

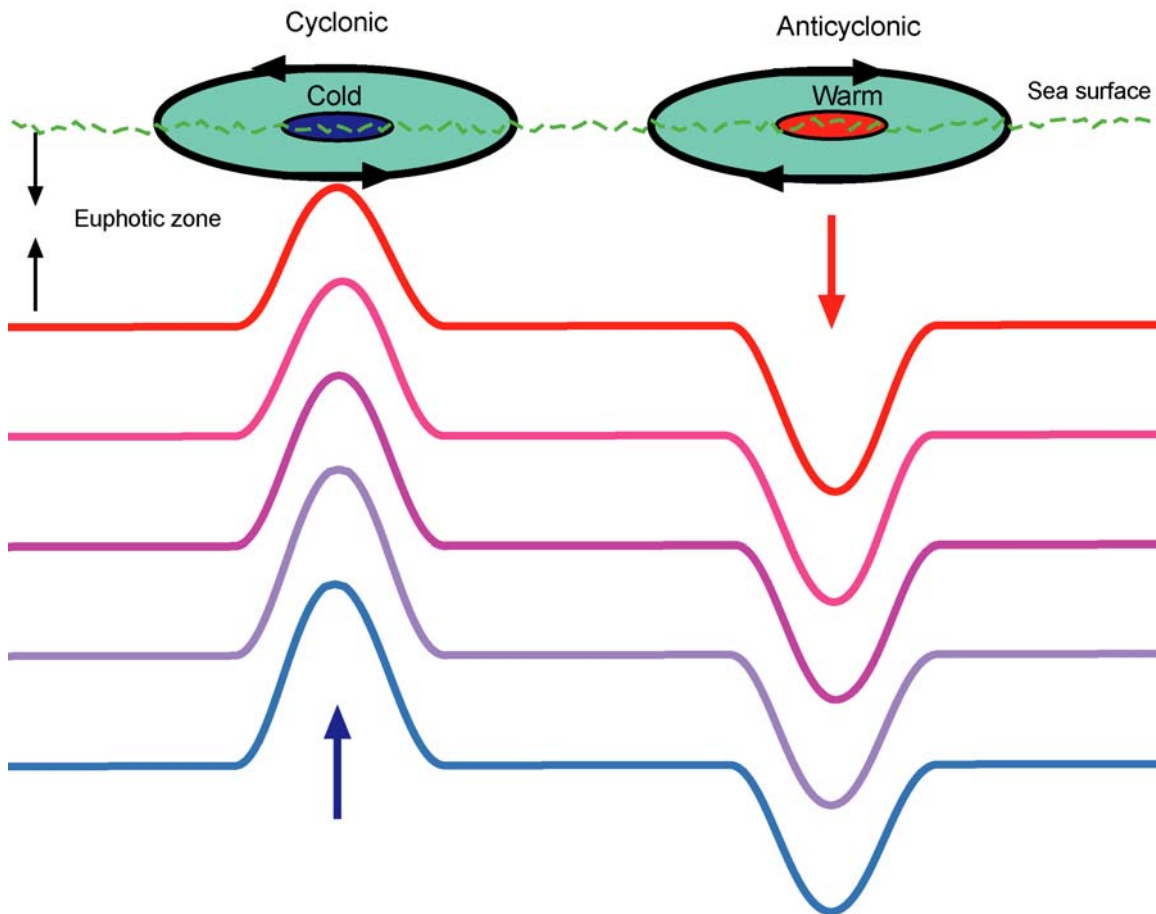
# Chapter 1 - Introduction

## 1.1 An overview of eddies

A 'traditional' picture of oceanic fields of temperature, salinity, density and current shows that the changes occurring in time and in space are slow and smooth. This notion of slowly and smoothly changing ocean was rendered illusory with the advent of high resolution sampling techniques. They revealed that the oceanic motions vary abruptly in time and in space and are more energetic. This variability arises from a host of features, like rings, vortices, lens, meanders, jets, filaments etc. Physical oceanographers group them in a generic term 'eddies' [Robinson, 1983]. However, in oceanographic literature it is the circulating water columns that are commonly referred to as eddies. These features having dimensions of the order of Rossby deformation radius (~100 km) are called mesoscale eddies and received great attention during the later half of the 20<sup>th</sup> century.

At planetary scales in the northern hemisphere, a northward moving parcel of water would turn right under the influence of Coriolis force. Consequently, water converges in a clockwise (anticyclonic) rotating eddy and diverges in an anticlockwise (cyclonic) eddy, leading to downwelling and upwelling respectively at their centers (Figure 1.1.1).

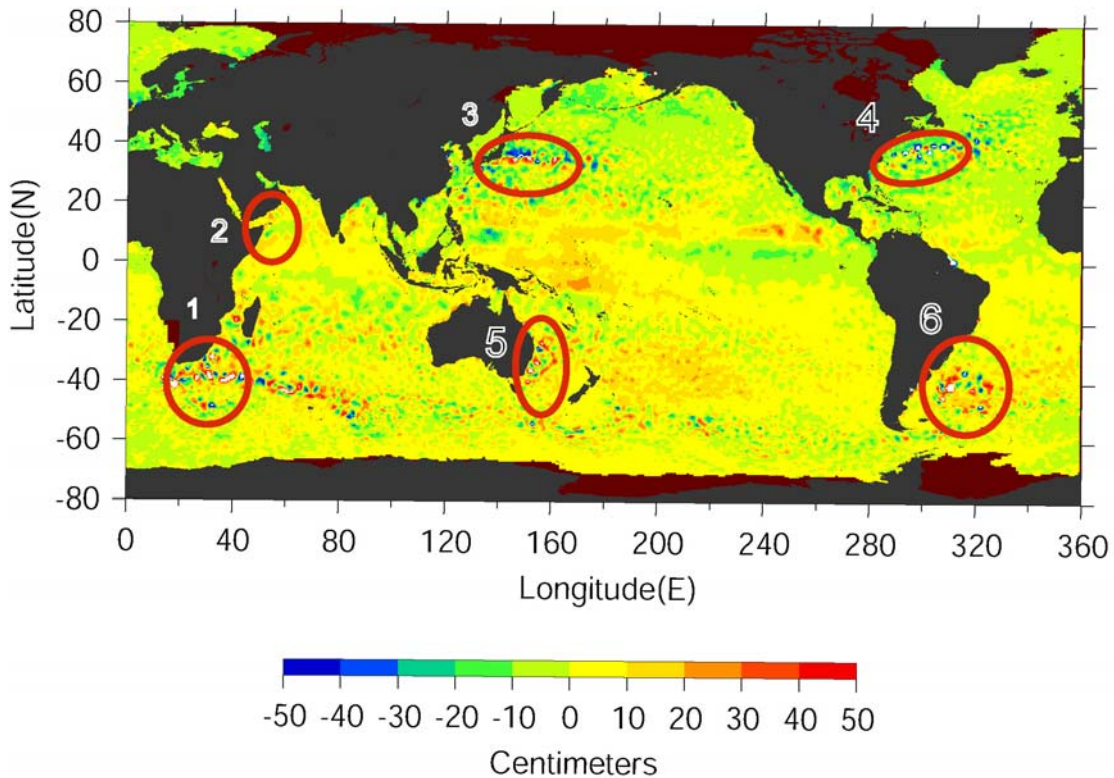
An examination of global picture of satellite sea-level anomaly (SLA) (Figure 1.1.2) shows that along the western boundaries of the ocean SLA tends to be heterogeneous, consisting of positive as well as negative anomalies, indicating strong eddy activity.



**Figure1.1.1** Schematics of a cyclonic and an anticyclonic eddy. In a cyclonic eddy the thermocline is uplifted due to the divergence at its centre, whereas the thermocline is depressed in an anticyclonic eddy due to convergence. This results in upwelling and downwelling respectively at their centres.

These are locations where currents are intense as a result of conservation of potential vorticity. These flows are called western boundary currents. These intense current regions are found to be the major eddy generating regions of the world.

For example the Gulf Stream (north Atlantic), Kuroshio (north Pacific), Somali current (north Indian Ocean), East Australian current (south Pacific), the Agulhas current (south Indian Ocean) are well known regions of eddy generation. The eddy kinetic energy found in these regions is several folds greater that the rest of the ocean [Wyrki *et al.*, 1976]



**Figure 1.1.2** Sea-level anomaly obtained from AVISO live access sever ( see chapter 2 for details) showing the major eddy dominated regions of the world. 1) Agulhas 2) Somali 3) Gulf stream 4) Kuroshio 5) East Australian current region 6)The Brazil-Malvinas confluence All these regions are located along the western boundary of the oceans and are characterised by intense current system known as the western boundary currents.

The causative factors for eddy generation in these regions are instabilities of these currents. These instabilities are categorized as barotropic and baroclinic instabilities, arising from the horizontal and vertical shear respectively of the horizontal currents [Pedlosky, 1979]. In case of baroclinic instability, the vertical shear can be related to the horizontal density gradient by the thermal wind relationship [Pond and Pickard, 1978]. Hence regions with horizontal gradients in density are susceptible to baroclinic instability. Barotropic instability, on the other hand, is depth independent and arises in currents with no vertical shear [Pedlosky, 1979]. A quantitative approximation of these instabilities can be made by computing the barotropic and baroclinic fluxes [eg. Boning and Budich, 1992]. The advantage with this approximation is that one can pinpoint what

type of instability is operating in a given region, but gives no idea of what are the mechanisms that generates such instability. *Stammer* [1997] using satellite altimetry showed baroclinic instability as the major mechanism of generating eddy energy in the ocean. Once generated they tend to propagate westwards because of the acquisition of relative vorticity by the displaced water parcel [*Cushman et al.*, 1990].

Eddies generated from the Gulf stream were the first to be studied experimentally and dates back to 1793 [*Robinson*, 1983]. The cold core eddies of these regions have a dimension of approximately 200 km and extends beyond 1000 m depth. These eddies are called rings and are the most energetic eddies studied till date. Studies showed that they develop from meanders towards the south of the stream [*Fuglister and Worthington*, 1947; *Iselin and Fuglister*, 1948] and play a significant role in removing salt and contributing to the primary productivity of the region [*The ring group*, 1981]. Warm core eddies too form in the region but towards the north of the Gulf Stream. Another eddy dominated region of World Ocean is the northwest Pacific, which is known for the poleward flowing Kuroshio current, a well known western boundary current. The Kuroshio current also generates warm and cold core eddies similar to the Gulf Stream [*Richardson*, 1983]. In the Indian Ocean, the best studied regions for eddies are the Somali and Agulhas current. Eddies in the Agulhas region play a vital role in inter-basin exchange of water across Indian and Atlantic oceans [*Lutjeharms*, 2006].

The first scientifically designed experiment to map eddies *in situ* and understand their dynamics was conducted in 1970 by USSR in the North Equatorial current code named as

POLYGON-70. The experiment used a suite of direct measurements to elucidate the, generating mechanism, energy level, spatial structure and the time evolution of the oceanic eddies [Kamenkovich *et al.*, 1986]. Subsequently, US lead Mid Ocean Dynamic Experiment (MODE) in the southwest of Bermuda in 1973 which revealed that ocean eddies are part of an energetic and structured variability field superposed on weaker gyre-scale circulation [The MODE group, 1978]. The USSR-US joint venture POLYMODE was the single largest experiment of its kind which investigated in more detail the dynamics of synoptic eddies in open ocean [Kamenkovich *et al.*, 1986]. During its execution many cyclonic as well as anticyclonic eddies of the dimension of deformation radius and smaller were encountered and studied. These experiments were conducted by occupying a pre-determined region in the ocean. Recent advancements in satellite altimetry allowed oceanographers to track eddies and study them individually. The recently concluded Mixing of Agulhas Ring Experiment (MARE) was one such kind in the Agulhas region which dealt with the role of eddies in inter-ocean exchange between Indian and Atlantic Ocean [van Aken *et al.*, 2003]. All these experiments unequivocally conclude that eddies are an important dynamical entity of ocean circulation.

## **1.2 The north Indian Ocean**

The regions of eddy generation, except Somali current, discussed above are away from the tropics and the current systems have a permanent existence. However, the Northern Indian Ocean (NIO) is different from the rest. It is landlocked approximately at the tropic of cancer. During summer, the heating of Asian land mass generates large land-sea pressure difference, which drives the Monsoon winds. These winds, having an annual

periodicity, are southwesterly during summer (June-September) and northeasterly during winter (November-February), and are considered to be the primary forcing mechanism of the NIO. As a result, much of the studies on the variability of the NIO revolve around the monsoonal reversal.

One of the most extensively studied regions in the NIO is the Somali current, which lies along the western margin of the Arabian Sea (AS). Here eddies develop in close association with the development of the boundary current [*Robinson, 1983*]. With the onset of summer monsoon strong anti-cyclonic gyre is established along the east coast of Africa [*Schott, 1983*], the western limb of which is the Somali current and is characterized by strong vertical shears [*Swallow and Bruce, 1966*]. The ‘Prime eddy’ generated out of this current deepens the isotherms resulting in a loss of heat of the order of  $10^{20}$  calories from the upper ocean to the deeper layers [*Bruce, 1979*].

Its eastern counterpart, the Bay of Bengal (BOB), is one of the least studied basins of the world ocean. Though lying in the same latitudinal belts both the seas are markedly different. On an average BOB is warmer and less saline and AS is cooler and more saline [*Levitus, et al 1994*, also see Figure 1.2.2 & 1.2.3]. This primarily arises from the fact that in the AS evaporation exceeds precipitation, whereas, in the BOB it is the precipitation that exceeds the evaporation ( $\sim 2 \text{ m yr}^{-1}$ ) [*Prasad, 1997*]. Three major river systems - the Ganges-Bhramaputra, Irrawadi-Salween and the Krishna-Godavari - drain into the BOB. The total runoff from the peninsular rivers, which peaks during summer monsoon, amounts up to about  $1.625 \times 10^{25} \text{ m}^3/\text{yr}$  [*Subramanian, 1993*] (Figure 1.2.1). This huge

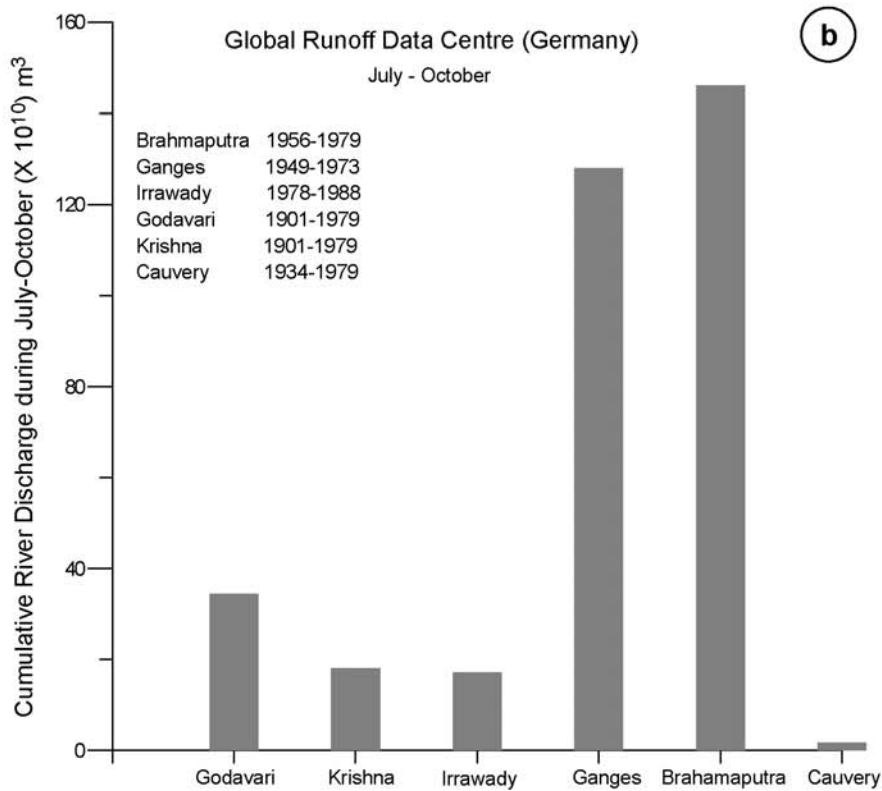
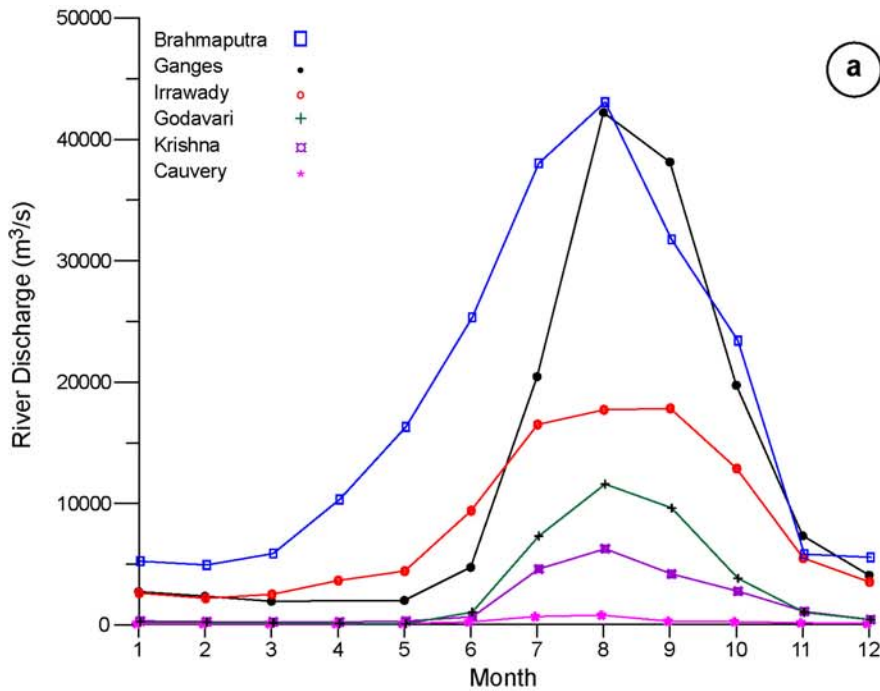
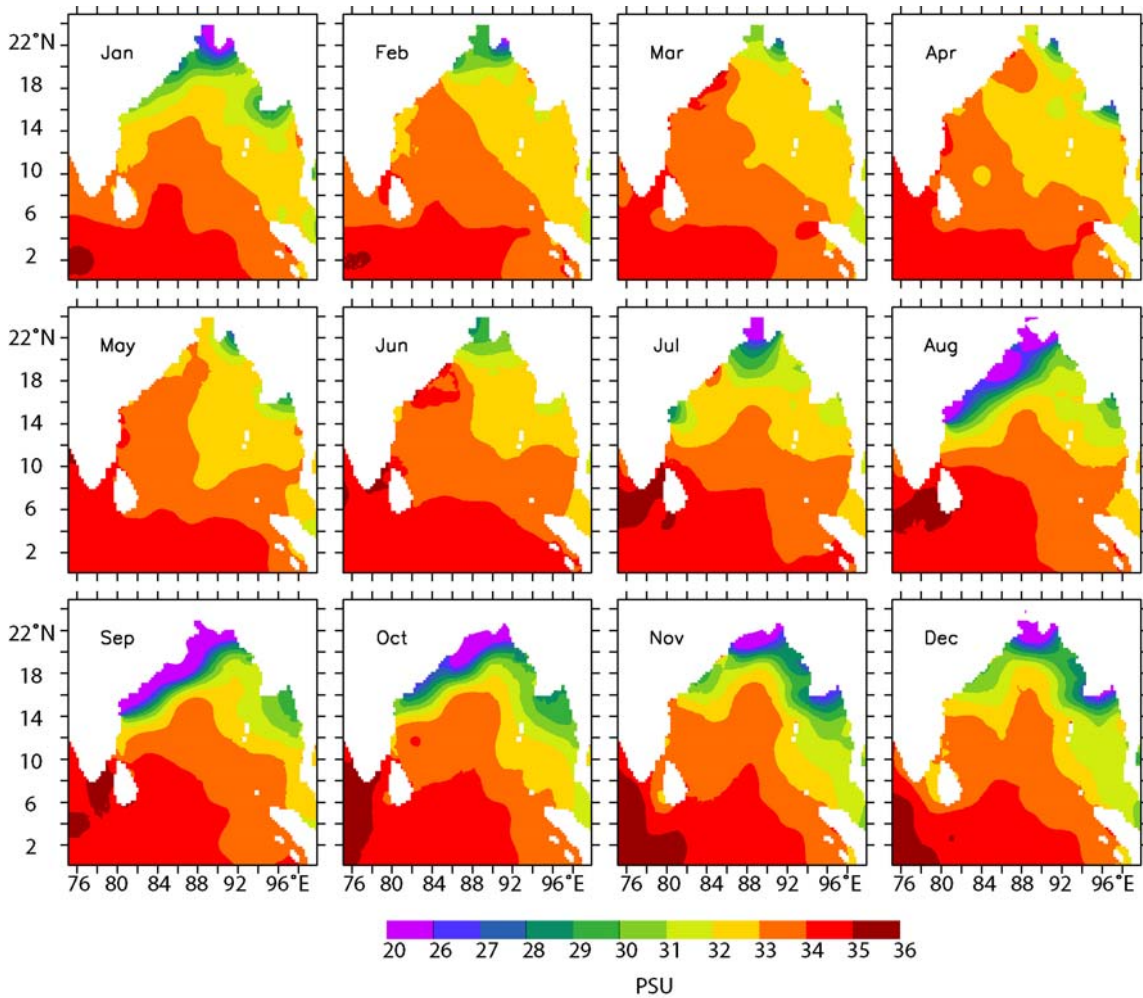


Figure. 1.2.1 Climatology of (a) monthly mean river discharge ( $m^3/s$ ) and (b) cumulative discharge ( $m^3$ ) during July to October of rivers Ganges, Brahmaputra, Irrawady, Godavari, Krishna and Cauvery. The river discharge data was obtained from Global Runoff Data Center, Germany (<http://grdc.bafg.de/servlet/is/2781/>).

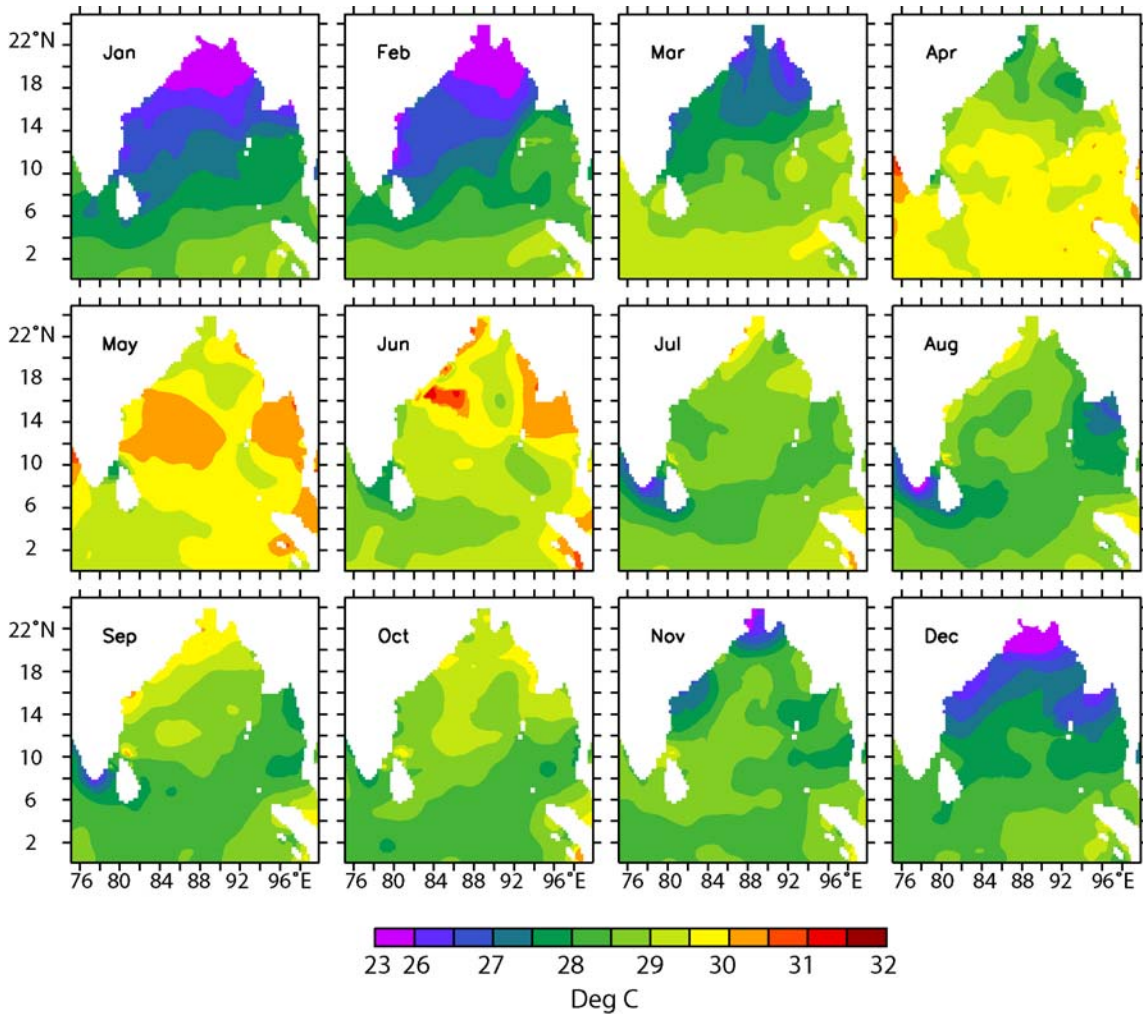




**Figure 1.2.2** Surface salinity (psu) in the BOB obtained from the WOA01 climatology [Conkright *et al.*, 2002]. Northern regions of the BOB is fresher through out the year than the southern BOB due to high river discharge.

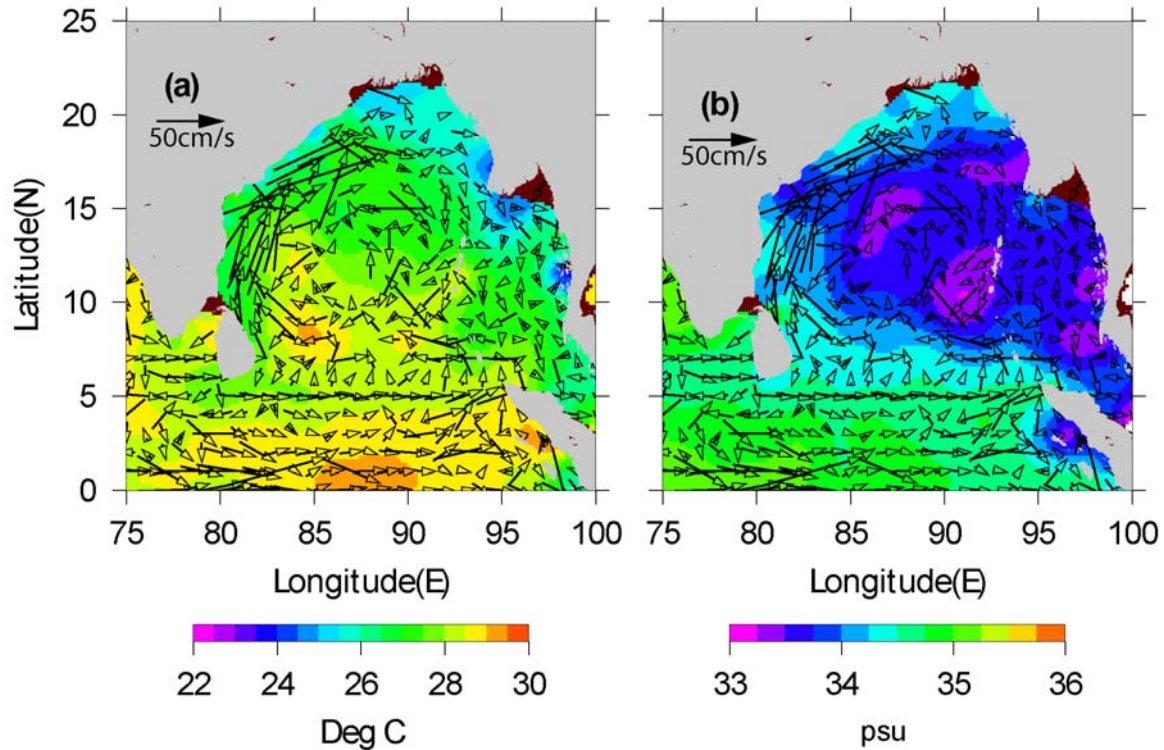
quantity of river runoff coupled with the excess precipitation induces large changes in the salinity, which is predominantly felt along its peripheries (Figure 1.2.2). However, the temperature shows much less variability except during winter (Figure 1.2.3). Low salinity with comparatively weak winds makes the BOB a highly stratified basin. The stability parameter in the BOB is 3-4 times greater than that in the AS [Prasanna Kumar *et al.*, 2002] making it increasingly difficult to perturb the BOB except during the cyclonic storm period.





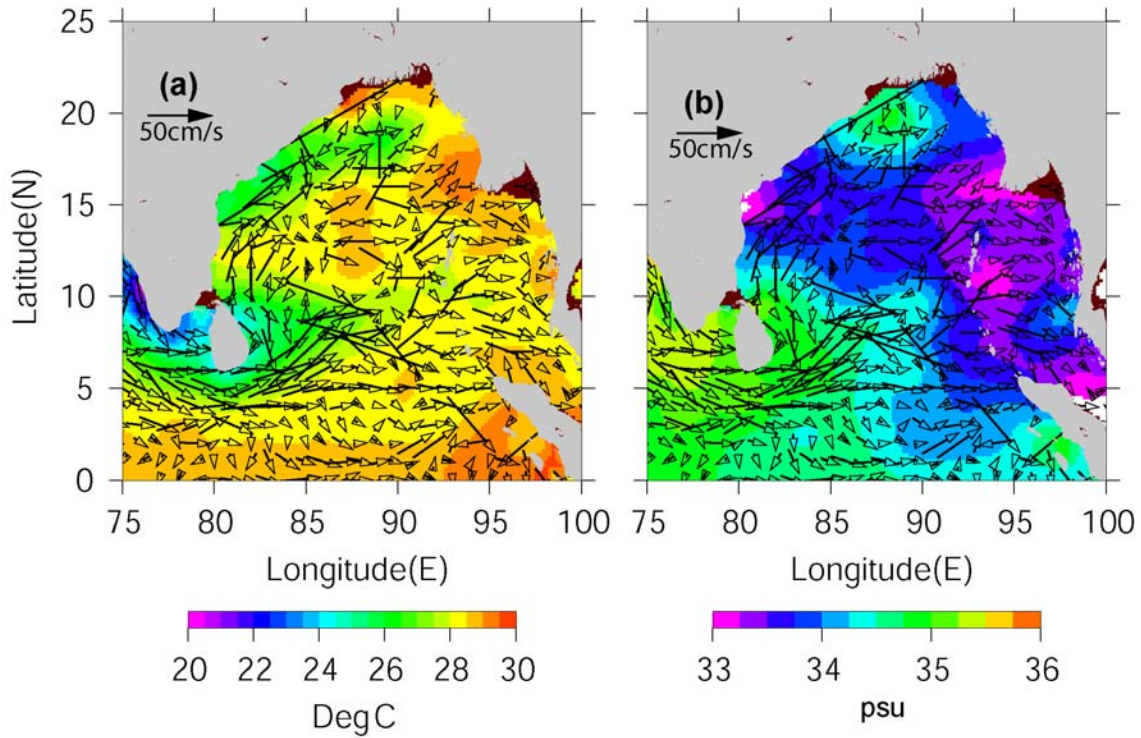
**Figure 1.2.3** Sea surface temperature (°C) in the BOB obtained from the WOA01 climatology [Conkright, et al., 2002].

Intense current regimes can be found in BOB too. The most striking one is the northward flowing East India Coastal Current (EICC) [Shetye et al., 1993] during spring intermonsoon (March-May) (Figure 1.2.4). Despite low wind speeds (~4 m/s) this current attains a peak velocity of ~100 cm/s. This is in direct contrast with the AS where maximum current speeds are obtained during summer monsoon when the winds are stronger. This contrast is explained in terms of the role of remote forcing by the westward propagating Rossby waves and coastally trapped Kelvin waves in the



**Figure 1.2.4.** Monthly mean climatology of (a) temperature ( $^{\circ}\text{C}$ ) and (b) salinity (psu) from WOA01 [Conkright *et al.*, 2002] overlaid with one-degree surface current vectors derived from NOAA ship drift data during April.

establishment of this current [Potemra *et al.*, 1991, Yu *et al.*, 1991, Vinayachandran *et al.*, 1996; McCreary *et al.*, 1996; Shankar *et al.*, 1996; Shankar *et al.*, 2002]. Studies indicate that this current is highly sheared in the vertical [Babu *et al.*, 2003], which is an important aspect when dealing with the instabilities. During fall intermonsoon (October), however, this current is equatorward. Another region of intense current is the southern BOB during summer when the southwest monsoon current flows into the BOB. This current flows around the Sri Lankan dome (SLD), a wind driven sea-level low [Vinayachandran *et al.*, 1998], carrying cold and high-saline waters into the warm and less-saline southern BOB during summer monsoon. Presence of SLD and the warmer and less-saline water to the east of it gives a frontal characteristic to the southern BOB during summer monsoon (Figure 1.2.5).



**Figure 1.2.5.** Monthly mean climatology of (a) temperature ( $^{\circ}\text{C}$ ) and (b) salinity (psu) from WOA01 [Conkright et al., 2002] overlaid with one-degree surface current vectors derived from NOAA ship drift data during July.

### 1.3 Eddies in the BOB

The important characteristics of the BOB that emerged from earlier studies are the occurrence of intense currents along the western boundary and in the southern Bay, the high stratification arising from warm and low-salinity waters, presence of westward propagating Rossby waves and coastally trapped Kelvin waves. Apart from the above features of the BOB, there had been reports of occurrence of eddy in the BOB way back in 1957. *Ramasastri and Balaramurty* [1957] reported the presence of eddy off Vishakhapatnam along the western boundary of the BOB during March-April and October-November. They noticed strong cross-shore temperature gradients during these seasons. Subsequently, *Rao and Sastry* [1981] reported cyclonic and anti-cyclonic flows and linked the nutrient distribution with these flows. Though indications of a western

boundary current was present in the earlier studies [eg, *Ramasastri and Balaramurty, 1957* and *La Fond, 1957*] it's presence was established by Legeckis [1987] based on satellite derived sea surface temperature (SST) data using Advanced Very High Resolution Radio meter and delineated two warm core eddies in the central and northern Bay during February 1985. Based on remote sensing (altimetry) and *in situ* observations *Gopalan et al. [2000]* showed strong inter-annual variability in the spatial location and intensity of eddies. Recent studies too indicated presence of eddies near the western boundary of the BOB during March-August [*Babu et al., 1991; Murty et al., 1993; Shetye et al., 1993; Sanilkumar et al., 1997; Babu et al., 2003 ; Prasanna Kumar et al., 2004*]. The *in situ* measurements show that these eddies mostly confines with in the upper 500 m of the water column [eg. *Babu et al 1991, Prasanna Kumar et al., 2004*] and have horizontal dimension of 200 to 300 km. A comparison of eddies at various locations is given in the following table (Table 1.1).

**Table 1.1.** Details of spatial scales associated with eddies observed at different geographic locations.

Region	Depth of sampling	Vertical extent of eddies	Horizontal dimension	Author
Gulf stream	2000 m 800 m	~ 2000 m ~ 800 m	~ 200 km ~200 km	Iselin, 1936, Richardson et al., 1978
Kuroshio	500 m	~500 m	~ 200 km	Bernstein et al ., 1977
East Australian current	900 m	~900 m	~ 200 km	Nilsson and Cresswell, 1980
Agulhas retroflection	?	> 2000 m	~ 200 km	Duncan, 1968
Somali Current	450 m	450 m	~400-600 km	Bruce, 1979
Bay of Bengal	1000 m 500 m	100-400 m 500 m	~ 350 km ~ 200 km	Babu et al., 1991 Sanilkumar et al, 1997

Though the presence of eddies in the BOB is revealed in many studies, very few of them have directly addressed their generation and evolution [*Prasanna Kumar et al., 1992* and *Babu et al., 1991*]. The present thesis is an attempt in that direction.

#### **1.4. Outline of the thesis**

Recently concluded Bay of Bengal Process studies had two observational tracks - one along central BOB and another in the western boundary. Examination of the hydrographic data along these track showed many undulations which can be characterized as eddies. This data has been supplemented with the satellite derived sea-level anomaly (SLA) to characterize eddies and to give a spatial context to the observed along-track hydrography and forms the content of chapter 2. The evolution and generating mechanisms of eddies along the western boundary and the open BOB forms chapter 3 and 4 respectively. After describing their characteristics and establishing their origin and evolution, the chapter 5 deals with their role in the hydrography and circulation. In chapter 6 the eddy mediated changes in the distribution of nutrients and chlorophyll are discussed. Chapter7 summarizes the major out comes of the study.

## Chapter 2 - Data and methods

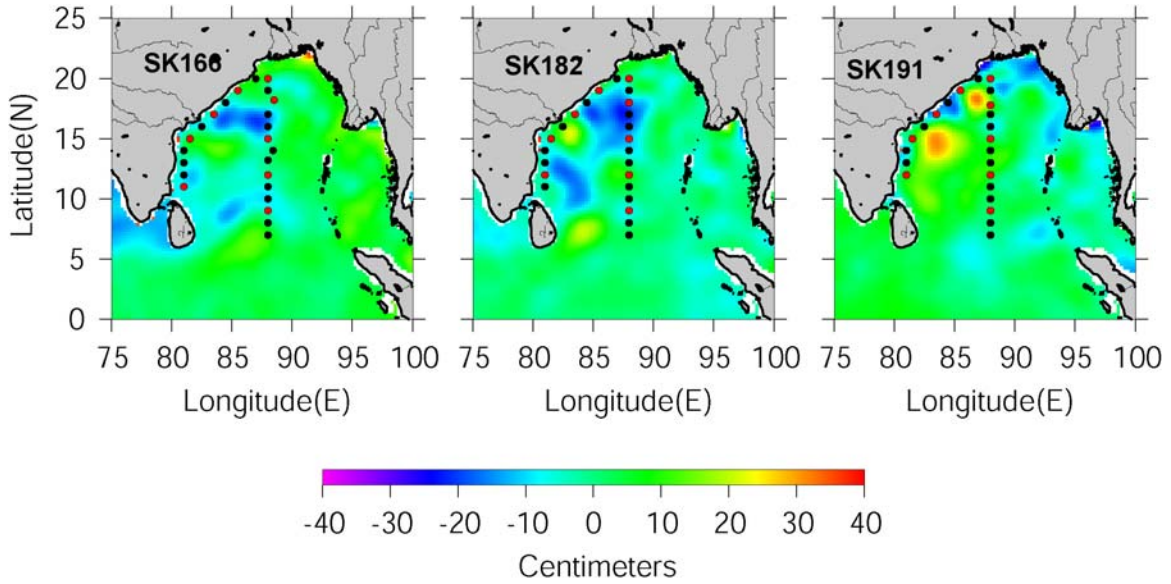
### 2.1 Introduction

In order to understand the characteristics of the eddies in the BOB and address their origin and evolution, a suite of data sets, both in situ as well as remote sensing, were utilized. *In situ* data used in this study is collected on board Indian research vessel ORV Sagar Kanya (SK) during 2001-2003 under a national programme Bay of Bengal Process Study (BOBPS).

### 2.2 *In situ* data

The *in situ* data used in the present study is the temperature and salinity profiles collected at stations along 88°E in the central BOB from 7°N to 20°N, and along the western boundary from 11°N to 20°N (Figure 2.2.1 ) during 3 seasons - summer monsoon (SK166, 10-July-2001 to 1-August-2001), fall intermonsoon (SK182, 17-September-2002 to 11-October-2002) and spring intermonsoon (SK191, 16-April-2003 to 6-May-2003) intermonsoon . Temperature and salinity profiles up to 1000 m depth were taken at one-degree latitude interval along the central and western boundary tracks using a Seabird 9/11 plus CTD (Conductivity-Temperature-Depth) system. The station interval along the western boundary was, however more than one degree. The raw data was processed using the software 'Seasoft' version 4.2.17. CTD salinity was calibrated against water samples collected simultaneously by a rosette sampler fitted with 10/30-L Go-Flo bottles and analyzed with a Guildline 8400 Autosol. Using the temperature and salinity profiles





**Figure 2.1.1** Cruise track along the central (88°E) and western BOB during the three seasons, summer monsoon (SK 166, 10 July - 1 August 2001), fall intermonsoon (SK 182, 17 September - 11 October 2002) and spring intermonsoon (April-May-2003) overlaid on average SLA for the period of each cruise.

geostrophic currents were computed w.r.t 1000m using the temperature and salinity data following Helland-Hansen method [*Pond and Pickard, 1978*].

In addition to the *in situ* data from the above mentioned 3 cruises, monthly mean climatology of temperature and salinity on a 0.25 x 0.25 degree grid from World Ocean atlas (WOA) 2001 [*Conkright et al., 2002*] is also used for computation of heat and salt content anomalies (discussed in chapter 5).

From the surface meteorological parameters (air temperature, wet bulb temperature, pressure, and wind speed and direction) measured at stations along both central and western boundary tracks in all the 3 seasons, wind data were used for the computation of Ekman volume transport ( $E_v$ ) using the following relationship.

$$E_v = \tau / \rho f$$



where  $\tau$  is the windstress at the surface,  $\rho$  is the sea water density and  $f$  is the Coriolis parameter. Windstress is computed using a constant drag coefficient of  $1.3 \times 10^{-3}$  (see chapter 5 for more details).

The data on nitrate, phosphate, silicate and chlorophyll *a* was taken from BOBPS data CD (Indian Oceanographic Data Centre product, National Institute of Oceanography, Goa, March 2007). The nutrient data (nitrate, phosphate and silicate) of BOBPS was generated from the water samples collected in the upper 1000 m from 19 discrete depths (near surface, 10, 20, 30, 40, 50, 75, 100, 125, 150, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 m) using 10/30L Go-Flo bottles attached to the CTD rosette and analyzed with a SKALAR auto-analyzer during summer and with spectrophotometer following *Grasshoff et al.* [1983] during fall and spring intermonsoons. In both cases, sensitivity for nitrate, silicate and phosphate was 0.1, 0.5 and 0.03 $\mu$ M respectively. The chlorophyll *a* data of BOBPS was obtained from water samples collected in the upper 120 m from 8 discrete depths (near surface, 10, 20, 40, 60, 80, 100 and 120 m) and concentrations measured using a TURNER design fluorometer.

### **2.3 Remote sensing data**

The spatial structure and the evolution of eddies were examined by analyzing 7-day snapshots of the merged sea-level anomalies of Topex-Posidon/ERS 1/2 satellites obtained from AVISO live access server (<http://las.aviso.oceanobs.com>) having a spatial resolution of 1/3<sup>rd</sup> of a degree during the period October 1992 to January 2004 [*Le Traon et al.*, 1998].

This is a proven tool in studying the mesoscale features of the ocean [*Le Traon and Dibarboure, 1999*]. They show that the error associated with this amounts to about 3-6% of the variance of the signal. In the BOB the mean error is  $\sim 3$  cm. Velocities from the sea-level anomalies were computed assuming the geostrophic relation

$$2\Omega\sin(\phi).V = g \tan(i)$$

where  $\Omega$  is the earth's angular velocity,  $\phi$  is the latitude,  $V$  is the velocity and  $\tan(i)$  is the slope of the sea surface [*Pond and Pickard, 1978*]. The error associated with the velocity computation amounts to  $\sim 20$  % of the variance [*Le Traon and Dibarboure, 1999*], which is small, but not negligible.

Twice daily Quik SCAT wind-stress (*Large and Pond* algorithm) obtained from PODAAC [*JPL Publication, 2003*] and Southampton Oceanography Center surface fluxes [*Josey et al., 2002*] was used to compute the curl of the wind-stress and is given by

$$\text{Curl}(\tau) = \partial\tau_y/\partial x - \partial\tau_x/\partial y$$

where  $\tau_x$  and  $\tau_y$  are eastward and north ward components of wind-stress.

Eddies formed out of baroclinic instability processes tend to follow the typical length scale, Rossby deformation radius ( $L_R$ ), a relative measure of stratification and the Coriolis force (discussed in chapter 3).  $L_R$  is computed assuming a two layer ocean using the formula,  $(\Delta\rho\rho_0^{-1}gh)^{0.5} f^{-1}$  [*Kamenkovich et al., 1986*] where  $\Delta\rho$  is the density drop across the main pycnocline,  $\rho_0$  a reference density,  $h$  is the depth of the pycnocline,  $f$  the Coriolis parameter .