Abstract of ECSN Flash Talks

Understanding the biophysical interactions in the tropical Indian Ocean in the changing climate

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Marine phytoplankton plays an inevitable role in global biogeochemical cycles, regulates the global climate and forms the base of the marine food web. The tropical Indian Ocean is a highly productive basin making it an excellent source of food and livelihood for the Indian Ocean rim countries. This high productivity is driven by the physical mechanisms associated with the summer monsoons. However, the Indian Ocean has been undergoing the fastest rate of warming amongst the tropical oceans since the 20th century. During the southwest monsoon, the phytoplankton blooms in the Indian Ocean are tightly coupled to climatic changes in sea surface temperature (SST) and winds. Using multi-sensor blended satellite observations of chlorophyll (a proxy for phytoplankton biomass) along with a suite of historical simulations from the CMIP earth system models, we find a decrease of up to 30% in phytoplankton in the western Arabian Sea and 20% in the models over the past five decades [1]. These chlorophyll trends are driven by increased ocean stratification caused by rapid warming in the Indian Ocean, which inhibits nutrient mixing from subsurface layers. Wind-induced upwelling trends and accompanying variations in chlorophyll are trivial during this period, indicating that SSTs have a larger role in influencing phytoplankton blooms than fluctuating winds.

Moreover, CMIP5 and CMIP6 Earth system models predict a significant decline in surface chlorophyll concentrations in the future [2,3]. Since phytoplankton are at the base of the marine food web and have immense capacity to regulate carbon sequestration in the ocean, the impact of climate change on these oceanic phytoplankton severely impacts the life in the ocean. Along with phytoplankton abundance, Intergovernmental Panel on Climate Change (IPCC) suggests phenology as one of the indicators of climate change. The seasonal bloom timings (e.g., bloom onset) of phytoplankton determine the availability of food for the aquatic food web; hence, any alteration in the phenology of phytoplankton impacts the higher trophic levels of the food chain, such as fisheries, thereby affecting people. This work studies the mean phenology of the Indian Ocean as well as the variability and shifts in the phytoplankton phenology as a result of climate change processes.

Continuous remote-sensed daily fields of ocean colour now span more than two decades and provide a unique opportunity to examine phenology. However, the persistent cloud cover of the summer monsoon leads to a significant percentage of missing values in daily ocean colour observations. This constrains the evaluation of phytoplankton phenology in the tropical Indian Ocean to date. Consequently, gap-filling is required. Common gap-filling methods, such as interpolation and

smoothing are limited to single-value imputation and ignore error estimates. Though convenient for datasets with fewer missing pixels, these techniques introduce potential biases in datasets having a higher percentage of gaps, such as in tropical Indian, where the satellite coverage is reduced by up to 40% due to the seasonally varying cloud cover during the summer monsoon. Therefore, we use the Monte-Carlo method, which is based on inferential statistics, to fill in the missing values in the ocean colour data [4]. Using this gap-filled data to estimate phenological parameters allows us to quantify uncertainty, otherwise often overlooked in scientific studies.

The seasonal cycle of phytoplankton blooms in the tropical Indian Ocean varies between regions, which is an additional important characteristic of the basin. This is because different hotspots in the Indian Ocean experience different biophysical interactions. Consequently, we use our gap-filled dataset and a machine learning algorithm to identify the bioprovinces in the Indian Ocean. After identifying the coherent clusters, we analyse the biophysical interactions and phenological indices (bloom initiation, peak, and termination) within each bioprovince. The study investigates the variability and shifts in phytoplankton phenology as a result of the warming of the tropical Indian Ocean. This will help advance our understanding of the marine ecosystem functioning in the tropical Indian Ocean.

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Air-Sea flux of DMS and its potential controls over the northern Indian Ocean during the post-monsoon season

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Dimethyl sulfide (DMS: CH3SCH3) is the most abundant volatile organic sulphur compound present in the remote marine atmosphere. DMS is the predominant natural sulphur source to the atmosphere globally, and accounts for >50% (~28 Tg(S) yr−1) of natural sulphur gas emissions (Lovelock et al., 1972; Andreae, 1990; Kloster et al., 2006). Moreover, DMS also play a significant role in modulating the atmospheric chemistry as well as climate. Oceans are the major source of DMS into the atmosphere. The production of DMS in surface seawater is primarily through enzymatic breakdown of Dimethylsulphoniopropionate (DMSP), a metabolite produced by phytoplankton during metabolic activities, grazer attack, senescence, change in physical parameters (like temperature and salinity), etc (Krist et al., 1991; Wolfe et al., 1997; Bullock et al., 2017). However, the release of DMS into the atmosphere is controlled by kinetic conditions near the air-sea interface, and expediates with increasing turbulence (Liss and Merlivat, 1986; Wanninkhof, 1992; Woolf, 1993). Thus, estimation of air-sea flux of DMS is not straight-forward, there lies a complex interplay of several environmental factors including local biogeochemistry, temperature of the surface seawater, and turbulent conditions near the interface.

The northern Indian Ocean (IO), particularly Arabian Sea is one the most productive Oceanic regimes. The northern IO experiences strong turbulence during summer monsoon due to seasonal reversal of winds, and intense cyclonic disturbances during inter-monsoon periods. Hence, the region is potentially a significant source of DMS emissions. However, the data over the regions is sparse, only a handful of studies have reported variability of DMS concentrations in the Arabian Sea (Shenoy and Kumar, 2007). The lack of studies over the northern IO is a large source of uncertainty chemistry-climate models.

To study the spatio-temporal variability of DMS and other Volatile Organic Compounds (VOCs) over the Arabian Sea and Bay of Bengal, we participated in two cruise campaigns (Fig.1), during September-November 2021. High time resolution in-situ measurements were collected using Gas Chromatography-Flame Photometric Detector/ Flame Ionization Detector (GC-FPD/FID) onboard. To estimate DMS flux, we used the two-layer exchange model by Liss and Slater (1974). Back-trajectory data was obtained from NOAA’s HYSPLIT model.

We aim to study the processes governing the variability of DMS flux over both the basins, and investigate its dependence on oceanic and meteorological parameters.

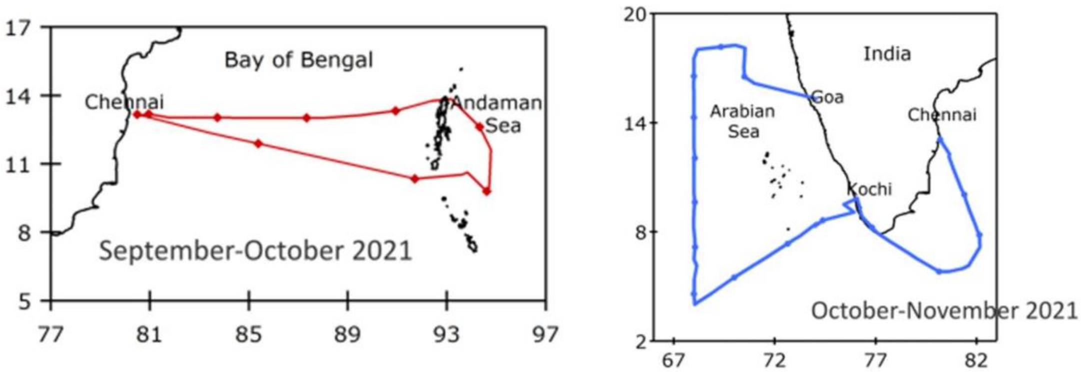

Fig.1: Cruise tracks of SK-373 (red) and SK-374 (blue) campaigns over the Bay of Bengal and Arabian Sea, respectively.

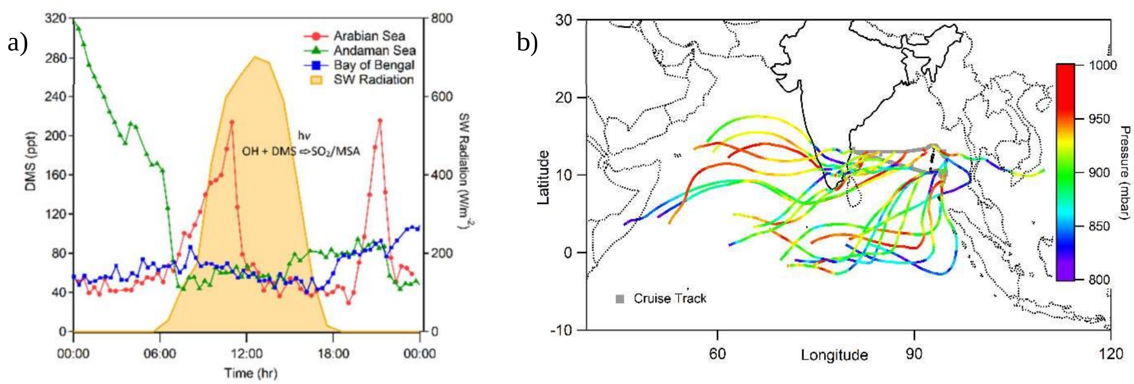

Fig.2: (a) Typical diurnal variation in DMS over different oceanic regimes, (b) 5-day backward trajectory from NOAA's HYSPLIT model at 500m amsl.

In our preliminary analysis, strong diurnal dependence can be observed with significant photochemical loss during noon period (Fig.2a). Background concentration indicates night time DMS activity in Arabian Sea. In the Bay of Bengal, the variation of DMS concentration follows that of relative humidity parameter, indicating the influence of fresh oceanic emissions. Relatively high level of DMS (>400 ppt) was observed over the Andaman Sea region, is suspected to be due to enhanced local oceanic biogenic sources and the transport of air masses from the southern/equatorial IO as seen form the back trajectory analysis (Fig.2b). DMS and concurrent Isoprene concentrations showed almost opposite variability trend over the Bay of Bengal, can be attributed to the change in local biogeochemistry including dissolved organic matter and phytoplankton species composition, OR terrestrial influence in few locations that showed transport of continental airmass in back-trajectory analysis. Overall, the level of DMS was found to be higher over the Arabian Sea.

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Investigating the surface chlorophyll bloom within the Seychelles-Chagos Thermocline Ridge and the role of the Indonesian Throughflow

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Introduction

The Seychelles-Chagos Thermocline Ridge (SCTR) is an region of open ocean upwelling within the south west Indian Ocean, approximately 5°S to 10°S and 45°E to 90°E. The SCTR refers to an elongated feature which joins two local minima in thermocline depth; the Seychelles Dome (SD) and Chagos Domes (CD) in the west and east respectively[1]. The upwelling, sustained year round by negative wind stress curl, planetary beta effect and Rossby wave interactions, is biologically important as it is associated with seasonally increased surface chlorophyll a (chl-a) concentrations[1,2,3]. The raised thermocline allows for surface chl-a blooms to develop as nutrients are uplifted towards the surface and subsequently entrained or advected into the euphotic zone[3].

Although the upwelling is present year-round, its intensity and spatial extent varies at seasonal times scales[4]. Over the SD, the uplift of the thermocline is characterised by a clear semi-annual signal, while the surface chl-a bloom shows a strong annual cycle with a single bloom season which peaks concurrently in time at both the SD and CD. Furthermore, the SCTR shows a strong western intensification, where the elongated ridge weakens and the SD strengthens from June to August. The western intensification results in differences between the ocean and surface chl-a bloom dynamics in west and east extremes of the SCTR. The CD appears weakened in the east concomitant to the seasonal entrance of the Indonesian ThroughFlow (ITF) in the basin, and shows an annual cycle in both the uplift of the thermocline and the surface chl-a bloom.

A key characteristic of the south west Indian Ocean is the seasonal shrinkage of the geostrophic ocean gyre, a circulation feature unique to the Indian Ocean. This occurs when the South Equatorial Counter Current (SECC) recirculates before arrival to Sumatra, in apparent synchronization with the annual influx of relatively warmer and fresher waters from the ITF[4]. Recently, it is has been demonstrated that the buoyancy flux introduced via the ITF drives the SECC recirculation and the associated seasonality of the geostrophic circulation[4]. We hypothesize this phenomenon drives the weakening of the remotely sensed signal of the surface chl-a bloom as it imposes a buoyant plume which counteracts the upwelling site over the CD.

In this work, we present the seasonal evolution of the surface chl-a bloom for both the western (SD) and eastern (CD) extremes of the SCTR, investigating the physical ocean drivers of the chl-a bloom from both *in situ* observations and remotely sensed data. We find the influence of the buoyancy fluxes from the ITF on the surface chl-a may be relevant to account for the observed variability at inter-annual scales and, therefore, discuss further the relationship between the strength of the ITF and the strength and spatial extent of the surface chl-a, especially over the east extreme of the tropical gyre, where the impact of the ITF is higher.

Data and methods

The data presented was obtained from open access data platforms. The *in situ* observations were obtained from the World Ocean Atlas (WOA18)[5,6,7]. WOA18 is an objectively analysed, gridded field with a horizontal resolution of 1°. The monthly climatologies are calculated from 1955-2017.

Remote sensing data of the Absolute Dynamic Topography (ADT) and chlorophyll-a (chl-a) concentrations were obtained from Copernicus Marine Service (CMEMS). ADT and derived velocities were accessed from a merged, L4 product with a spatial resolution of 0.25°, averaged monthly (SEALEVEL_GLO_PHY_L4_MY_008_047). The chl-a concentrations were obtained from the a merged L4, with a 4km spatial resolution. The data extracted ranged from 1997-2021 and averaged monthly (OCEANCOLOUR_GLO_BGC_L4_MY_009_104).

Results

Figure 1 shows the monthly evolution (every second month) of the SCTR through a set of basin-wide vertical sections where ocean properties have been zonally averaged within the latitudinal range 5.5°S – 11°S. This figure is an updated version of Figure 11 in Aguiar-González et al., 2016[4]. The entrance of the ITF in the basin, propagating westward, is highlighted as the buoyant plume embedded by the isohaline of 34.8 (and fresher waters) in the east.

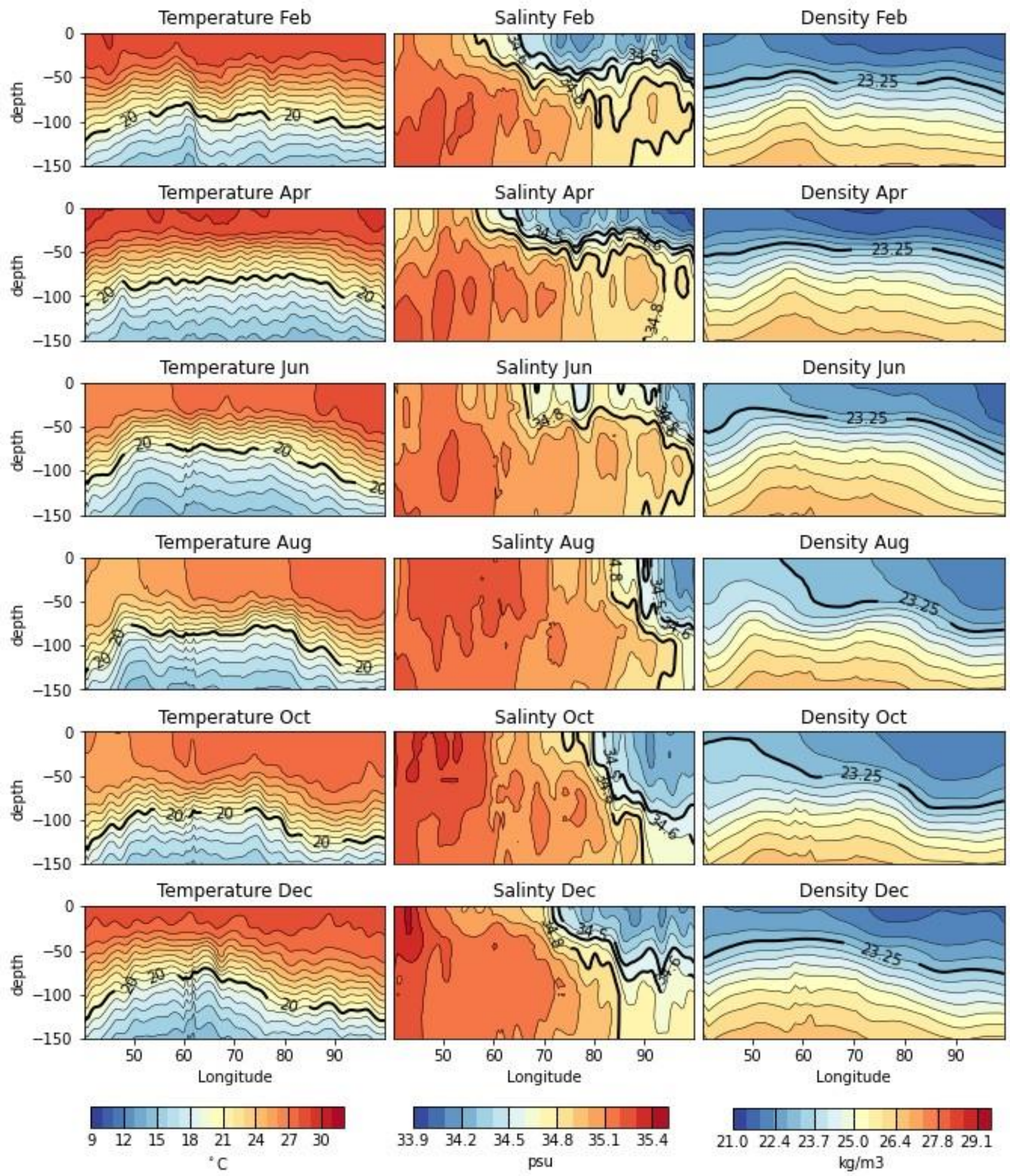

Figure 2) Zonally-avaraged vertical sections of temperature (column 1), salinity (column 2) and density (column 3) from the World Ocean Atlas (WOA18). The variables are monthly climatologies from the period 1955-2017. The slices were average latitudinally from 5.5°S to 11°S, covering the latitudinal extent of SCTR. Every second month was shown for brevity.

February and April showed the ITF at the furthest westward position as a shallow warm, less saline layer from the surface down to 60m depth. The new input of fresh, warm waters from the ITF occurs from June onwards, penetrating to depths down to 100 meters and forcing the 20°C isotherm downwards in the eastern basin (latitudes > 80°E). The impact of the ITF is weaker in the western margin of the basin, especially from August to October, when the isopycnals are tilted upward. From December onwards, the ITF propagates as a plume of shallow warm, less saline waters reaching its most westward extension in April and down to 60 meters depth.

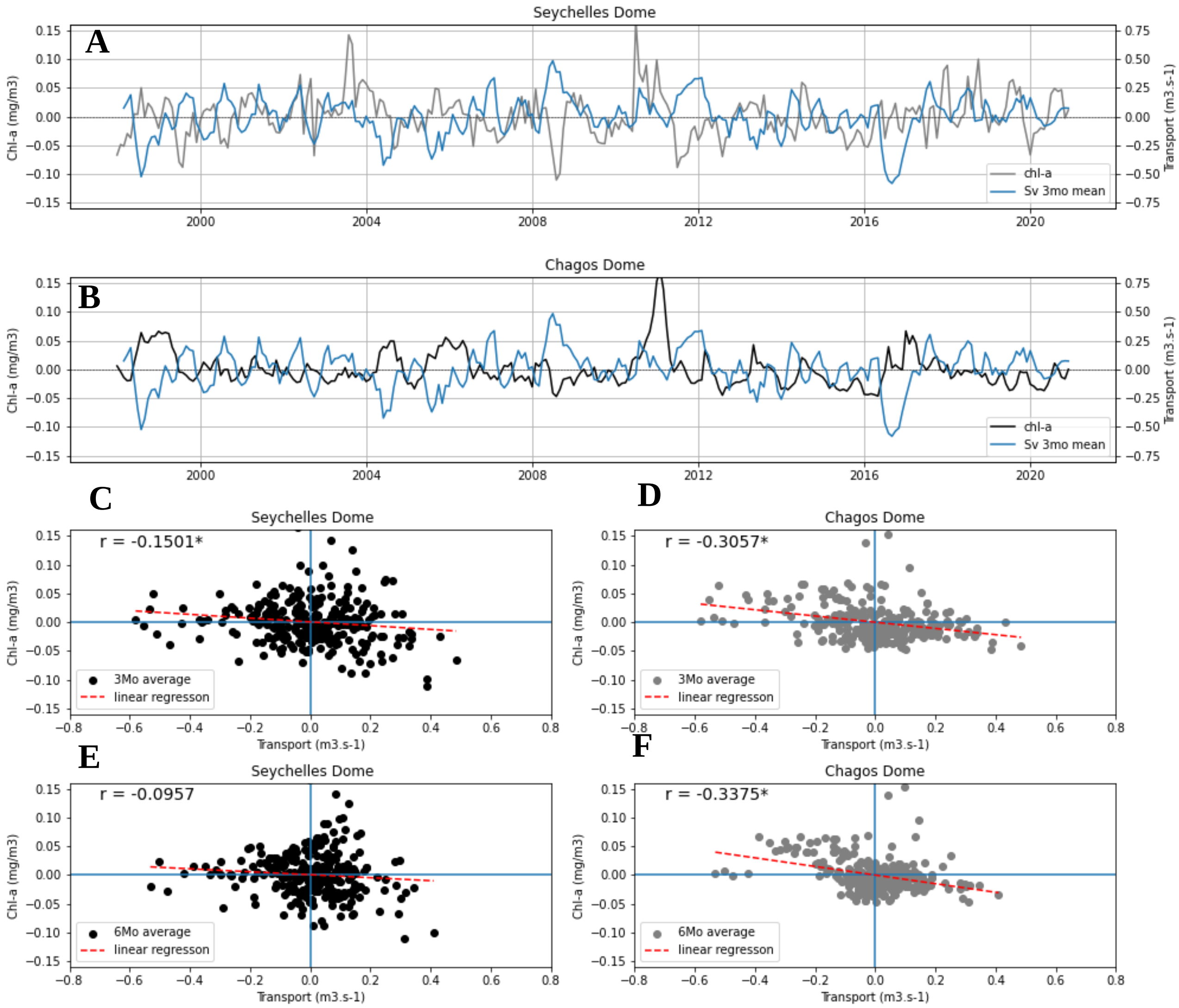

Figure 2. (a, b) Mean monthly anomalies of surface chl-a and ITF transport (three month running mean) through a section from 3°S to 13°S and 45°E to 70°E for the SD and CD. The surface chl-a were averaged spatial within boxes set at the location of the SD and CD determined by ADT. (c, e) Scatter plots and correlation between the monthly anomalies of ITF and surface chl-a concentration over the SD for the three month and six month running mean, the star indicates a significant correlation. (d, f) The same as in panels c and d but for the CD.

Following the pattern displayed in Figure 1, we hypothesize that the entrance of the ITF in the basin may be weakening the upwelling site over the CD and, therefore, the local development of the surface chlorophyll bloom. We explore this hypothesis in Figure 2, analysing the inter-annual variability of ITF volume transport and its likely impact on the development of the surface chl-a bloom, spatially averaged over the SD (panel a) nd CD (panel b). The strength of the ITF was inferred by calculating the transport through a section from 3S to 13S and 45°E to 70°E, assuming constant flow to a depth of 10m. The transport was calculated from geostrophic velocities derived from ADT. The monthly anomalies of the transport were average using a three month running mean and six month running mean in order to account for the lag of the westward propagation of ITF, which Figure 1 showed to be in order of three to six months. For both the three and six month running mean we find an inverse significant correlation (r) of -0.30. and -0.34, respectively, for the CD (panels d and f). Positive (negative) anomalies in transport through the section were associated with decrease (increased) surface chl-a concentrations. This correlation supports our hypothesis that the ITF may impact the surface chl-a bloom through buoyancy fluxes, which depress the thermocline and increases stratification. The correlations for the SD showed little to no relationship with correlations (r) of –0.09 and -0.15 (panels c and e), indicating the influence of the ITF may be limited to the eastern extreme of the SCTR. In addition to the correlations, years with extreme anomalies are analysis to further support further our hypothesis (Figure 2 a, b).

Conclusions and future work

The strength of the ITF appears to impact the surface chl-a within the Chagos Dome. The relationship is likely due to the buoyancy flux where strong inputs from ITF suppresses the thermocline and ‘caps’ the Chagos Dome with warm, less saline waters. Accordingly, our results suggest that the influence of the ITF may be an important factor for surface chl-a within the SCTR on inter-annual, annual and longer-term time scales. Idealised model experiments will be used to further investigate the relationship between the IFT and the spatio-temporal variability of the chl-a bloom within the SCTR.

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Recent progress on bio-optical studies along 110° E in the southeast Indian Ocean

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Abstract

Bio-optical properties of ocean waters along 110° E in the southeast Indian Ocean were investigated during a research voyage carried out on *R/V Investigator* in May-June 2019. This voyage was part of the second International Indian Ocean Expedition (IIOE-2), and replicated the route taken by the *HMAS Diamantina* in May-June 1963 as part of the first International Indian Ocean Expedition. Bio-optical observations were used to find out an appropriate optical proxy for phytoplankton carbon and relation between phytoplankton carbon and chlorophyll. The comprehensive data sets along a 3300 km transect started from mesotrophic conditions (chlorophyll concentration of 0.5 mg m^{-3}) around 40°S to oligotrophic conditions (0.04 mg m^{-3}) towards 10°S. The data set comprises both inherent and apparent optical properties, particle characteristics, biogeochemical quantities such as phytoplankton pigments and particulate organic carbon. Photosynthetic parameters were also determined from ^{14}C incubations. Combining this unique dataset, satellite data and model-based approaches, will allow better understanding and predictability of dynamics of phytoplankton and associated productivity on a regional and global scale. This data set also improves our understanding of the relationship between phytoplankton carbon, optical properties, and ultimately satellite ocean colour observations. These data not only are useful for answering optics-related questions but also help improving our understanding of how optical properties and biogeochemical variables are related in biogeochemical models. Assimilation of such data, especially the contribution of phytoplankton (size-specific and pigments) and non-algal particles to the particulate backscattering coefficient will provide new opportunities to enhance the performance of coupled optical- biogeochemical models.