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Krishna-Godavari River Water Transport in the Western Bay of Bengal: Impact of Surface Circulation

Akurathi V S Chaitanya[1,*] and Arthur R James[1]

[1] Department of Marine Science, Bharathidasan University, Tiruchirappalli – 620024, Tamilnadu, India

ABSTRACT

Monsoonal rainfall over central Indian sub-continent during summer season (June - September) feeds Krishna-Godavari (KG) river system every year. The interannual variations of rainfall over KG river basin modulate the runoff contributions of KG into the Bay of Bengal. Then the surface circulation plays a major role in transporting these freshwater into the rest of the Bay of Bengal. In this study we used the $1/4^0$ horizontal resolution numerical ocean model simulations with river runoff flux as passive tracer component to understand the spreading of KG river plume in western Bay of Bengal. The model physics such as sea level, surface currents and Salinity data were validated successfully with in situ / satellite measurements. The climatology of KG tracer concentrations shows the spreading of river plume towards the central Bay of Bengal till September and later transport along the southern India and Sri lanka coast by the end of December. ENSO/IOD and mesoscale eddies play a major role on spreading KG water over western Bay of Bengal. The interannual variations of catchment area rainfall and river runoff play an important role in wider spreading of freshwaters.

Keywords: Krishna-Godavari river runoff, EICC, Passive tracer model, ENSO, IOD, Eddies

* *Corresponding author (A.V.S. Chaitanya).*
E-mail: chaitu.ocean1@gmail.com

INTRODUCTION

Bay of Bengal receives large amount freshwater supply through the monsoonal rainfall and the major continental river systems such as Brahmaputra, Ganges, Irrawaddy and from the minor rivers Mahanadi, Godavari, Krishna, Cauvery. This freshening contribute to reduction in surface salinity upto ~15 psu near river mouth and about ~1 - 5 psu much further away from source (Chaitanya et al., 2014). This strong freshening over the Bay of Bengal lead to formation of barrier layer below the mixed layer due to density driven surface stratification (Pankajakshan et al., 2007). The oceanic heat content stored in the barrier layer enhances the development and strengthening of cyclone intensity (Neetu et al., 2012). The maximum of freshwater from ocean precipitation and Runoff from Ganges-Brahmaputra and Irrawaddy in north/northeastern Bay of Bengal during summer monsoon, later these freshwater are advected by surface circulations to the rest of the Bay of Bengal largely along the east coast of Indian by the permanent western boundary current known as East Indian Coastal Current (EICC) during post-monsoon (Shetye et al., 1993, Chaitanya et al., 2014). The EICC & surface circulation over bay are controlled by the seasonal reversing monsoonal circulation, which is anti-clockwise during winter monsoon October-December and clockwise in the rest of the year (Shankar et al., 2002, Shetye et al., 1993).

The equatorial wind forcing also contributes to this gyral circulation and strengthens the flow of EICC during the post monsoon through coastally trapped down welling kelvin wave propagation all along the bay (McCreary et al., 1996). In addition to this local and remote wind forcing, the density stirring mesoscale eddies play an important role in transporting the fresh water and heat transport (Hareesh Kumar et al., 2013). The typical horizontal and timescales of these mesoscale eddies are vary from 10-100km and few weeks to few months respectively. In the western boundary of the Bay of Bengal (Cheng et al., 2013), the large scale eddies emerged from instabilities of strongly horizontally sheared motions, particularly from the seasonally reversing East Indian Coastal Current (EICC). The baroclinic instability induced horizontal density gradients are also slightly small scale eddies of order of tens of kilometers. Both these processes lead to hot spots of eddy energy in the vicinity of western boundary currents.

In this present study we considered Godavari-Krishna River, together contribute more than 60% out flow among east flowing Indian peninsular rivers. The water resource for rivers are largely fed by the Indian summer monsoon more than 75% every year, resulting floods some years and droughts other periods. The temporal changes are more influenced by the extreme weather events. In recent decades, the relation between positive trend in extreme rainfall events over central India to the positive trend of surface latent heat flux and sea surface temperatures over the tropical Indian Ocean recognized by Guhathakurta & Rajeevan (2008). The variability of Godavari river catchment area rainfall over 1951-1990 period has been studied Nageswara Rao (1999). Monsoonal rainfall variability is maximum observed in Godavari basin (17%) than the all-India monsoon rainfall (11%). Over the Krishna river basin annual and monsoonal precipitation trends show significant negative deviations from the normal (Harshavardan et al., 2020)

We used numerical ocean tracer modeling approach to examine the seasonal and interannual Krishna-Godavari water transport in the Bay of Bengal by the surface circulations. Also we look into the impact of climate modes such as ENSO and IOD on the spatial distribution of Krishna-Godavari river tracer. The structure of the paper is as follows, Section2 describes the numerical model configuration and the in situ/satellite SSS, SLA and current data used to validated the model physics. The model validation and tracer concentration seasonal and interannual evolution presented in section 3 and also discretized the relative importance of circulation features and climate modes on interannual spreading of river plume. Finally we concluded the results and suggested the future prospective in section 4.

Data & Methodology:

The Krishna river basin area lies between 13° - 19° 30' N and 73° 23' - 80° 30' E and drains an area of 2.59x10^5 km^2 (Raghunath, 2006) and the Godavari river basin (16° 16' - 22° 36' N and 73° 26' - 83° 07' E) covers an area of 3.13x10^5 km^2 in the central and southern part of the Indian subcontinent. Figure 1, shows the geographical location of this two rivers catchment area and the other major river systems draining into the bay. The interannual runoff data for the rivers are downloaded from India Water Resource Information System (https://indiawris.gov.in/wris/#/). IndiaWRIS is started by the central water commission together with National Remote Sensing Center (NRSC) for an integrated state-of-the-art information system in which all relevent data and information about water resources of India can be stored, managed and made available to users. For the precipitation over river catchment area used in this study is from Tropical Rainfall Measuring Mission (TRMM) 3B42 available at three hourly, 0.25° × 0.25° gridded product (Huffman et al. 2007) over the 1998–2011 period. It is a merged product from multi-satellite and in situ data from rain gauges. The annual cumulated climatological rainfall patterns is presented on Figure 2a, display maximum rain occurs over western edge of the catchment area for the Krishna river and over the eastern part of the Godavari river. The annual cycle of the catchment area rainfall attains maximum peak from May to July and the Krishna-Godavari river discharge attains one month after the catchment are rainfall Jun to

August/September (Figure 2b) with an annual average discharges of Godavari and Krishna are 2750 and 715 m^3/sec respectively.

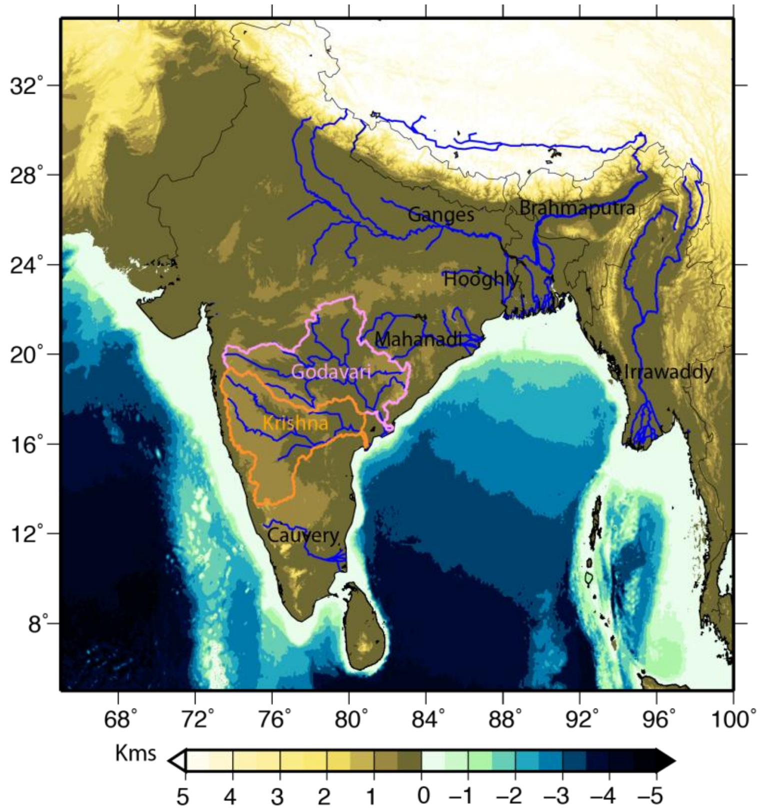

Fig 1: All mojor river systems draining into the Bay of Bengal known as Ganges, Brahmaputra, Irrawaddy, Mahanadi, Godavari, Krishna and Cauvery (blue lines over the land). Godavari-Krishna river catchment are indiacated with Pink and orange line. The colors shows the bathymetry and tropography of the study area.

The regional Bay of Bengal ocean model configuration (79E-100E, 3N-23N) is implemented using Nucleus of European Modeling of Ocean (NEMO) ocean general circulation modeling system described by Madec (2008). This model solves primitive equations discretized on an Arakawa C-grid on horizontal resolution of $1/4^0$ with 75 vertical levels, evaluates the tracers (Temperature and Salinity) and the horizontal components of velocities as prognostic variables and the vertical velocity is diagnosed using continuity equation. The turbulent closure model vertical mixing scheme is used to resolve the prognostic equation of turbulent kinetic energy (Blake and Delecluse, 1993). The boundary conditions for the model taken from interannual global $1/4^0$ simulation from the Drakkar project (Drakkar Group, 2007). The model use CORE bulk formulae (Large and Yeager, 2004) for the surface fluxes computation using 6-hourly ERA-Interim interannual reanalysis data (Dee et al., 2011) for momentum, heat and freshwater fluxes. The River runoffs are taken from Fekete et al., (2002) climatological discharge estimates for the major river systems and for the Indian peninsular river we used interannual discharge estimates downloaded from Indian WRIS describe above. In NEMO the TOP is permanent feature towards biogeochemical modeling to provide the physical constraints/boundaries for oceanic tracers. The component called MY-TOP in NEMO framework allows to evaluate the dispersion processes spanning from the implementation of a dye passive tracer. In the current study we used this tool for understanding the dispersion processes for river plume from Krishna-Godavari river system into the Bay of Bengal.

In order to validate the model simulated Sea Level we used the delayed time $1/4^0$ gridded Sea Level Anomaly (SLA) downloaded from the altimeter products were produced by Segment Sol Multimissions d'Altimétrie, d'Orbotogrphie et de Localisation Précise/Multimission Altimeter Data Processing System (SSALTO/DUACS) and distributed by Archiving Validation, and Interpretation of Satellite Oceanographic (AVISO) data with support from CNES (https://www.aviso.altimetry.fr/duac) (Dibarboure et al. 2011). For the surface currents observations we used the Geostrophic and Ekman Current Observatory (GEKCO) surface current data from January 2000 to December 2016 (Joel et al., 2013), that provides geostrophic and Ekman currents separately on a $1/4^0$ grid. The geostrophic currents are derived from the sea level (described above). The Ekman currents are derived using mean wind field data from the ku-band microwave scatter meter (SeaWinds) onboard the QuikSCAT satellite, distributed by the Centre ERS d'Archivage et de Traitement (CERSAT) (see Sudre et al., 2013 paper for more details). Chatterjee et al., (2012) prepared a North Indian Ocean Atlas (NIOA) SSS climatology at 1^0 x 1^0 monthly intervals, this data includes all available in situ Conductivity - Temperature-Depth (CTD) stations observations from Indian oceanographic cruises. This data was prepared by using the similar procedure to that of World Ocean Atlas 2009 to fill the spacial gaps and smoothing the data at space scales shorter than 4^0. Data coverage extensively good along the western boundary by adding the indian ocean oceanographic cruise data compared to WOD09.

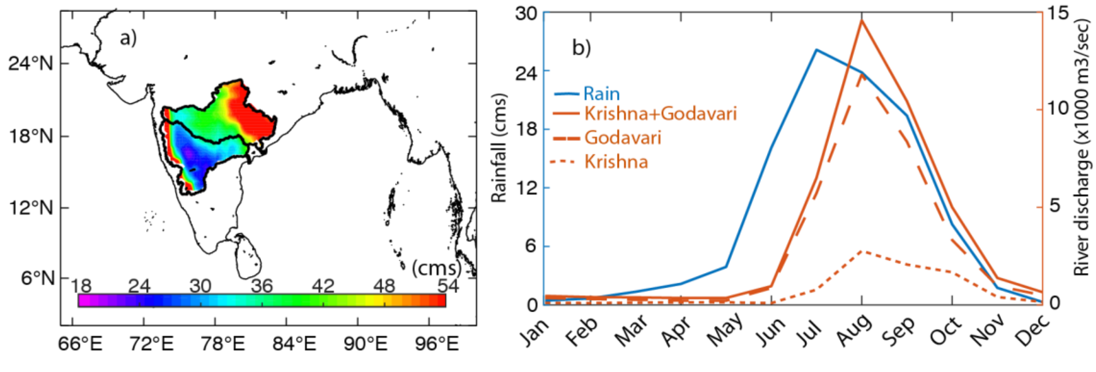

Fig 2: Annual cumulated rainfall over Krishna-Godavari catchment area (a) and (b) the monthly evelution of catchment area rainfall and the river discharge into the Bay of Benal.

RESULTS & DISCUSSION

In this section we first validate the model simulated physical parameters. Figure 3, shows the monthly climatology of GEKCO currents and AVISO sla (panels a, b, c, g, h, i) and model surface currents and sla (panels d, e, f, j, k, l). The observations and model currents show similar patterns of pole ward EICC with clockwise gyral circulation from early February to the peak summer monsoon July, and later due to weakening of summer monsoon breaks the northward EICC flow at middle of Indian coast and starting of anticlockwise gyral like circulation over northern bay from August to a fully established equator ward EICC by the end of the year is clearly visible from the both model and observations data. The model also reproduced the sea level anomaly patterns as shown in the satellite observations (Figure 3).

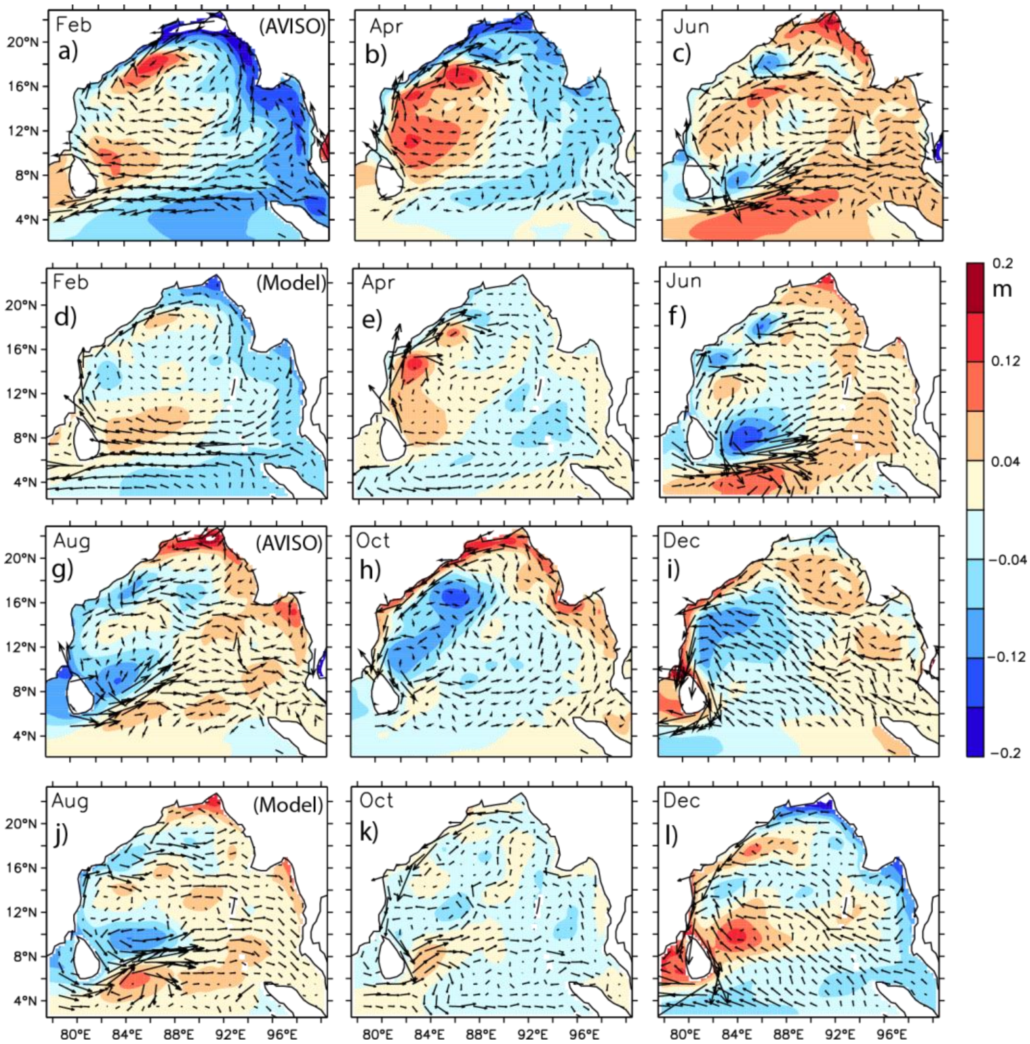

Fig 3: Monthly SLA climatology from AVISO over lapped with GEKCO currents (a, b, c & g, h, i) and (d, e, f, j, k, l) similar to those in (a, b, c & g, h, i) but ploted from BB4 Model sumulated SLA and surface currents.

The sea surface salinity over Bay of Bengal from NIOA climatology presented in Figure 4 (panels a, b, c, g, h, i) shows freshening signal over the north throughout the year and along the east coast of India during and after the summer monsoon. The model simulated sea surface salinity (Figure 4, panels d, e, f, j, k, l) also shows the strong freshening along the Indian coast during and after summer monsoon and the rest of the year over the northern Bay of Bengal. This model and coarse resolution observations, both display low salinity waters spread from the northeast to central Bay of Bengal during April-May. Due to the coarse resolution and data smoothing done over 4^0 x 4^0 on climatological data, less likely we see strong freshening signal very close to coast and wide spread of little low salinity waters over central Bay of Bengal compared to the model simulated data.

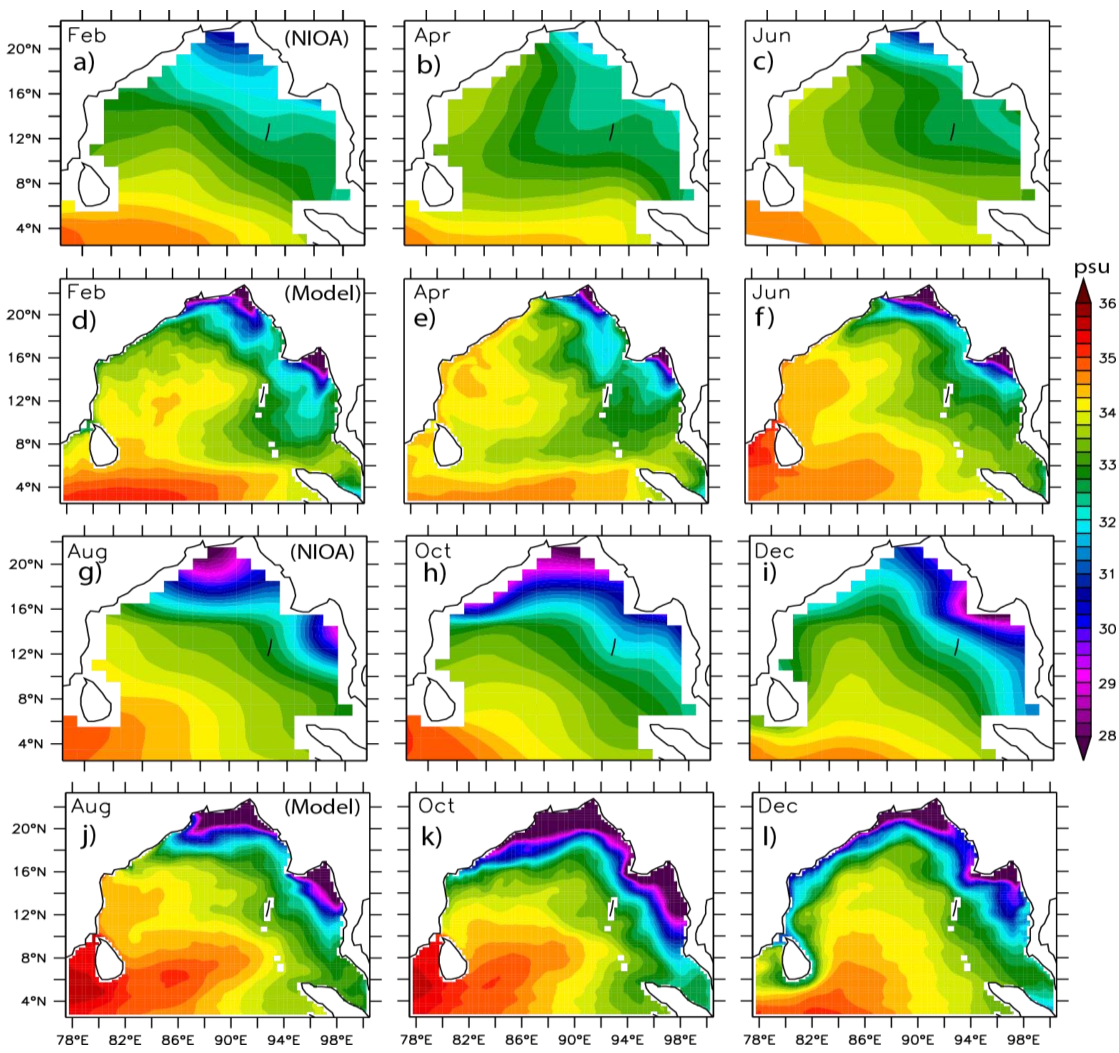

Fig 4: Monthly SSS climatology from NIOA (a, b, c & g, h, i) and (d, e, f, j, k, l) similar to those in (a, b, c & g, h, i) but ploted from BB4 Model sumulated SSS.

MY_TOP tracer module is activated in NEMO – OGCM regional ocean model setup to simulate the passive tracer concentrations online along with physical model. The passive tracer is initiated in the model at the Krishna – Godavari river mouth and assigned the real time runoff estimation values, which is used to force the physical model at every model time step. The passive tracer is set to zero on 1st of April every year for unnecessary accumulation of tracer concentrations in successive years, that means the runoff concentration is continuously added to the passive tracer at river mouth from April to March. This cutoff process will allow us to check the impact of interannual variations without aggregation of previous year freshwater quantity.

The tracer model is run for 19 year from 1993 - 2011, the monthly evolution of climatological KG tracer concentrations from May to December are presented in Figure 5. KG waters are evenly spread around the mouth with higher concentrations as a narrow tongue directly into the offshore from May to September (Figure 5a - 5e). Then it change its direction towards north - south From October to December (Figure 5f - 5h), the off shore KG waters slowly pushed towards northern Indian coast north of KG river mouth and the KG waters close to river mouth are spread to south along the coast as a narrow coastal tongue.

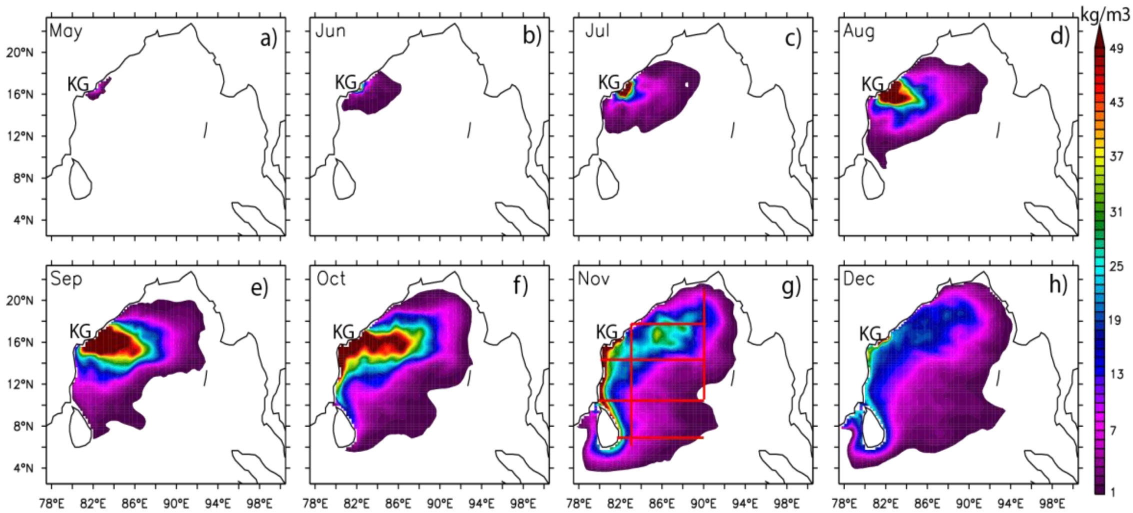

Figure 5: The monthly climatology (May – Dec) of KG tracer concentrations computed over the period 1993-2011. The red lines on panel g, indicate the selected vertical (V1 & V2) and horizontal (H1, H2, H3 & H4) time-sections.

The El-Nino Southern Oscillation and Indian Ocean Dipole are the major influencing climatic episodes on the Bay of Bengal physical processes. ENSO is an coupled ocean atmospheric phenomena with two opposite phases, one is known as El-Nino, is a warm phase of the ENSO contribute to the above average Sea Surface Temperature (SST) in central and tropical Pacific Ocean (Philander, 1990). This lead to a weakening or reversal of easterly winds to westerly winds and reduced rainfall over Indonesia while increase over eastern Pacific. The second one is known as La-Nino, is a cooling phase of ENSO contribute to below average SST in central and eastern Pacific Ocean lead enhancing the easterly winds and rain over Indonesia-surrounding regions, reduced over central Pacific Ocean. The ENSO index for this study downloaded from https://ggweather.com/enso/oni.htm. Another climatic mode IOD, is an oceanic phenomena over Indian Ocean characterized by the zonally dipole SST anomaly patterns. Saji et al. (1999) and Webster et al. (1999) have demonstrated the IOD conditions over Indian ocean Independent of ENSO. During positive phase of IOD, the eastern equatorial Indian Ocean cooler SST anomalies than the western equatorial Indian Ocean with strong easterly winds. Where as in negative phase of IOD the cool SST anomalies are found over western Indian Ocean than eastern Indian Ocean, this enhances the westerly winds over equator. As a consequence of the dipole mode induces easterly (westerly) equatorial winds developed the equatorial planetary waves such as upwelling (down welling) kelvin and rossby waves. The data for the IOD index to identify the positive / negative IOD years are from http://www.bom.gov.au/climate/iod/. Over the period of 19 years from 1993 – 2011, total six El-Nino, eight La-Nino, three positive IOD, three negative IOD years and three years without any climatic modes presented, list of years corresponding to each event is displayed in Table 1.

Table 1: KG water transport presence across the horizontal / vertical sections the KG tracer threshold considered to represent in this table is 20 kg/m^3 concentrations.

Climate mode	**years**	**V1**	**V2**	**H1**	**H2**	**H3**	**H4**
El-Nino	2002, 2004, 2009	yes	no	yes	yes	no	no
La-Nino	1995, 1999, 2000, 2005, 2007, 2008, 2011	yes	no 1995, 2008	yes	yes	yes	yes 1995, 2008
+IOD	-	-	-	-	-	-	-
-IOD	1996, 1998	yes	no	yes	yes	yes	yes
El-Nino & +IOD	1994, 1997, 2006	yes	yes 1997	yes	yes	yes 1997	no
La-Nino & -IOD	2010	yes	yes	yes	yes	yes	yes
Normal years	1993, 2001, 2003	yes	yes	yes	yes	yes	yes

In order to evaluate the interannual variation on the KG water spreading due to climatic events impact on circulation, we selected six time series sections in that two time - latitude sections (red lines, Figure 5g) along 83.5^{0}E (V1) and 90^{0}E (V2) longitudes and four time – longitude sections along 17.5^{0}N (H1), 14.5^{0}N (H2), 10.5^{0}N (H3) and 7.5^{0}N (H4). The interannual KG runoff input into the Bay of Bengal (Figure 6c) display huge variability due to the impact of climatic modes such as El-Nino, La-Nino, +/- IOD on the KG river catchment area rainfall. Figure 6a and 6b, shows the interannual KG tracer transport crossing the longitudes ~150 and ~900 km away from the river mouth. In all the years the KG waters crosses the V1 line between July-October and between 12^{0}N to 18^{0}N (Figure 6a), where as in some year this continuous till next year March particularly in the years occur together with +IOD and El-Nino (1994, 1997 and 2006). V2 section (Figure 6b) shows the KG water transport more pronounced in year with +IOD and El-Nino except some years for example 2001 & 2008.

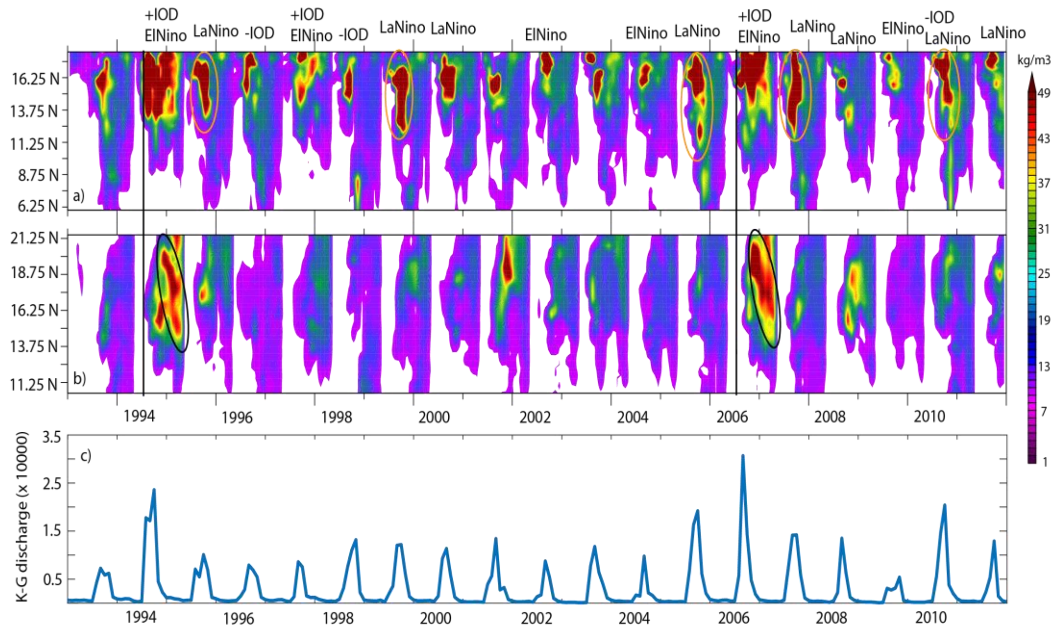

Fig 6: The monthly time-latitude section of KG tracer concentrations along the a) 83.5^{0}E (V1), b) 90^{0}E (V2) and the interannual monthly KG runoff (b).

Similarly we also looked into the time-latitudinal sections one north (H1) of the KG river mouth and three south of the river mouth (H2, H3 and H4) presents in Figure 7. The KG waters are largely transported to the north crossing H1 section during October – Mar in the year associated with +IOD & El-Nino. H2 section conforms the KG water transport every year in October – December very close the coast and some years with early spread of fresh water around 200 – 400 km away from the coast. Section H3 also shows presence of KG water transport during November-December very close to the coast but with some exception for those years with El-Nino. Where as KG waters cross H4 section only some years, majority of KG waters lies inside the bay north of 10^{0}N latitude.

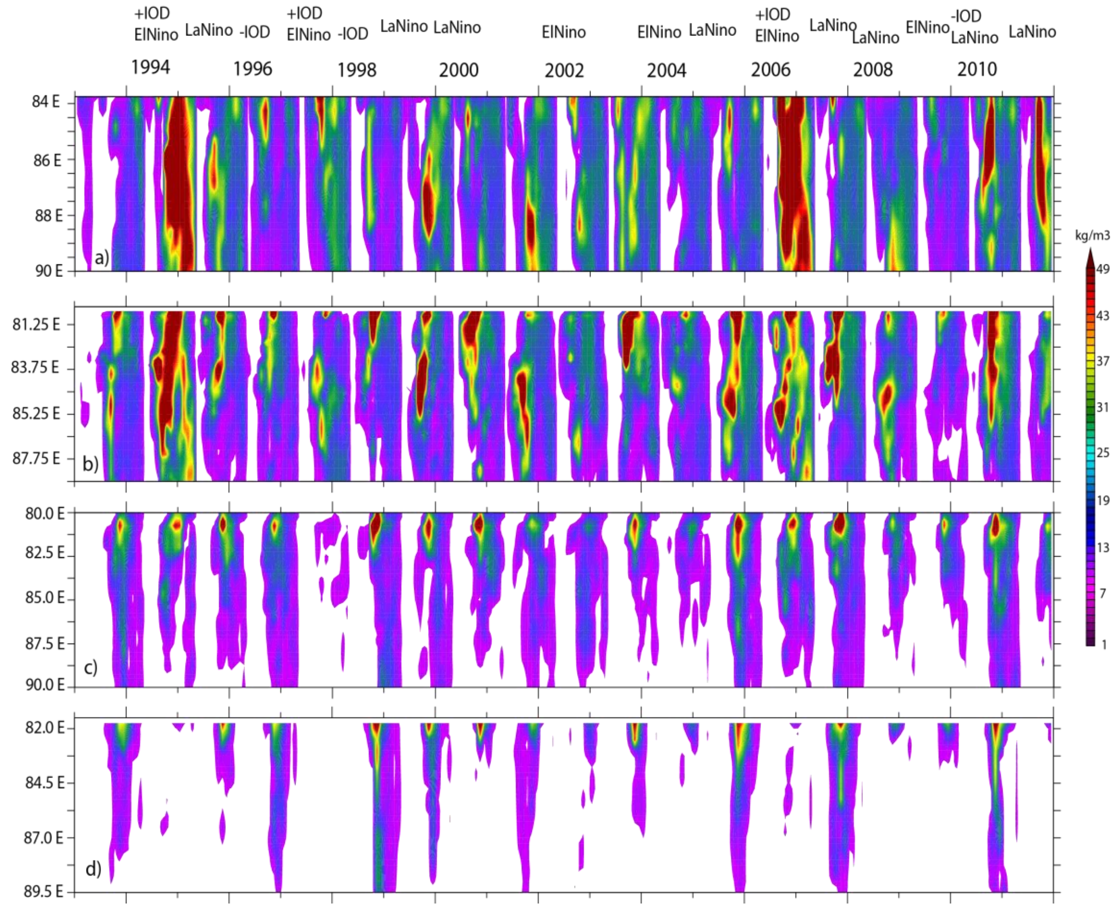

Fig 7: The monthly time-longitude section of KG tracer concentrations along the a) 17.5^{0}N (H1), b) 14.5^{0}E (H2) c) 10.5^{0}N (H3) and d) 7.5^{0}E (H4).

In this section we try to compare the spatial patterns of KG water transport due to the each climatic event. Figure 8, shows the August – November spatial spread for the selected years associated with (1994, a1-a4) El-Nino together with +IOD, (1996, b1-b4) –IOD, (1997, c1-c4) El-Nino together with +IOD and weak KG runoff, (1999, d1-d4) La-Nino, (2002, e1-e4) El-Nino, (2003, f1-f4) Normal year without any co-existence of climate modes and (2010, g1-g4) La-Nino associated with –IOD. During El-Nino the surface circulation transports KG waters largely into the northern bay by the end of November, where as in normal years without any climate mode the southward transport along the east coast of southern India and Sri lanka is noticed. Similar to normal year the La-Nino, -IOD and both together presence enhances the narrow southward flow along the southern Indian coast and Sri lanka. During August-September the KG waters shots directly into the off shore as like as in climatological maps (Figure 5c-e).

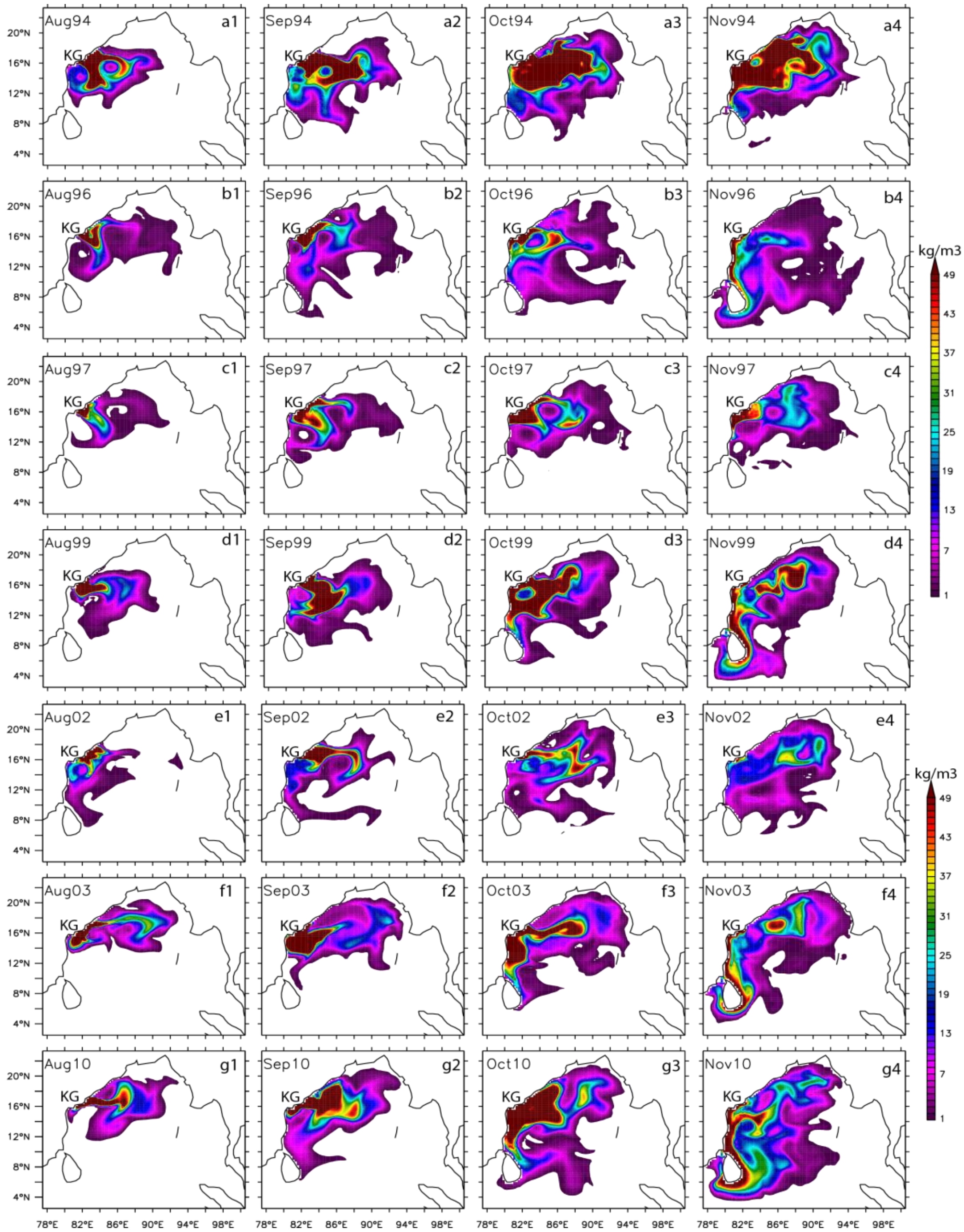

Fig 8: The monthly evolution of KG tracer concentration from August-November for different years associated with climate modes impact, a) El-Nino with +IOD (1994), b) –IOD (1996), c) El-Nino with +IOD (1997) associated with below average KG runoff, d) La-Nino (1999), e) El-Nino (2002), f) Normal year without ENSO/IOD (2003) and g) La-Nino with –IOD (2010).

Apart from this climate modes impact on tracer transportations, one can also notice recirculating mesoscale structures, which transport KG water in loops independent of climatic modes. These circulating features are largely seen at the edge of plumes every month every year at different locations. But there are few mesoscale eddies co-exist every year more or less at similar place, for examples a clockwise re-circulating feature south of KG river mouth close to the Andhra coast (left panels in Figure 8). Most of these recirculating mesoscale eddies are prominent in the western Bay of Bengal and there are filament like structures at the far edge of KG plume. The cross-sectional transport of KG waters plotted in Figure 6 & 7, were synthesized in Table 1. We considered the concentration crossing the vertical and horizontal sections with a threshold of about 20 kg/m^3 at any location. the KG waters cross the all sections during La-Nino associated with –IOD and normal years, where as the years with only either La-Nino or –IOD display no cross-sectional transport along the V2 section as strong as in normal year. Except for the year 1995 and 2008 a freshwater blob found between 14^0 -17^0N is could be due to the mesoscale eddies over the central Bay of Bengal. The most KG waters trapped in the central Bay of Bengal and do not allow to transport KG waters much further south along the coast of Sri lanka. The positive IOD always co-occur with El-Nino and some year only El-Nino itself, during these years the cross-sectional flow of KG water is observed only across V1, H1 and H2, but for the years 1994 & 2006 El-Nino & +IOD years show strong transport which crosses the section V2 and H3 is due to strong runoff input from the KG river system and the associated mesoscale eddies over the western Bay of Bengal.

CONCLUSIONS

The model simulated tracer concentrations for KG river transport over the Bay of Bengal analyzed to understand the seasonal and interannual variability. The seasonal transportation from June-December display offshore transport towards the central Bay of Bengal during early summer and later from the end of the monsoon it starts flow along the southern east coast of India and Sri lanka. In the view of ENSO/IOD the interannual variability of KG tracers over the period 1993 - 2011 shows that the KG tracer southward spread is restricted to the north of 10^0N during El-Nino and El-Nino associated with +IOD. During La-Nino and –IOD display strong southward spreading. The cross-sectional horizontal and vertical transport conforms the impact of ENSO/IOD on the spatial spreading of KG waters. The maps of KG water spatial spreading in different years and cross-sectional flow time-sections also confirms the existence of mesoscale eddies and transporting of KG waters to the much further offshore by trapping in their core.

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