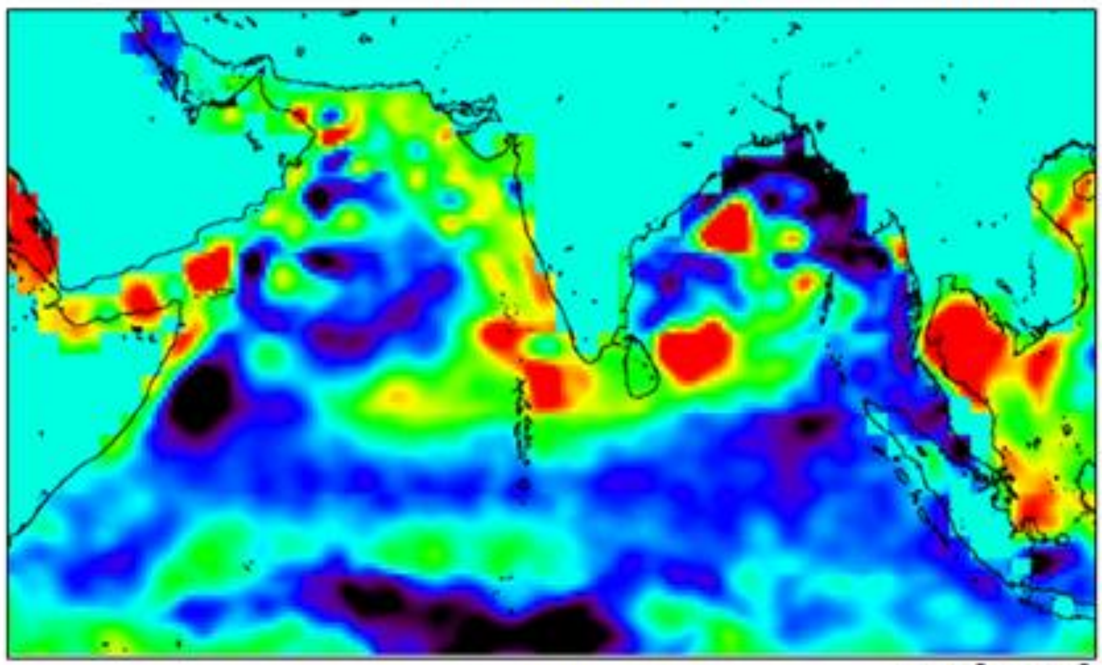
Indian Space Research Organisation

Eddy Kinetic Energy
of the North Indian Ocean

40°E, 30°N

Areas of clod and warm core eddies



January, 1993

110°E,10°S

Ocean Science Group
Earth and Climate Science Area

National Remote Sensing Centre

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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°E to 110°E and 10°S to 30°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

$$\text{RMS}=[[\text{Sum SLA}(t)]/n]^{½}$$

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.

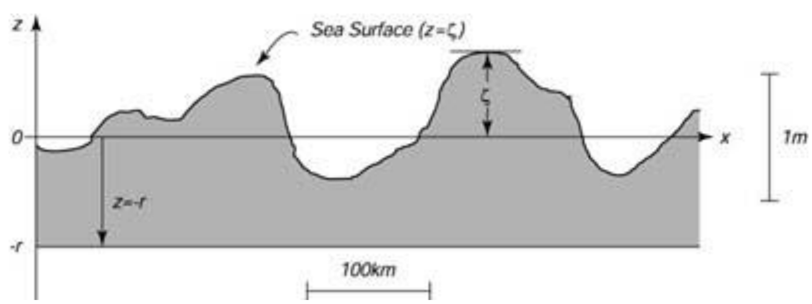

Figure.1 Sketch defining z and r, used for calculating pressure just below the sea surface (http://oceanworld.tamu.edu/resources/ocng_textbook/chapter10/chapter10_03.htm Robert H. Stewart, stewart@ocean.tamu.edu)

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.

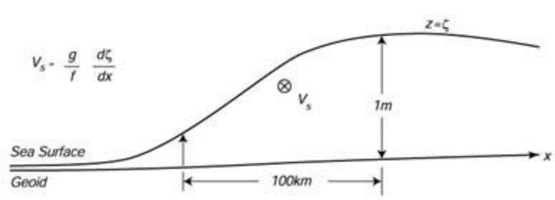

Figure.2 The slope of the sea surface relative to the geoid (drawn as by Robert H. Stewart)

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, Φ = 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,

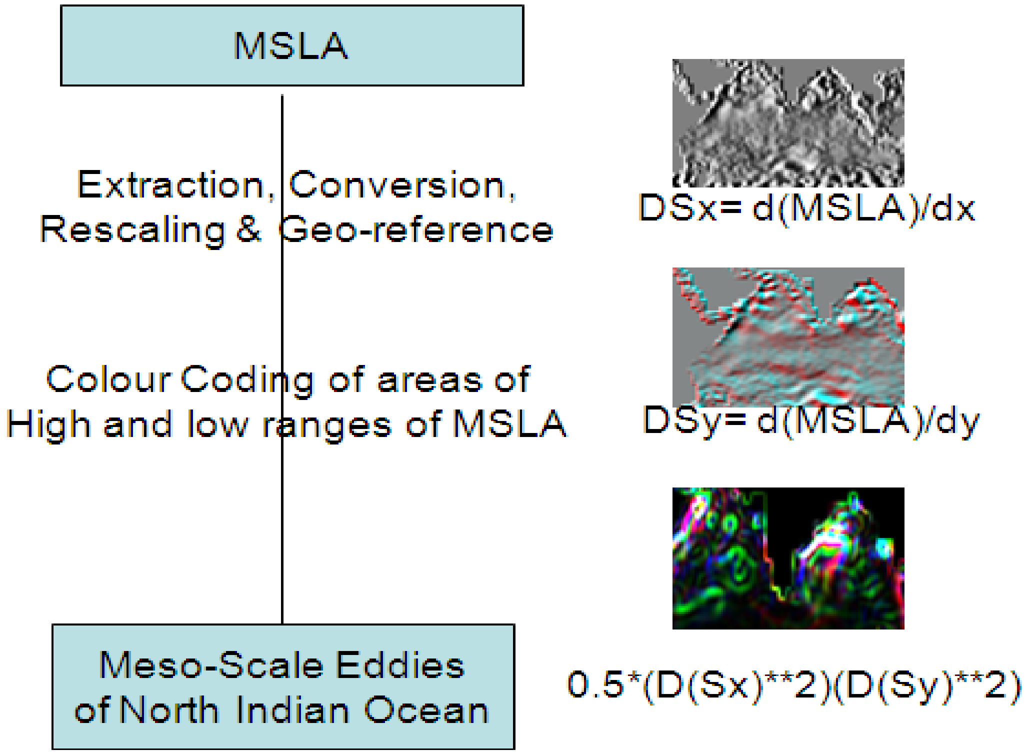

Figure 3: EKE derivation flow chart.

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. The EKE estimation followed the methods as shown in http://www.altimetry.info/ html/use_cases/data_use_case_mesoscale2_en.html. The monthly EKE showing the boundaries of major eddies and areas showing the warm and cold core eddies of the north Indian Ocean (Fig.4a and 4b). Further details are provided through the data sets organized in the NRSC website for visualization as well as data for further observation and analysis.

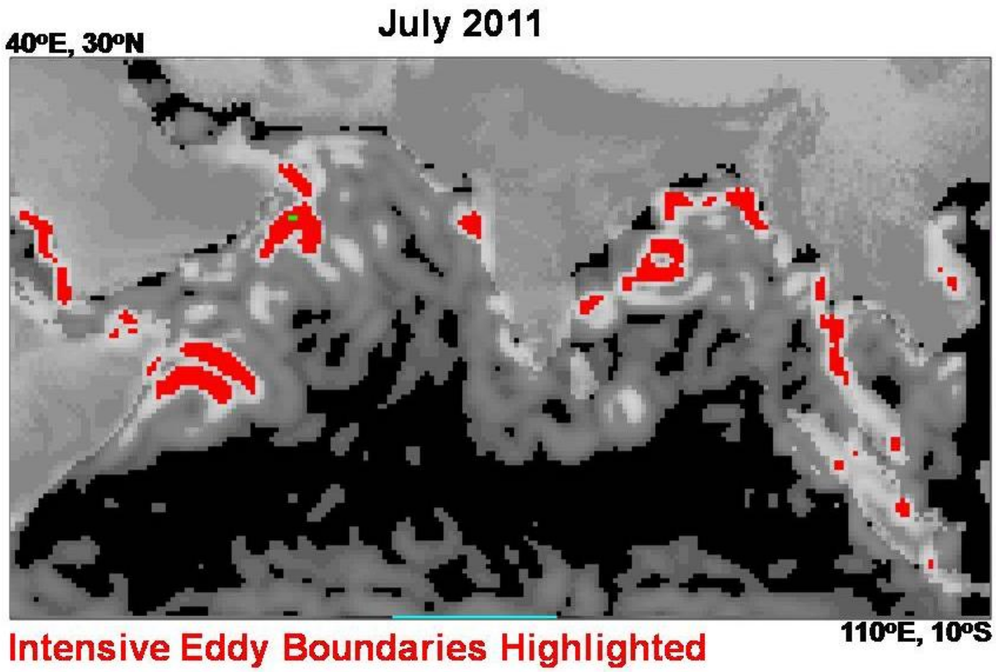

Figure 4a: EKE of July 2011 showing boundaries of the ocean current.

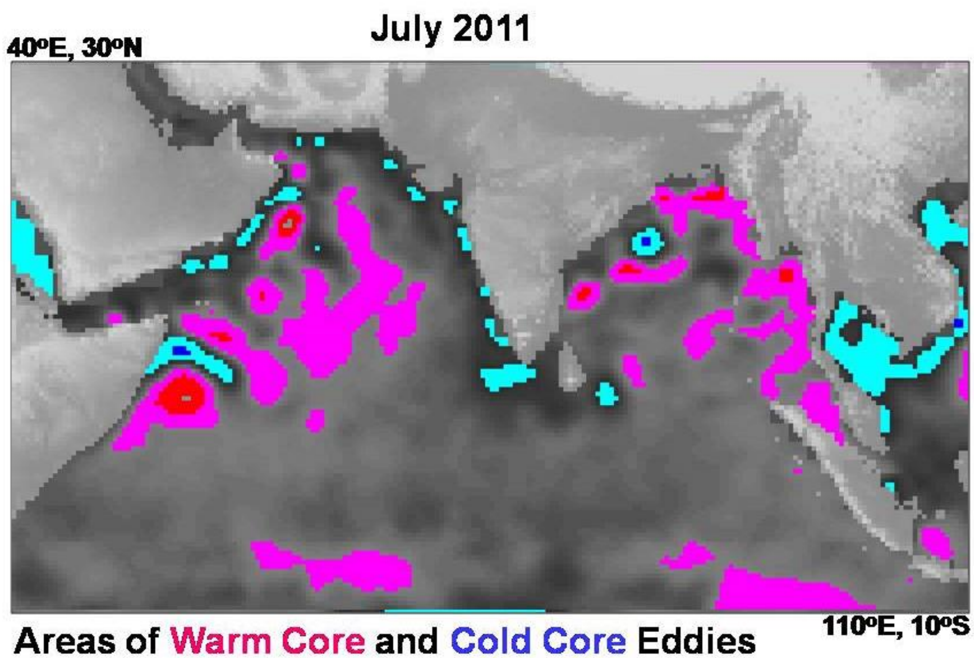

Figure 4b: Eddy Indexed MSLA of July 2011 showing areas of the ocean current.

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Files are organized on monthly basis for their data in ascii format along with image for viewing in JPG format. Name of the files in the databases are as follows,

Data Files of eddy Kinetic Energy are as follows,	eke_year_mon.dat
Image files as.	eke_year_mon.JPG
Eddy Indexed MSLA files as,	msla_year_mon.dat
Eddy Indexed image files as,	msla_year_mon.JPG

Data files of are in generic binary format with floating point values for a matrix of 832x 480 observation. The land part is masked to zero or topography values. The data is for the north Indian Ocean from 40^{o}E, 30^{o}S to 110^{o}E, 10^{o}S. These can be opened using sample header file in the database.

5. Applications of EKE

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). 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.

Eddy Kinetic Energy (EKE) of Indian Ocean (30N,30E to 30S, 120E) estimated form SSHA fields of altimeter data. The spatial distribution of EKE indicate intensity level of ocean dynamics. The side images show monthly fields of EKE in year 2011 of the Indian Ocean. Intense dynamics is observed in the western boundaries of the North Indian Ocean, particularly in the western part of the Bay of Bengal and the Arabian Sea. High value of EKE show in the boundary of meso-scale ocean eddies.

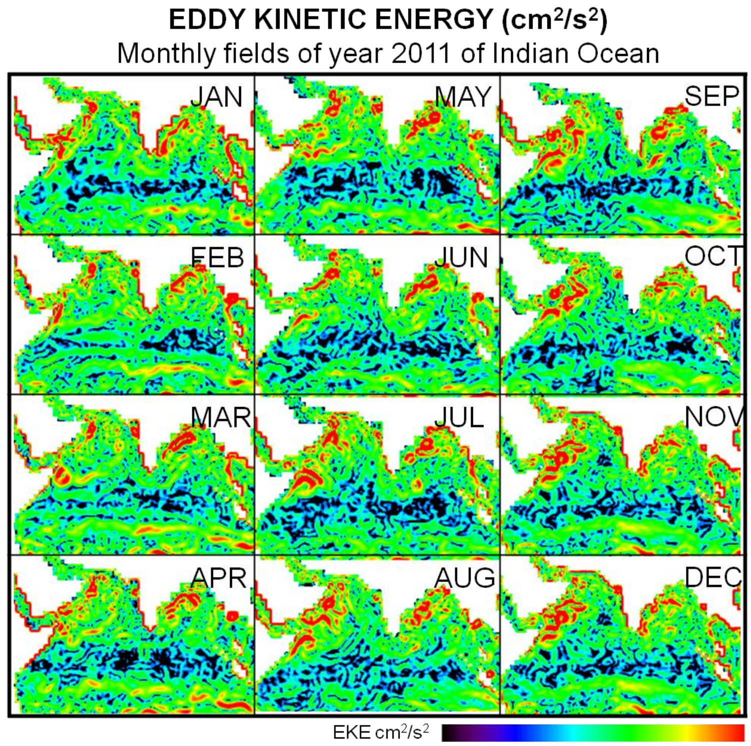

Figure 5: Monthly EKE fields of 2011 for the north Indian Ocean.

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 Socotra 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).

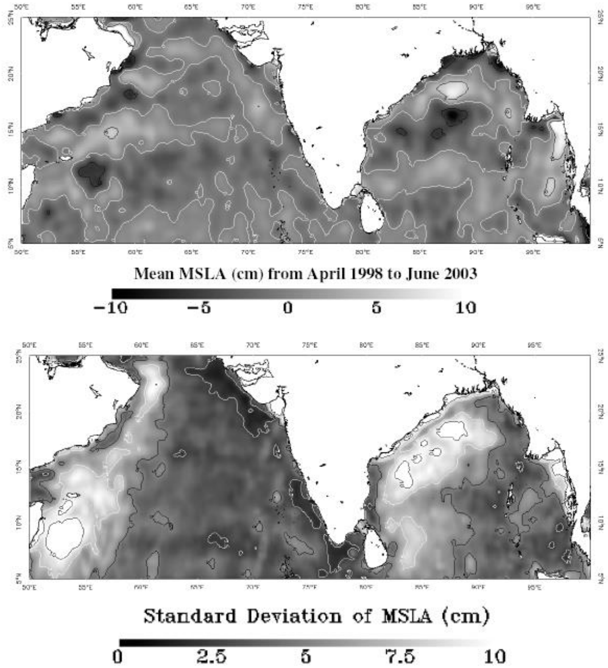

Figure 6: Mean and standard deviation of Mean Sea Level Anomaly for data from April 1998 to June 2003.

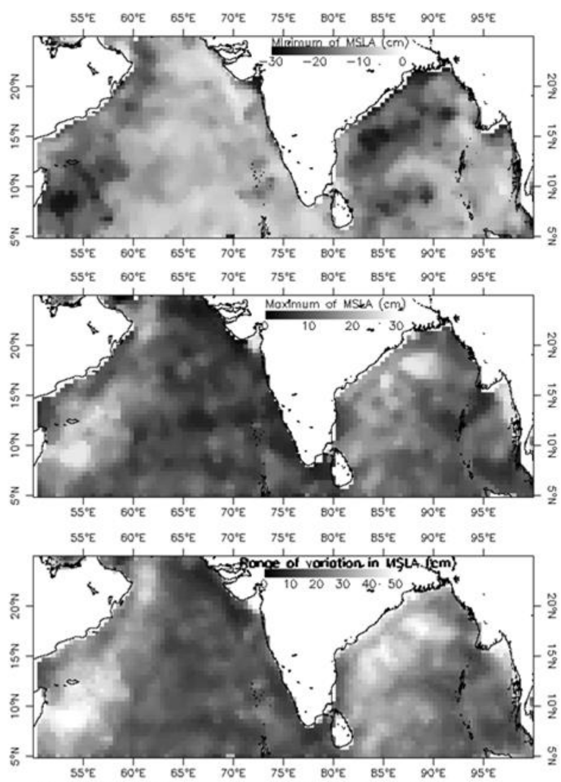

Figure : Minimum, Maximum and the range of variation observed for monthly mean sea level anomaly from April 1998 to June 2003.

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

4.1 Arabian Sea Eddies

Spatio-temporal variation in circulation over Indian Ocean can be resolved to eddy and gyres with varying intensity and sizes. The most reported as 'The Great Whirl' of the Arabian Sea along with eddies off Somalia Coast and Socotra Island are associated with Somali current, the western boundary current of the north Indian Ocean. The currents followed a seasonal pattern under the influence of monsoon wind, which often reported of having inter-annual changes in its intensity, shape and size of the eddies. Besides, a dipole eddy has also been reported in the north western Bay, off the Oman coast. The hydrographic studies have also reported seasonal eddies in the Laccadive Islands. The MSLA and EKE followed eddies reflected in the literary of the drifting buoys and SST and chlorophyll distribution of the Arabian Sea (Figure 8).

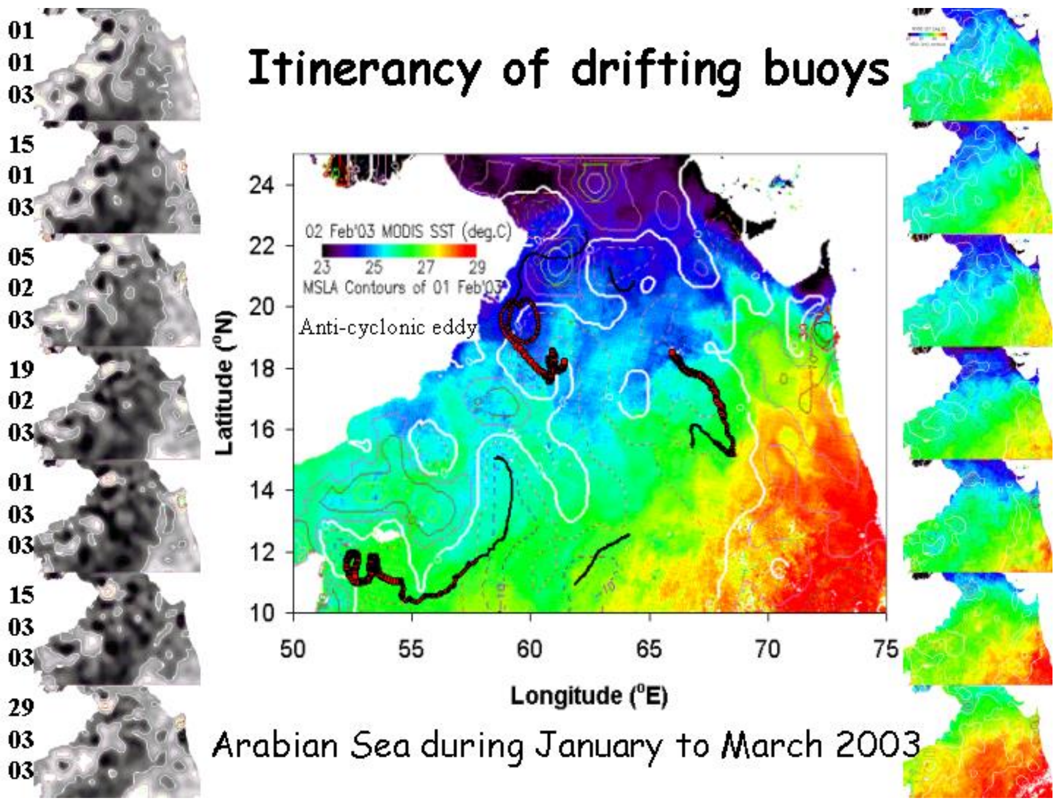

Figure 8: Eddy field with selected profiles of Temperature and salinity against depth profile in the western Arabian Sea.

4.1.1 The Great Whirl

The Great Whirl; often reported as the Southern Eddy (SE) forms south of 5^{o} N from a retroflection of the northward flowing Zanzibar current. This eddy consists of fresher water and is rather large at 400-600 km in diameter. The SE is not always present, but historical evidence was found 37 out of 63 years (1906-1968). Located between the SE and its northern cousin, the Prime Eddy, is a large wedge of cold water from the intense coastal upwelling associated with the southwestern Somali Current. (Sean Robinson, http://www.oc.nps.navy.mil/ ~paduan/ OC4331 /projsum/u01/ robinson_somalicurrent.html). Figure 9 reflects the eddy formation along the coast of Africa as seen in August 2003 and their weekly fields. The hydrographic profiles too reflected the dynamics of the eddies, one of the major dynamic process in the Arabian Sea.

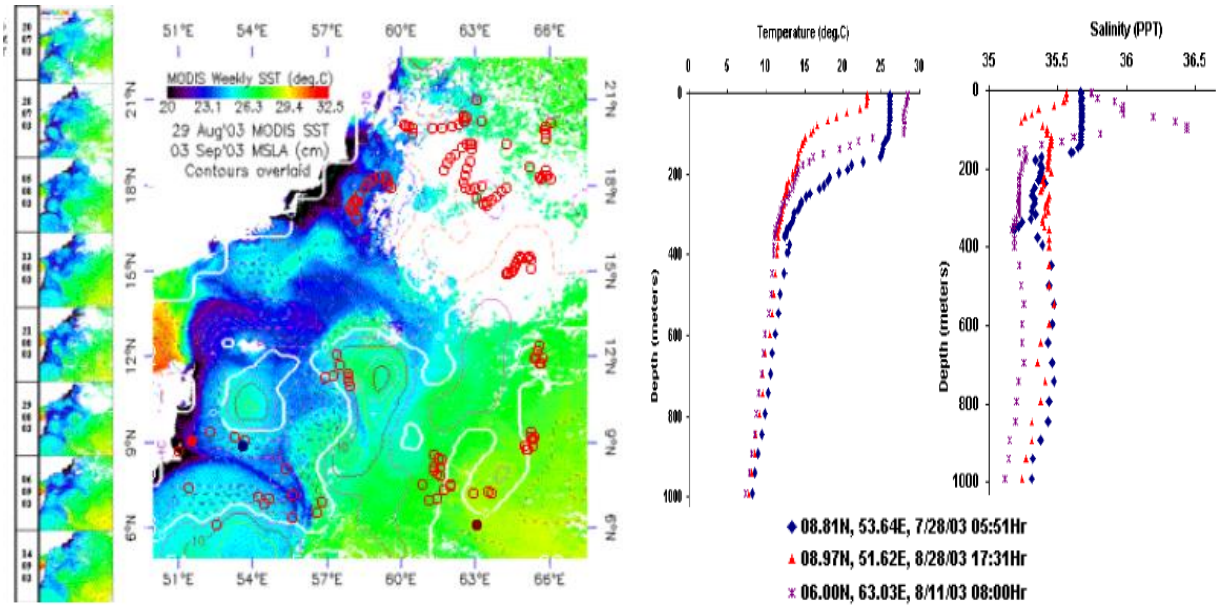

Figure 9: Temporal changes in eddy field SST overlaid with SSHA in the western Arabian sea that amplify Somali current eddy and Socotra eddy field in August 2003.

4.1.2 Somali Eddy

The eddy reported off the coast of Somalia is often reported as the Prime Eddy (PE) which forms at ~8 ^{o} N and is developed from horizontal shear instability (Bruce) or from barotropic instability (Jensen). PE is also rather large (400-600 km in diameter) and like the SE remains stationary until mid-August. Then the SE will migrate north to join the PE and form the "Great Whirl". The Great Whirl is a large anti-cyclonic eddy (600-800 km in diameter) with a large mass transport (58 Sv) that causes the constant southward SC undercurrent to temporally disappear. The Great Whirl is responsible for the recirculation of the increased transport associated with the southwest SC and can survive for 3 months after the onset of the northeast monsoon.

4.1.3 Socotra Eddy

Located east of Socotra Island, around 12oN, 54oE, this third eddy is in the north of the Great Whirl (Pl. see Figure 9) and can have a diameter of 400 km with a cross-section mass transport of 23 Sv. The Socotra Eddy does not develop until late summer and is the last eddy to form in the SC system.

4.1.5 Oman Eddy

The dipole eddy observed off the coast of Ras al Hadd with MSLA data of 21 October 2003 corresponded well the features in the SST and Chlorophyll fields of MODIS data (Figure 10) Long term observation during January 2002 to June 2003 in the fortnight mode with MSLA and SST from MODIS data indicate genesis and decay of the meso-scale eddies in the area. The anti-cyclonic eddy during the pre-monsoon months split into a dipole eddy with a cyclonic eddy that has grown till beginning of June 2003. The MODIS SST indicates the cold water Jet from south. The wind jet took off the coast off the Ras al Hadd developing bipole eddies under the influence of the east Arabian current. The Oman coastal current was also seen associated with the bipole eddies of the area with the onset of the Southwest monsoon (figure 11). The multiple eddies in the western Arabian Sea is an indicator of high EKE as reflected in the energy fields. Their seasonality as seen in 2002 and 2003 with SSHA and SST provide a scope of similar products like EKE in climatic study (Figure 12).

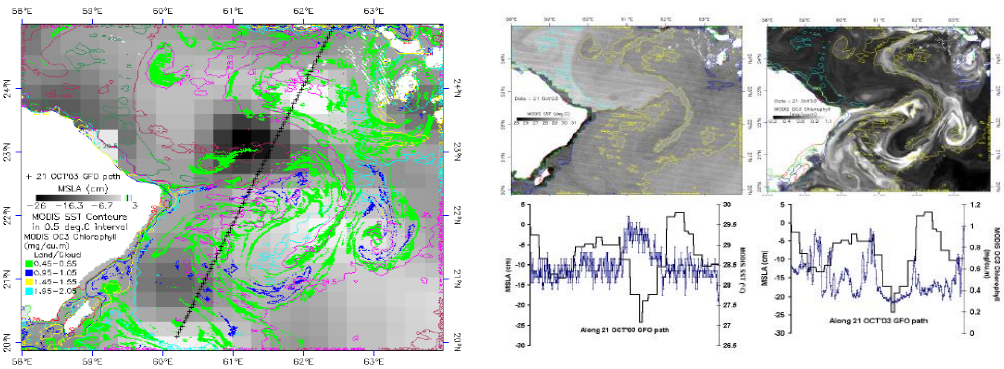

Figure 10: Ocean chlorophyll and temperature around ocean eddies of the western Arabian Sea.

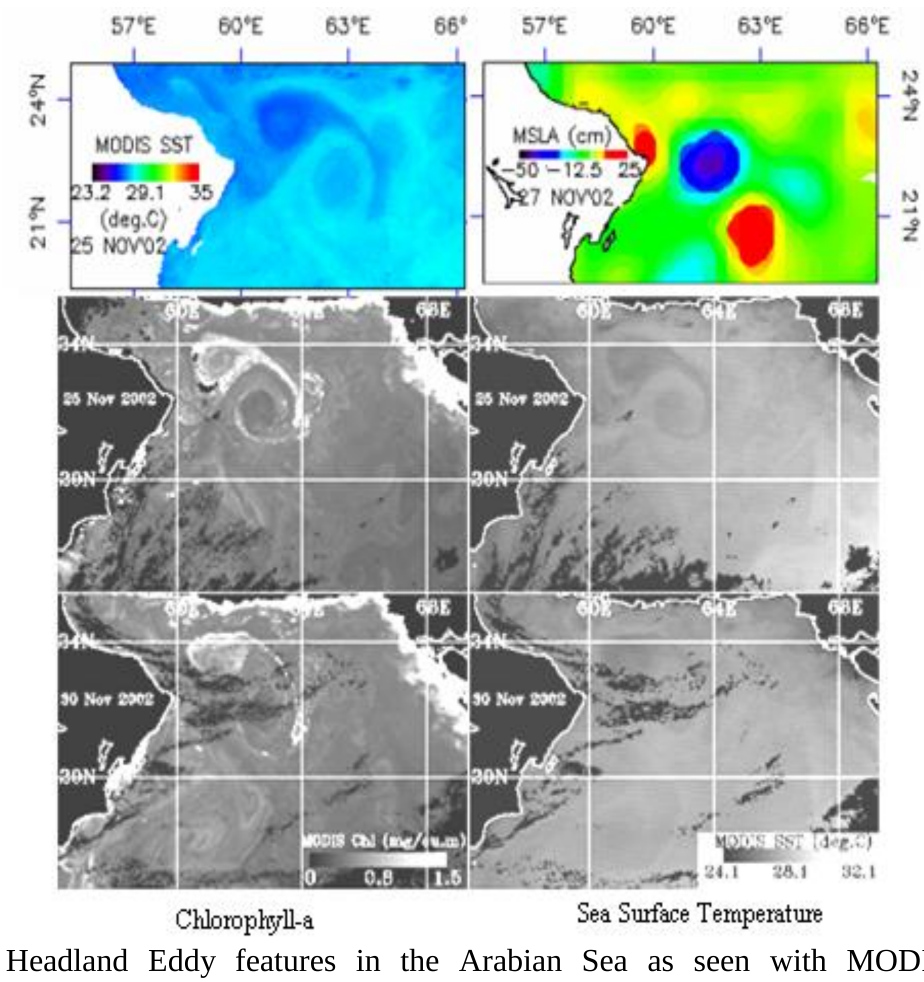

Figure 11: Headland Eddy features in the Arabian Sea as seen with MODIS SST and Chlorophyll-a along with SSHA observations.

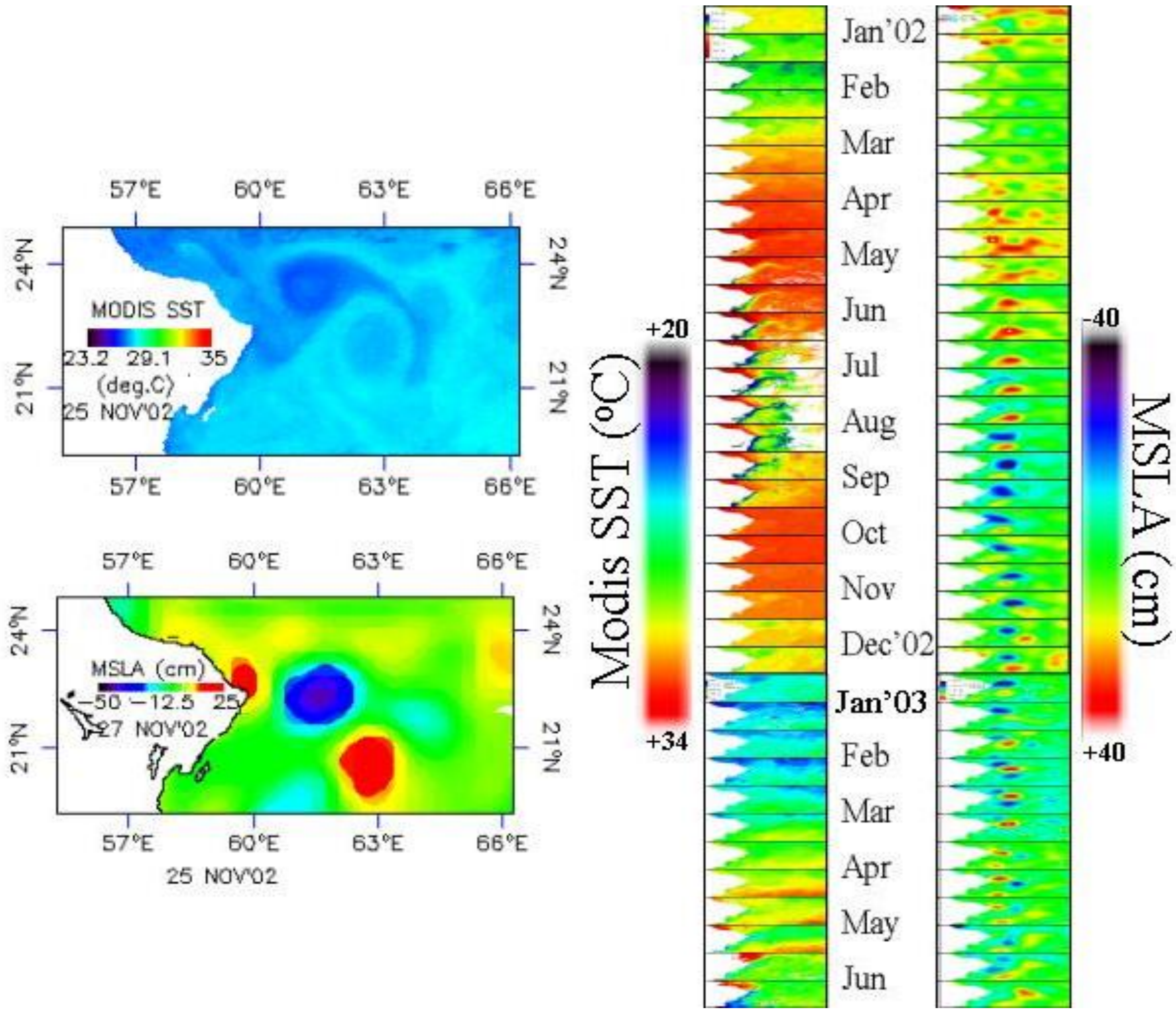

Figure 12: Seasonal variability of the Persian Gulf eddies in the western Arabian Sea in 2002 and 2003.

4.1.4 Laccadive Eddy

The Laccadive High is a large (500-800 km diameter) seasonal anti-cyclonic eddy formation found in the upper 300-400 m of the eastern Arabian Sea during the northeast monsoon. In some ways it is a mirror like counterpart to the Great Whirl, which develops during the southwest monsoon off the Somali coast. The LH occurs at the same latitude but on the opposite side of the basin (located east of the Laccadive Islands) during the reversed monsoon. It is different from the Great Whirl, however, in its formation process, its intensity, and its decay. The formation of multiple (2-3) eddies during the northeast monsoon. These eddies are approximately 200km in diameter and form off the southwest coast of India and propagate westward at approximately 17 cm/s. (Bruce et al, 1994; 1998). During the northeast monsoon, multiple (2-3) eddies of ~200km in diameter form off the southwest coast of India and propagate westward at ~17 cm/s. (Bruce et al, 1994; Bruce et al, 1998). These Laccadive High eddies have a SSH amplitude of ~15 cm and are detectable by Satellite Altimeters. The generating mechanism appears to be a combination of local and remote forcing. The local forcing appears to be the intense negative wind stress curl off the SW coast of India during the NE monsoon. The remote forcing appears to be an intraseasonal signal originating in then Bay of Bengal. Eddies (Rossby Waves) from Eastern Boundary. Wind forced Kelvin Waves around the coast of India.

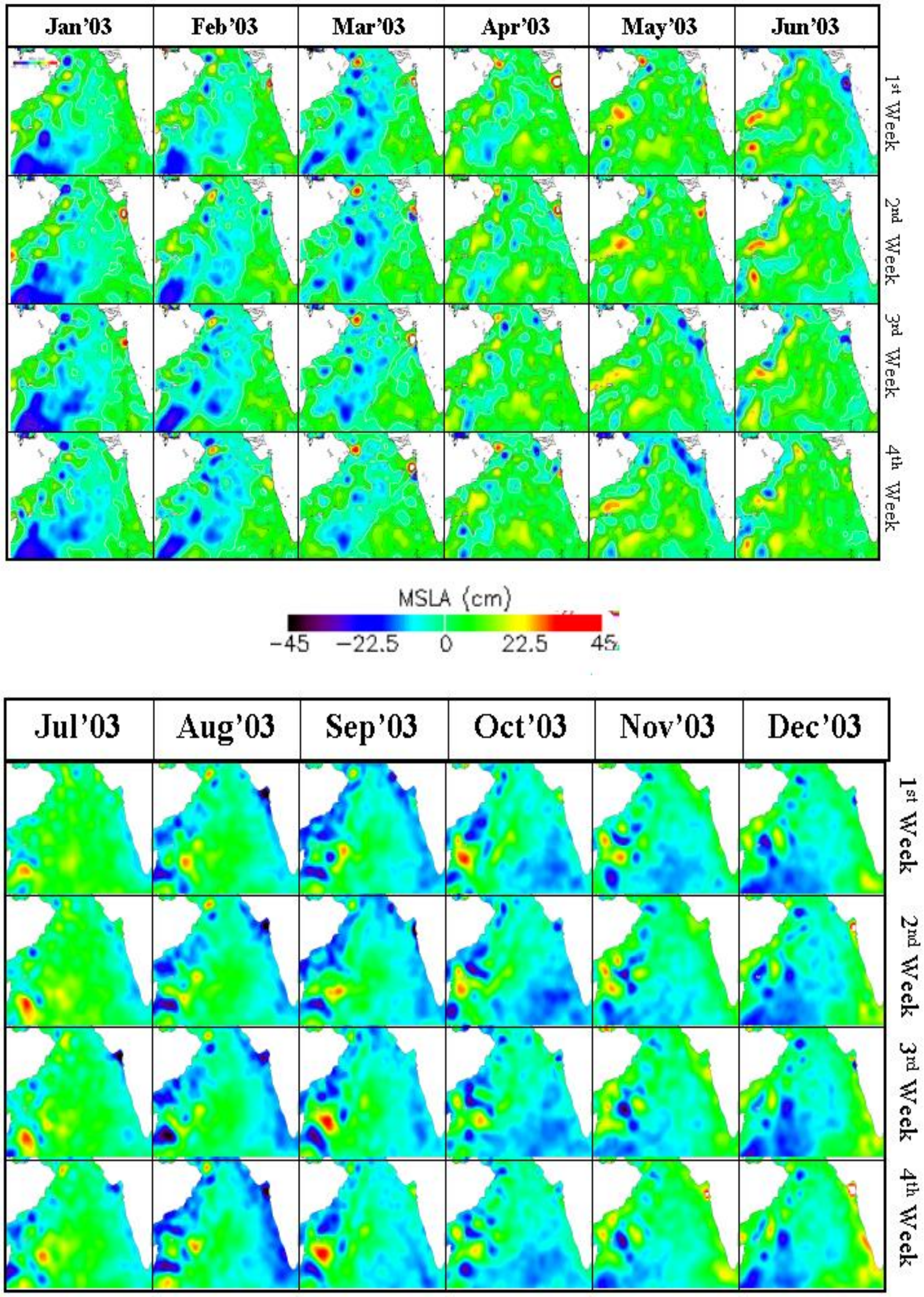

Figure 13: Eddies of the Arabian Sea in 2003.

The Arabian Sea eddies as seen in Figure 13 and the EKE field need further analysis and interpretation to explain the prevailing processes.

4.2 Bay of Bengal Eddies

The eastern counterpart of the Arabian Sea in the north Indian Ocean is well known for influx of highest river fluxes under the influence of monsoon rain over the Indian subcontinent. This induces strong stratification in the upper layers of the northern Bay influences dynamics of the bay waters in association with monsoon wind. This lead to several seasonal eddies in the Bay of Bengal. The observations made with Ocean colour fields over surface temperature followed the MSLA field of the region (Figure 14). Varkey et al (1996) with hydrographic studies reported a three-gyre system with a seasonal northern gyre and Andaman gyre along with persistent clockwise southern Gyre. The northern and southern gyre observed in the western Bay is associated with the East Indian Coastal Current, a western boundary current in the Bay of Bengal. Similar to the Somali current, East Indian coastal current is associated with these eddies in the Bay of Bengal. Hydrographic studies in the northern Bay also indicate existence of dipole eddies at the head of the Bay (Sasmal, 1988). Some of the transitional eddies also reported in the eastern Bay of Bengal (Varkey et al, 1996). However, a little effort has been made to study the details of such eddies with satellite data. Some of the observations made with MODIS data are as follows.

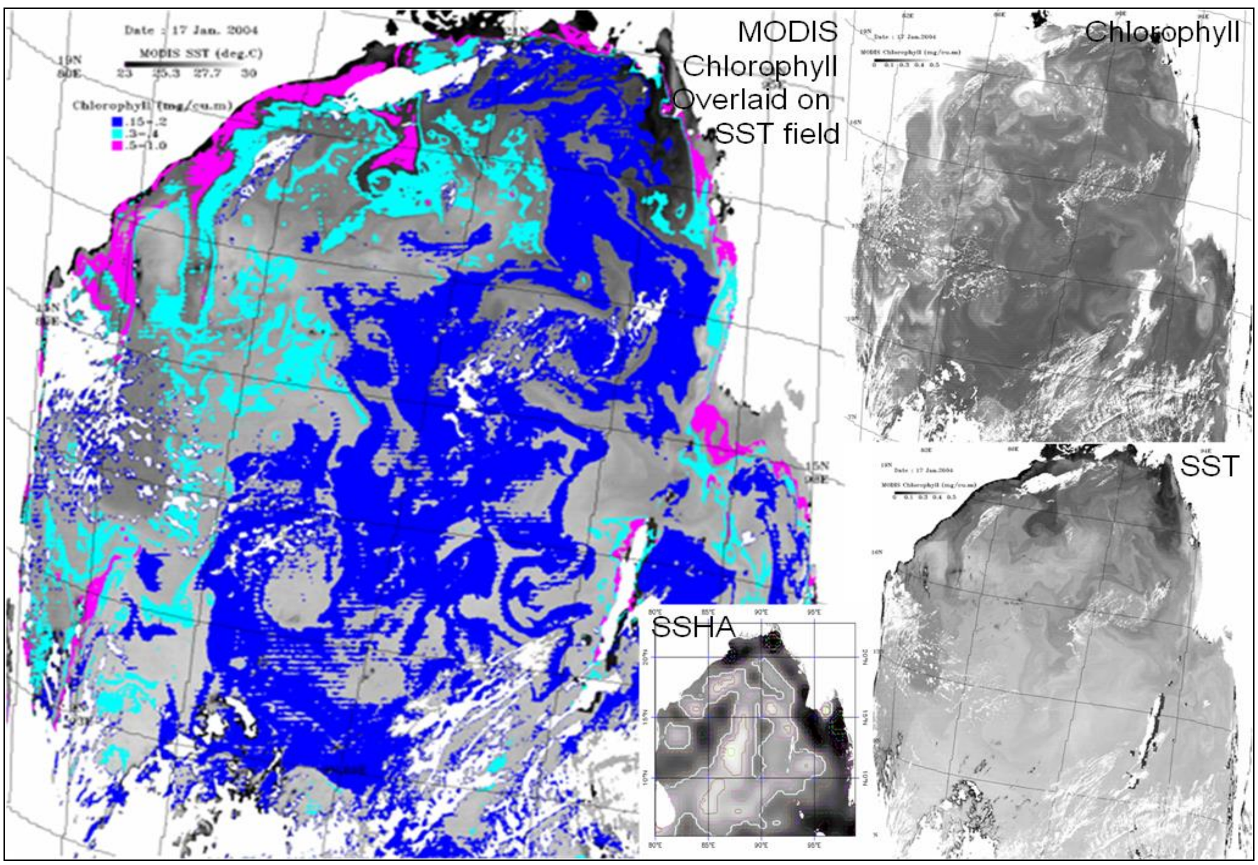

Figure 14: MSLA, and MODIS derived SST and Chlorophyll-a fields in the Bay of Bengal on 17 January 2004.

4.2.1 Northern Gyre

The northern gyre (G1), between the western boundary and 13°N, 89°E; is clockwise during winter and anticlockwise in summer. One of the eddies with a spiral feature observed with SST data of MODIS in the Bay of Bengal on April, 16, 2003 also found to have its corresponding feature in the MSLA observations. The warm core eddy off the coast of Orissa along the east coast off India is found driving a spiral feature of anti-cyclonic flow in the thermal field (figure 15). This is found to bring the offshore warm water close to the Orissa coast. Further north another anti-cyclonic eddy is observed with relatively cold water than its southern counterpart. To the south of the spiral eddy, another circular field of flow relatively cold core is also observed off the North Andhra coast. While the MSLA field of the area indicates relatively high values in the south and offshore region, while low values are observed in the coastal region (Figure 16).

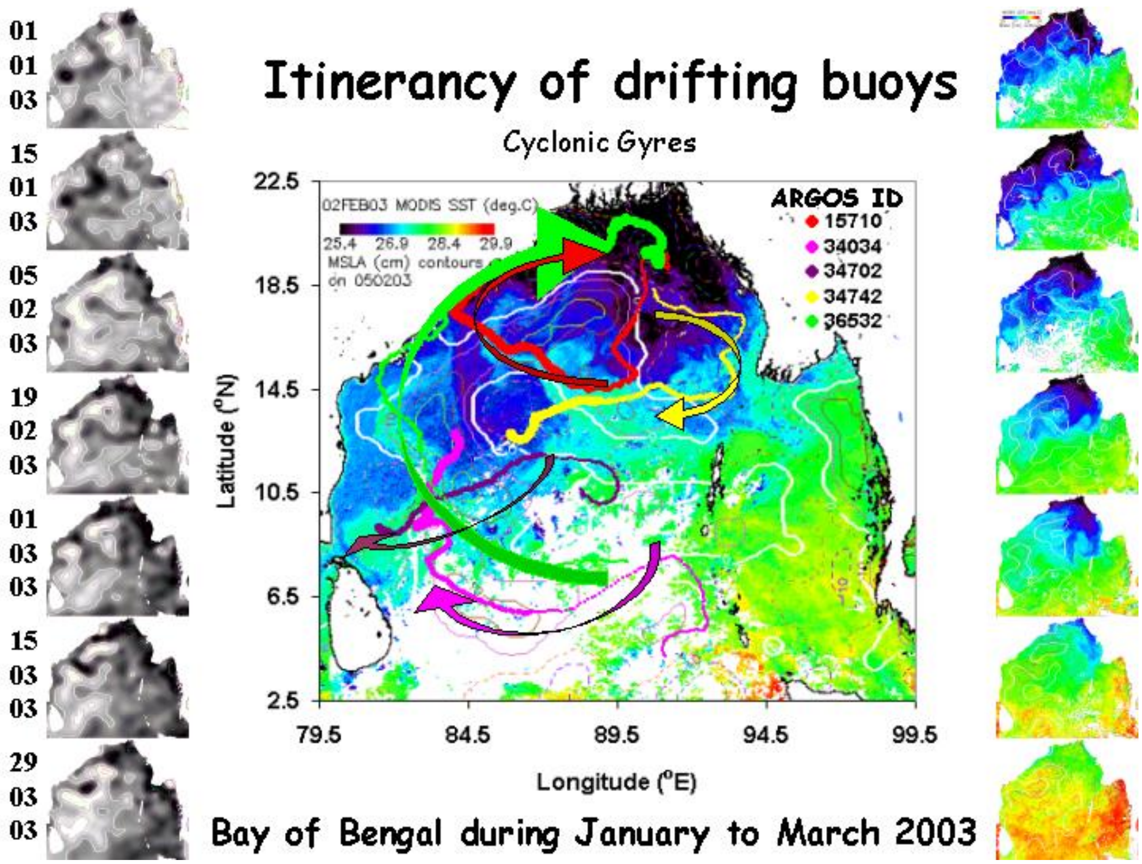

Figure 15: MSLA, and SST fields of the Bay of Bengal in January to March 2003.

4.2.2 Southern Gyre

A southern gyre (G2) in the area south of 13°N in the Bay of Bengal is clockwise during as reported by Varkey (1996) in winter with its center lying around 85oE, 8oN. This covers most of the southern Bay in winter, while the eddy structure collapses in the summer with a overall eastward flow.

4.2.3 Western Eddies

The multiple eddies of cold and warm core in nature are seen in the western Bay of Bengal (figure 16). Their association with sediment transport and wildlife migration is well known. As the eddies are sources for productive area displacement, their enhancement and representation through EKE field is significant.

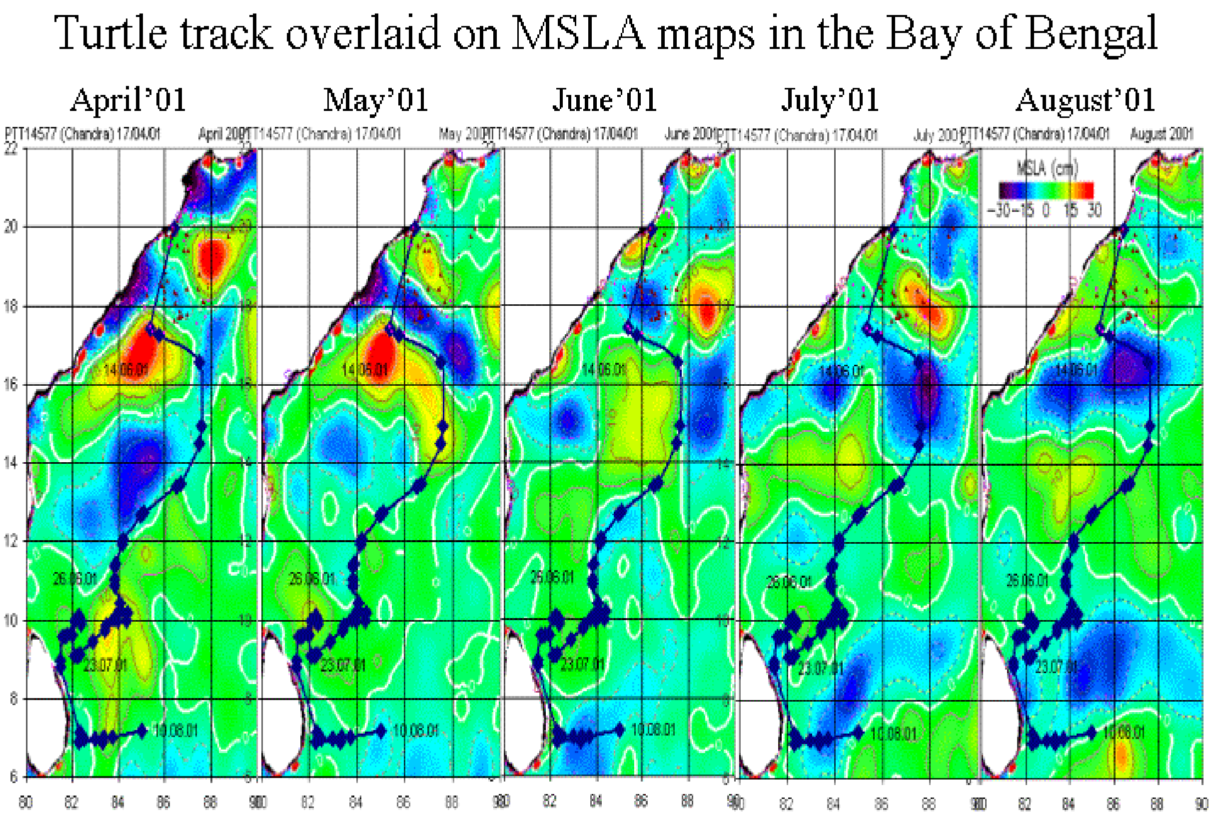

Figure 16: MSLA based eddy fields in the western Bay of Bengal during 2001.

4.2.4 Andaman Eddy

In the Andaman Sea, east of the Bay of Bengal, the oceanic flow changes direction twice during the year. (Potemra et al., 1991). Model layer thickness reveals coastal Kelvin waves propagating along the coast, traveling the entire perimeter of the Andaman Sea and the Bay of Bengal. This wave excites westward propagating Rossby waves into the interior of the Bay. Similar results are found by McCreary et al. (1993). They find that even in the absence of wind forcing in the Bay of Bengal, deepening of the upper-layer in the eastern Bay is still present in July as in the main-run, demonstrating that this is remotely forced from the equator via the reflection of a down welling-favorable equatorial Kelvin wave. Reflection of Rossby waves from the eastern boundary is also observed. Figure 17 of monthly fields of MSLA can be followed to see the Anadaman sea variations of energy field. The intensity and seasonal changes in the MSLA field is an indicator of eddy filed and the energy field. The warm core eddies in the western bay during premonsoon months. The eddy changed to cold core events in the post monsoon months as seen in the MSLA fields in 2003 (figure 17).

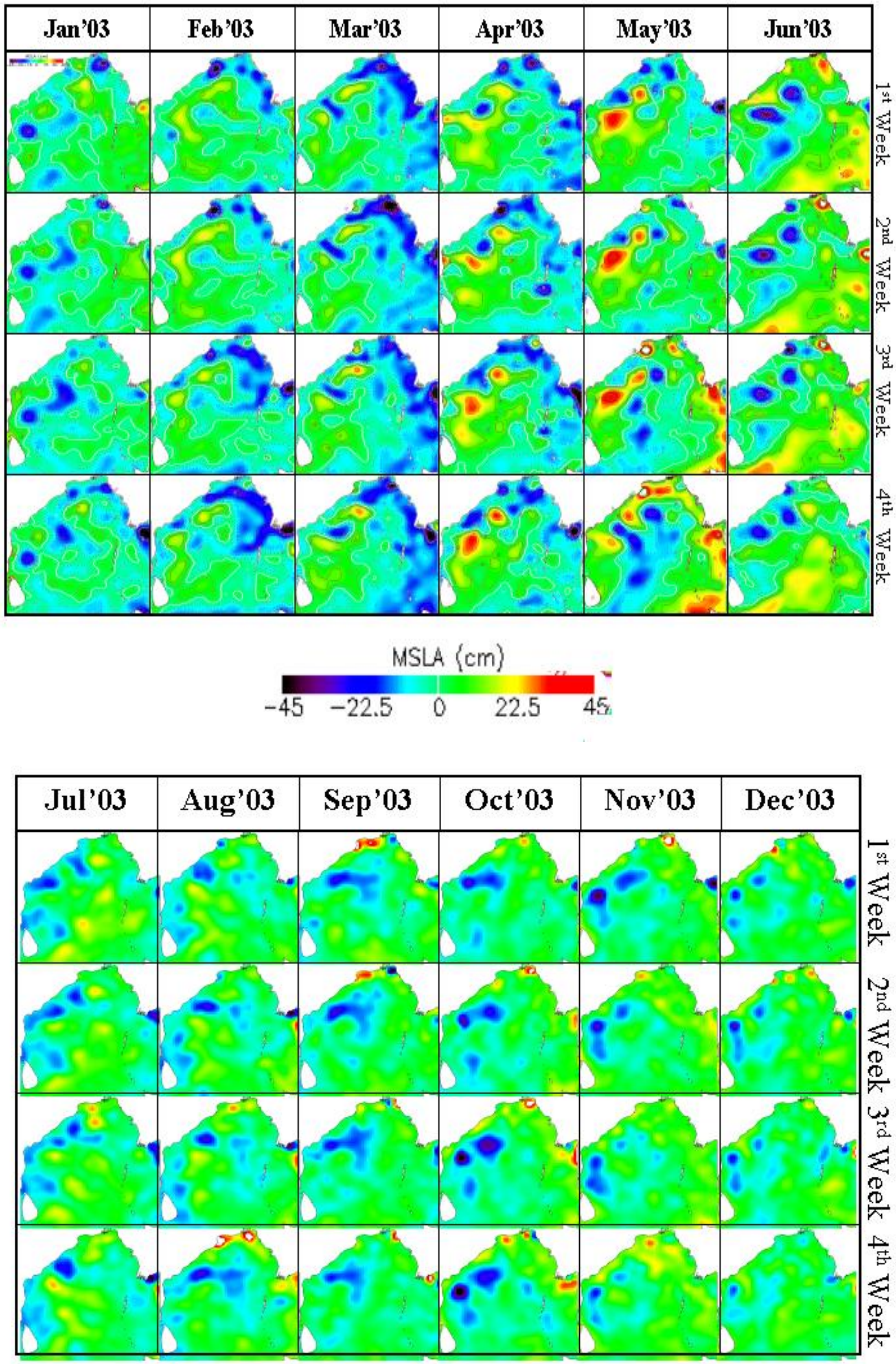

Figure-17: Eddies of the Bay of Bengal in 2003.

5. Future works on the EKE

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 (Figure 18) 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.

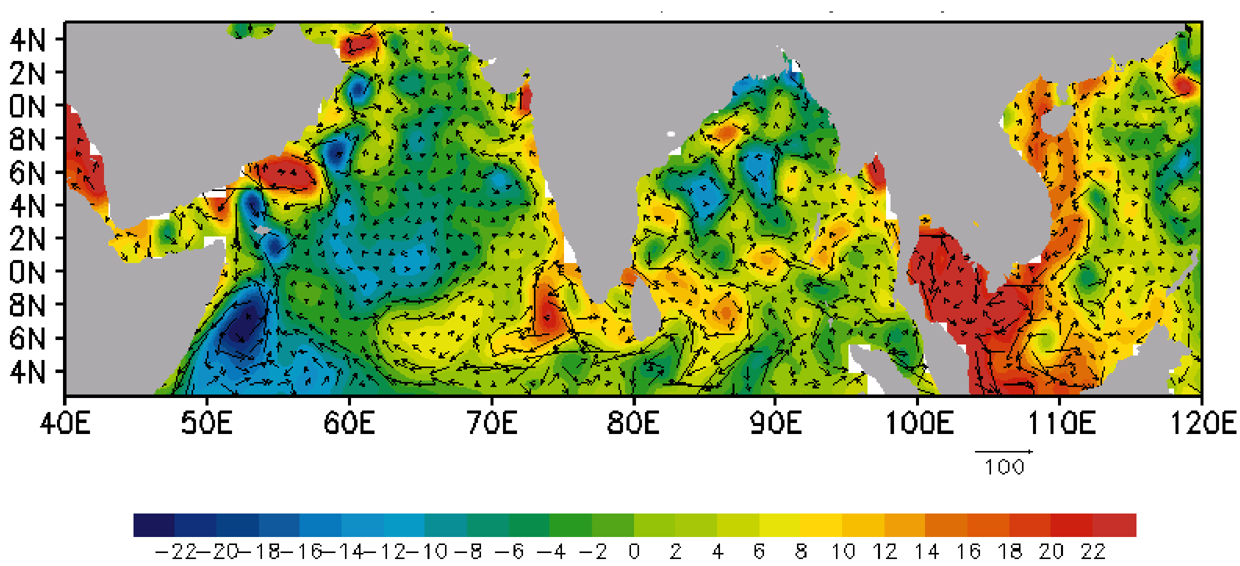

Figure 18: SSHA and geostrophic current of January 2010 in the north Indian Ocean.

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 (Figure 19).. The utility of such products can be seen in the study of productivity and ocean dynamics with the change in season

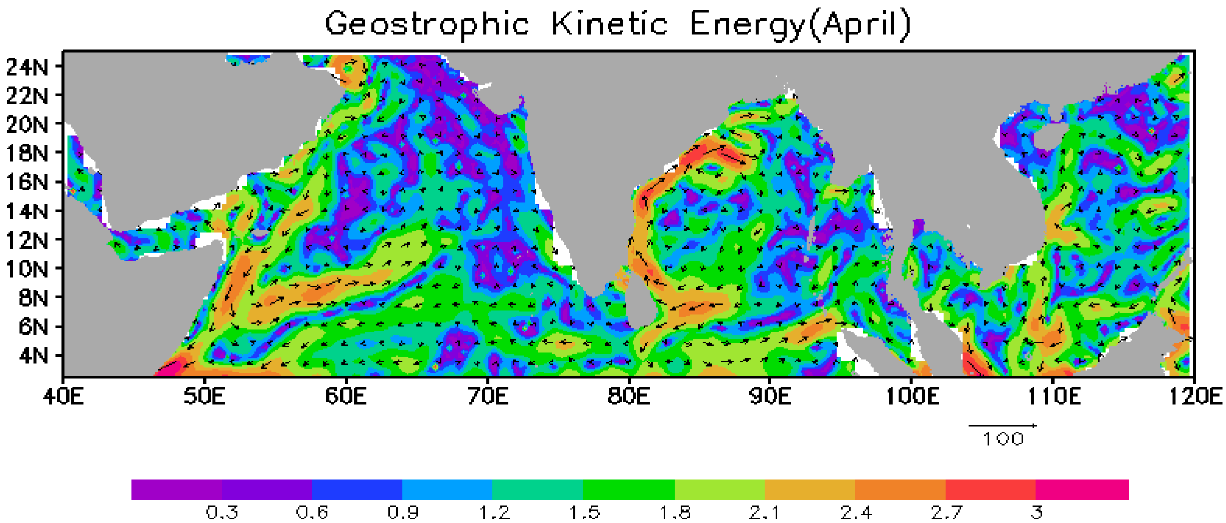

Figure 19: Fields of kinetic energy in April show boundary areas of strong geostrophic current.

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.

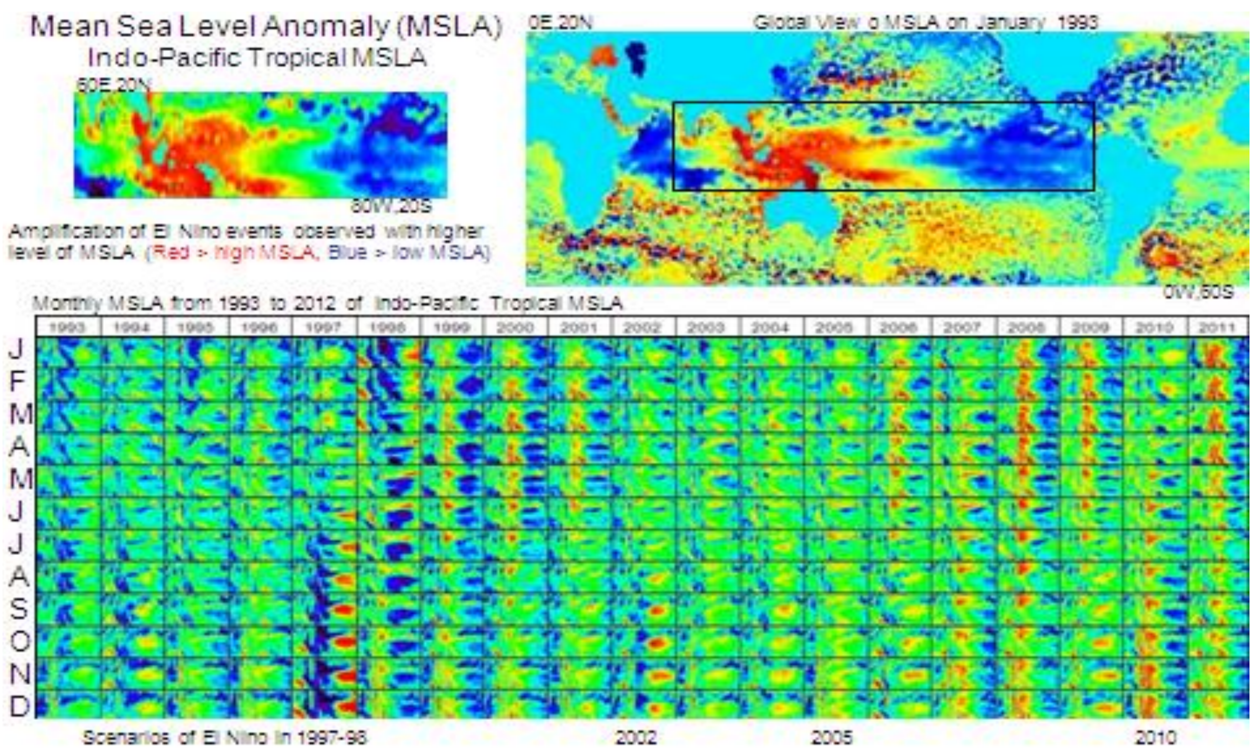

Figure 20: 1993-2011 MSLA show intense ocean surface dynamics corresponding climate change in equatorial waters of Indo-Pacific region.

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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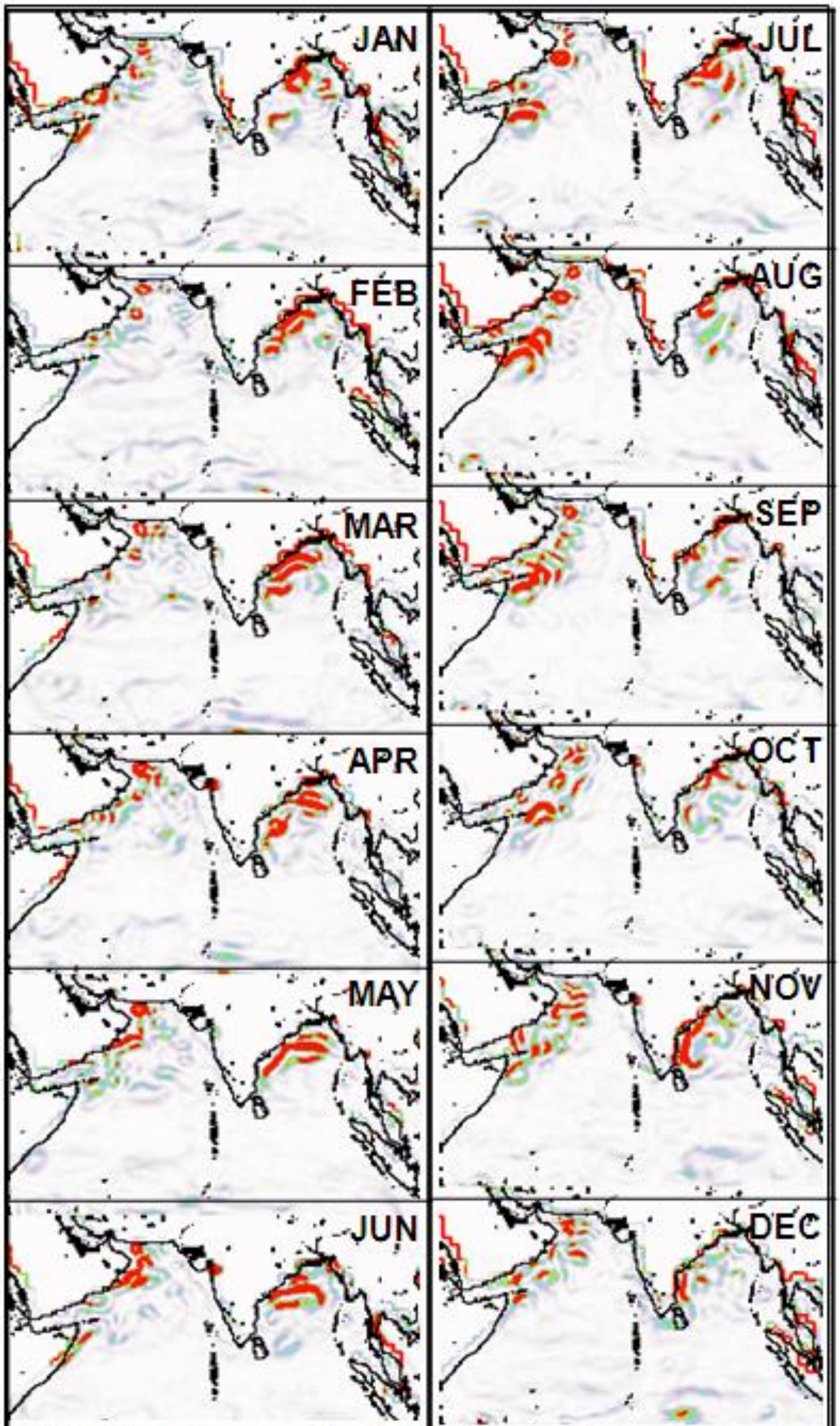
Meso-scale Eddies of the North Indian Ocean

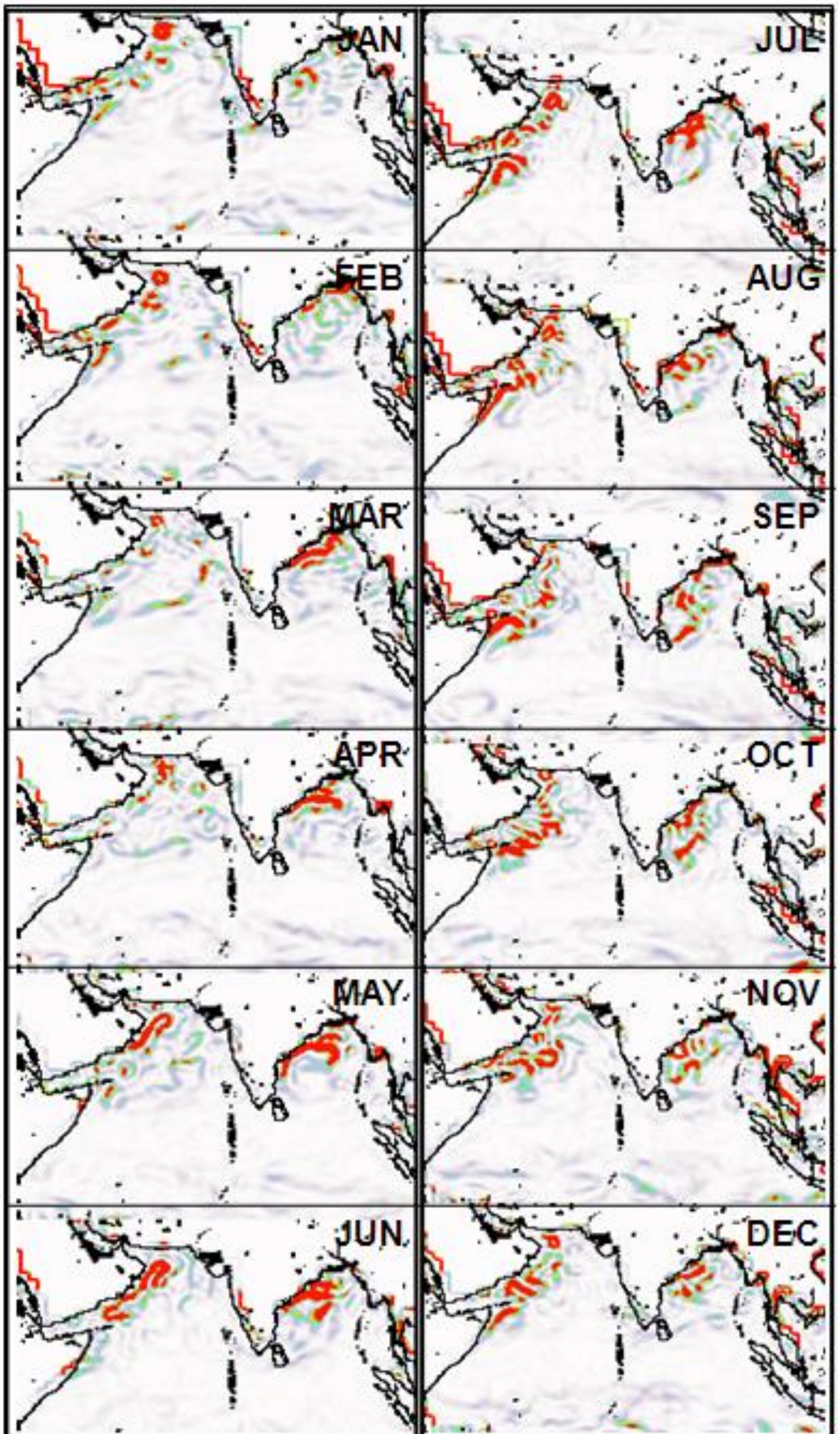
Monthly Eddy Kinetic Energy

Showing boundary of meso-scale eddies

From year 1993 to 2011



High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
1993



High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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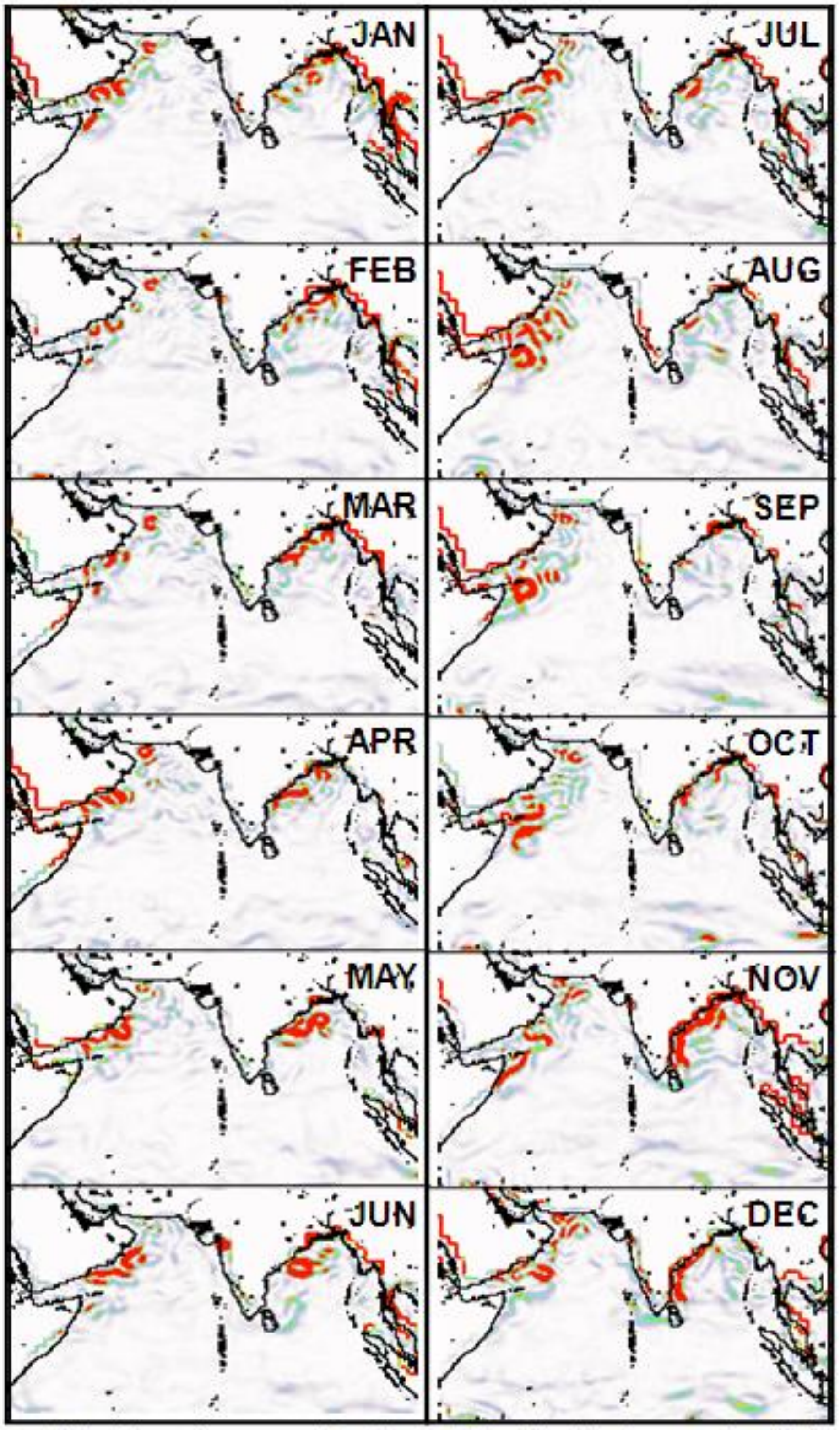

High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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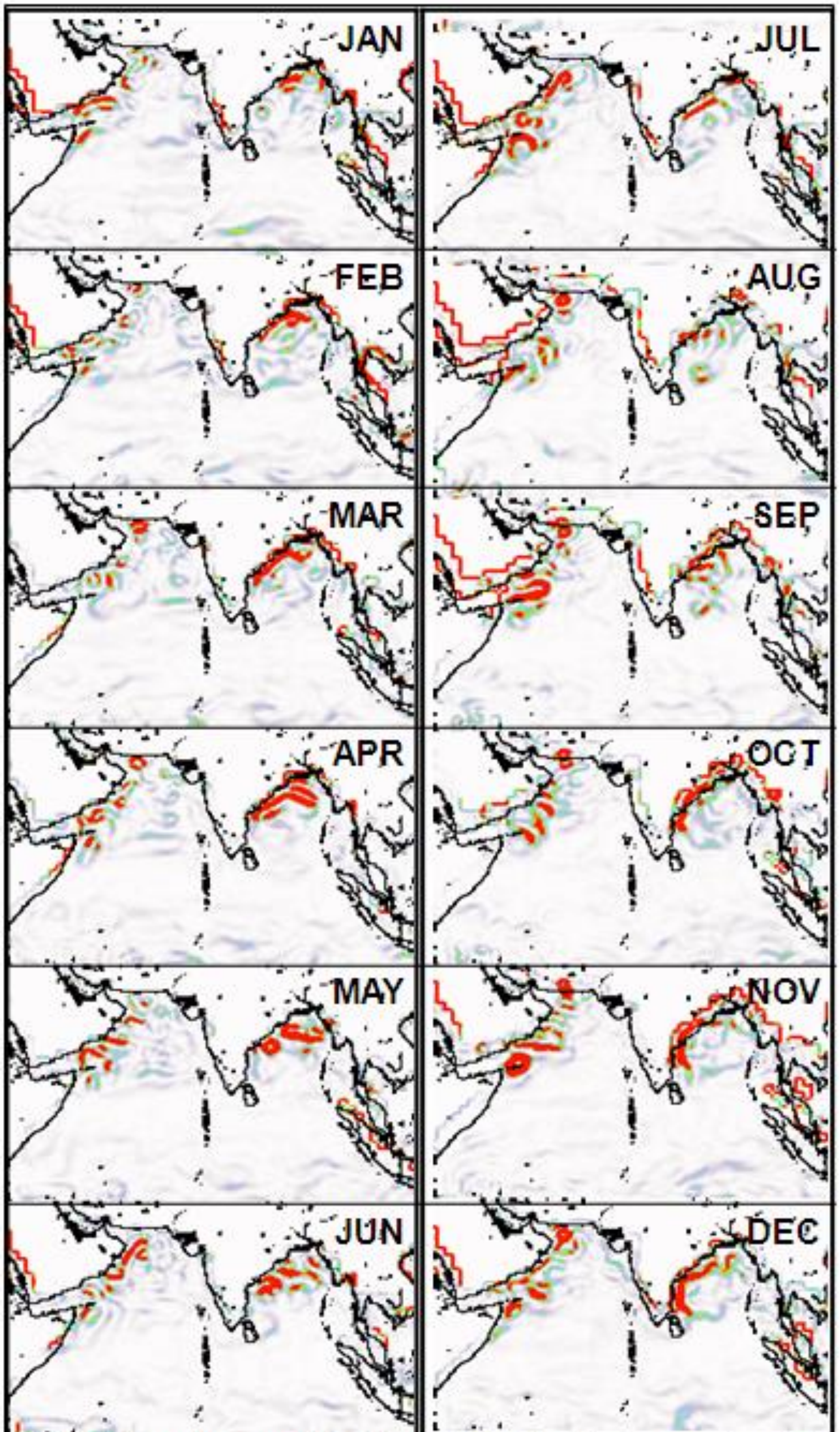

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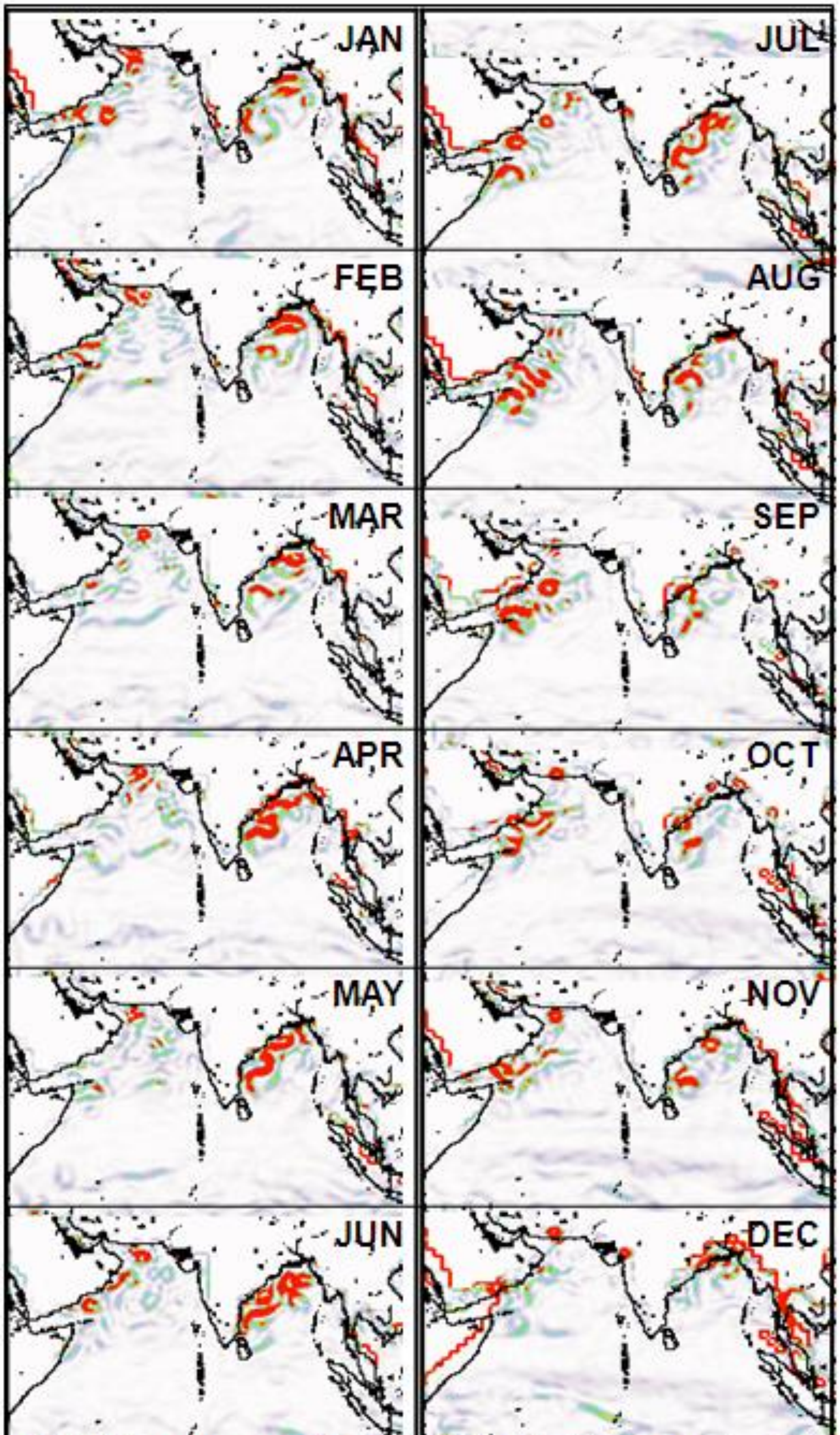

High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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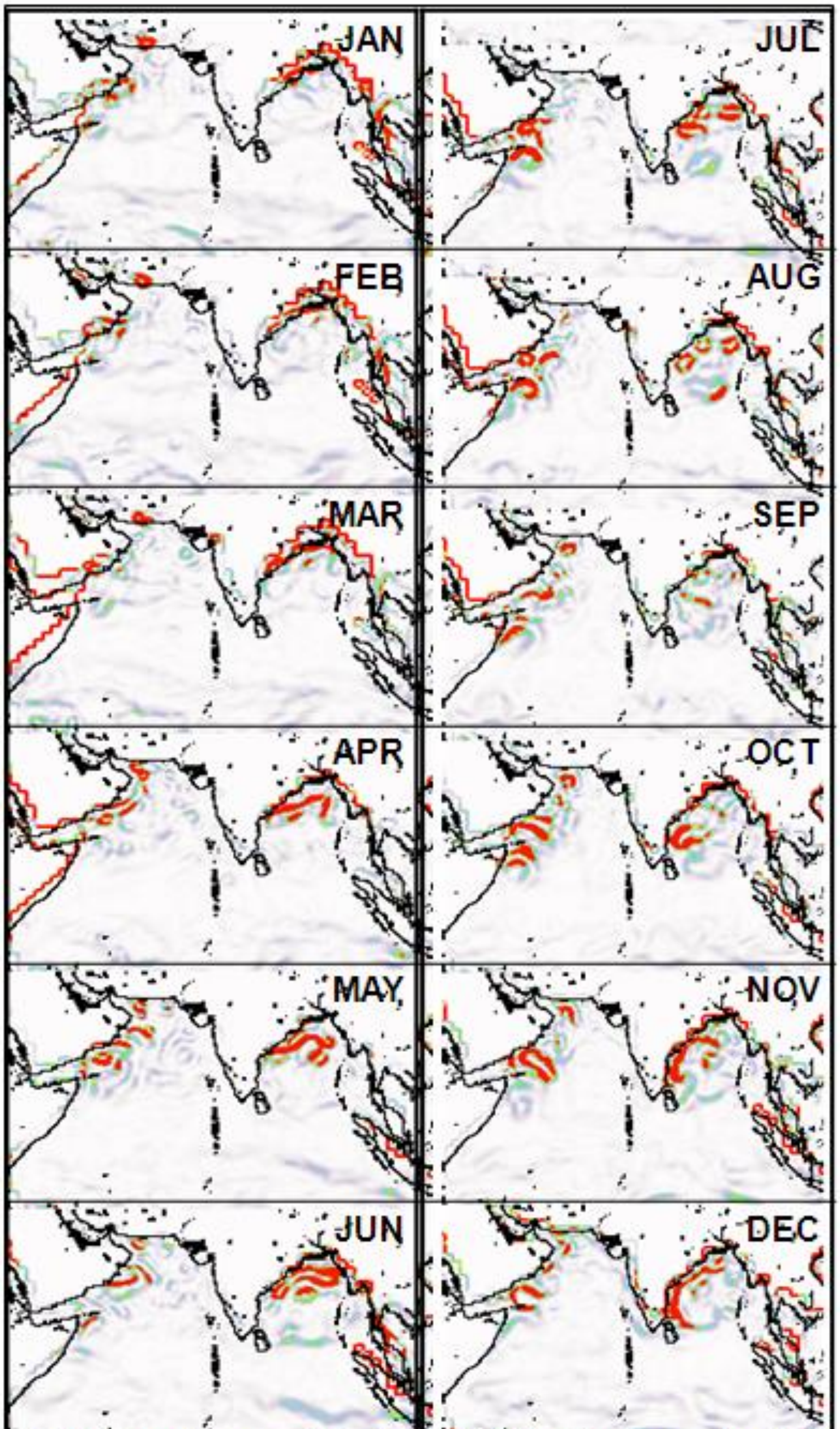

High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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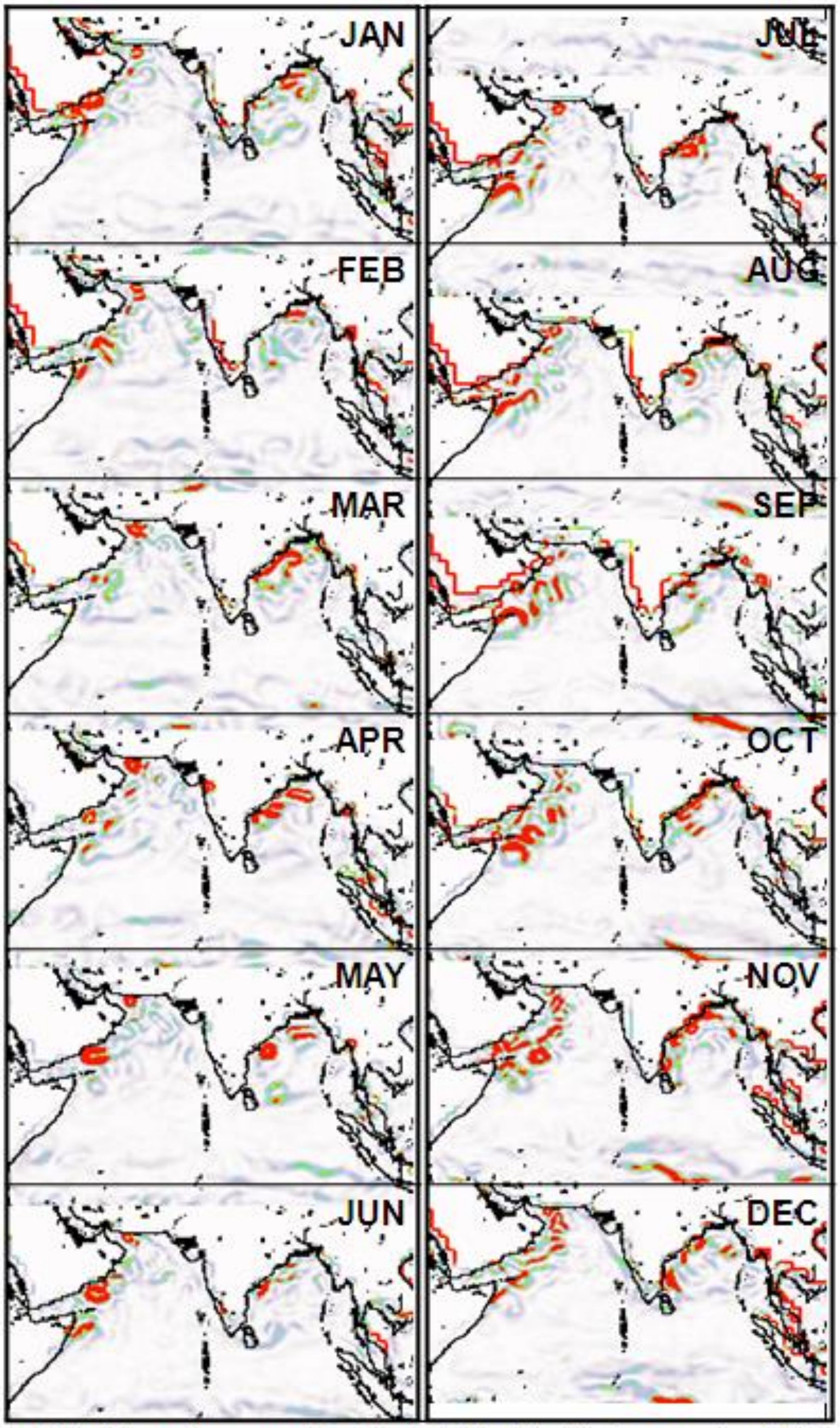

High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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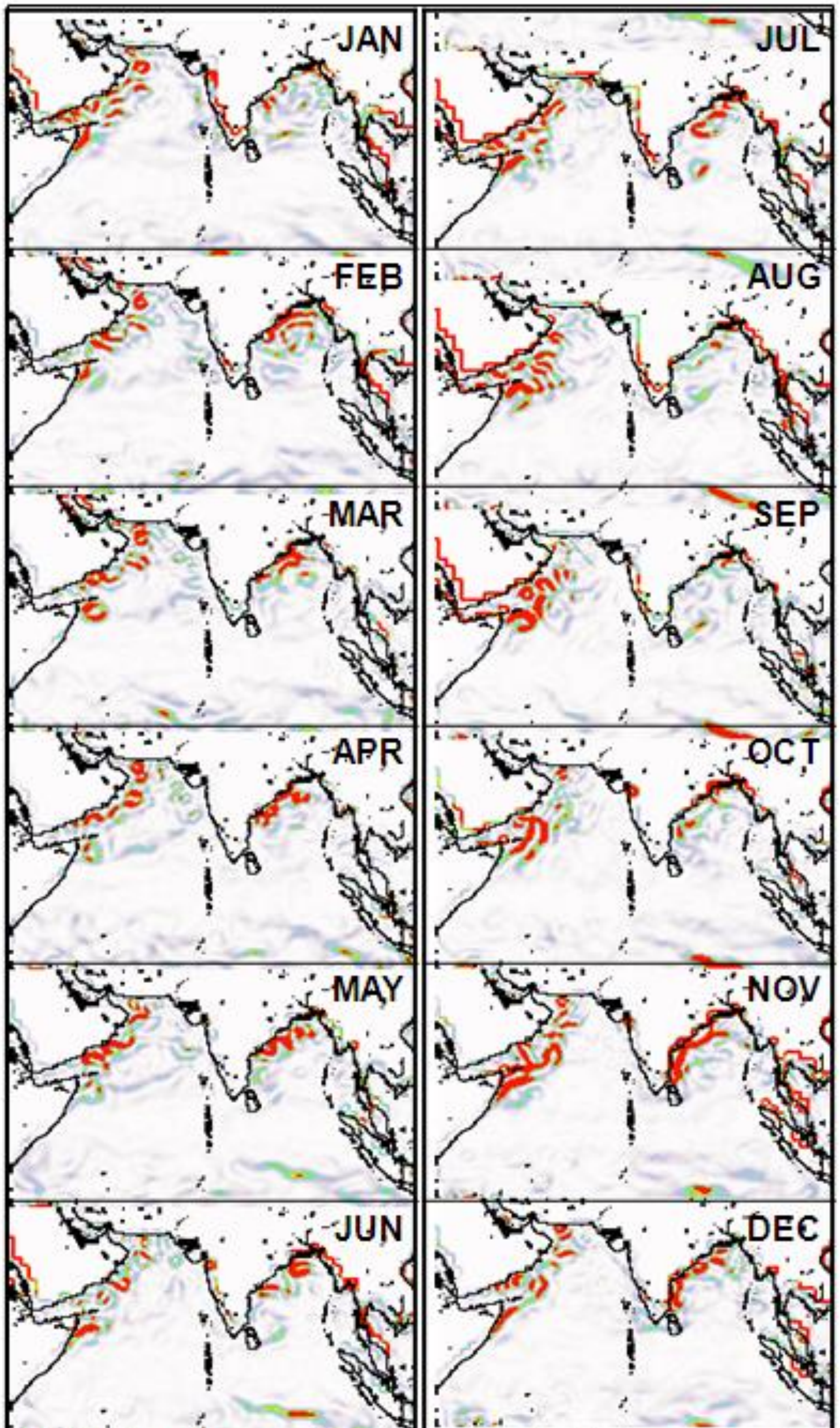

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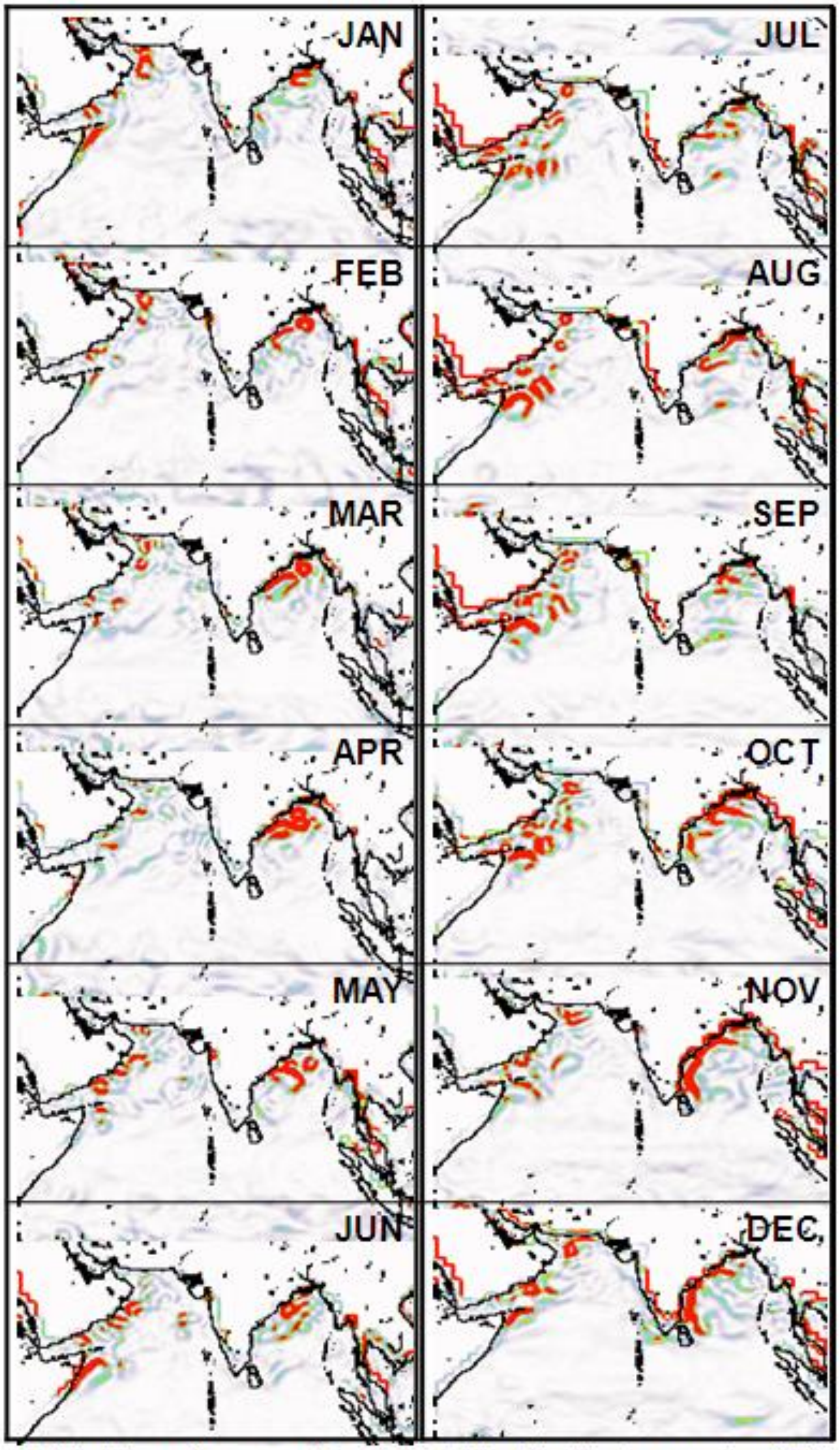

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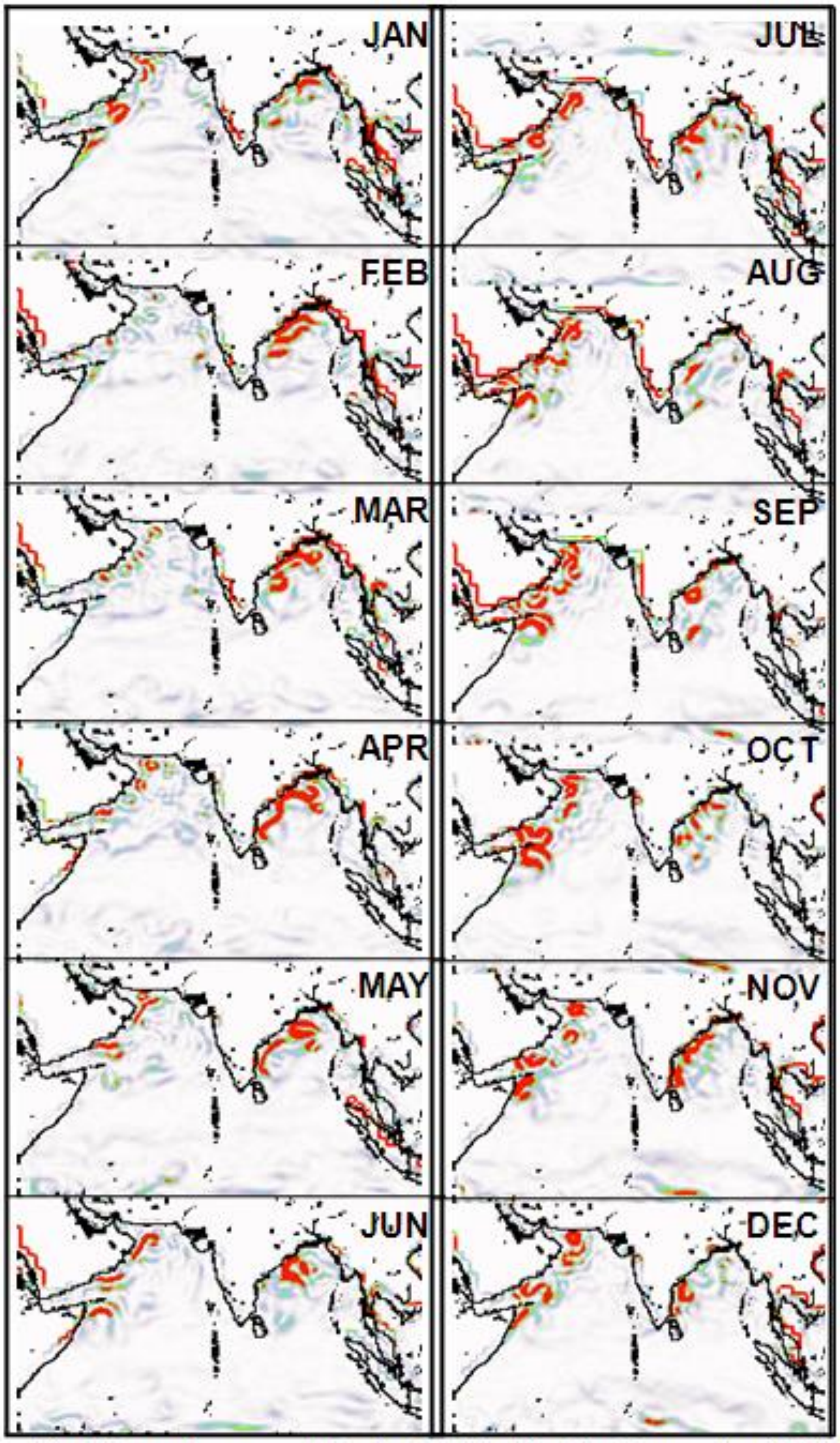

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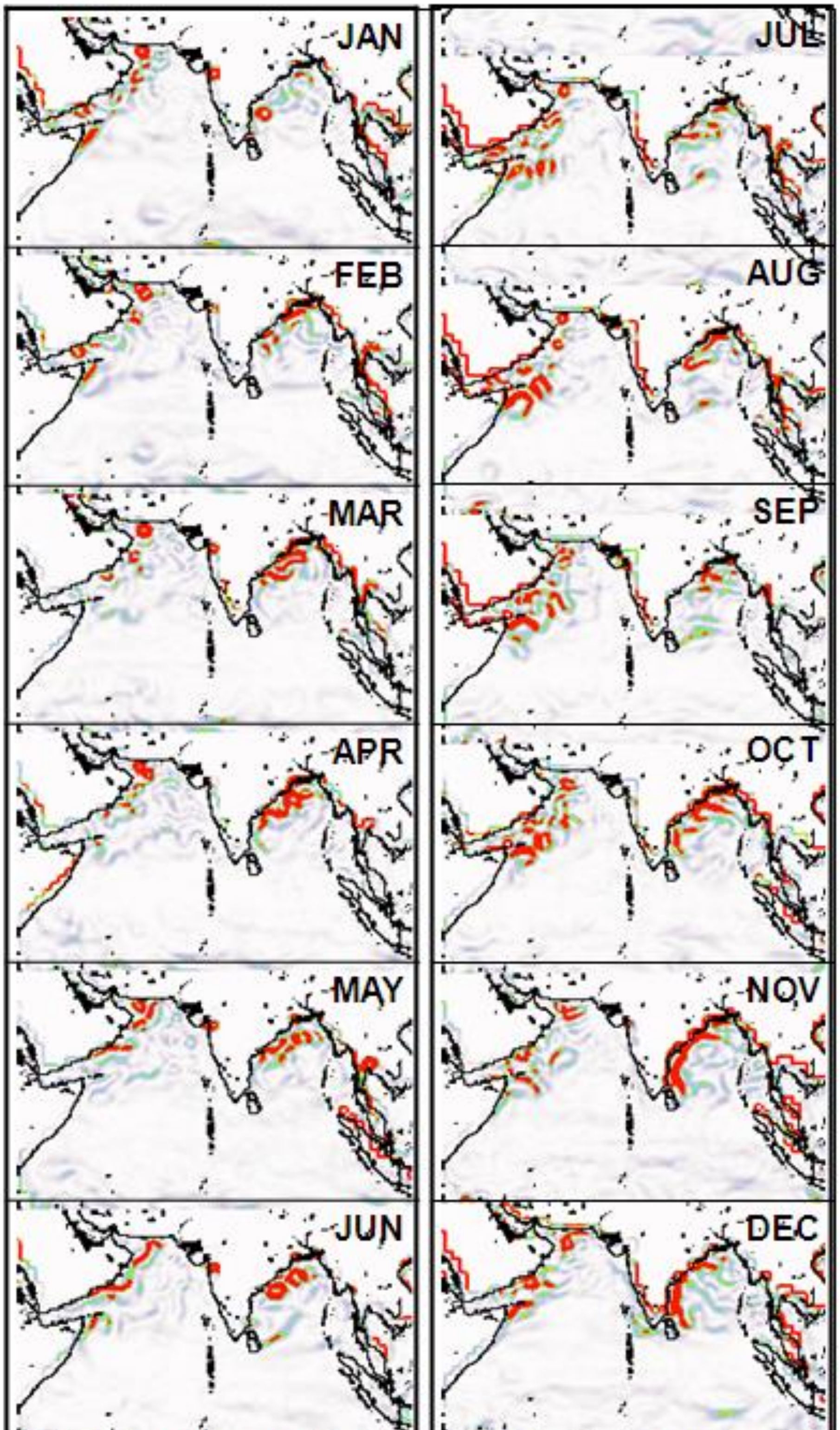
2002



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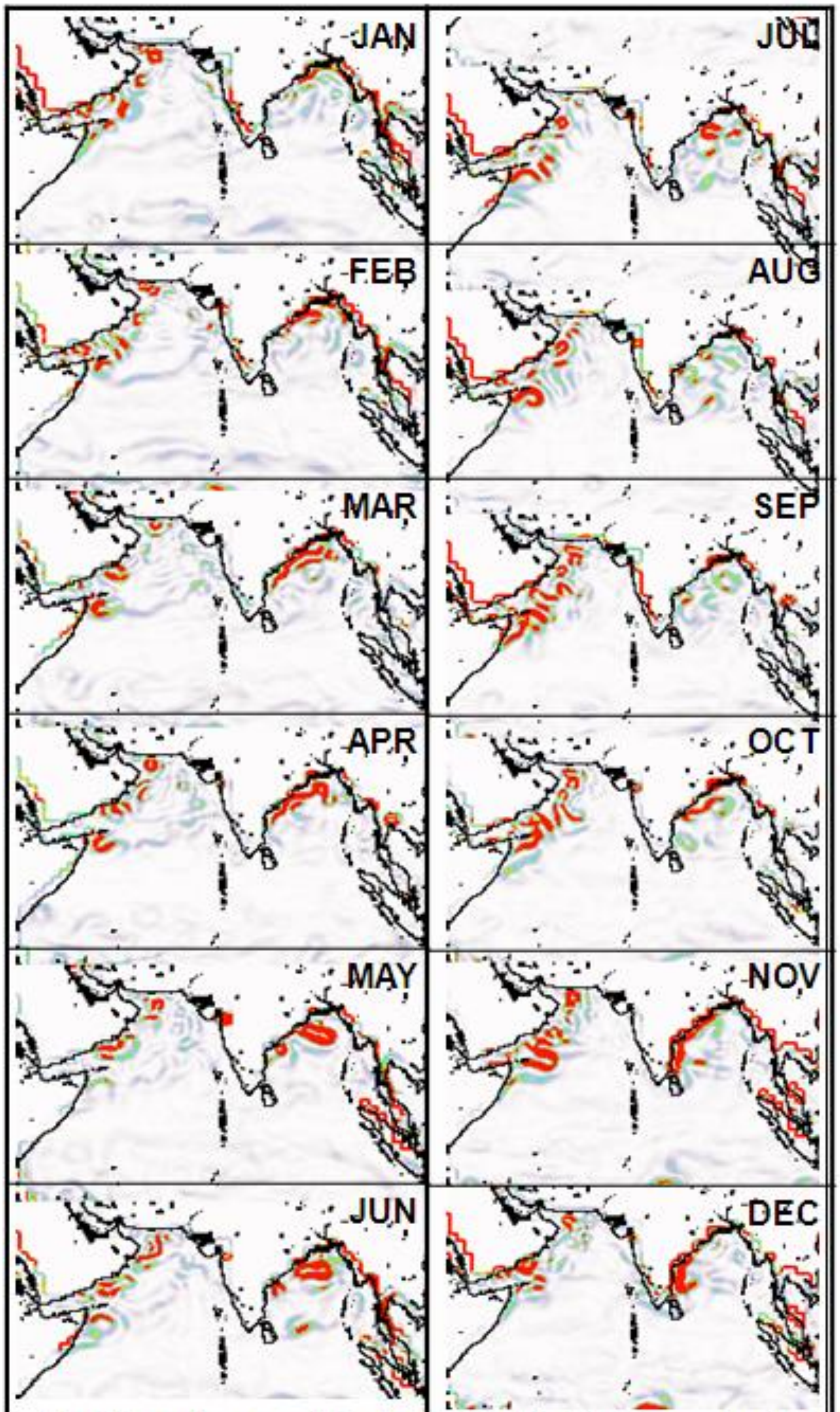

High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
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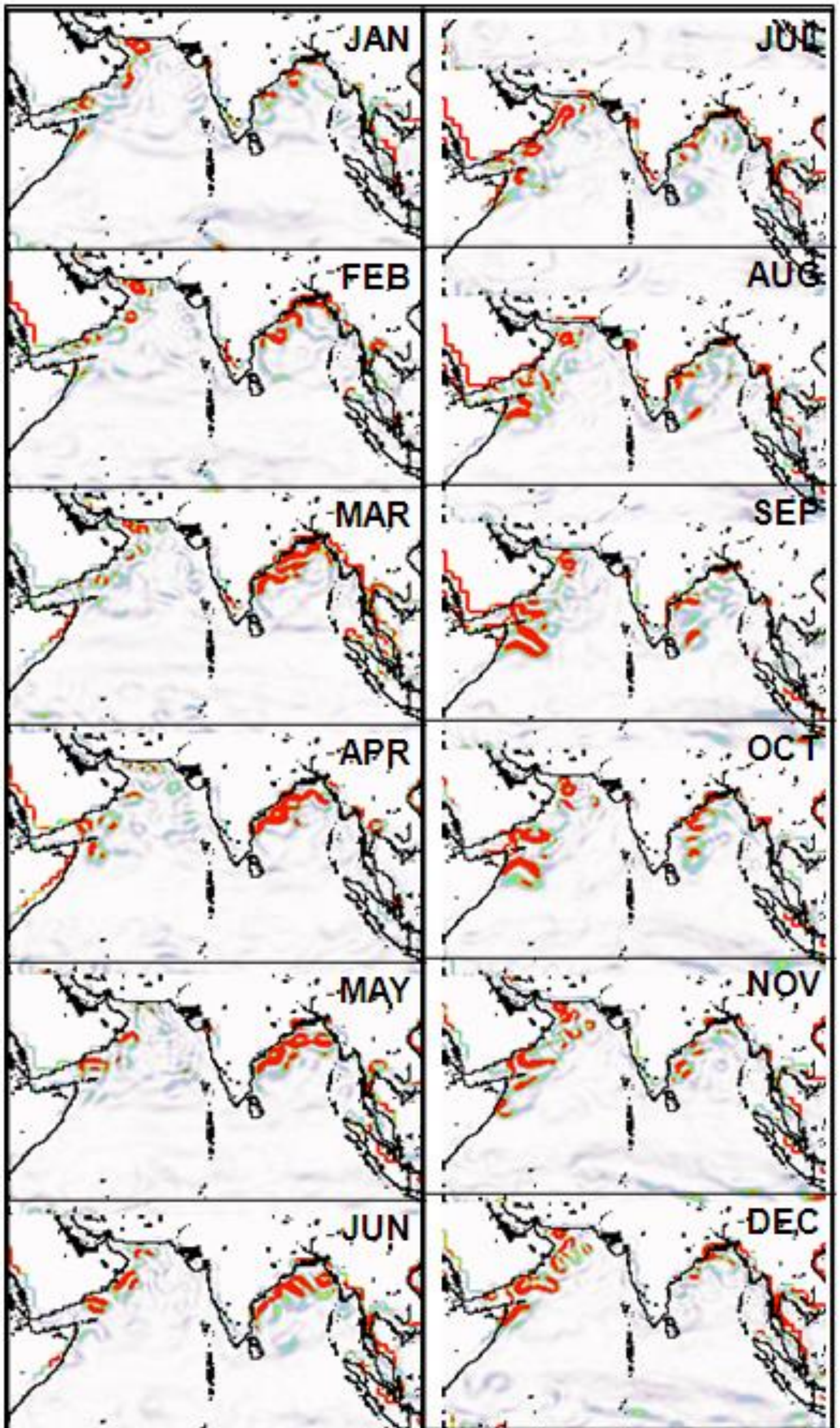

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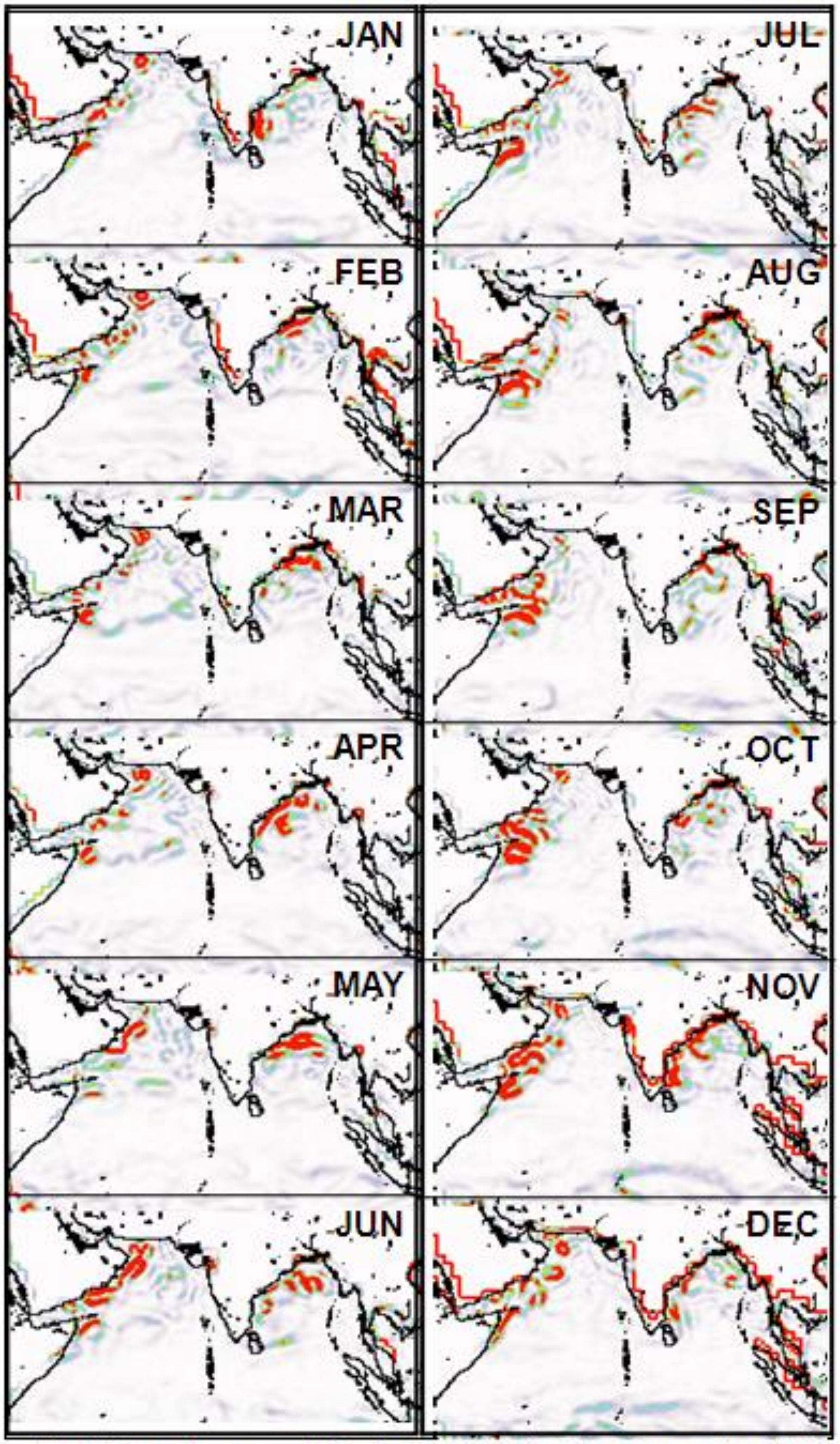
2005



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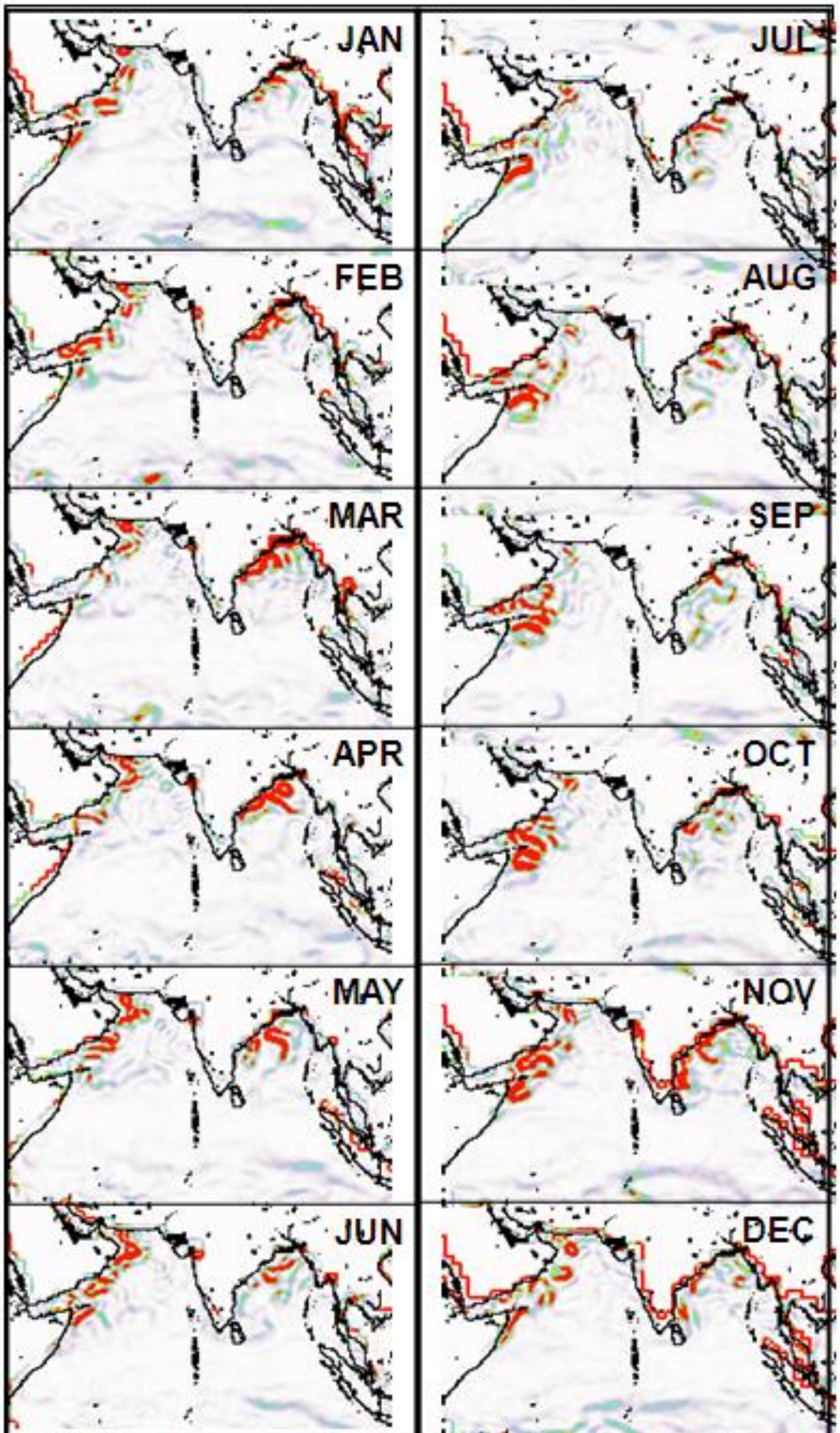
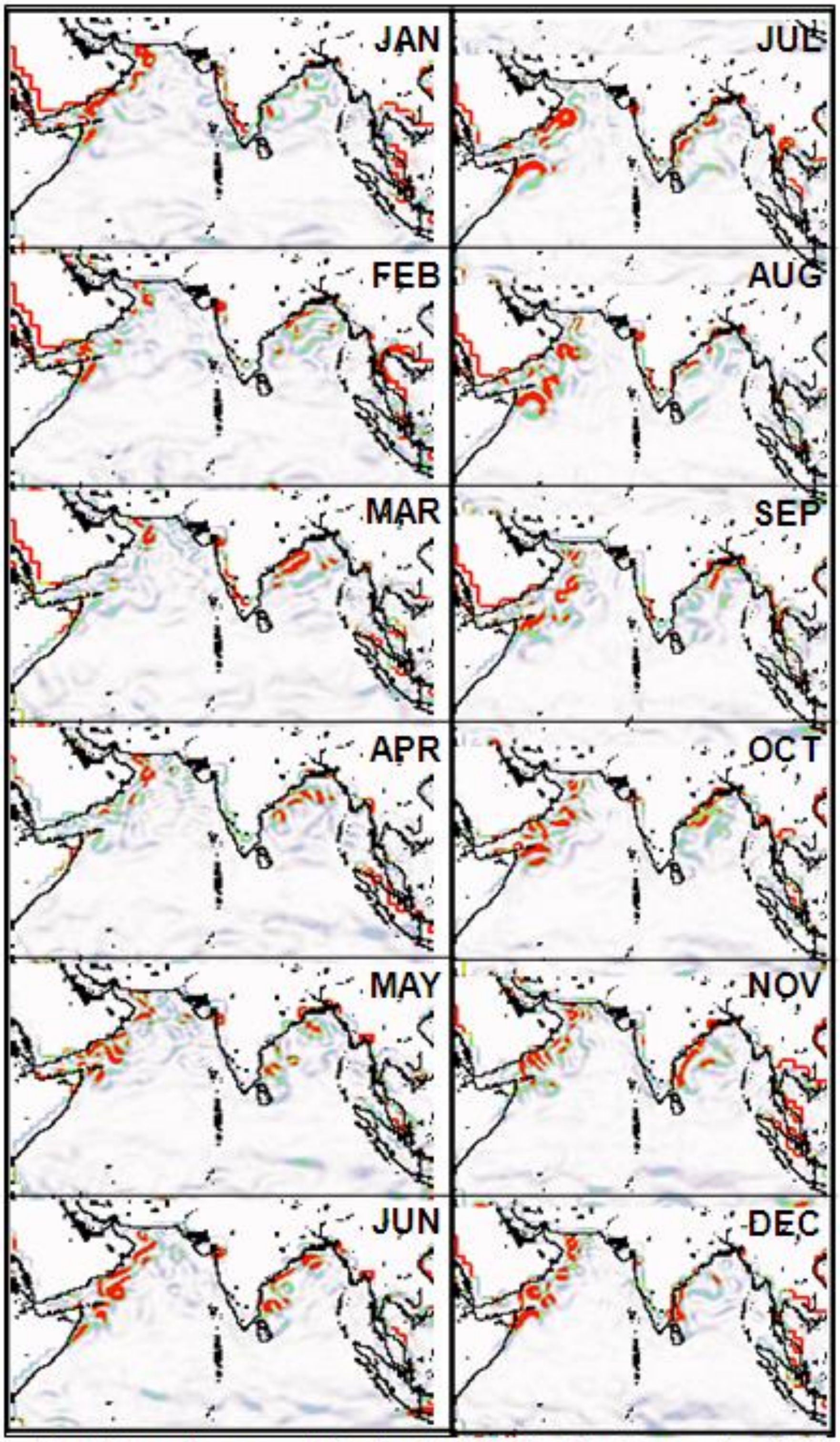
2006



High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
2007



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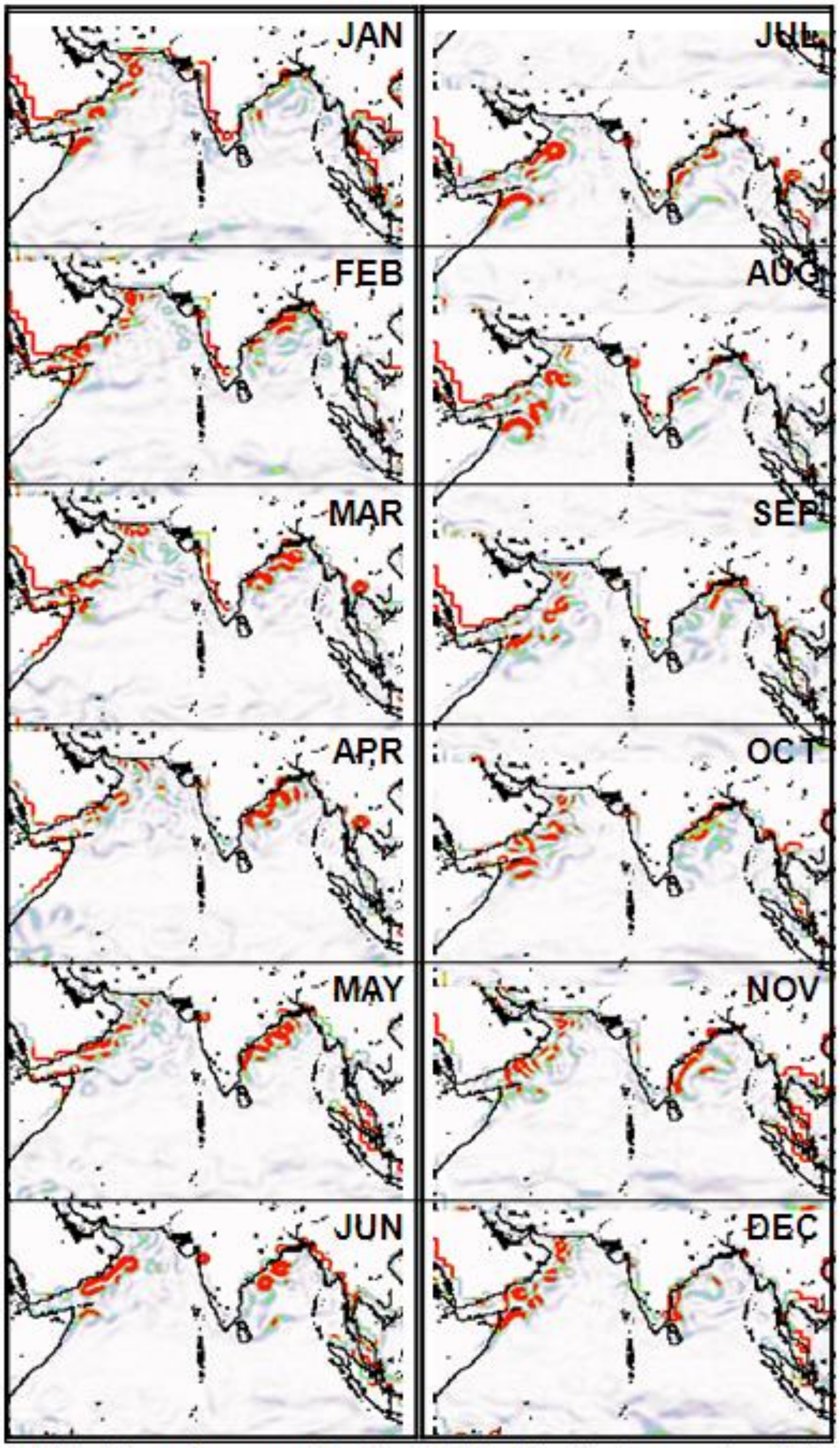
2008



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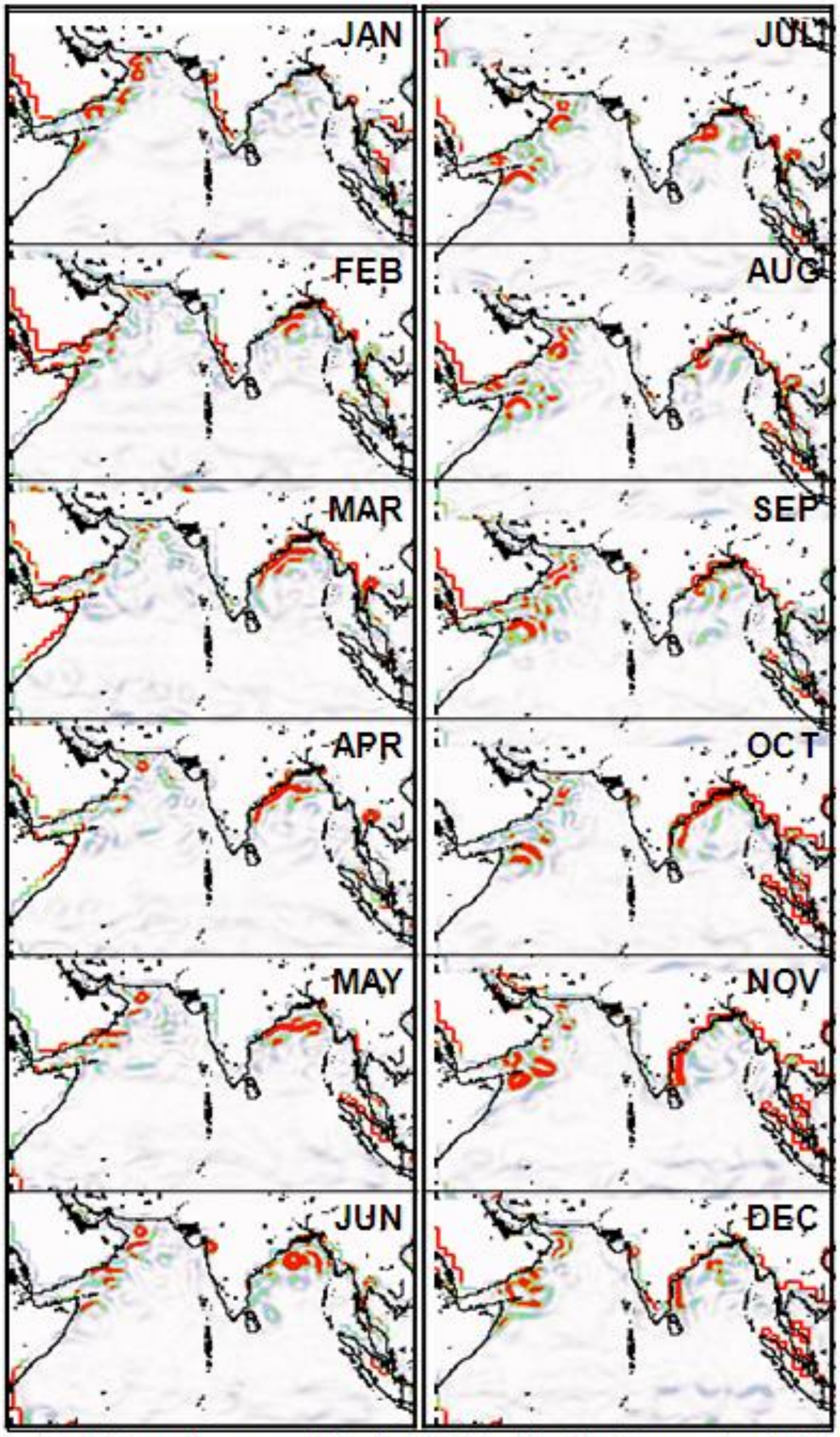
2009



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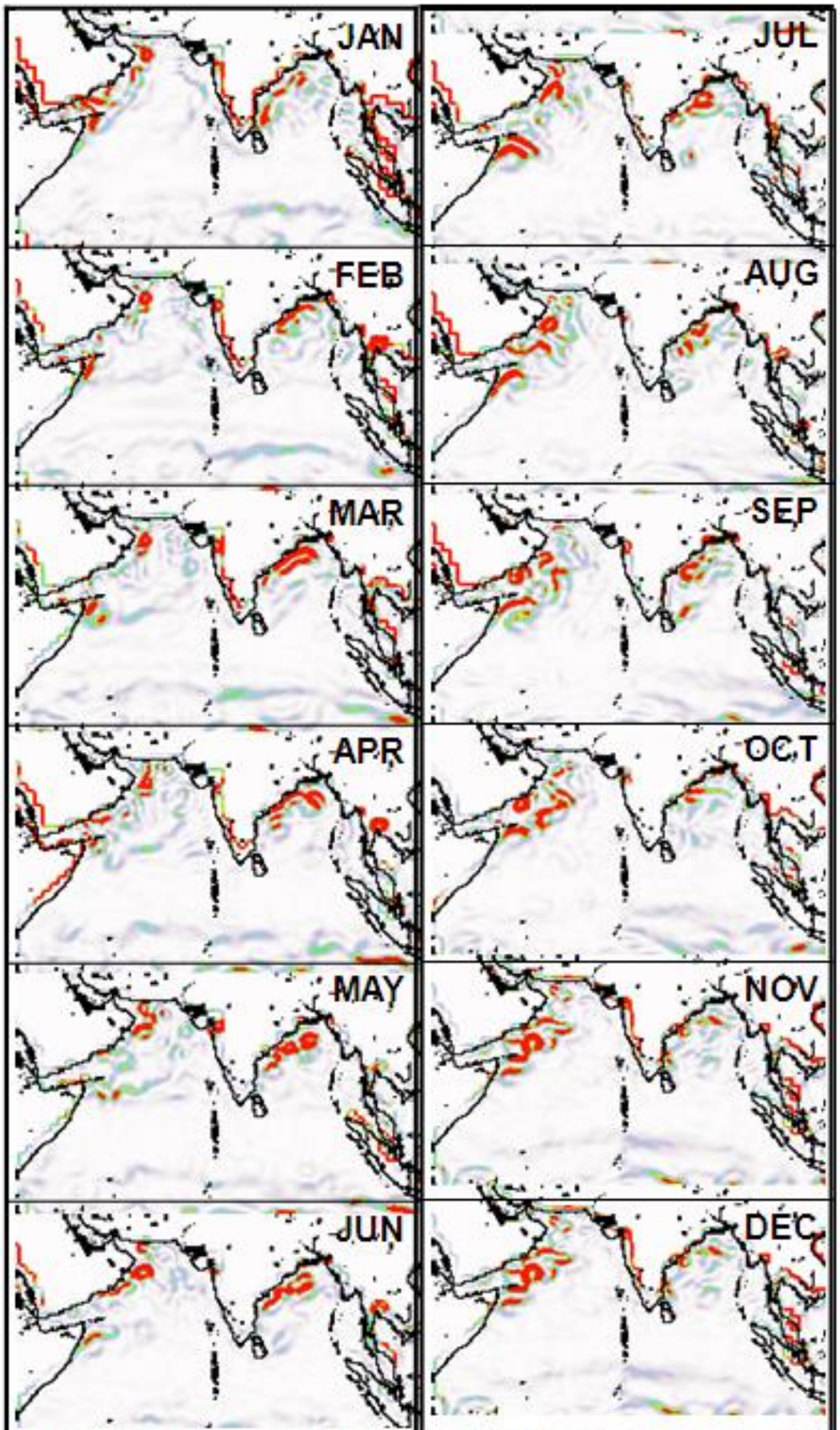
2010

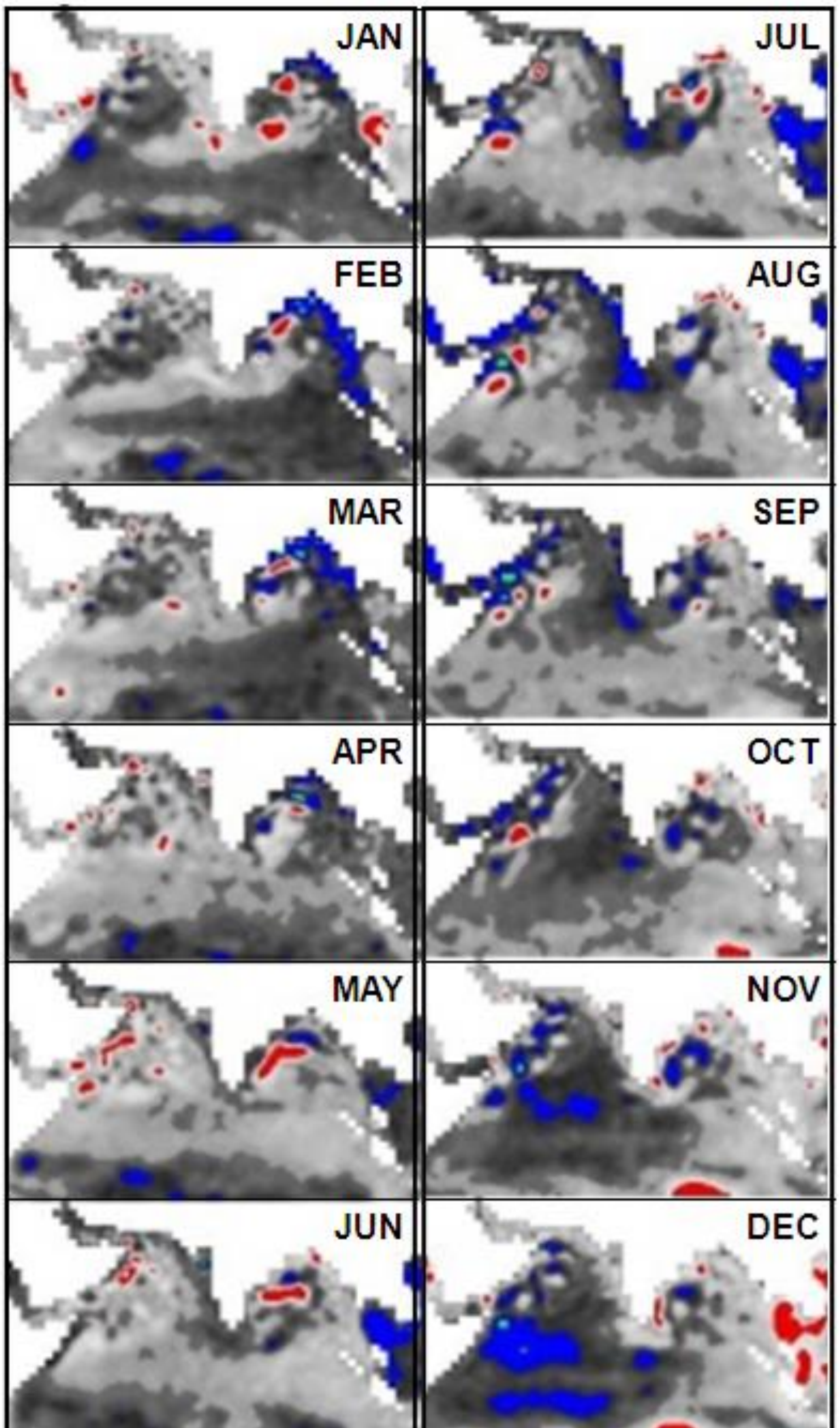


High intensity areas (Red) of Eddy Kinetic Energy (cm^2/s^2)
2011

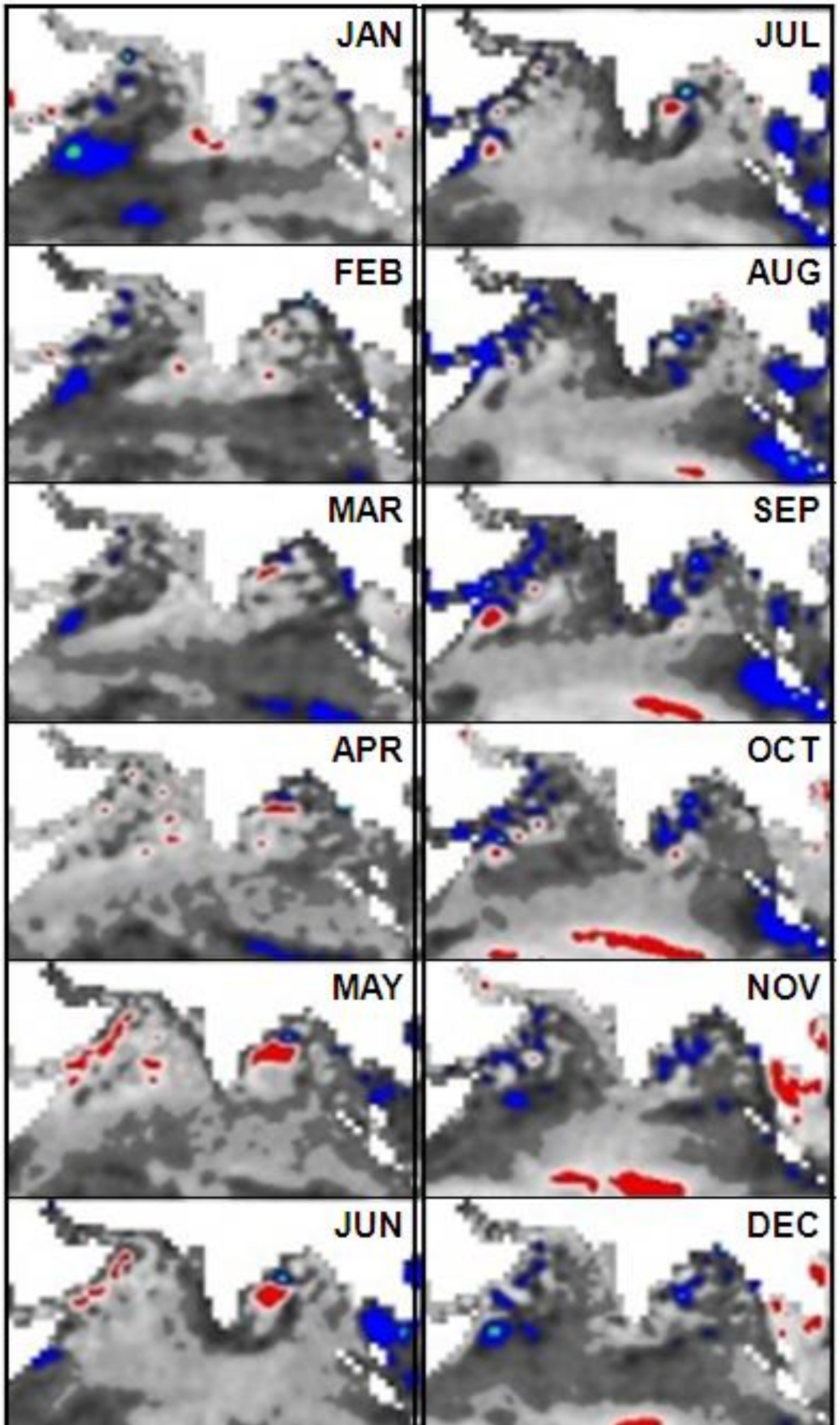
Monthly Sea Level Anomaly

Showing warm and cold core eddies

From year 1993 to 2011



Eddies of cold core (Blue) & warm core (Red) area
1993



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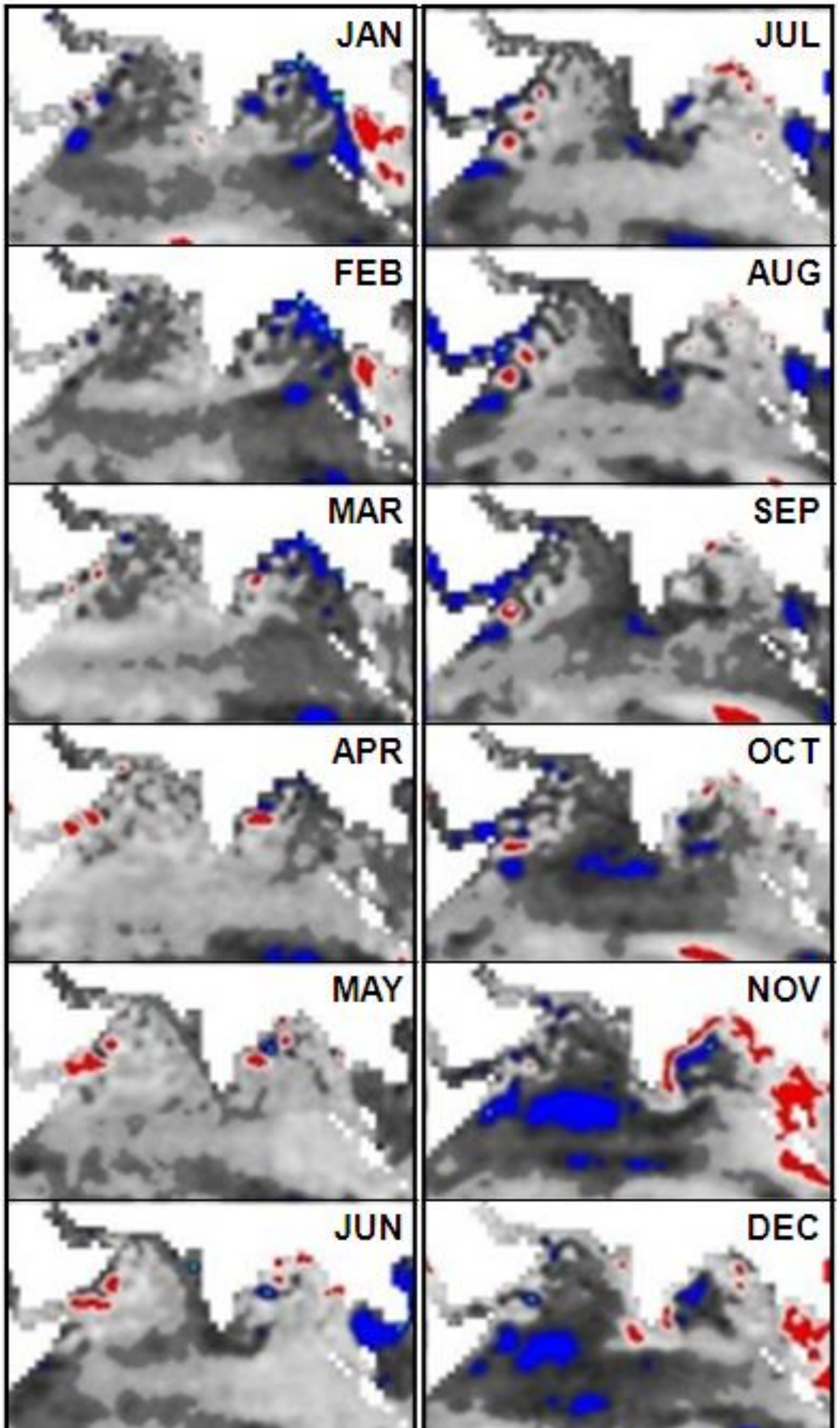
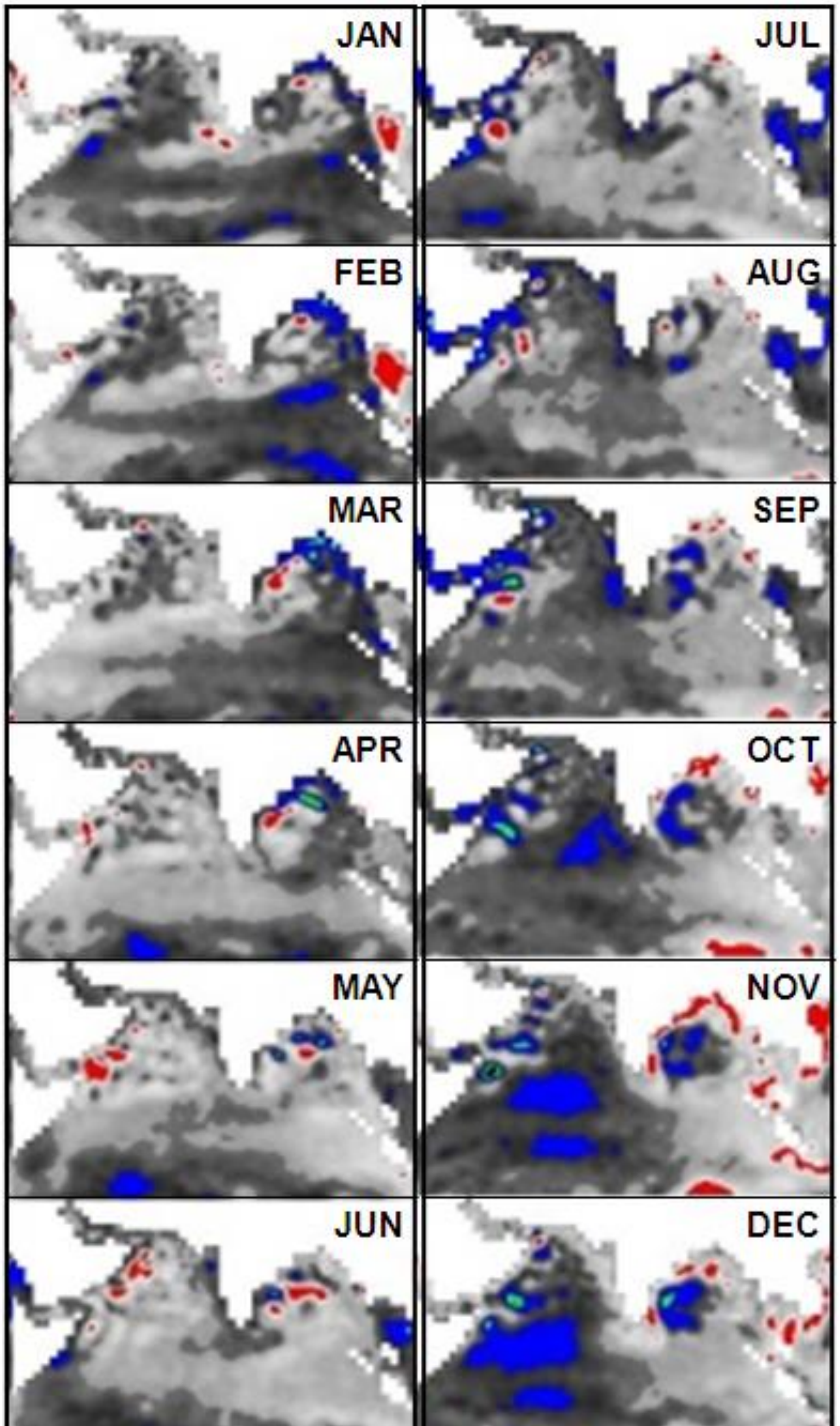
1994



Eddies of cold core (Blue) & warm core (Red) area
1995



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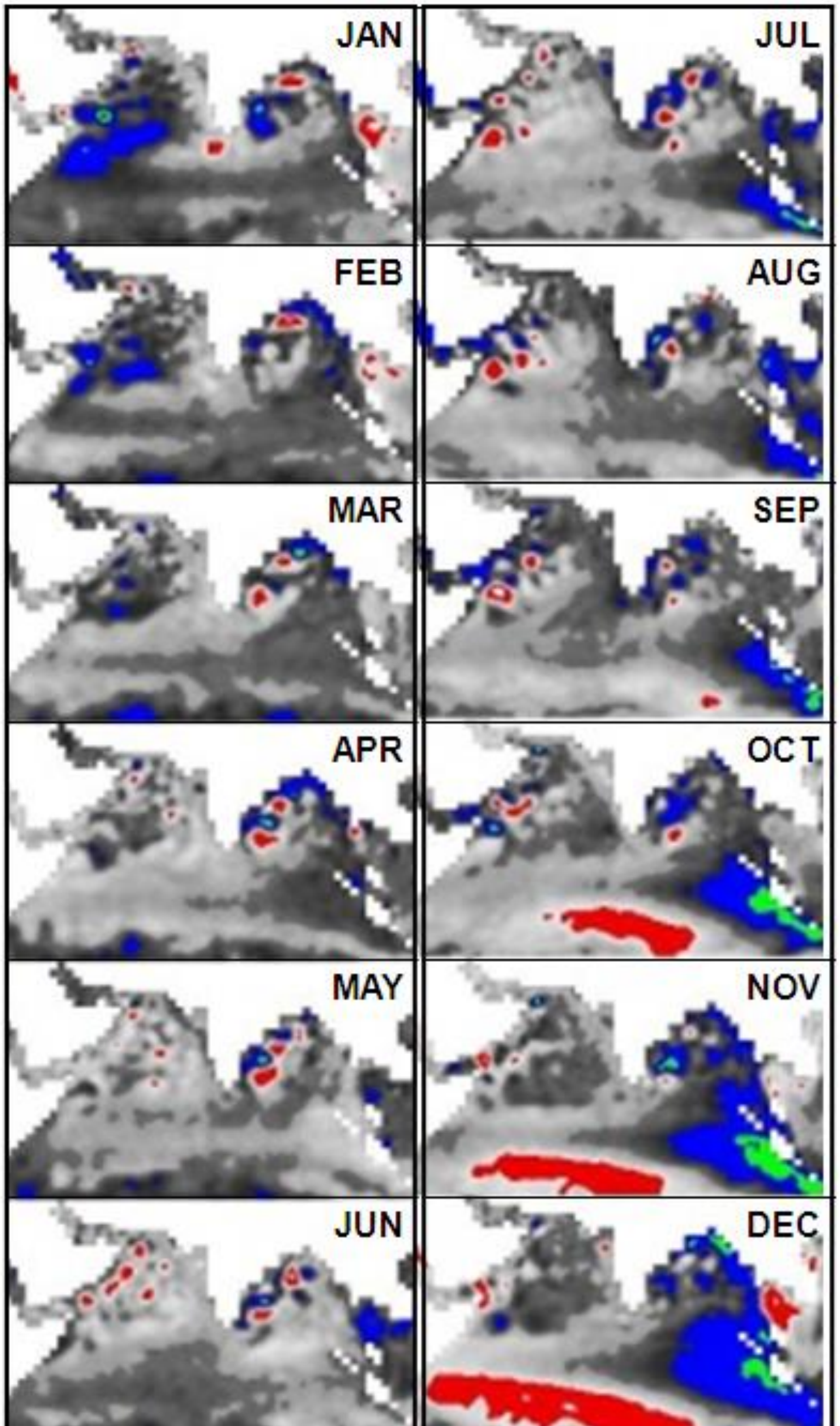
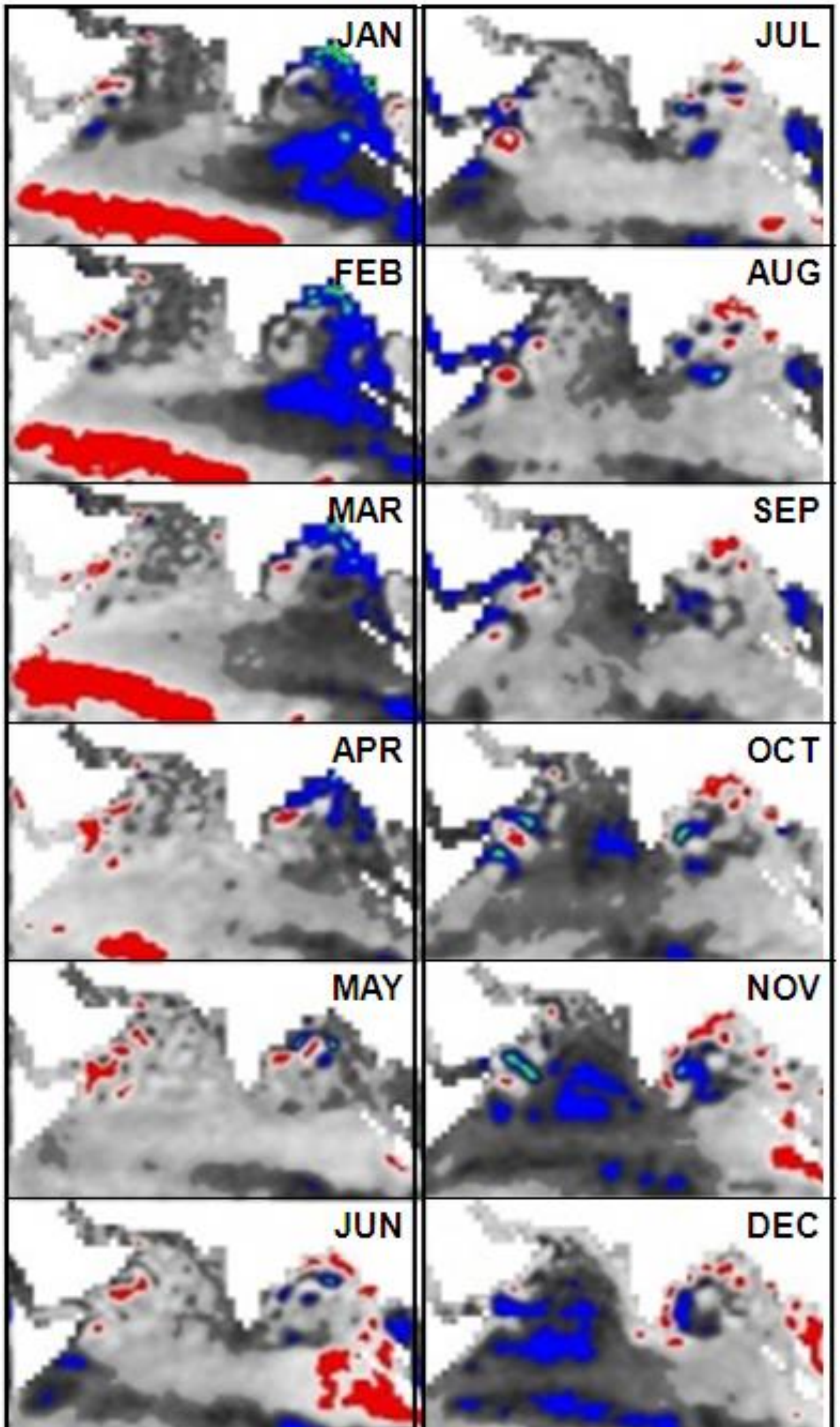
1996



Eddies of cold core (Blue) & warm core (Red) area
1997



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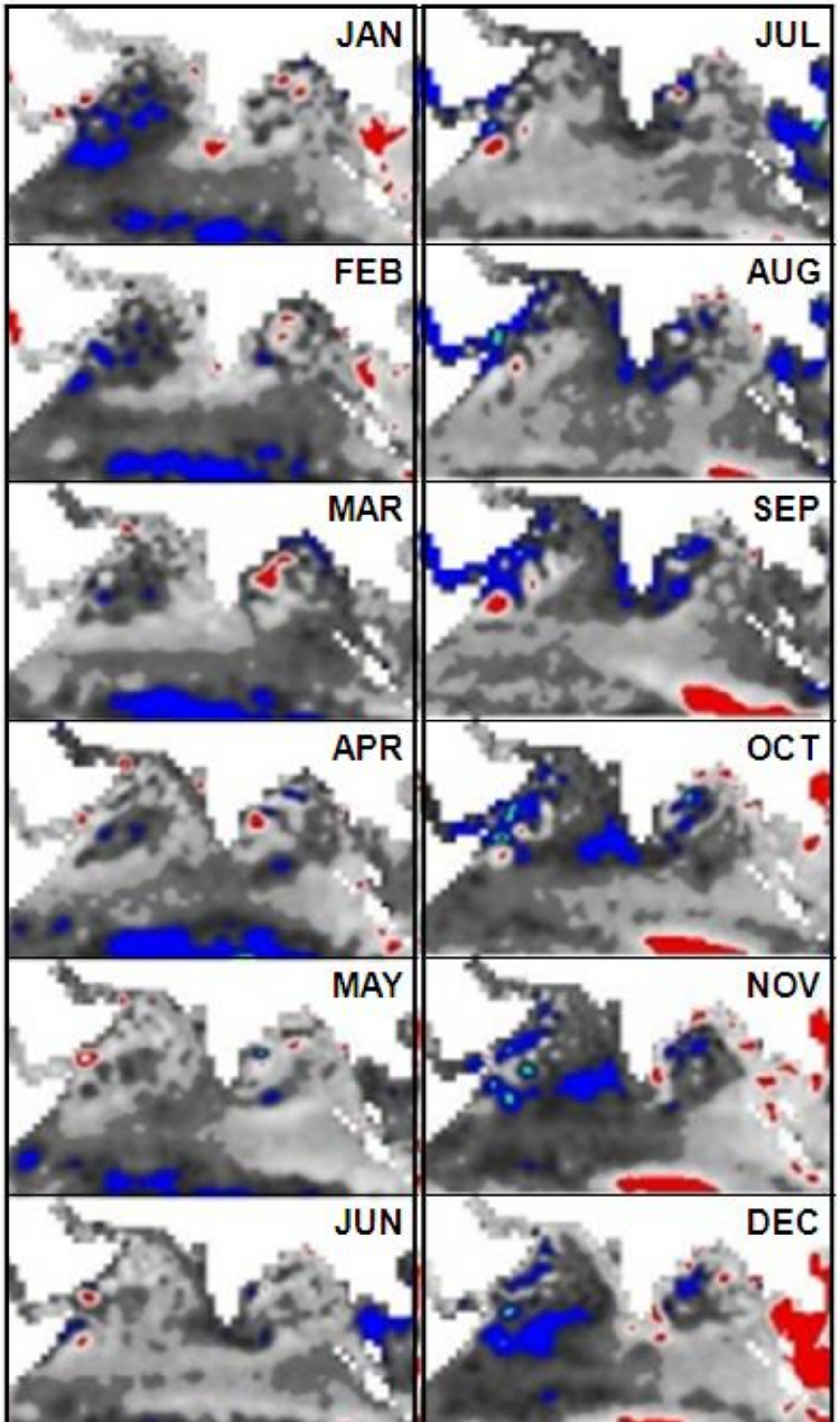
1998



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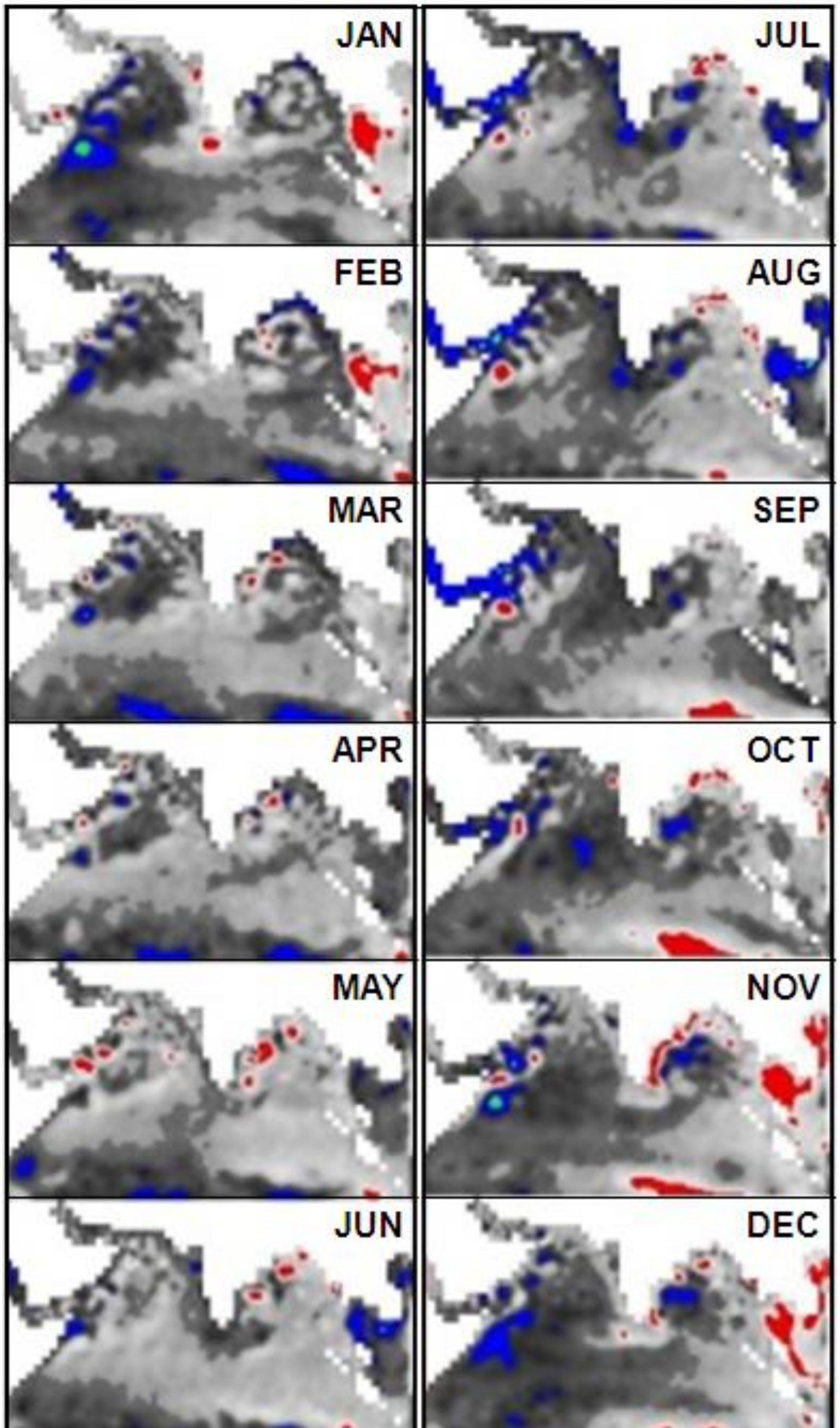

Eddies of cold core (Blue) & warm core (Red) area
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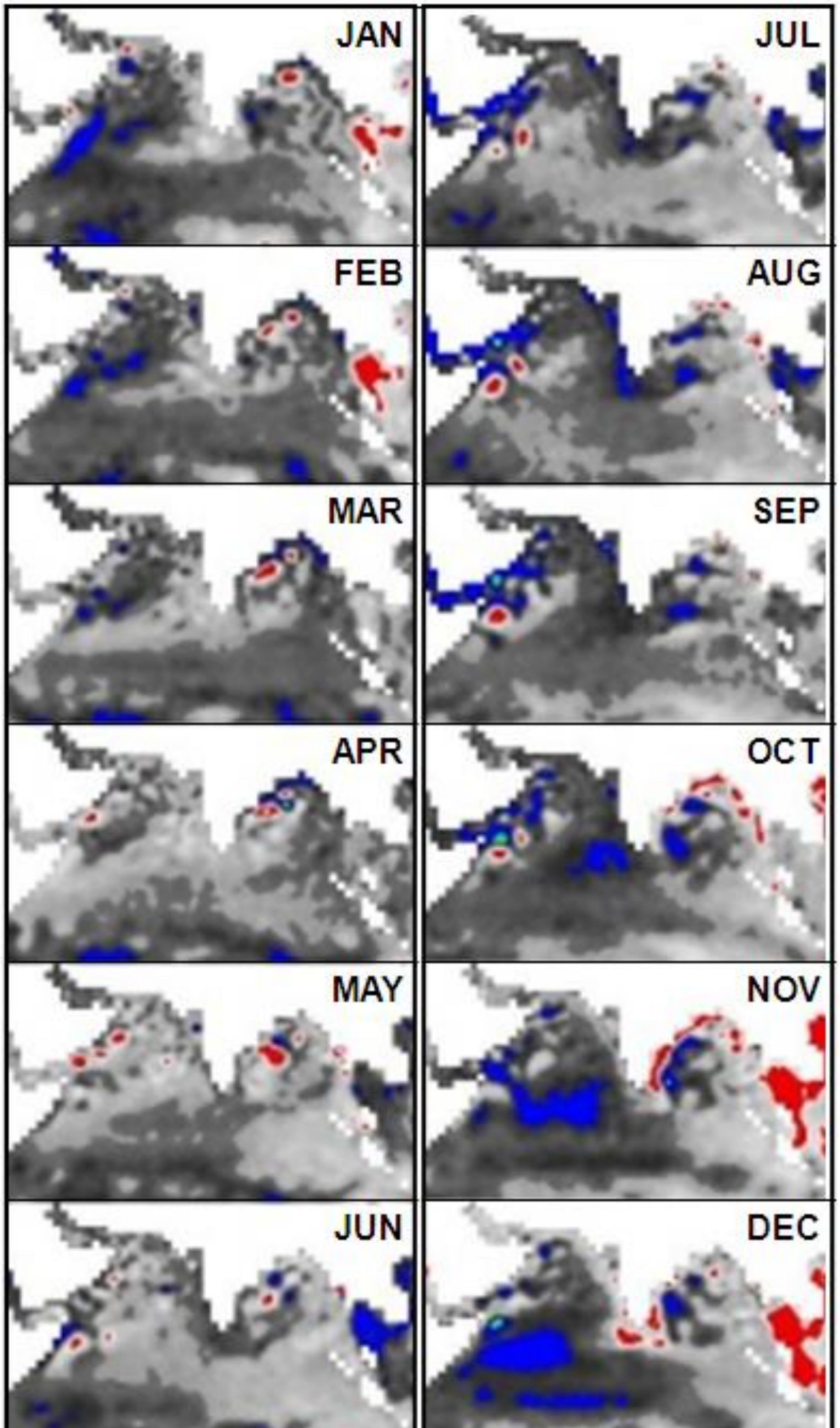

Eddies of cold core (Blue) & warm core (Red) area
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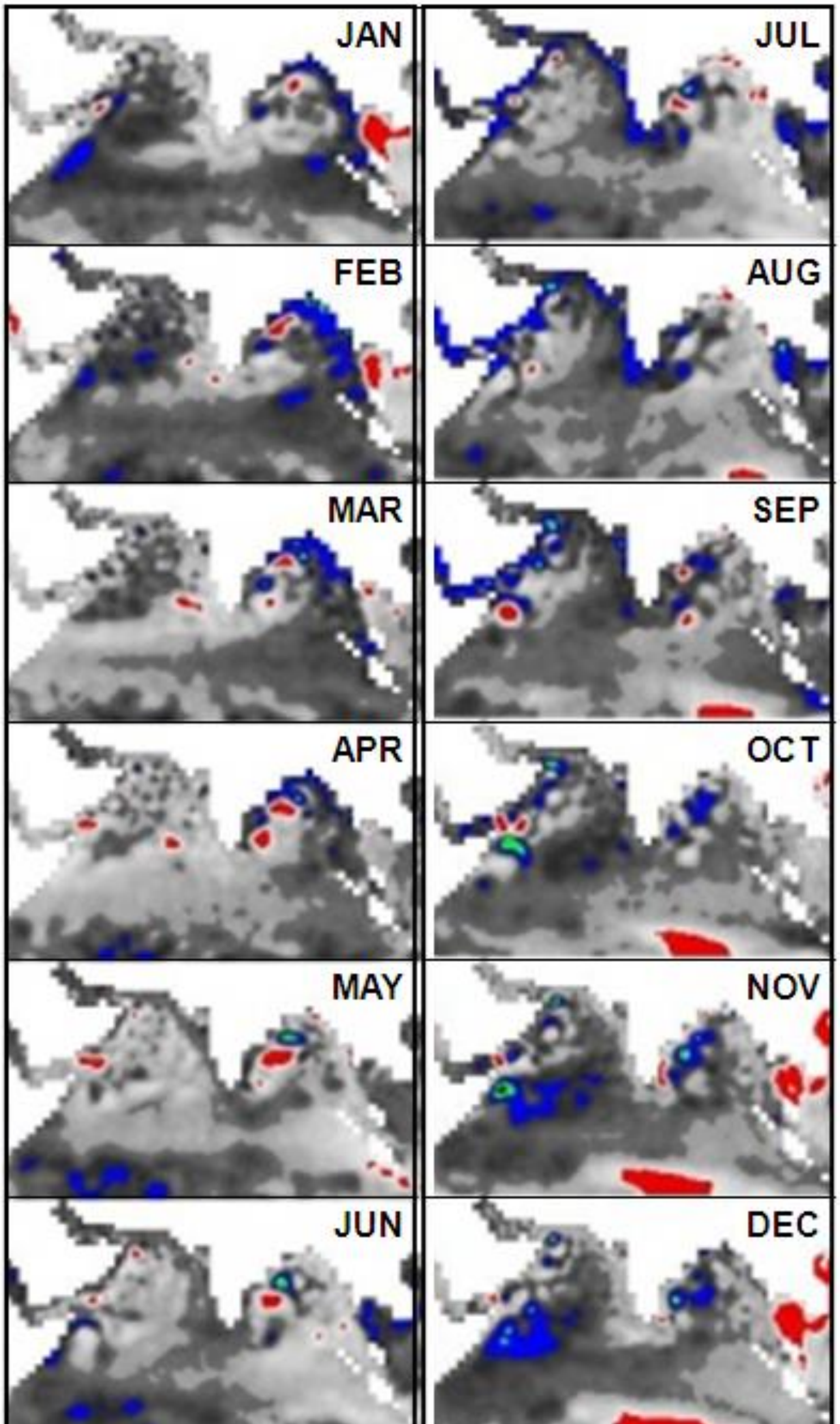

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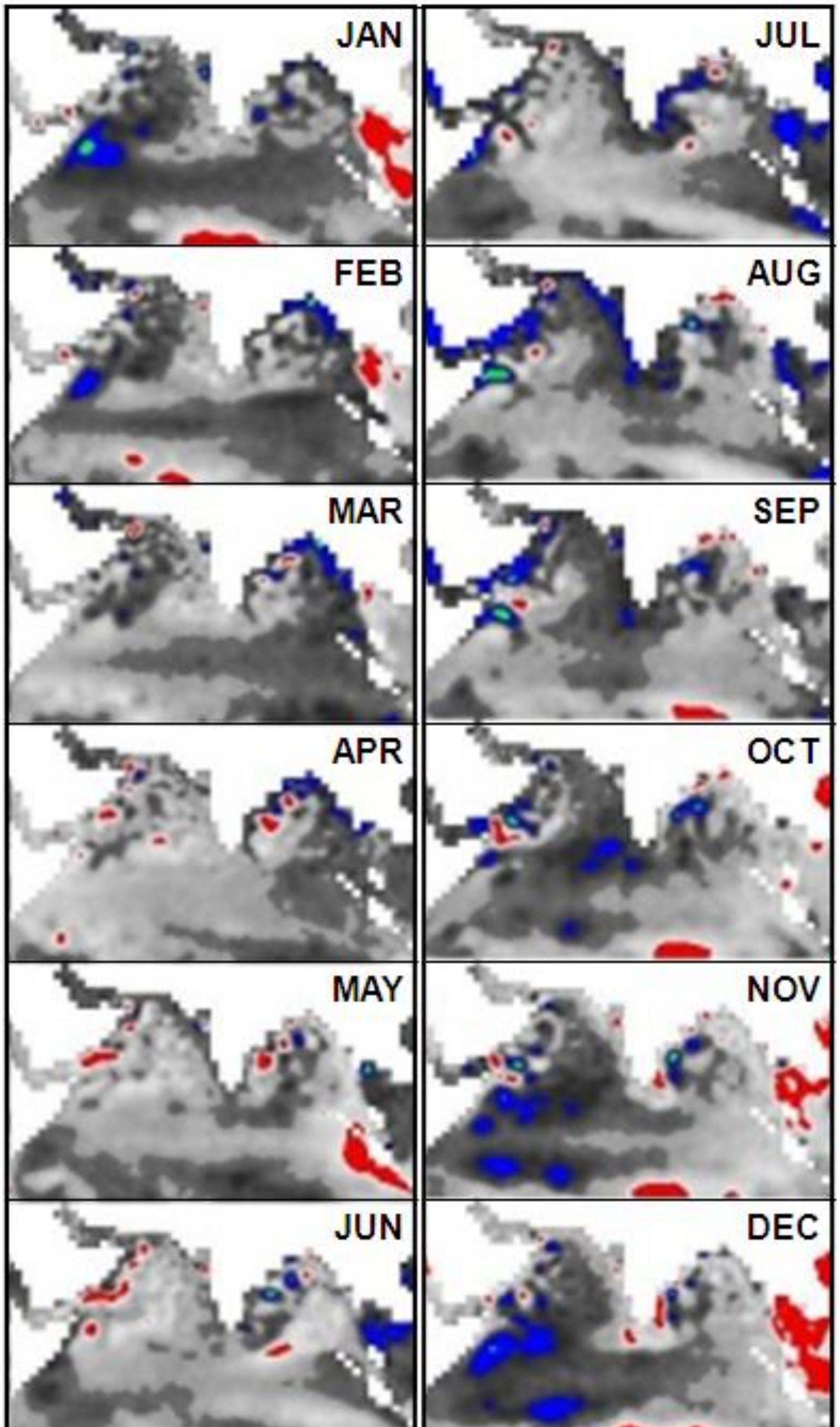
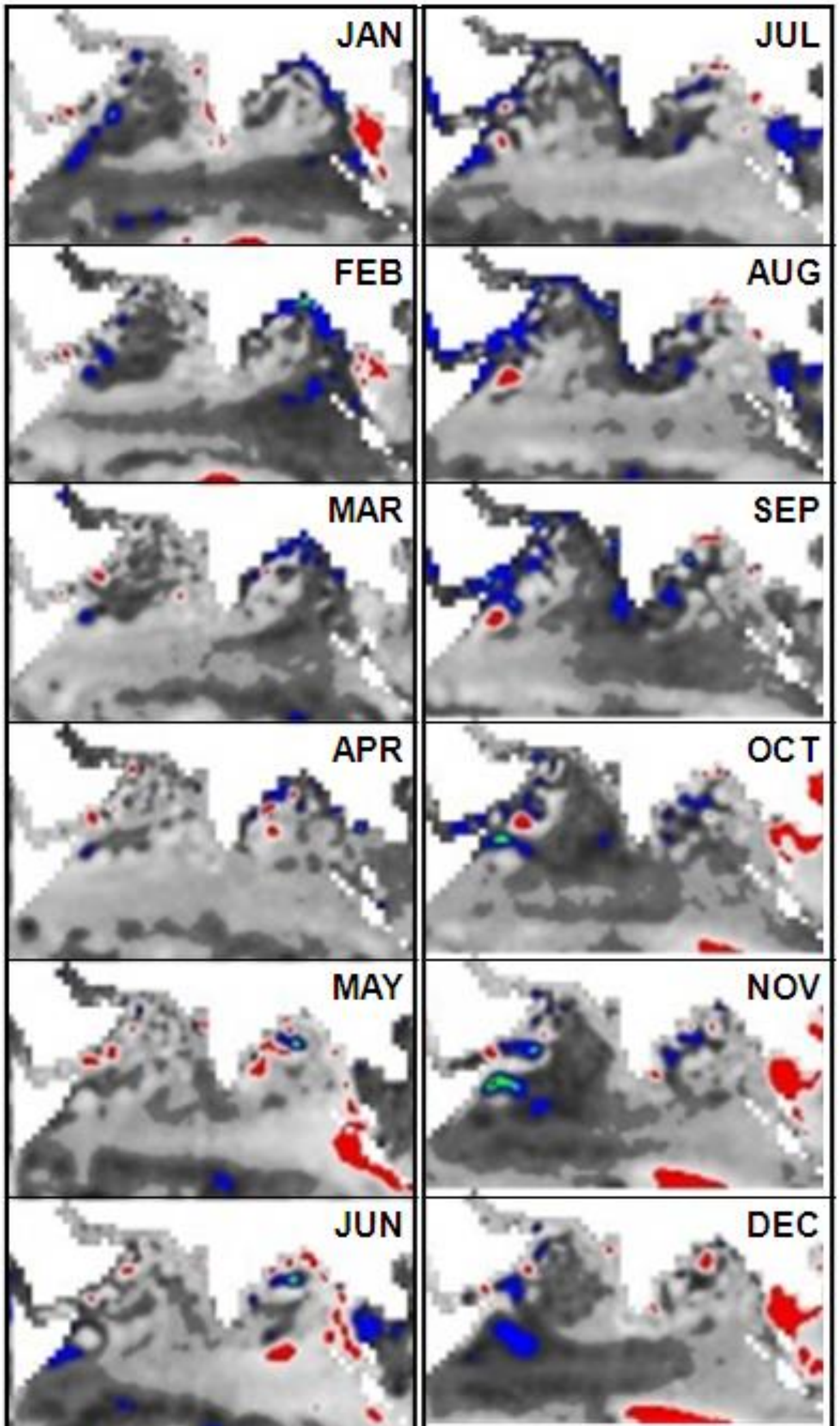
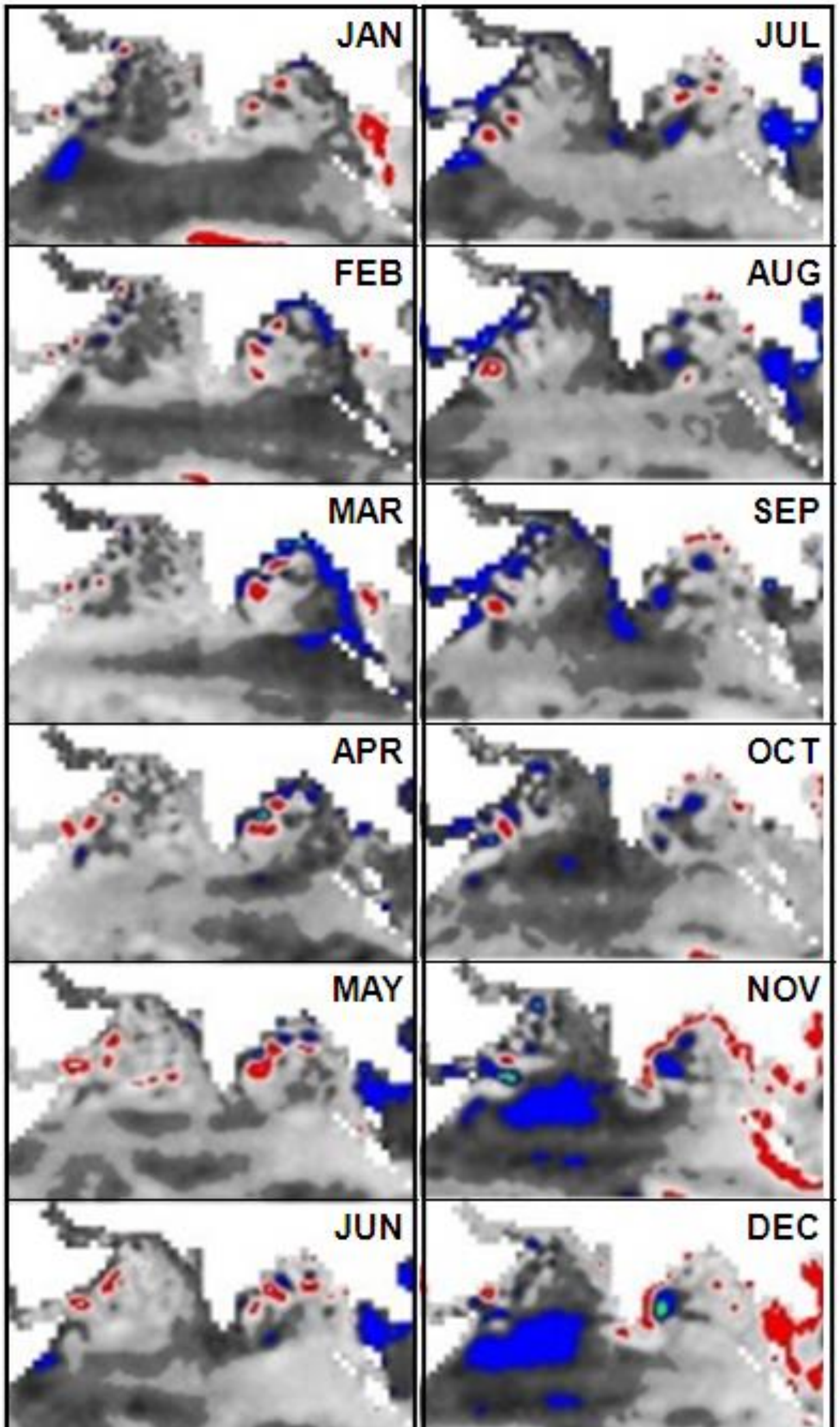


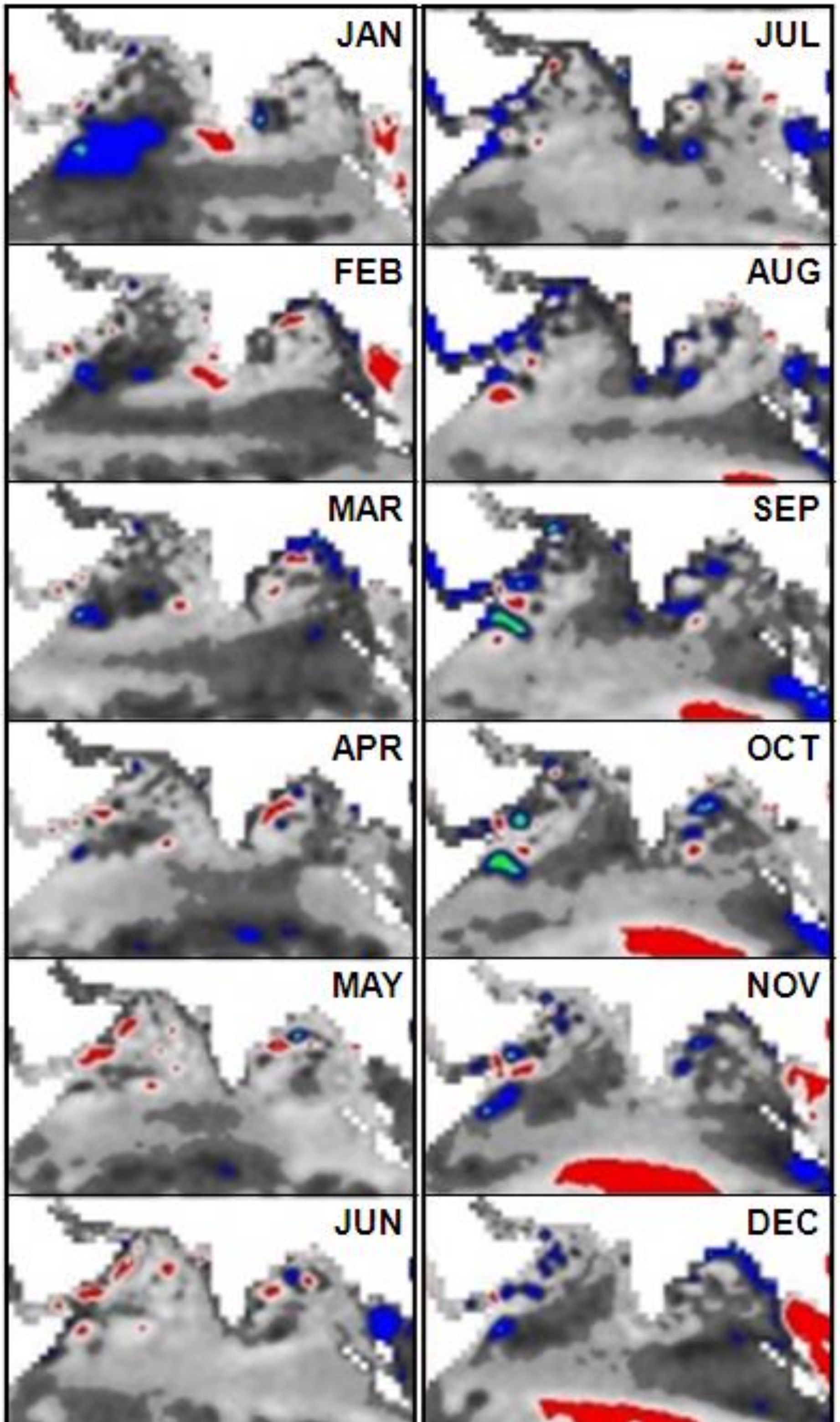
Eddies of cold core (Blue) & warm core (Red) area
2003



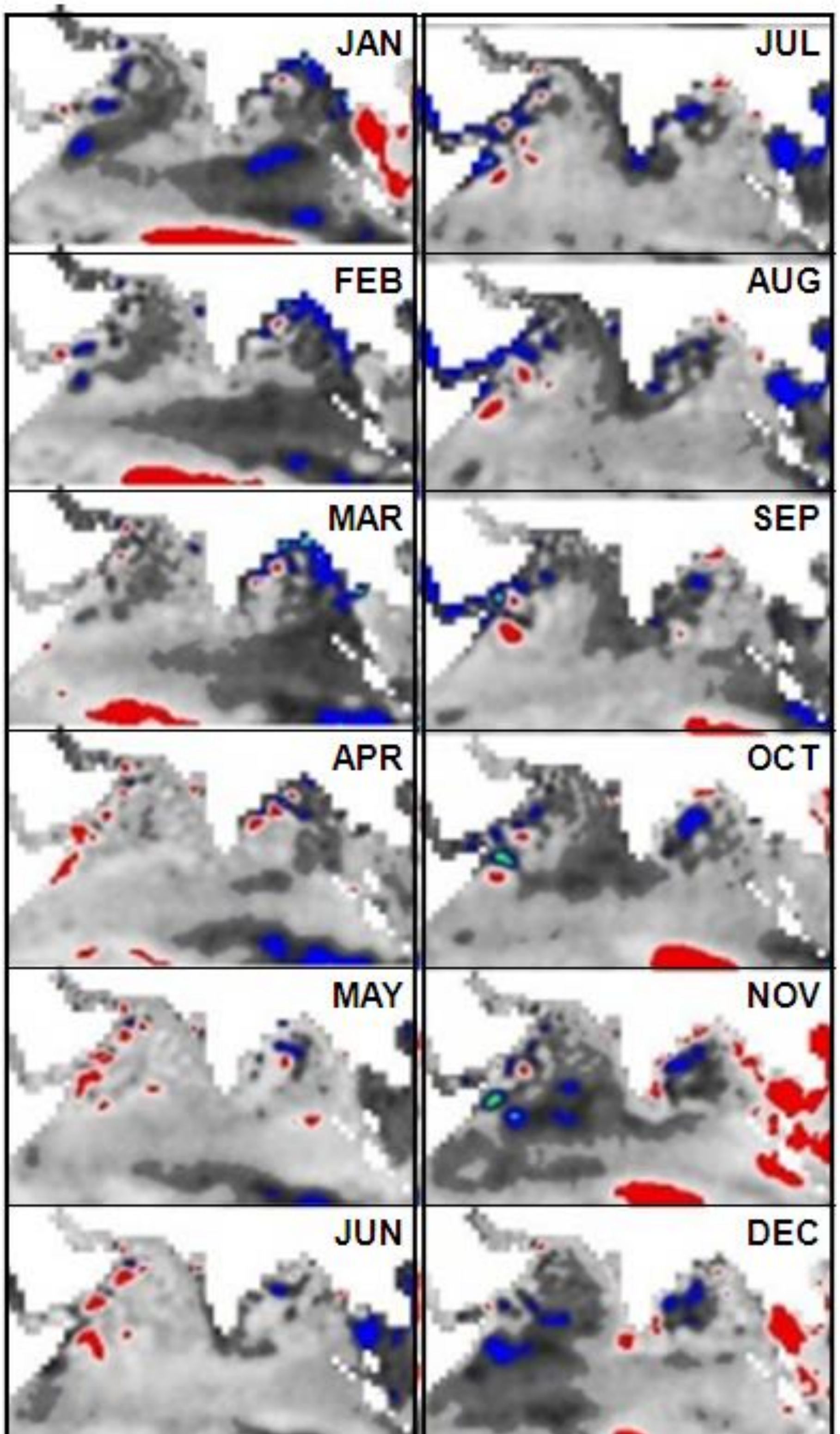
Eddies of cold core (Blue) & warm core (Red) area
2004



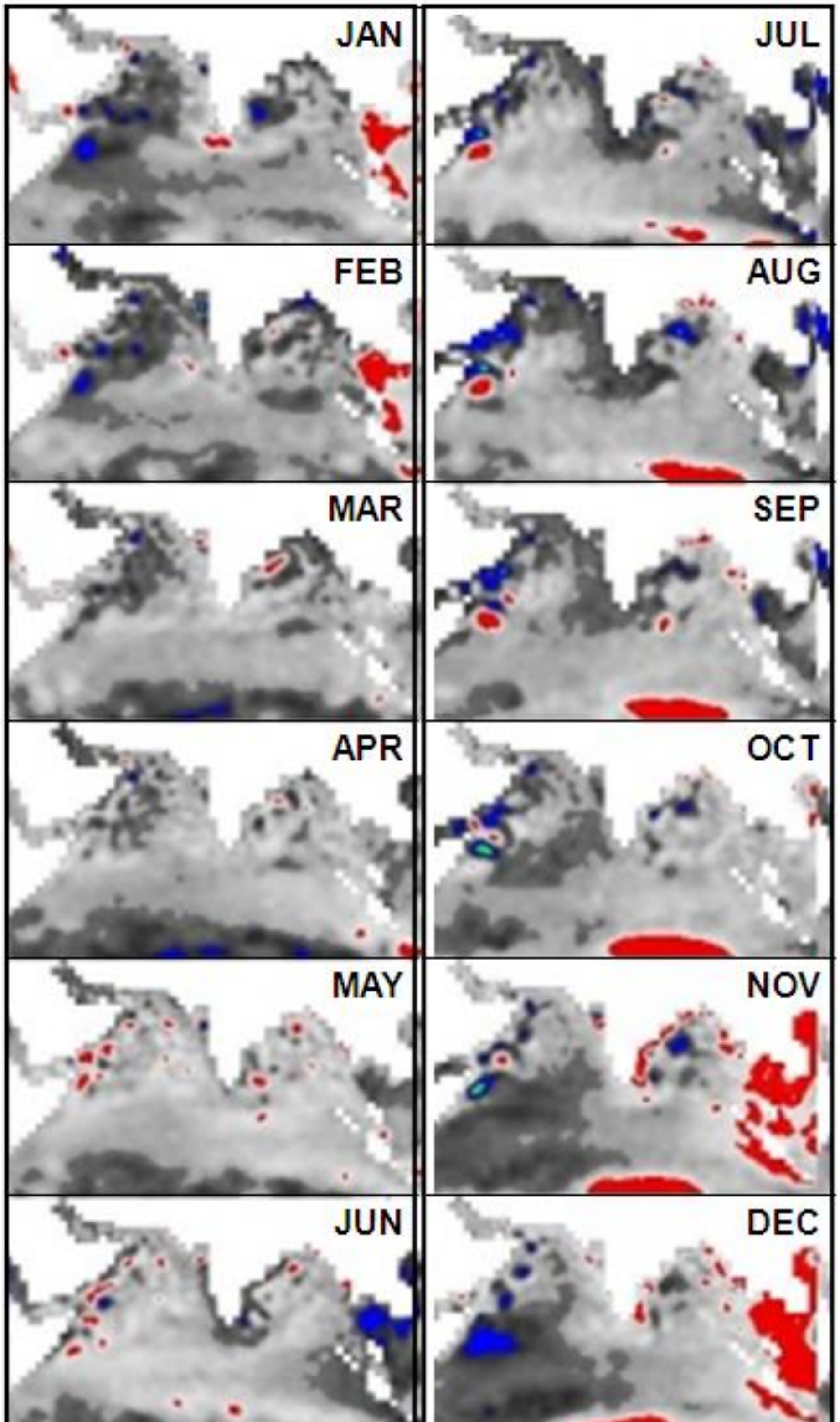
Eddies of cold core (Blue) & warm core (Red) area
2005



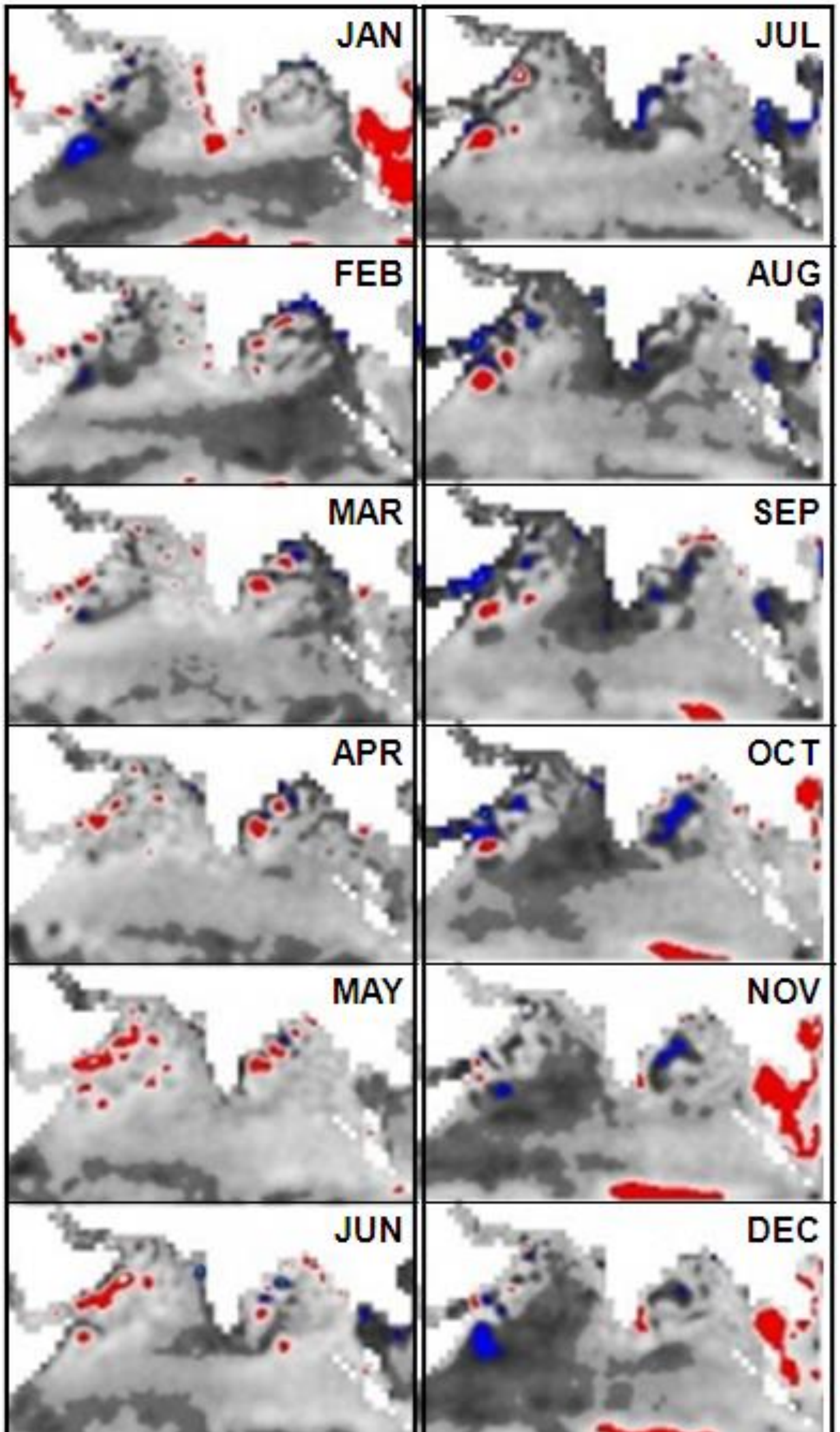
Eddies of cold core (Blue) & warm core (Red) area
2006



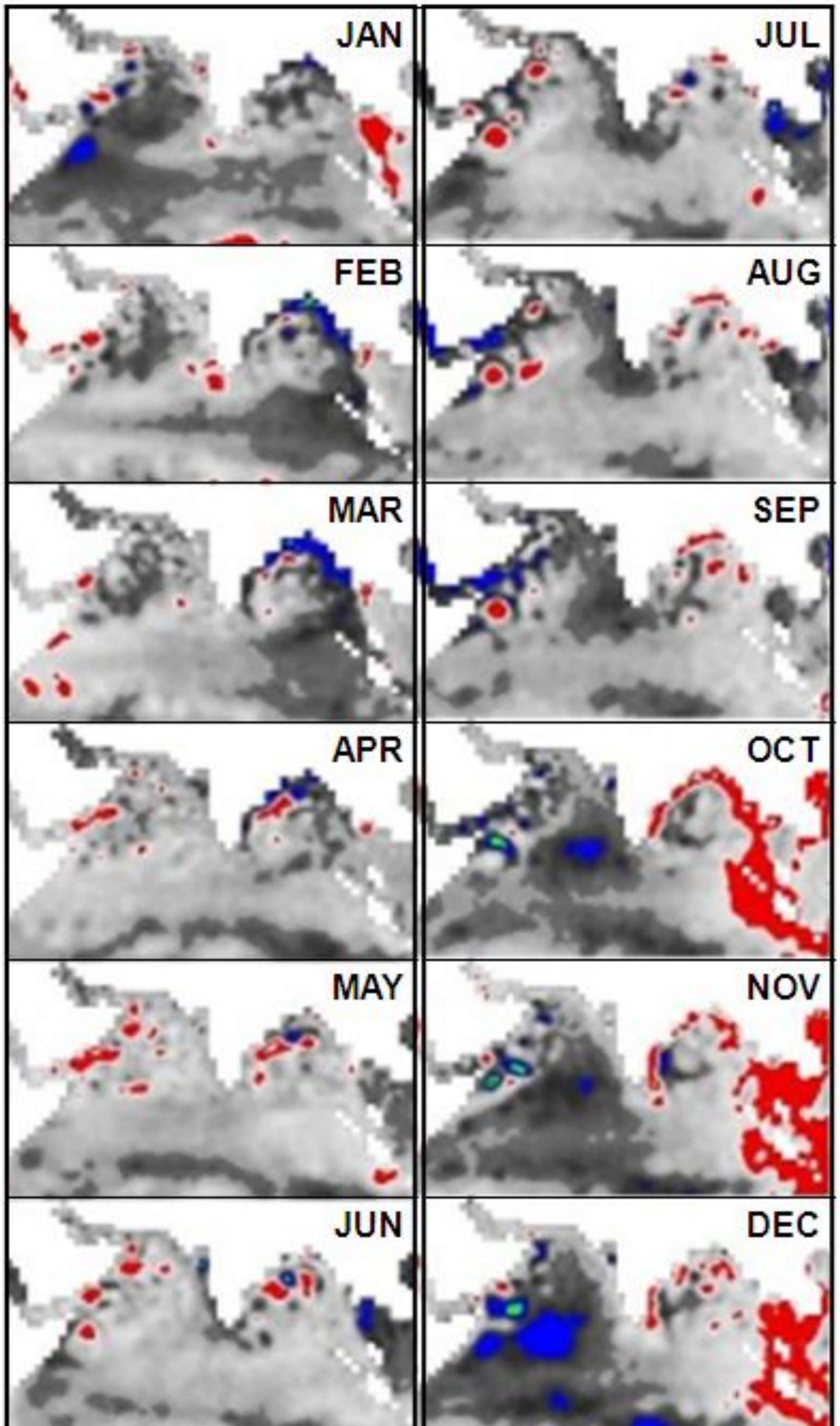
Eddies of cold core (Blue) & warm core (Red) area
2007



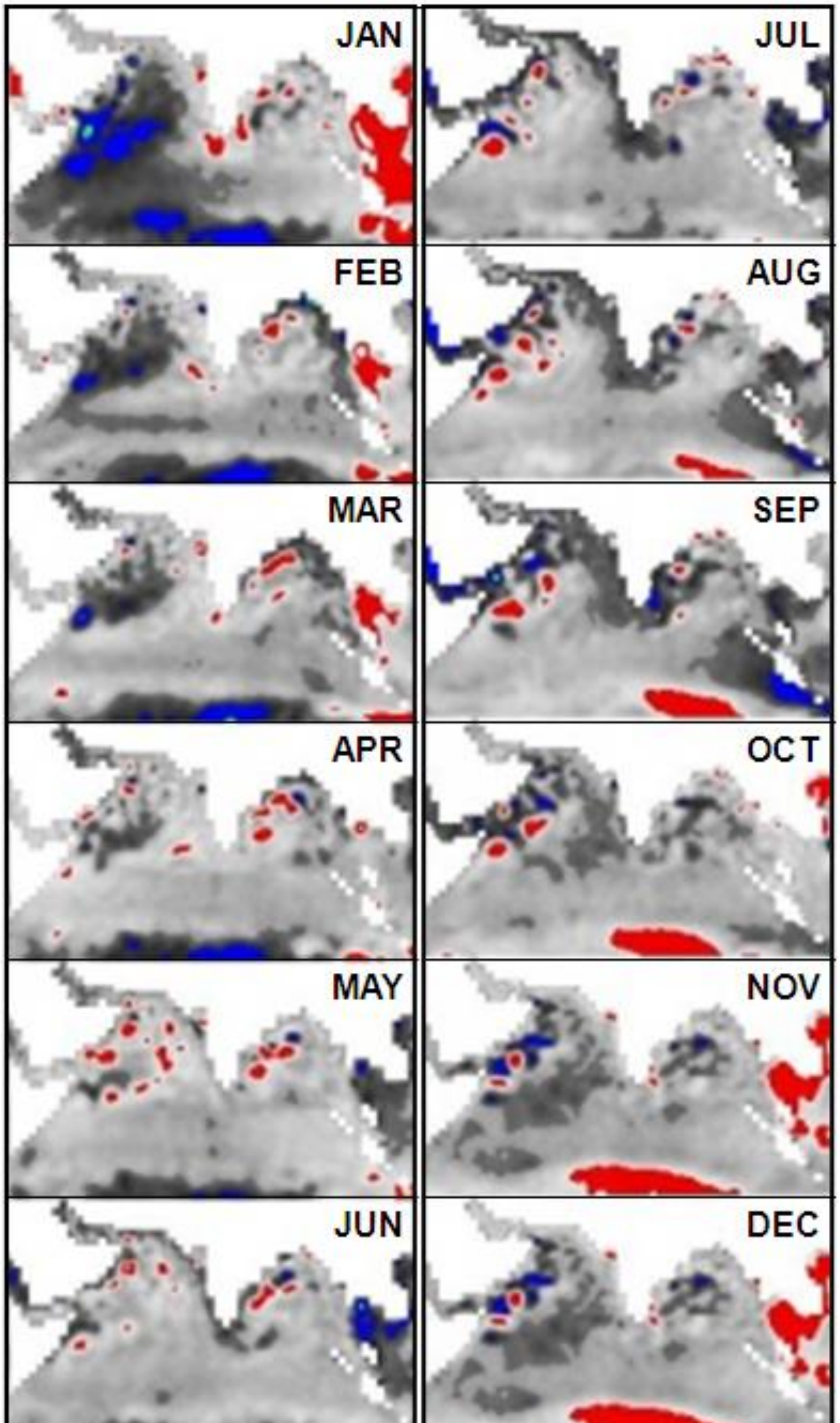
Eddies of cold core (Blue) & warm core (Red) area
2008



Eddies of cold core (Blue) & warm core (Red) area
2009



Eddies of cold core (Blue) & warm core (Red) area
2010



Eddies of cold core (Blue) & warm core (Red) area
2011

NRSC – ECSA – OSG –TR/2013

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