Spatio-temporal variability of zooplankton standing stock in eastern Arabian Sea inferred from ADCP backscatter measurements

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Abstract

The study focuses on the zooplankton standing stock in the eastern Arabian sea (EAS) and aims to understand its spatio-temporal variation using ADCP(acoustic Doppler current profiler) backscatter measurements. The ADCP moorings were deployed at multiple locations on the continental slope of the west coast of India; of which we have used data from October 2017 to January 2023. The ADCP (operating frequency 153.3 kHz) uses backscatter from or sediments or organisms such as copepods, ctenophores, salps and amphipods greater than 1 cm to calculate current profile. The conversion from backscatter to biomass is based on volumetric zooplankton sampling at the respective locations. Analysis of the data over 25-140 m shows that the backscatter and zooplankton biomass decrease from the upper ocean (215 mg m^{-3} biomass contour) to the lower depths. Seasonal variation is noticed in the monthly climatology zooplankton standing stock (integral of

the biomass over the 20-140m water column) along with change as we move to northward slope moorings in EAS. Complementary parameters (mixed layer depth, net primary production, Chl-a, sea surface temperature) is used to explain the processes leading to growth or decay in zooplankton biomass and on their migratory behaviour. Additionally, we have studied the effect of wind induced vertical mixing events. The findings of this research will contribute to a better understanding of the zooplankton dynamics in the EAS and provide valuable insights into the seasonal and annual cycles of zooplankton standing stock.

1 Introduction

1.1 Background

Zooplankton plays a vital role in food web of pelagic ecosystem by enabling the hierarchical transport of organic matter from primary producers to higher trophic levels impacting the fish population and the carbon pump of the deep ocean [Ohman and Hirche, 2001, Le Qu et al., 2016]. They are presumably the largest migrating organisms in terms of biomass [Hays, 2003] which occurs in Diel Vertical Migration (DVM). Zooplanktons depend not only on phytoplankton but other environmental parameters (e.g. Mixed layer depth, insolation, Oxygen, thermocline, nutrient availability, chlorophyll concentration and daily primary production). The biological productivity of the ocean is essentially connected with physics and chemistry [Subrahmanyan, 1959, Ryther et al., 1966, Qasim, 1977, Nair, 1970, Banse, 1995, McCreary et al., 2009, Vijith et al., 2016]. The dynamic ocean results in varying physico-chemical properties, leading to bloom and growth of planktons in favourable conditions. The changes are strongly influenced by the seasonal cycle in the North Indian Ocean (NIO; north of $5\,^{o}$N of Indian Ocean). The eastern boundary of Arabian Sea contains the West India Coastal Current (WICC; [Patil et al., 1964, Ramamirtham and Murty, 1965, Banse, 1968, Shetye et al., 1991, McCreary Jr et al., 1993, Shankar and Shetye, 1997, Shetye and Gouveia, 1998, Maheswaran et al., 2000, Amol et al., 2014, Chaudhuri et al., 2020, 2021]) which reverses seasonally, flowing poleward (equatorward) during November to February (June to September).

The direct consequence of this reversal is the seasonal cycle of thermocline, oxycline and thickness of mixed Layer Depth (MLD) induced by upwelling favourable conditions in summer and downwelling favourable conditions in winter in eastern Arabian Sea (EAS). Further, the phytoplankton biomass and chlorophyll concentration changes with the season [Subrahmanyan and Sarma, 1960, Banse, 1968, Lévy et al., 2007, Vijith et al., 2016]. Upwelling in summer monsoon leads to maximum chlorophyll growth in the entire EAS [Banse, 1968, Banse and English, 2000, McCreary et al., 2009, Hood et al., 2017]. During winter monsoon, the convective mixing induced winter mixed layer [Shetye et al., 1992, Madhupratap et al., 1996b, Lévy et al., 2007, Vijith et al., 2016, Shankar et al., 2016, Keerthi et al., 2017] results in winter chlorophyll peak in northern EAS (NEAS) while the downwelling Rossby waves modulate chlorophyll along the southern EAS (SEAS) albeit limited to coast and islands [Amol et al., 2020]. (For a detailed description on EAS division, please refer figure 1 of [Shankar et al., 2019].

The zooplankton grazing peak is instantaneous with no time delay from peak phytoplankton production [Li et al., 2000], but its population growth lags [Rehim and Imran, 2012, Almén and Tamelander, 2020] depending on its gestation period and other limiting aspects. While some studies suggest that the peak timing of zooplankton may not change in parallel with phytoplankton blooms [Winder and Schindler, 2004], others indicate that lag exists between primary production and the transfer of energy to higher trophic levels [Brock and McClain, 1992, Brock et al., 1991]. A recent work [Aparna et al., 2022] had shown that peak zooplankton population may never occur even with a bloom in phytoplankton such as in SEAS, leading to the collapse of ecological models and succeeding food webs of higher trophic levels.

The conventional zooplankton measurements, where only few snapshot/s of the event is captured gives an incoherent or incomplete understanding in terms of spatio-temporal variation of zooplankton [Ramamurthy, 1965, Piontkovski et al., 1995, Madhupratap et al., 1992, 1996a] as much information is revealed by later studies [Jyothibabu et al., 2010, Vijith et al., 2016, Shankar et al., 2019, Aparna et al., 2022] using high resolution data. Calibrated acoustic instruments such as Acoustic Doppler Current Profiler (ADCP) along with relevant data can be utilised to understand small scale variability [Nair et al., 1999, Edvardsen et al., 2003, Smith and Madhupratap, 2005, Smeti et al., 2015, Kang et al., 2024], the complex interplay between the physico-chemical parameters and ecosystem [Jiang et al., 2007, Potiris et al., 2018, Shankar et al., 2019, Aparna et al., 2022, Nie et al., 2023], the zooplankton migration [Ursella et al., 2018, 2021] and their seasonal to annual variation [Jiang et al., 2007, Hobbs et al., 2021, Liu et al., 2022, Aparna et al., 2022].

1.2 ADCP backscatter and zooplankton biomass

At present, there are two types of acoustic samplers: non-calibrated single frequency acoustic profiler such as ADCP or calibrated multi and mono frequency acoustic profilers such as zooplankton acoustic profiler (ZAP) and Tracor acoustic profiling system(TAPS). The use of acoustics as a proxy for zooplankton biomass estimation can be traced to [Pieper, 1971, Sameoto and Paulowich, 1977] and earlier studies which used echograms to approximate the large-scale horizontal extents [Barraclough et al., 1969], and small scale vertical extent [McNaught, 1968]. The relationship between backscatter and the abundance and size of zooplankton was described by [Greenlaw] wherein it was pointed out that single frequency backscatter can be used to estimate abundance if mean zooplankter size is known. This paved the way for use of single frequency acoustic profiler. A drastic increase in study temporal and spatial variation of zooplankton biomass using backscatter-proxy came in 1990s by introduction of high frequency echosounders, with studies [Flagg and Smith, 1989, Wiebe et al., 1990, Batchelder et al., 1995, Greene et al., 1998, Rippeth and Simpson, 1998] methodically showing acoustic backscatter estimated zooplankton biomass in various shelf and slope locations around North Atlantic, North pacific location. The foundation for further research that investigated the potential of acoustic backscatter from ADCPs and multi frequency echosounders in assessing zooplankton biomass and comprehending zooplankton dynamics in diverse maritime habitats was established by these initial explorative experiments.

Acoustic backscatter and zooplankton biomass have been better understood as a result of technological and methodological developments over time. Net sampling augmented ADCP backscatter have been used to study DVM and the spatial and temporal variability of zooplankton biomass by [Cisewski et al., 2010, Smeti et al., 2015, Guerra et al., 2019] in various marine regions, such as the Southwestern Pacific, the Lazarev Sea in Antarctica and the Corsica Channel in the north-western Mediterranean Sea. The zooplankton biomass variation in the Arabian sea has been studied during JGOFS programme in 1990s [Herring et al., 1998, Nair et al., 1999, Fielding et al., 2004, Smith and Madhupratap, 2005]. However, their studies were limited to the cruise duration as vessel mounted ADCPs were predominantly used; hence longterm data was sparsely produced. The first such study to fully exploit the immense potential of ADCPs in EAS was carried out by [Aparna et al., 2022] using ADCP moorings deployed on continental slopes off the Indian west coasts [Amol et al., 2014, Chaudhuri et al., 2020].

1.3 Objective and scope of the manuscript

A network of ADCPs has been installed off the continental slope and shelf on the west coast of India. This ADCPs have enabled a rigorous view of intraseasonal to seasonal scale variability [Amol et al., 2014, Chaudhuri et al., 2020]. Initially a network of 4 ADCPs (off Mumbai, Goa, Kollam and Kanyakumari) on continental slope, it has been extended to include 3 more moorings (off Okha from 2018, Jaigarh and Udupi from 2017). In the recent study [Aparna et al., 2022] have used ADCP moorings off Mumbai, Goa and Kollam to explain the temporal variability of zooplankton biomass. The study showed that the zooplankton peaks (and troughs) is not only non-uniform in latitude but also heavily influenced by the oxygen minimum zone, MLD and the seasonal upwelling/downwelling conditions. Stark contrast in the phytoplankton bloom and subsequence growth of zooplankton or the lack thereof was observed in the EAS regimes.

We build upon the existing work by extending to include the newly incorporated ADCPs so as to have a better understanding in the latitudinal variation of zooplankton biomass in EAS. The paper is organized as follows, datasets and methods employed are described in detail in Secion 2. Section 3 describes the observed seasonal cycle of zooplankton biomass and standing stock. The role of mixed layer depth, net primary production, sea surface temperature, wind forcing and circulation in determining the biomass is discussed in results section 4, with conclusion in section 5.

2 Data and methods

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Table 1: ADCP deployment detatils at the locations. The temporal resolution is 1 hour, bin size(vertical resolution) 4 m. All ADCPs are operated at 153.3 kHz. The moorings are at a water column depth of 950 - 1200 m on the continental slope and are serviced on yearly basis according to ship availability. The 6th column consists of Reference echo intensity (Er) for each beam, while the 7th column contains the corresponding RSSI conversion factor [?].

	Date		Depth			
Station (Position; ^{o}E,^{o}N)	Deployment	Recovery	Ocean	ADCP	Er	Kc
Okha (67.47, 22.26)	01/10/2018	01/12/2019	996	118	37 , 37 , 37 , 36	0.42 , 0.44 , 0.42 , 0.43
	01/12/2019	04/12/2020	1166	312	39 , 36 , 38 , 36	0.42 , 0.44 , 0.42 , 0.43
	04/12/2020	08/03/2022	1021	144	41 , 37 , 38 , 37	0.42 , 0.44 , 0.42 , 0.43
	08/03/2022	01/01/2023	1019	142	37 , 38 , 39 , 36	0.42 , 0.44 , 0.42 , 0.43
Mumbai (69.24, 20.01)	09/11/2017	29/09/2018	1025	150	36 , 34 , 39 , 42	0.40 , 0.40 , 0.40 , 0.40
	29/09/2018	29/11/2019	1122	125	35 , 36 , 39 , 42	0.40 , 0.40 , 0.40 , 0.40
	29/11/2019	02/12/2020	1143	164	37 , 34 , 39 , 43	0.40 , 0.40 , 0.40 , 0.40
	02/12/2020	06/03/2022	1125	142	36 , 34 , 39 , 42	0.40 , 0.40 , 0.40 , 0.40
	07/03/2022	02/01/2023	1103	158	37 , 34 , 40 , 43	0.40 , 0.40 , 0.40 , 0.40
Jaigarh (71.12, 17.53)	27/10/2017	27/09/2018	1039	198	32 , 35 , 33 , 32	0.45 , 0.45 , 0.45 , 0.45
	27/09/2018	30/10/2019	1032	164	32 , 35 , 33 , 31	0.45 , 0.45 , 0.45 , 0.45
	03/11/2019	30/11/2020	1142	264	32 , 36 , 33 , 32	0.45 , 0.45 , 0.45 , 0.45
	30/11/2020	05/03/2022	1099	119	33 , 36 , 34 , 32	0.45 , 0.45 , 0.45 , 0.45
	03/04/2022	26/06/2022	1120	136	68 , 71 , 69 , 66	0.45 , 0.45 , 0.45 , 0.45
Goa (72.74, 15.17)	03/10/2017	25/09/2018	1000	174	35 , 37 , 34 , 35	0.44 , 0.44 , 0.40 , 0.41
	25/09/2018	16/10/2019	969	145	38 , 36 , 36 , 34	0.44 , 0.44 , 0.40 , 0.41
	16/10/2019	29/11/2020	966	143	44 , 38 , 36 , 43	0.44 , 0.44 , 0.40 , 0.41
	29/11/2020	03/03/2022	985	157	35 , 40 , 35 , 38	0.44 , 0.44 , 0.40 , 0.41
	03/03/2022	05/01/2023	984	159	35 , 38 , 35 , 34	0.44 , 0.44 , 0.40 , 0.41
Udupi (74.04, 12.5)	05/10/2017	06/10/2018	1028	176	44 , 46 , 29 , 35	0.45 , 0.45 , 0.45 , 0.45
	06/10/2018	18/10/2019	1027	179	32 , 38 , 30 , 36	0.45 , 0.45 , 0.45 , 0.45
	18/10/2019	11/12/2020	1018	168	33 , 37 , 31 , 38	0.45 , 0.45 , 0.45 , 0.45
	11/03/2022	06/01/2023	1036	155	31 , 32 , 32 , 33	0.45 , 0.45 , 0.45 , 0.45
Kollam (75.44, 9.05)	07/10/2017	08/10/2018	1174	200	43 , 55 , 45 , 43	0.49 , 0.50 , 0.49 , 0.50
	08/10/2018	20/10/2019	1160	123	49 , 62 , 46 , 46	0.49 , 0.50 , 0.49 , 0.50
	20/10/2019	13/12/2020	1209	176	52 , 61 , 54 , 55	0.49 , 0.50 , 0.49 , 0.50
	13/12/2020	13/03/2022	1129	91	49 , 51 , 46 , 47	0.49 , 0.50 , 0.49 , 0.50
	13/03/2022	08/01/2023	1149	164	41 , 48 , 43 , 41	0.49 , 0.50 , 0.49 , 0.50
Kanyakumari (77.39,6.96)	16/11/2016	08/10/2017	1096	252	37 , 36 , 37 , 37	0.42 , 0.44 , 0.42 , 0.43
	08/10/2017	10/10/2018	1055	181	32 , 34 , 38 , 35	0.45 , 0.45 , 0.45 , 0.45
	10/10/2018	22/10/2019	1075	180	36 , 34 , 39 , 36	0.45 , 0.45 , 0.45 , 0.45
	22/10/2019	14/12/2020	1060	167	33 , 35 , 36 , 35	0.45 , 0.45 , 0.45 , 0.45
	14/12/2020	14/03/2022	1184	287	34 , 36 , 36 , 35	0.45 , 0.45 , 0.45 , 0.45
	14/03/2022	10/01/2023	1069	172	33 , 36 , 42 , 36	0.45 , 0.45 , 0.45 , 0.45

Table 2:
Volumetric samples of zooplankton of various stations. The tags corresponds to cruise and particular station. The sampling depth range is standardised for later years for bin range of 0-25m, 25-50m, 50-75m, 75-100m, 100-150m

Sample number	Tag	Lat(^{o}N)	Lon(^{o}E)	Date	Time (IST)	Sampling depth range (m)
1-3	G1	15.18	72.79	25 Sep 18	452	50–25, 100–50, 150–100
4-6	G2	15.16	72.71	25 Sep 18	2108	50–25, 100–50, 150–100
7-10	G2	15.16	72.71	25 Sep 18	2137	40–20, 60–40, 80–60, 100–80
11-14	J1			26 Sep 18	2000	40–20, 60–40, 80–60, 100–80
15-17	J2			27 Sep 18	2000	50–25, 100–50, 150–100
18-21	J2			27 Sep 18	2100	40–20, 60–40, 80–60, 100–80
22-25	M1	20	69.19	28 Sep 18	2135	40–20, 60–40, 80–60, 100–80
26-27	M1	20	69.19	28 Sep 18	2205	50–25, 100–50
28-29	M2	20.01	69.2	29 Sep 18	2035	50–25, 100–50
30-33	M2	20.01	69.2	29 Sep 18	2057	40–20, 60–40, 80–60, 100–80
34-37	U1			5 Oct 18	2000	40–20, 60–40, 80–60, 100–80
38-40	U1			5 Oct 18	2100	50–25, 100–50, 150–100
41-43	U2			6 Oct 18	2000	50–25, 100–50, 150–100
44-47	U2			6 Oct 18	2100	40–20, 60–40, 80–60, 100–80
48-51	K1	9.06	75.42	8 Oct 18	421	40–20, 60–40, 80–60, 100–80
52-54	K1	9.06	75.42	8 Oct 18	449	50–25, 100–50, 150–100
55-56	K2	9.04	75.4	8 Oct 18	2027	50–25, 100–50
57-60	K2	9.04	75.4	8 Oct 18	2045	40–20, 60–40, 80–60, 100–80
61-64	G2	15.16	72.74	16 Oct 19	829	50–25, 75–50, 100–75, 150–100
65-67	G3	15.16	72.74	16 Oct 19	1812	50–25, 75–50, 100–75
68-70	K2	9.02	75.42	20 Oct 19	840	50–25, 75–50, 100–75
71-74	K3	9.04	75.43	20 Oct 19	1934	50–25, 75–50, 100–75, 150–100
75-78	KK1			22 Oct 19	742	50–25, 75–50, 100–75, 150–100
79-82	KK2			22 Oct 19	1925	50–25, 75–50, 100–75, 150–100
83-86	J1			30 Oct 19	324	50–25, 75–50, 100–75, 150–100
87-89	J2			4 Nov 19	946	75–50, 100–75, 150–100
90-92	M2	19.98	69.22	29 Nov 19	1434	50–25, 75–50, 100–75
93-96	M3	20.01	69.23	30 Nov 19	958	50–25, 75–50, 100–75, 150–100
97-100	O1	22.24	67.49	1 Dec 19	937	50–25, 75–50, 100–75, 150–100
101	O2	22.25	67.46	1 Dec 19	1957	150-100
102-105	G3	15.68	73.22	28 Nov 20	930	50–25, 75–50, 100–75, 150–100
105-108	G4	15.32	73.22	29 Nov 20	1558	50–25, 75–50, 100–75, 150–100
108-110	J2	17.85	71.21	30 Nov 20	1458	75–50, 100–75, 150–100
111-114	J3	17.91	71.21	1 Dec 20	1052	50–25, 75–50, 100–75, 150–100
115-118	M4	20.03	69.38	2 Dec 20	2016	50–25, 75–50, 100–75, 150–100
119.00	O2	22.41	67.8	4 Dec 20	953	150-100
120-123	O3	22.41	67.79	4 Dec 20	2011	50–25, 75–50, 100–75, 150–100
124-127	K3	9.11	75.72	12 Dec 20	2335	50–25, 75–50, 100–75, 150–100
128-131	K4	9.06	75.74	13 Dec 20	1507	50–25, 75–50, 100–75, 150–100
132-134	KK1	7.62	77.63	14 Dec 20	1226	50–25, 75–50
135-138	KK2	7.62	77.63	14 Dec 20	2047	50–25, 75–50, 100–75, 150–100
139-142	G4	15.32	73.21	3 Mar 22	823	50–25, 75–50, 100–75, 150–100
143-146	G5	15.68	73.21	4 Mar 22	1030	50–25, 75–50, 100–75, 150–100
147-150	M5	19.99	69.23	7 Mar 22	957	50–25, 75–50, 100–75, 150–100
151-154	O3	22.24	67.5	8 Mar 22	806	50–25, 75–50, 100–75, 150–100
155-158	U3	12.5	74.04	12 Mar 22	1156	50–25, 75–50, 100–75, 150–100
159-160	K4	9.04	75.42	13 Mar 22	1027	50–25, 75–50, 100–75
161-164	KK3	6.97	77.4	15 Mar 22	1220	50–25, 75–50, 100–75, 150–100

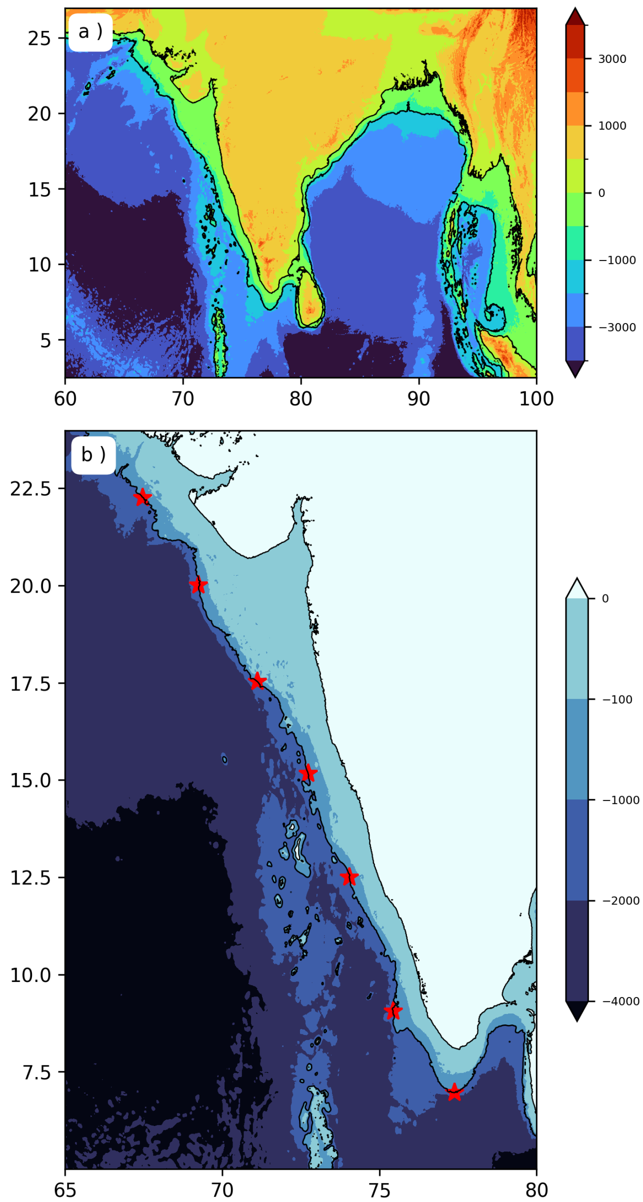


Figure 1: Map showing region of interest. The slope moorings are deployed at 1000 m depth.

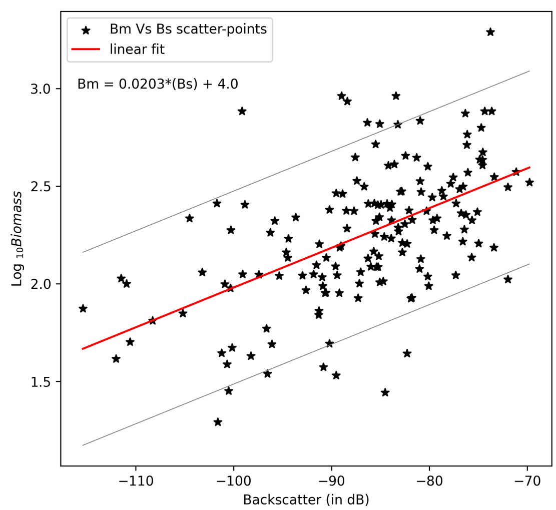


Figure 2: The linear fit line of Biomass (taken in log of biomass) and Backscatter. The linear fit line is within the error range of previous result of [Aparna et al., 2022] onto which latest zooplankton volumetric sample data is added.

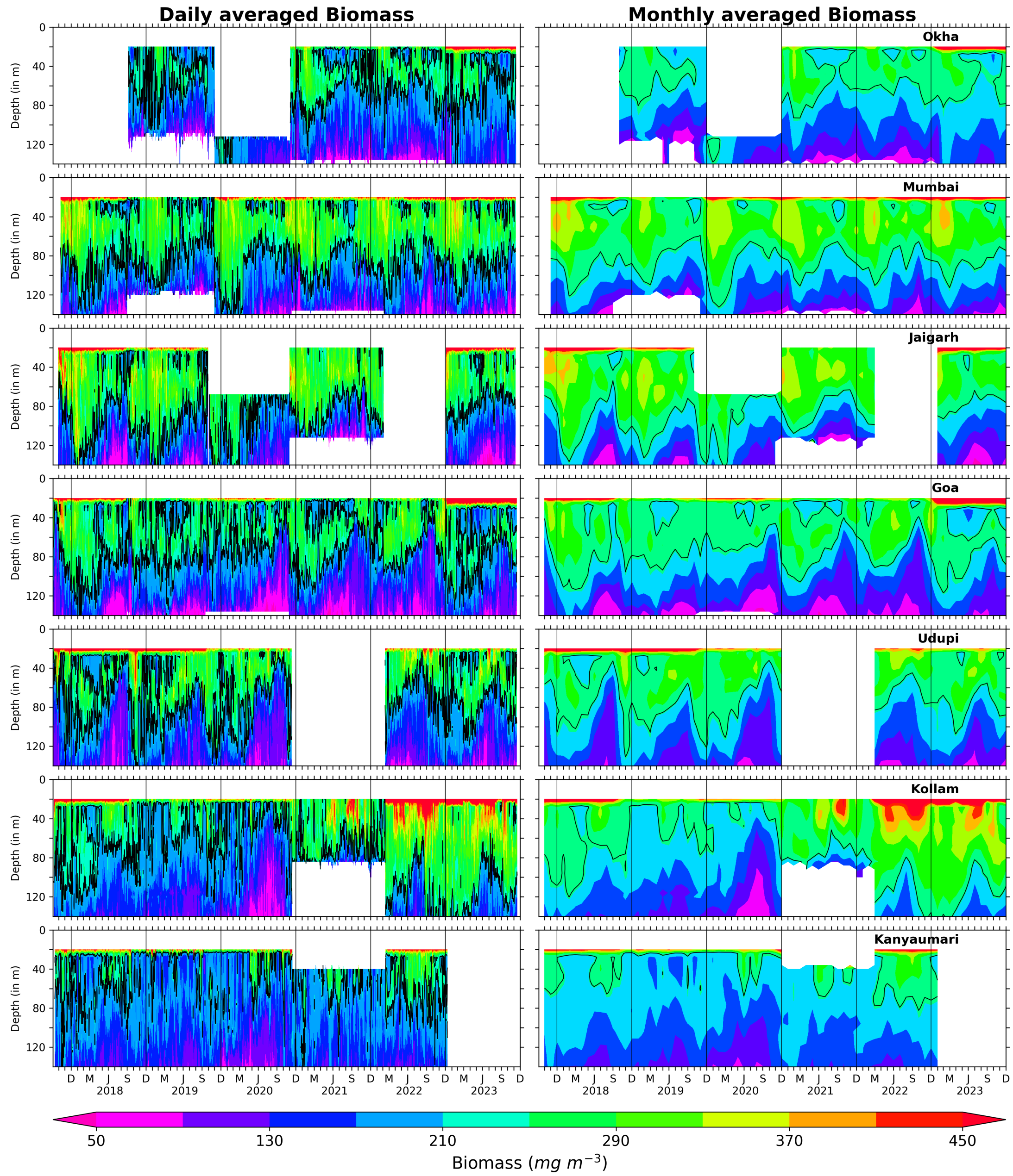


Figure 3: The Daily and monthly averaged biomass for EAS moorings, north (top) to south (bottom). The dark contours are marking 215 mgm^{-3}.

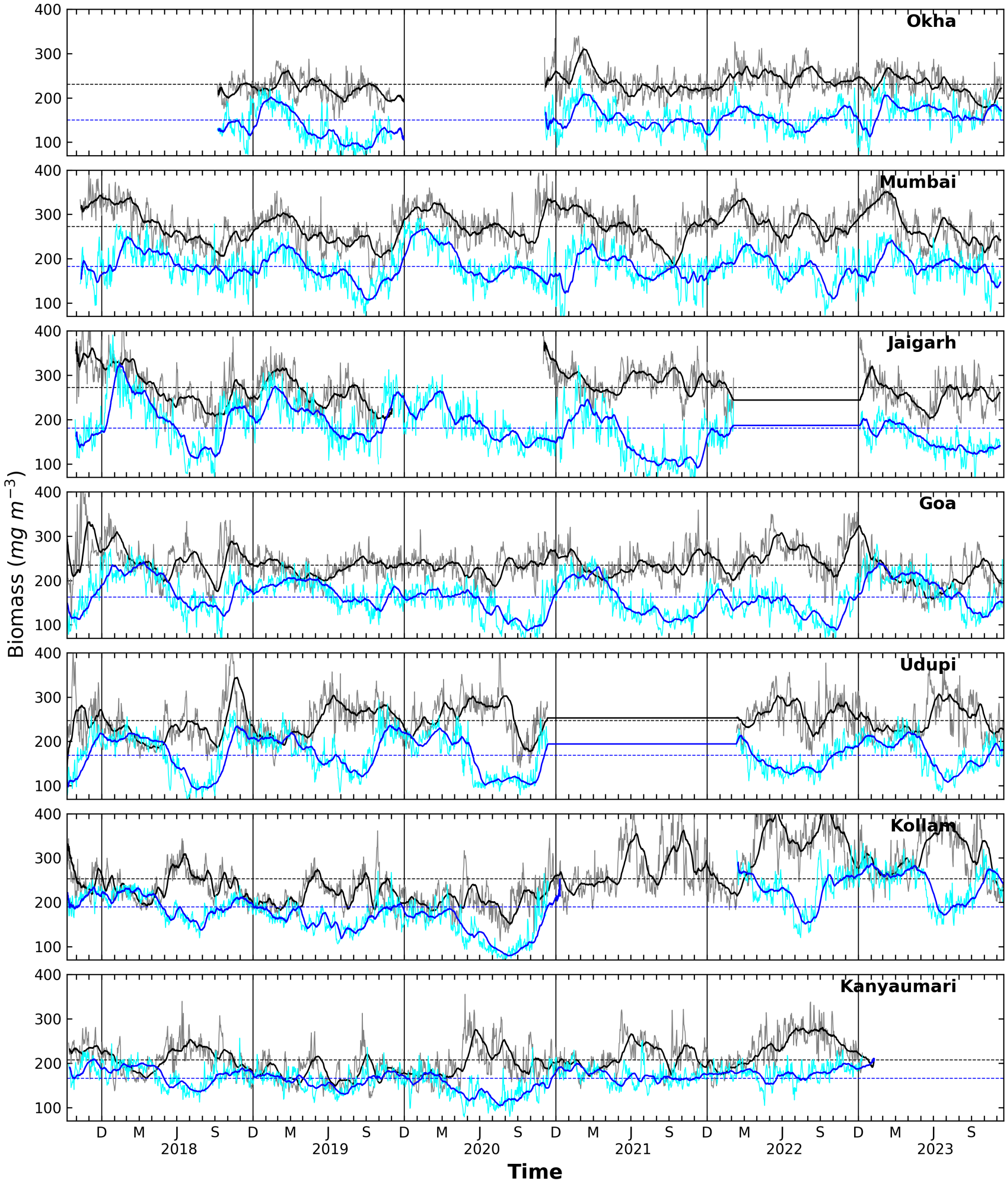
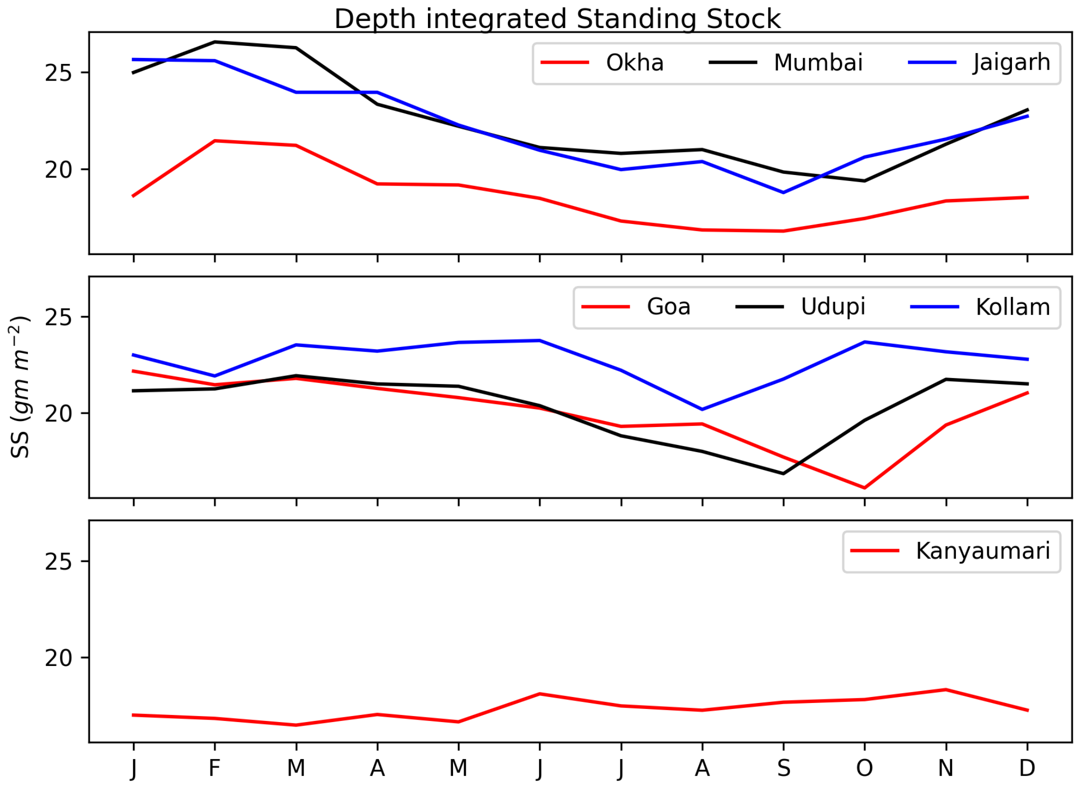


Figure 4: The daily biomass at depth of 40 m and 104 m for all locations shown by grey and cyan curves. The black and blue lines shows the 30 day rolling averaged biomass.



Depth integrated Standing Stock
Okha
Mumbai
Jaigarh
Goa
Udupi
Kollam
Kanyaumari
SS ($gm\ m^{-2}$)
25
20
J
F
M
A
M
J
J
A
S
O
N
D

Figure 5