database created in a monthly mode are used in the present context. The SSHA extracted from the PO.DAAC web site are generated blending different altimeter data products from corrected range information with due correction with reference to sensor, atmosphere, gravity and ocean surface noise. The products available as OGDR, IGDR and GDR in along track paths in 1 Hz frequencies are girded and mapped to one third of a degree and available from web servers over AVISO and PO.DAAC. For the present estimations of EKE, the girded data are used as the zonal and meridional component of geostrophic velocities. The EKE was estimated as half of the sum of the squares of zonal and meridional components of geostrophic velocities. The SSHA maps of the area are studied with reference to EKE helps to understand dynamics in the north Indian Ocean. The EKE fields has its significance with reference to monsoon currents and corresponding rainfall that drives the economy in the Southeast Asian countries. The area is also used extensively for commercial transportation of cargo through marine routes passing through Arabian Sea and southern Bay of Bengal. The EKE fields help in better and faster navigation in safe environment identifying fronts and current boundaries at the sea.

3. Study Area

The north Indian Ocean is considered for the present study. The area within 40^{o}E to 110^{o}E and 10^{o}S to 30^{o}N was studied keeping in view of its complexity and dynamic nature. The region is exposed to strong wind the drive monsoon rainfall that supports the socio-economic life over India. The seasonal change in radiation and monsoon wind associated with enclosed land boundary in the north provide complex dynamic setup in the north Indian Ocean. The changes brought under the changing dynamics establish eddies and flows that migrate over space and time. This leads to variation in local weather, since the energy and mass exchanged through air-sea interface vary over time. The changes are reflected in the EKE fields and planned to monitor with advanced methods and sensors like SARAL AltiKa in future.

4. Data and Methodology

Ocean eddies and their energy fields over the Indian Ocean were studied and mapped earlier using altimeter data (Ali et al, 1998; Rasmi Sharma et al, 1999). With time altimeter systems changed improving the MSLA estimated from Geosat to advances made with Jason and Saral data. The recent work adopts an improvement over the existing databases with resolution and accuracy. The background data was PO.DAAC based merged and girded MSLA data remapped into quarter degree database. The method of EKE estimation have been explained through different modes of publication and technical reports including a tutorial over the JPL web site as http://www.altimetry.info/html/use_cases/data_use_case_mesoscale2_en.html. Basic Radar Altimetry Toolbox v1.1, User Manual also provides methods for computing EKE from altimeter data.

Eddy Kinetic Energy (EKE, cm^2/s^2) is estimated from meridional and zonal components (u and v) of geostrophic current as,

$$EKE=1/2x(u^2+v^2)$$

The geostrophic components currents are deduced from the meridional and zonal gradient of sea level anomaly as,

$$u=-(g/f)xd(SLA)/dy$$
$$v=(g/f)xd(SLA)/dx$$

where, g is gravity and f the Coriolis parameter. Finite difference method is adopted to generate maps of geostrophic currents from SLA fields.

This is a key indicator of meso-scale variability that corresponds to ocean dynamics and frontal boundaries showing the areas of intense flow with strong horizontal shear. The variability in the current field represented by eddy circulation mostly represented as meso-scale features. Mostly studied with reference to surface slope variation with reference to mean surface derived, as

$$\text{mean SLA}=(1/n)\text{x}(\text{Sum SLA}(t))$$

While the variance field is estimated as

$$\text{RMS}=[[\text{Sum SLA}(t)]/n]^{1/2}$$

Which vary as much as 400 cm^2/s^2 in the areas of Kuroshio region in the western Pacific Ocean (http://www.altimetry.info/html/use_cases/data_use_case_mesoscale2_en.html). Using merged data of Sea Level Anomalies (MSLAs), the mesoscale studies carried out using maps of Absolute Dynamic Topography (MADT) obtained as,

$$\text{MADT}=\text{MSLA}+\text{MDT}$$

Where, MDT is the Mean Dynamic Topography. 'Absolute Dynamic Topography' represents the general ocean dynamics, whereas 'Sea Level Anomalies' focus on its variable component.

Western boundary currents such as the Kuroshio convey a lot of energy and generate strong turbulence systems. While SLAs and geostrophic currents illustrate eddies, EKE (Eddy Kinetic Energy) fields allow enable us to focus on meso-scale variability; statistics are especially necessary to quantify particularly important for quantifying this phenomena.

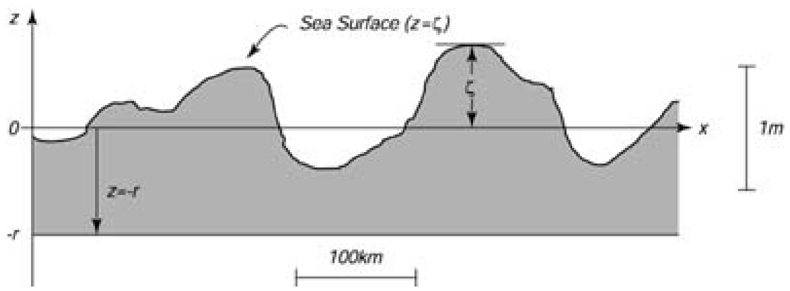


Figure.1 Sketch defining z and r, used for calculating pressure just below the sea surface (http://oceanworld.tamu.edu/resources/ocng_textbook/chapter10/chapter10_03.htm Robert H. Stewart, stewart@ocean.tamu.edu)

The geostrophic approximation applied at z = 0 leads to a very simple relation: surface geostrophic currents are proportional to surface slope. Consider a level surface slightly below the sea surface, say two meters below the sea surface, at z = -r. A level surface is a surface of constant gravitational potential, and no work is required to move along a frictionless, level surface. The pressure on the level surface is:

$$p = \rho\, g\, (\zeta + r)$$

assuming ρ and g are essentially constant in the upper few meters of the ocean. Substituting this into (10.7a, b), gives the two components (u_s, v_s) of the surface geostrophic current as,

$$u_s = -(g/f)\ (\partial\zeta/\ \partial\zeta y\ );$$

$$v_s = (g/f)\ (\partial\zeta/\ \partial\zeta x\ );$$

where, g is gravity, f is the Coriolis parameter, and ζ is the height of the sea surface above a level surface, often referred as surface topography.

Topography results from tides, ocean currents, and changes in barometric the pressure that produce the inverted barometer effect. Because the ocean's topography is due to dynamical processes, it is usually called dynamic topography, which is approximately one hundredth of the geoid undulations. This implies to dominance of local variations of gravity that reflects in the sea surface. Typically, sea-surface topography has amplitude of ±1 m. Typical slopes are $\partial z/\partial x$ ~ 1-10 micro-radians for v = 0.1 – 1.0 m/s at mid latitude. The influence of currents is much smaller. The height of the geoid, smoothed over horizontal distances greater than roughly 400 km, is known with an accuracy of ±1 mm from data collected by the Gravity Recovery and Climate Experiment GRACE satellite mission.

The topography of the sea surface ζ is the height of the sea surface relative to a particular level surface, the geoid; and we defined the geoid to be the level surface that coincided with the surface of the ocean at rest. Thus, according to the surface geostrophic currents are proportional to the slope of the topography, a quantity that can be measured by satellite altimeters known geoid.

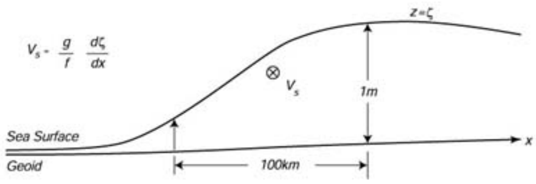


Figure:2 The slope of the sea surface relative to the geoid (drawn as by Robert H. Stewart)

where ($\partial z/\partial x$) is directly related to surface geostrophic currents v_s. The slope of 1 meter per 100 kilometers (10^{-6}rad) is typical of strong currents. V_s is into the paper in the northern hemisphere. The geoid is a level surface; it is a surface of constant geopotential. To see this, consider the work done in moving a mass m by a distance h perpendicular to a level surface. The work is W = mgh, and the change of potential energy per unit mass is gh. Thus level surfaces are surfaces of constant geopotential as, $\Phi = gh$.

The EKE estimation for the Indian region is based on the use of girded data of SSHA acquired from PODAAC and AVISO ftp sites (for latest data after 2002) in weekly and monthly modes. The SSHA fields are merged All the data sets were stacked in the image processing environment of Envi software and a directional filter was carried out in x and y axis to derive the velocity components, which is squared and summed to half of their result as follows,

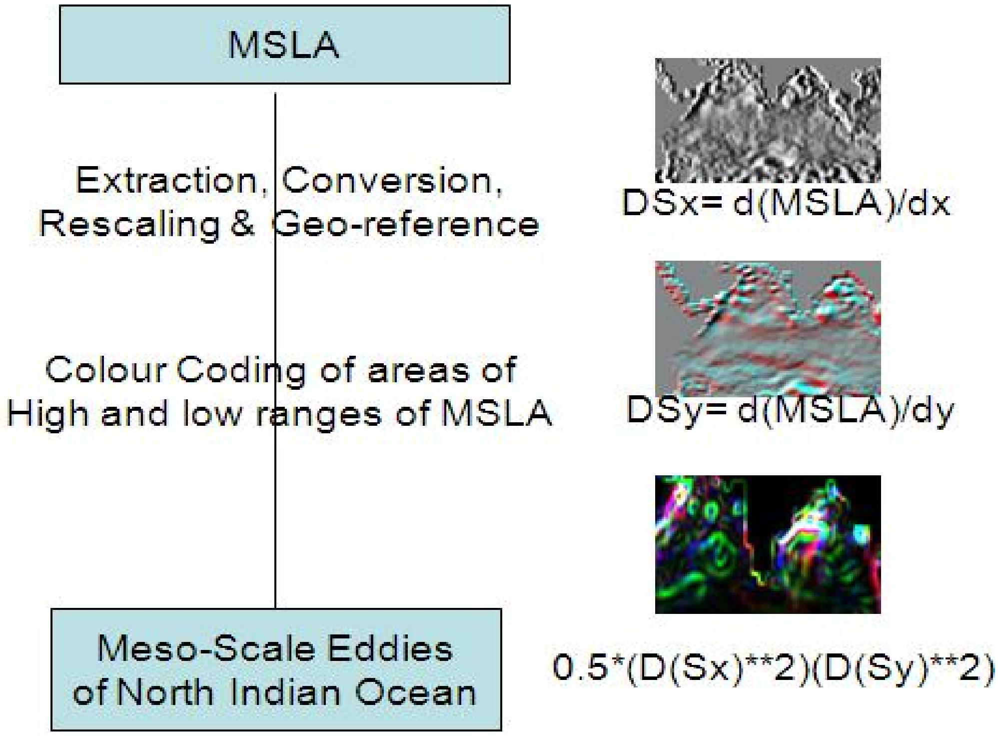
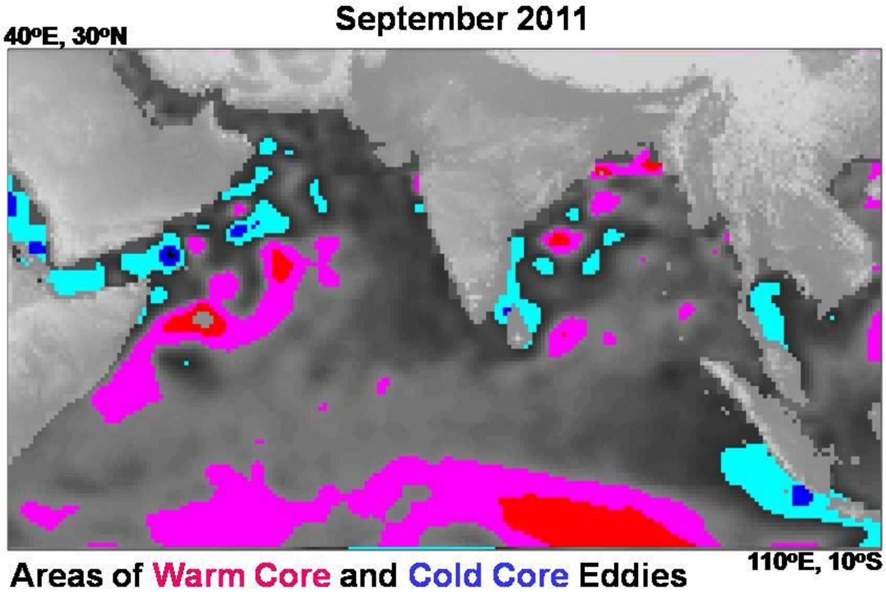


Figure 3: EKE derivation flow chart.

MSLA : Monthly Sea Level Anomaly (alternatively may be referred as monthly Sea Surface Height Anomaly).

Methods adopted here is similar to the one used else where in the present context. Aviso provides a technique similar to the present one. JPL and BRAT software that process Altimeter data has the scope of developing such products. The products generated are available in the binary mode, which can be transformed to any other types of data format using Envi image processing module of output generation. The results followed similar results as displayed elsewhere with Aviso and JPL web sites.



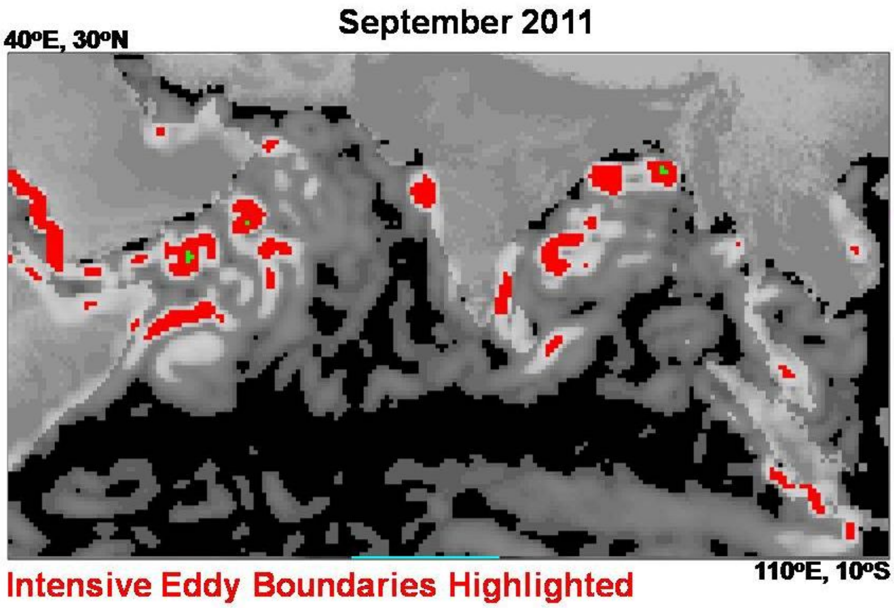


Figure 4a: The MSLA of north Indian Ocean indexed to show area of warm and cold core eddies (upper part) and EKE (in the lower part) showing intensive eddy boundaries for the month of September 2011 (a monthly database of EKE from 1993 to 2011 is organized in the NRSC website).

5. Results and discussion

The monthly EKE fields along with MSLA for years between year 1992 to 2011 (plates 1-38). High values of EKE in the western boundaries indicate westward intensification of the flow. Seasonal pattern and regional variations in the eddy fields are also observed. The region being influenced by strong monsoon winds, the eddy fields exposed to reversing current thus bringing an intensified field of variability in the EKE in the northern Indian Ocean. Earlier studies restricted to sea level anomaly have also shown similar observations with strong fields of dynamics in the western region (Ali et al. 1998). The regions around Socotra, Somalia, Saudi Arabia, Laccadive Islands show high values with strong currents in the Arabian Sea during south west monsoon months (Allan, 1983; Rixen et al, 1996, Sankar and Shetye, 1997). While the Bay of Bengal experience a similar observation with cold and warm core eddies along the east coast of India (Rao and Sree Ram, 2005; Varkey et al, 1996). May of the eddies and associated processes were studied with eventual dynamics related to cyclone heat potential, cyclone productivity, island wake eddies and productivity at the sea (Ali et al, 2007; Rao et al, 2006; and Sasmal, 2006; Sasmal and Panigrahy, 2006; and Sasmal et al, 2004).

The eddy boundaries are well defined by EKE indicating flow of mass and energy field in the areas of their estimation. Their monthly variation is an indication of seasonal dynamics in the north Indian Ocean (figure-5).

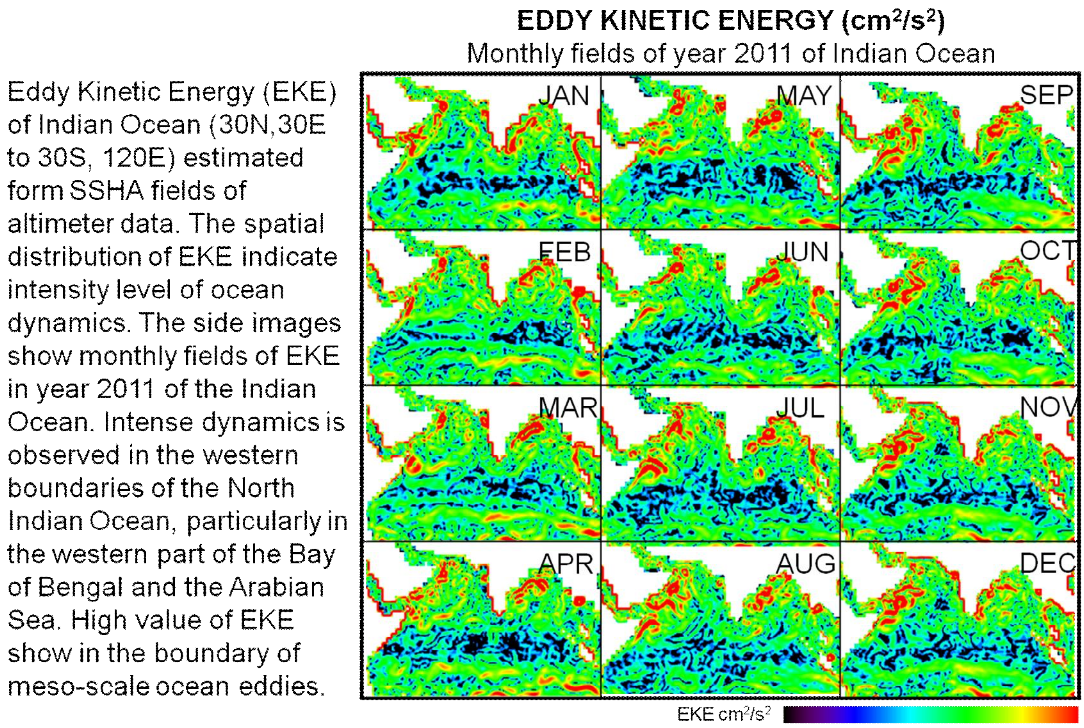


Figure 5: Monthly EKE fields of 2011 for the north Indian Ocean.

High values of EKE are seen along the coastal boundaries is seen mostly in the west coast of India, This indicate westward intensification of flow pattern in the ocean basins. In spite of being a monsoon induced flow in the northern Indian Ocean, the flows and circulation remains intensified in the west unlike other major basins.

The statistics of the MSLA for the monthly fields from April 1998 to June 2003 indicate high values in the northern Bay of Bengal and their meridianal variation indicate two tire gyres in the Arabian Sea and the Bay of Bengal (figures 6 & 7). These found getting intensified in the western part of the seas. In the Arabian Sea intensified flows are associated with major eddies of the region like, Somali eddy off the coast of Somalia, Sacora eddy around Socora Island. The eddy fields are also continued further north along the coast till the Persian Gulf. While the eddy fields are amplified in the northern part of the Bay of Bengal. The MSLA remained high on the east coast of the Andaman Islands and similarly around the Laccadive Islands. The gyres followed the anti-cyclonic flow intensified in the west as explained as westwards intensification under influence of rotational tendency of the Earth’s motion. However, the revolution introducing the variation in heat potential on the earth’s surface and atmosphere change in wind direction from North-East to South-West influences eddies on the ocean surface. They are reflected on the EKE fields. The range of values and minimum and maximum of MSLA has also supported such observations (Figure 7).

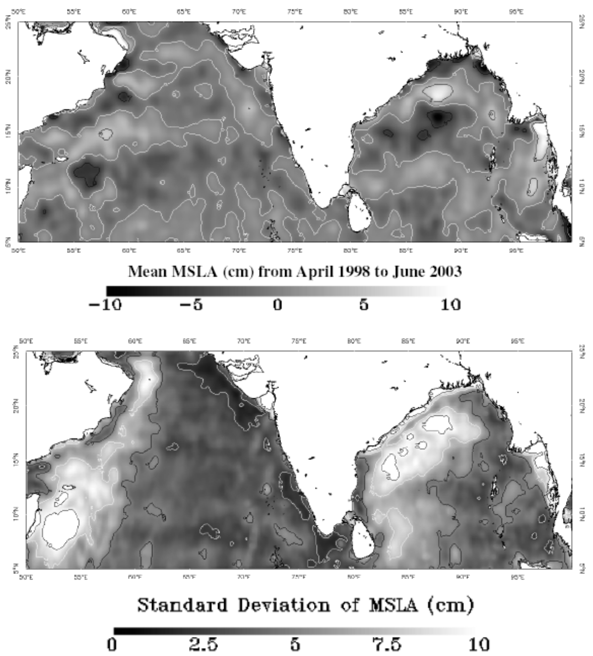


Figure 6: Mean and standard deviation of Mean Sea Level Anomaly for data from April 1998 to June 2003.

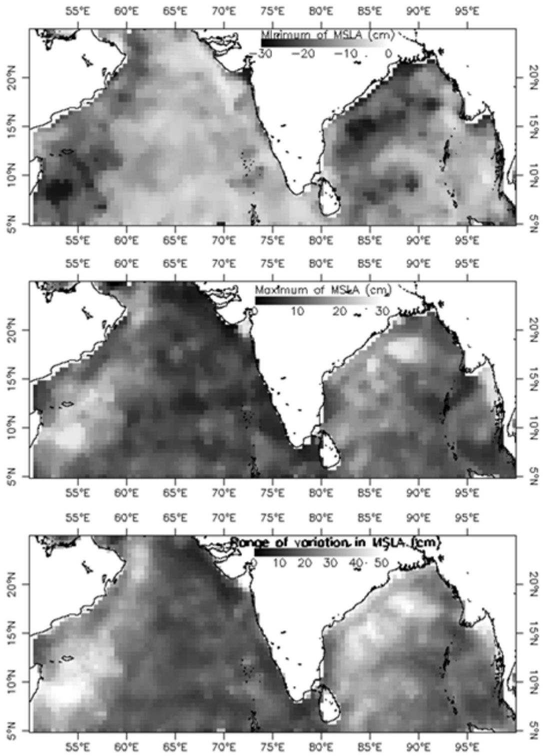


Figure : Minimum, Maximum and the range of variation observed for monthly mean sea level anomaly from April 1998 to June 2003.

Figure 7: Minimum, maximum and range values of SSHA data for north Indian Ocean from April 1998 to June 2003.

5. Conclusions

The EKE fields of altimeter data available in monthly mode for the north Indian Ocean. The regions of high variability and high and low mean fields of SLA are of significant as hot spots for future exploration. The northern part of the Bay of Bengal experience a high variance and high sea level elevation indicating a converging field of ocean mass. The anti-cyclonic field of circulation associated with accumulated heat potential needs further attention in terms of circulation, cyclone genesis, intensification and migration; water mass dispersion and fresh water flux into the region. The study need to be extended to other regions of Indian and global oceans. Besides, SARAL data products on MSAL also be used to generated EKE fields for Indian region and as well as in the global waters.

The EKE being the variance field of surface ocean current that result from geostrophy and ocean surface wind, need further attention. Temperature and salinity fields at the sea drive the water masses the ocean. The wind at the sea surface transferred momentum to the sea surface need evaluation of their energy fields respectively. This helps to examine the change in forcing factors in the seas around India and their influence on the dynamics at the sea and associated weather.

The EKE also helps to characterize ocean surface dynamics identifying boundaries of ocean surface circulation and strength. Intensification of flow in western boundary of the seas during pre-monsoon months and upwelling in eastern part need further analysis. The utility of such products can be seen in the study of productivity and ocean dynamics with the change in season

The EKE represented through MSLA in long term is also expected to address the issues related to climate change. The ocean dynamics in the equatorial sea of Indo-pacific as depicted from MSLA is evident as that amplify the well known El Nino and Southern Oscillation (ENSO) event. Thus, spatial and temporal analysis of EKE in finer resolutions of time and space is recommended for a detailed study.

MSLA decadal fields are followed with MSLA database. This has shown equatorial dynamics in the Indo-Pacific region known for Monsoon and ENSO (El Nino –Southern Oscillation) studies. The amplification of sea level changes during 1998 ENSO situation and 2010 scenario reflected in the Monthly MSLA database indicating their further utility and analysis.

The EKE find its utility in study and analysis of ocean dynamics and helps explains the processes of mass convergence and dispersion. Mostly explain ocean circulation in relation to exchange of heat and mass across the boundaries of different ocean basins and at the interfaces. The MSLA which subdued the marginal fields of ocean circulation are amplified in the EKE indicating their better utilities in process studies

The work recommends further interpretation analysis of Eddy Kinetic Energy fields and methods of estimation to improve quality of the product. Further interpretation of EKE fields will provide a scope to bring to knowledge on the processes prevailing in the northern Indian Ocean.

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Ocean Science Group
(Earth and Climate Science Area)
National Remote Sensing Centre
ISRO (Govt. of India, Dept. of Space)
Hyderabad- 500 037