Variability of Ocean Features and their Impact on Cyclogenesis over Arabian Sea During Post Monsoon Season

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Variability of ocean features and their impact on cyclogenesis over Arabian Sea during post monsoon season

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Arabian Sea (AS), the western sector of North Indian Ocean (NIO) produce smaller number of tropical cyclones as compared to Bay of Bengal. Though limited in numbers, the cyclones over Arabian sea are catastrophic by character. This make west coast of Indian subcontinent vulnerable to these hazards. The post-monsoon cyclogenesis over this region is known to be modulated by both monsoon rainfall and the El-Niño accompanied with positive Indian Ocean Dipole events. No single phenomena, however, can fully explain the variability observed in AS region.

In this study, it is observed that apart from several known atmospheric forcings, inter-annual variability of ocean heat content (OHC) influence the post-monsoon AS cyclogenesis. The OHC of this region is partially modulated by the changes in salinity. Heat exchanges between the South West Indian Ocean (SWIO) and AS also modulates the OHC over AS. This remote influence is facilitated largely by the variability in the equatorial currents. Further it is seen that the recent trend of increased OHC post-2011 matches with the enhanced sea surface carbon over AS.

1. Introduction:

Arabian Sea (AS) which represents the western part of North Indian ocean (NIO), is relatively calm in terms of convective activities as compared to the eastern sector i.e. Bay of Bengal (BoB). Climatologically, more cyclones form in BoB as compared to inert AS (Sahoo and Bhaskaran 2016). This in-equal cyclogenesis is primarily because the ocean/atmospheric dynamics over these regions are entirely different. It is well known that atmosphere plays a critical role in cyclogenesis. Several studies like Ali et al 2013 and 2007, Shay et al 2000, Goni et al. 2003 etc also highlighted important role of ocean in modulation of cyclone track and intensity. In this paper emphasis is only on the ocean forcing for cyclogenesis over AS. The distribution asymmetry of cyclones between AS and BOB has been vividly discussed in Sattar and Cheung, 2019. An active convective season in AS is often associated with a less active convective season over BoB. This phenomenon is more pronounced in post monsoon months of October-December (Evan and Camargo, 2011; Sattar and Cheung, 2019). From ocean preview, BOB and AS are very different. Over BoB, active river discharge makes upper layer of the ocean fresh. This make the ocean stratified with shallow mixed layer depth (MLD). A stratified ocean retain heat in upper layers (Akhil et al 2014) making BoB a hotspot for cyclone formation.

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AS, on the other hand have much less river discharge unlike BoB, making it more saline region that normally produce less number of cyclones. AS is known to be comparatively more active for cyclogenesis during the El-Niño years accompanied with positive phase of Indian Ocean Dipole (IOD) as compared to a simple El-Niño Years (Sumesh and Ramesh Kumar 2013)**.** The seasonal distribution of the tropical cyclones over the Arabian Sea is bimodal. Cyclone formation peaks during pre-monsoon phase of May-June and during post-monsoon phase of October-December. During both these phases the cyclones causes the storm surges accompanied with large amplitude wind waves and tides. On an average 1-2 cyclones form over AS, most are intense enough to cause an impactful landfall. These makes AS cyclones hazardous for the west coast of India. (Murthy and Sabh 1984). In an interesting study Evan and Camargo (2011) showed that cyclones of May and June over AS are associated with early and late monsoon onset, respectively. The cyclones in November are associated with high sea level pressure over BoB. Thus, an active cyclonic season in AS implies non-occurrence in BoB. Off late in the post monsoon months, AS has shown a significant rise in the cyclonic activities. The persistence of AS cyclones from 2011 onwards makes the perception about its innerness quite precarious. Increasing cyclonic activity over AS was also linked to global warming by Prassana kumar et al 2009 and Murakami et al 2017. Albeit there are studies conducted on AS cyclone climatology and inter annual changes in environmental factors modulating cyclogenesis, yet studies discussing the inter-annual variability of physical and chemical properties of underlying oceans that may be important for changing behaviour of the AS is rare.

In this study, we observe the inter-annual changes of the Ocean Heat Content (OHC) are significantly correlated with variability of cyclogenesis over AS during the post monsoon month of Oct-Dec of 1979-2017. The study aims at better understanding of the ocean processes that could possibly contribute towards the variability of OHC in this region. OHC variability over AS is found to be influenced by the local changes in physical and chemical properties of ocean. One important local property is variability in freshening which is found to modulates OHC by regulating heating of the upper ocean. The phase of increased OHC over AS interesting matchup with higher partial pressure of sea surface carbon over Arabian sea. Heat exchange between the South Western Indian Ocean (SWIO) and AS is also an important aspect that influence OHC.

2. Data and Methods

We explore best track data from 1979-2019 available from U.S. Navy's Joint Typhoon Warning Centre (JTWC) to look into long term record of cyclones over AS. The mean precipitation over AS and adjoining SWIO was analysed to observe its dependence on ENSO events. This is done using Climate Prediction Centre (CPC) Merged Analysis of Precipitation (CMAP) data. Ocean salinity and temperature fields are taken from Ocean Re-Analysis (ORAS4) data provided by European Centre for Medium Range Weather Forecast (ECMWF). Using ORAS4, ocean heat content and its freshening is studied. Prior to its use, ORAS4 data is validated using temperature/salinity profiles from in-situ ARGOs. Observation based gridded monthly SPCO2 is used to analyse ocean carbon content and its correlation with SST. SST data used here is collected from ECMWF Reanalysis (ERA) interim datasets. A brief description of the data and methodology is provided below.

According to JTWC, over AS, total 88 cyclones formed during January-December of 1979-2019. Out of these, 27 were pre-monsoon (Apr-Jun) cyclones and 53 during post-monsoon (Oct-Dec). Our study strictly restricts to post monsoon phase. Best-track information of JTWC provide date/time of genesis and maximum sustained wind speed with locations. Cyclones vary

in terms of occurrence, intensity and duration. For determining inter-annual variability of cyclone-intensity, one must consider all of these simultaneously. A decent way to do this is computing accumulated cyclonic energy (ACE) for each cyclone of a year and then adding them up. Mathematically ACE is represented in equation-1 below as:

$$\mathbf{ACE = 10^{-4} \sum V^2_{max}} \qquad \mathbf{(1)}$$

The maximum wind speed (V_{max}) is considered till landfall. Some cyclones formed in BoB, and after landfall crossed southern coast of India and came to AS. We have considered only those data points which are in the AS (50°E-75°E,0°N-25°N). The ACE hence calculated is used to study the inter-annual variability of cyclonic activity over AS. The years are categorized as El-Niño, La-Niña or normal years based on the Oceanic Niño Index (ONI) defined by NOAA. The ONI is used for detecting El Niño (warm) and La Niña (cool) events in the tropical Pacific. It is the running 3-month mean SST anomaly for the Niño 3.4 region (i.e., 5°N–5°S, 120°–170°W). Events are defined as 5 consecutive overlapping 3-month periods at or above the +0.5° anomaly for warm (El Niño) events and at or below the −0.5° anomaly for cold (La Niña) events. (http://ggweather.com/enso/oni.htm). Further the classification of years on basis of positive/negative Indian Ocean Dipole (IOD) events is taken bureau of meteorology (bom.gov.au). Table -1a and b shows this year wise categorization. Rainfall over AS and adjoining SWIO is modulated by these ENSO events. Inter-annual variability of rainfall over this region corresponding to the El-Nino/La-Nina and phases of IOD is studied using the CMAP data. CMAP data sets are monthly, global gridded precipitation at spatial resolution of 2.5°X2.5°. It contains gauge data along with five type of satellite based precipitation estimates from Global Precipitation Index (GPI), OLR Precipitation Index (OPI), Special Sensor Microwave/Imager (SSM/I) in scattering and emission mode and Microwave Sounding Unit (MSU).

ORAS4 from ECMWF is valuable resource for climate variability studies available at 0.5° spatial resolution from 1958-2017. It is based on a data-assimilative numerical ocean model called Nucleus for European Modelling of the Ocean (NEMO). 3D-Variational data assimilation technique (Balmaseda et al. 2013) is used for assimilation of altimeter data in this model. Though, the data is temporally extensive yet the first two decades of the data has to be used with caution. This is because of large uncertainties in absence of proper altimeter data. In this study the surface/subsurface temperature, salinity and current information from this reanalysis is extensively used in this study for the period of 1979-2017. ORAS4 has known limitation of underestimating the Atlantic meridional circulation and having large errors in surface salinity. Therefore, this data has been validated using the Argo profiles prior to its use. ORAS4 temperature profiles has been used to compute the ocean heat content over the SWIO and AS which is mathematically given as:

$$\mathbf{Heat\ Content} = \int_0^D \rho C p T dz$$

Here ρ is the density. Usually the density is salinity dependent, however for simplicity in calculation this is taken constant over AS. Cp is the specific heat at a constant pressure and T is the temperature of dz is infinitesimal depth of water. The calculation is limited between the surface to a depth D. One may consider D=2000m or even more. However, Häkkinen et al. 2016 shows heat content up to 2000 m produces similar trend as that up to 700 m except for higher amplitudes. Thus, in this case D is taken as 700m. Further to analyse the heat exchanges between AS and SWIO, the meridional transport has been calculated using the ORAS4 data. Here

$$\textbf{Meridional Transport} = \rho Cp \iint_0^{700} vT dx dz$$

where dx and dy represents the small interval of longitude and latitude respectively.
The observation based global monthly gridded sea surface partial carbon die oxide is available from Max Plank Institute from 1982-2019. The reanalysis is based on an artificial neural network and is available at 1X1° spatial resolution (Landschützer et al 2017). To understand the way carbon, influence the ocean heat, its correlation with SST is explored. The 6-hourly data of SST from ECMWF Reanalysis i.e. ERA Interim has been utilized. The data is available in real time mode. The duration of the data is 1979 onwards. The data assimilation system used to produce ERA interim datasets is based on 2006 release of IFS (cy31r2) with a 4D vibrational data assimilation scheme. The data is of high quality and extremely useful multivariate climate data set (Dee, 2011).

3. Validation of ORAS4

Since we have utilized ORAS4 temperature and salinity extensively for this study, a gross validation was carried out using in-situ measurements ARGO. Argo profile (ID-2901337) provided by Indian National Centre for Ocean Information Services (INCOIS) is used for the comparison of temperature and salinity profile for the year 2012. Choice of this validation year is not arbitrary. In this year the Argo data discontinuity was minimum. Argo observations, located within 0.5°x0.5° grid were taken into account to compute the average observed monthly temperature. The average of four data points from ORAS4 within 0.5°x0.5° grid were computed to obtain average ORAS4 temperature and then these were inter-compared. The Argo observations were also linearly interpolated till 700m depth along the Z-axis at same vertical grid points as in ORAS4 data. The observed monthly mean was computed by taking the time average of Argo data for a particular month. The position of the Argo was also computed by taking the average of Longitudes/Latitudes over a given month. The variation in position of Argo while it is moving in vertical direction for a time-step has not been considered, which may be possible source of error in observed temperature fields.

The comparison of ORAS4 and Argo temperature for different months in year 2012 is shown in Figure 1. Clearly the temperature of Argo and ORAS4 agree with one another. Up to 700m we find good match between the duos. The RMSE of month of August is maximum out of all months i.e. 0.73, however the correlation coefficient exceeds 99% for all months. When it comes to salinity (Figure 2), up to 200m the ORAS4 matches well with Argo. However, after 200 m the salinity biases increases for AS. The surface salinity has a small bias for months of April, May and August; however, ORA is able to capture the largescale variability of the salinity over time. Therefore, while analysing the inter-annual variability of the salinity data from ORAs4, in this study we restrict ourselves to a depth between surface to 100m.

4. Results and Discussions

Long term post-monsoon precipitation over AS and adjoining areas like SWIO shows limited rainfall over Arabian Sea (AS) as compared to SWIO. CMAP monthly precipitation rate over the western part of Indian Ocean is shown in Figure 3. It clearly indicates that monthly averaged precipitation between 50°-70°E for October-December is high in SWIO. But towards AS, the precipitation decreases. Though limited in terms of occurrence, over AS these precipitation event has a strong inter-annual variability. Over SWIO the inter-annual variation of post monsoon rainfall rate between October to December and total 3 monthly precipitation rate has been shown in Figure 4. The years are classified into normal/El-Niño/La-Niña years

represented by black, red and green respectively. The combination of dash and dash-dots shows associated positive and negative phases of IOD. Very clearly, the precipitation is largely influenced by these air sea interaction processes. The years of El-Niño with a positive IOD has high precipitation over SWIO.

When we consider cyclonic events over neighbouring AS which contributes towards the mean precipitation of this region, such clear-cut conclusion cannot be drawn. AS has strong inter-annual variability in ACE as shown in Figure 5. In this figure time series of ACE from 1979-2019 (41 years) has been shown. The years are further categorized into normal/El-Nino/La-Nina years with dash and dash-dots representing associated positive and negative phases of IOD. It is noteworthy to see that the variation in ACE is modulated with occurrences of El-Niño/La-Niña and positive and negative phases of IOD. Particularly El-Niño or a positive IOD or both together enhances the ACE to a great extent. The cyclonic activities over AS shows kind of persistence between 1992-1998 and 2003-2004. Of late however cyclonic activities over AS has gradually increased and it is more pronounced after 2011. Thus, it is evident that no single event can explain cyclogenesis over AS to the fullest. In this regard, ocean as a system is very less discussed. We thus systematically analyse, first the local ocean conditions over AS and then the conditions that persists in SWIO and equatorial Indian Ocean that can be remotely influence the AS cyclones.

In order to investigate the local ocean conditions, we analyse Ocean Heat Content (OHC) over the AS computed using Equation 2. The ORAs4 data is utilized for this purpose. The Figure 6a shows the OHC over AS from 1979-2017. The Figure 6a indicates increase in OHC of AS post 2011. The figure 6b shows the correlation coefficient between the OHC and ACE over AS. The correlation here is generated using a moving window of five consecutive years or a pentad. Clearly the correlation took over in the pentad from 2007-2011 and there on it increases monolithically. Thus OHC is undoubtedly the ocean parameter which plays key role in cyclone energies.

It is well known that OHC is often modulated by freshening of the ocean. The fresh stratified layer with lower salinity, traps enormous heat in the upper layer of the ocean increasing the OHC. This process of stratified ocean trapping heat is much discussed for BOB. Thus, corresponding variability in salinity is analysed for AS too and is shown in the Figure 7**.** Some of the quick look examples of such salinity modulated OHC are 1982, 1994, 1997 and 2015. In all these years salinity was less implying fresh upper layer of the ocean that can trap heat. This freshening could be a probable impact of good monsoon rainfall.

To a contrary, few noteworthy years of exceptions are also there. In these years freshening theory does not uphold. In 2004 salinity was comparable to 2015 but post –monsoon heat content was much less. In 2011, 2014, 2017 heat content was high enough, but salinity was also high. These exceptions are a clear-cut indication of an alternate forcing. To stepwise analyse these alternatives, we firstly considered the inter-annual variability of ocean surface carbon die oxide (CO2). Figure -8 shows time series of anomaly of partial pressure of CO_2 at ocean surface. We can clearly infer from figure -8 that the partial pressure of the carbon has monotonically increased after 2011 with high positive anomaly. 2003 and 2004 also shows higher pCo2 over AS. However, if these two are connected events or not is a matter of detailed study. To investigate this aspect, we analyse the SST from ERA interim data set and find the these are indeed spatially correlated (figure -9) with high level of statistical significance. Figure -9a) shows the correlation of SST and CO2 over the entire globe and 9b shows T –value for significance test of these correlation. It clearly implies that over North Indian Ocean the SST is highly correlated with the CO2 and therefore it could be one of the key factor controlling the

ocean heat. The trend of increasing cyclones after 2011 is effect of increased OHC corresponding to an enhanced ocean carbon content.

Apart from these local characteristics and their impact on cyclogenesis, North Indian Ocean (NIO), is known for getting boosts of ocean heat and energy from Southern Indian Ocean. Bhowmick et al 2019 has shown that BOB receives extra shots of heat energy during La-Niña years from the Western Pacific via south eastern Indian Ocean. Thus we cannot rule out a similar possibility for AS. Being in close proximity to AS, SWIO can extend its influence remotely over AS. However, these two areas are known to be separated by the strong equatorial currents. Also, since the spatial distance is much between the two, it is required to observe the heat content of this region prior to the post-monsoon. Hence, we observed the OHC of SWIO between Mays to Septembers. The figure10 shows the OHC in SWIO along 10S. Very clearly after 2011 there was normal variability in the OHC of this area with usual modulation by El-Niño and La-Niña events along with positive and negative phases of IOD. Between 2011 -2017 there is a peak in OHC during 2015 followed by 2014 and 2011 where the ACE of AS also increases significantly.

However, before drawing an inference about influence of OHC of SWIO on AS cyclones it is necessary to analyse the way this heat gets into AS since there is strong equatorial current that stands in between. Therefore, the meridional transport of heat along the equator is analysed and is shown in Figure 11. It in general speaks about the kind of heat exchanges between AS and SWIO. In September and October, the meridional heat transfer is negative implying a southward propagation of heat, where the AS loses heat to SWIO. On the other hand, during November and December it is positive, meaning AS gaining heat from SWIO. After November 2007 we see a persistent positive transport of heat to AS from SWIO. Very clearly from this plot it can be seen that 2011 onwards the meridional transport for November and December between SWIO and AS is a northward propagation of the heat and energy and this exchange has increased. In all the exceptional years like 2011, 2014 and 2017, AS was heat-fed from SWIO. Even 2015 have got a fair supply of heat energy during November and December. The years 2003 and 2004 was having an upper ocean heat content of similar magnitude, however the 2004 was significantly more fresh and stratified than 2003. This ideally should imply a larger heat content for 2004 which however was not observed. This is typically because in 2004 the meridional heat transport from September-November was negative draining out heat from AS. However, 2004 has seen a significant ACE predominantly due to local freshening impact. 2003 on the other hand had got a fair supply of heat with positive meridional transport from SWIO (which was warmer in 2003) contributing for a decent ACE. Between 1992 to 1998 the ACE of AS was maintained without much variability. The OHC in this phase was also similar except large values in 1997 which is attributed to low upper ocean salinity. However, in 1997 most AS heat was transported towards south, making the available ocean energy for cyclone comparable with other years between 1992-98. Years 1992, 1994, 1995 and 1998 shows very large OHC in SWIO, but there was only significant meridional transport in 1992 and 1998.

Heat exchanges between AS and SWIO however can never happen unless the intermediate currents facilitate such exchanges. We analyse the inter-annual variation of zonal and meridional currents as shown in figure12. These are 700m average zonal and meridional currents along the equator. Very clearly the years which are having a higher meridional transport towards AS from SWIO are accompanied by a weakening of the zonal currents in the post monsoon months between September to November.

Thus, it can be inferred that from ocean point of view, AS cyclones are correlated to ocean heat content (OHC). The OHC is controlled by complicated combination of two factors. Firstly, local factor in which OHC of AS is found to be modulated by the increasing carbon content of

ocean and variability of salinity. Secondly there is remote influence of heat exchanges that takes place between AS and SWIO. This heat exchange is driven by post-monsoon meridional heat transport and is facilitated by weakening of the zonal equatorial currents.

5. Conclusion

Long term variability of accumulated cyclone energy (ACE) over Arabian Sea (AS) during the post monsoon month is analysed using cyclone records from JTWC. This is done from oceanic perspective. Records indicate that there are discrete phases of cyclonic activities over AS. Short spells of activity are from 1992-1998 and 2003-2004. Monotonic rise in AS cyclones is observed from 2011 onwards. In this study role of ocean parameters towards modulation of cyclone variability is studied. Ocean Heat Content (OHC) is found to play a critical role. The study shows, OHC over AS, is mostly governed by amalgamation of two factors. One of them is local and the other is a remote ocean process.

A reduced salinity due to good monsoon rainfall traps heat in upper parts of the ocean due to stratification, increasing the OHC. This is the first local process. Further, after 2011 the monotonic enhancement of partial pressure of carbon is found to be highly correlated to the SST of AS and therefore certainly modulates the local OHC.

When we discuss the remote impact, heat exchanges between AS and South Western Indian Ocean (SWIO) is important. We systematically examined these exchanges in light of intermediate equatorial currents. In many years the SWIO is contributing towards the heat content of AS promoting cyclonic activities, while in some years we find AS drains its heat to SWIO. This happens through meridional heat transport between them. The analysis of zonal and meridional current shows that the exchange of this heat is facilitated by weakening of the zonal equatorial currents during Novembers and Decembers. Thus apart from the atmospheric parameters, it is important to carefully consider the ocean salinity, heat content and transport between AS and SWIO for better predictability of the cyclones over this region.

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Declarations

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Conflicts of interest/Competing interests: Not Applicable

Authors' contributions

Suchandra A Bhowmick: Concept, experiment, analysis and writing.

Anup Mandal: Experiment and writing

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Figure and Tables

Table -1a: The El-nino/La-nina events were categorized from Oceanic Nino Index (ONI)

ONI > 0.5	**1982,1986,19871991,1994,1997,2002, 2004,2006,2009,2014,2015,2018**
ONI < -0.5	**1983,1984,1988,1995,1998,1999,2000, 2005,2007,2008,2010,2011,2016,2017**
-0.5<ONI< 0.5	**1979,1980,1981,1985,1989,1990,1992, 1993,1996,2001,2003,2012,2013,2019**

Table -1b: The Indian Ocean Dipole(IOD) conditions in different years

Positive IOD years	**Negative IOD years**
1982,1983,1994,1997, 2006,2012,2015,2019	**1981,1989,1992,1996, 1998,2010,2014,2016**

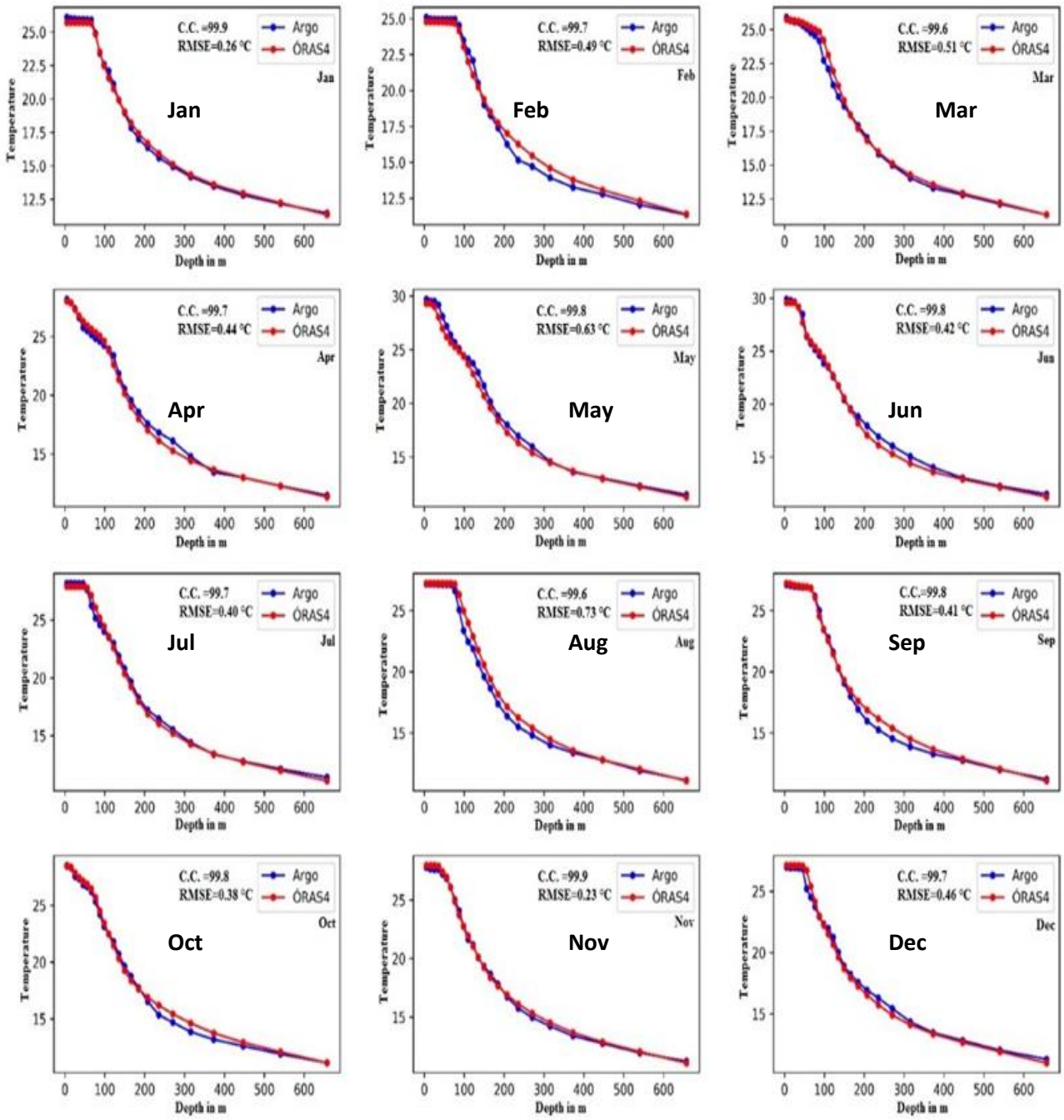


Figure-1 The Comparison of the ORAS4 temperature profile with an Argo measurement over Arabian Sea for 2012

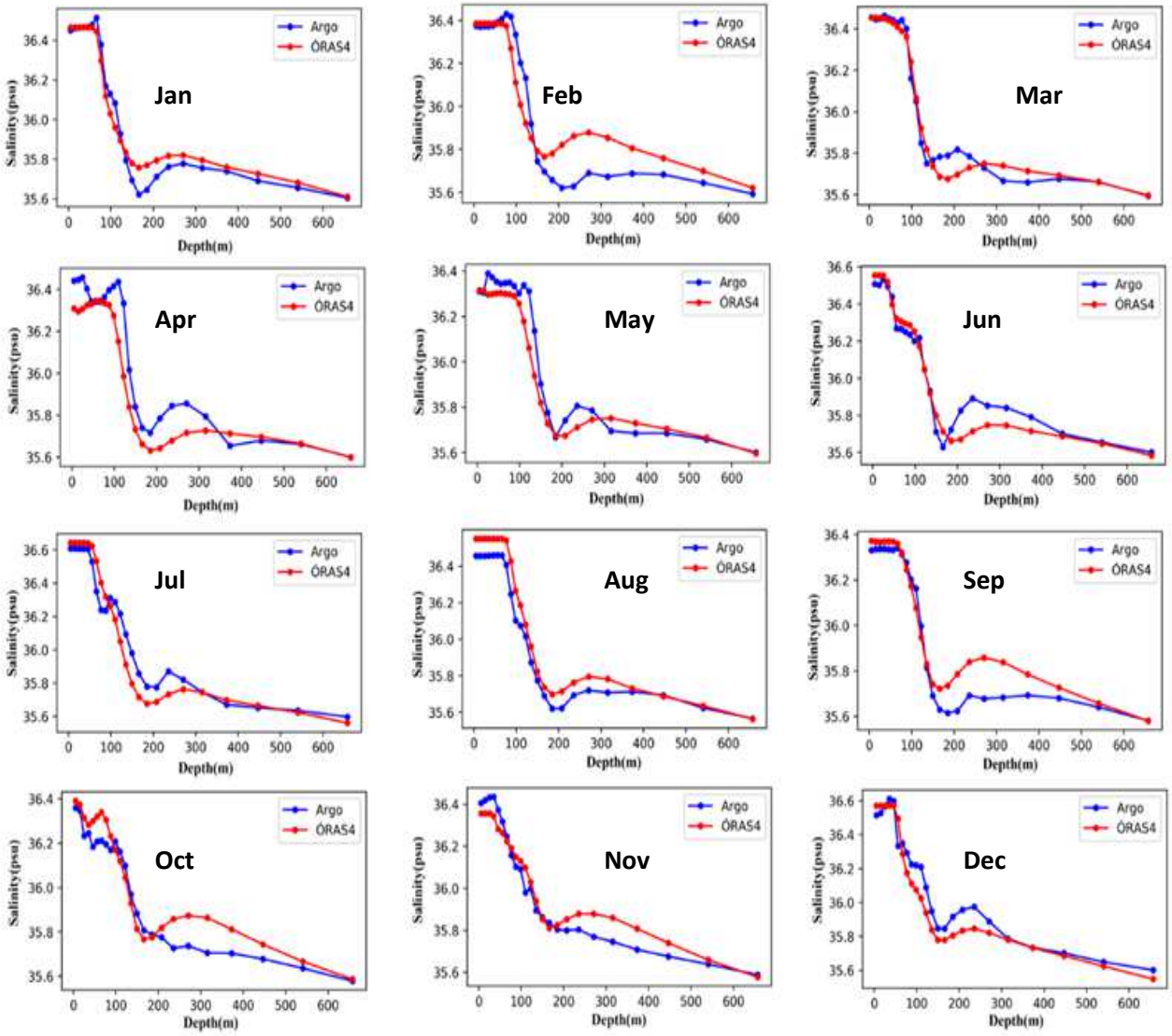


Figure-2 The Comparison of the ORAS4 salinity profile with an Argo measurement over Arabian Sea for 2012

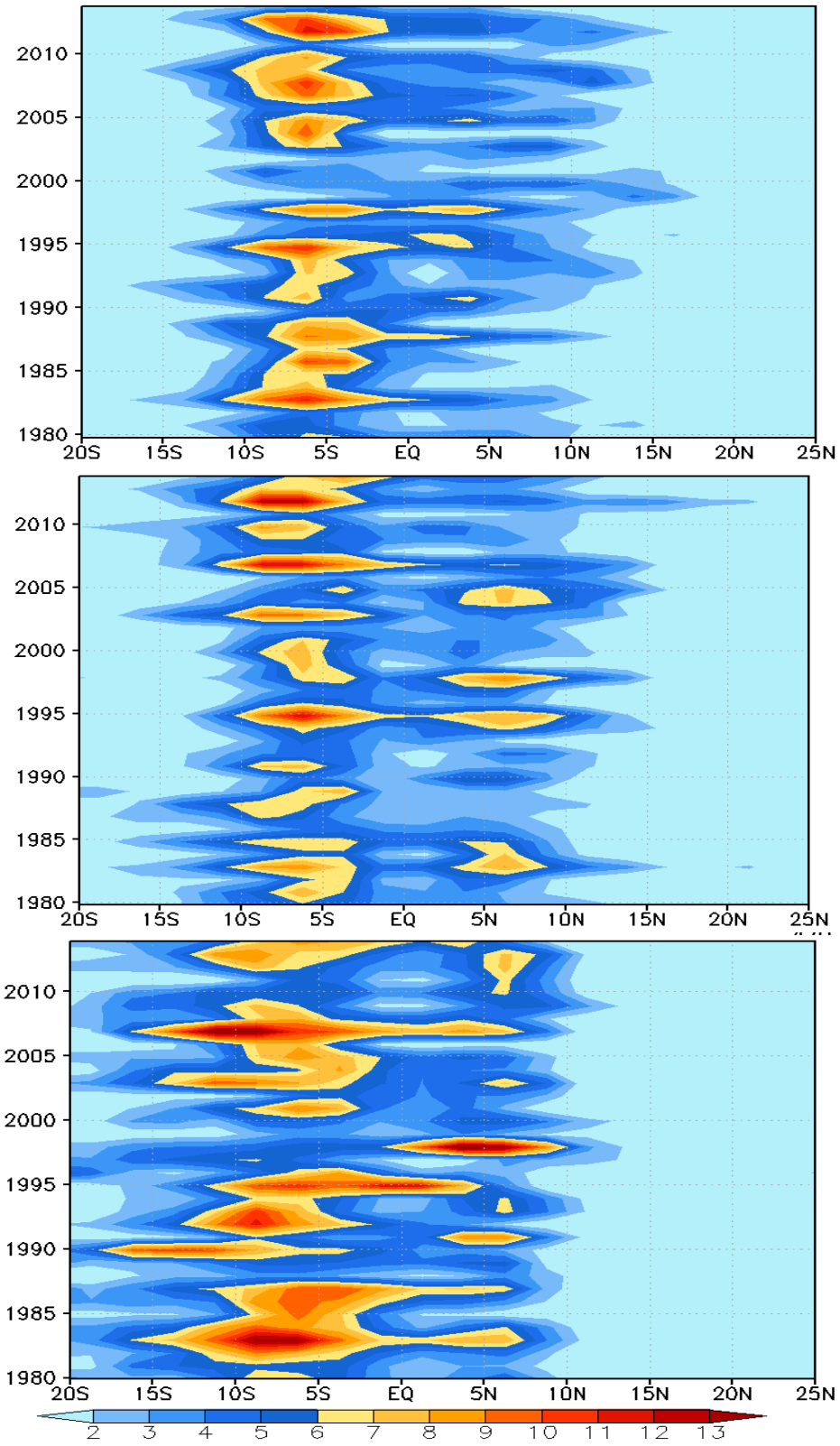


Figure-3: Inter-annual variation of average monthly rate of precipitation (mm/day) from CPC Merged Analysis of Precipitation (CMAP) averaged between 50°-70°E i.e. over Arabian sea

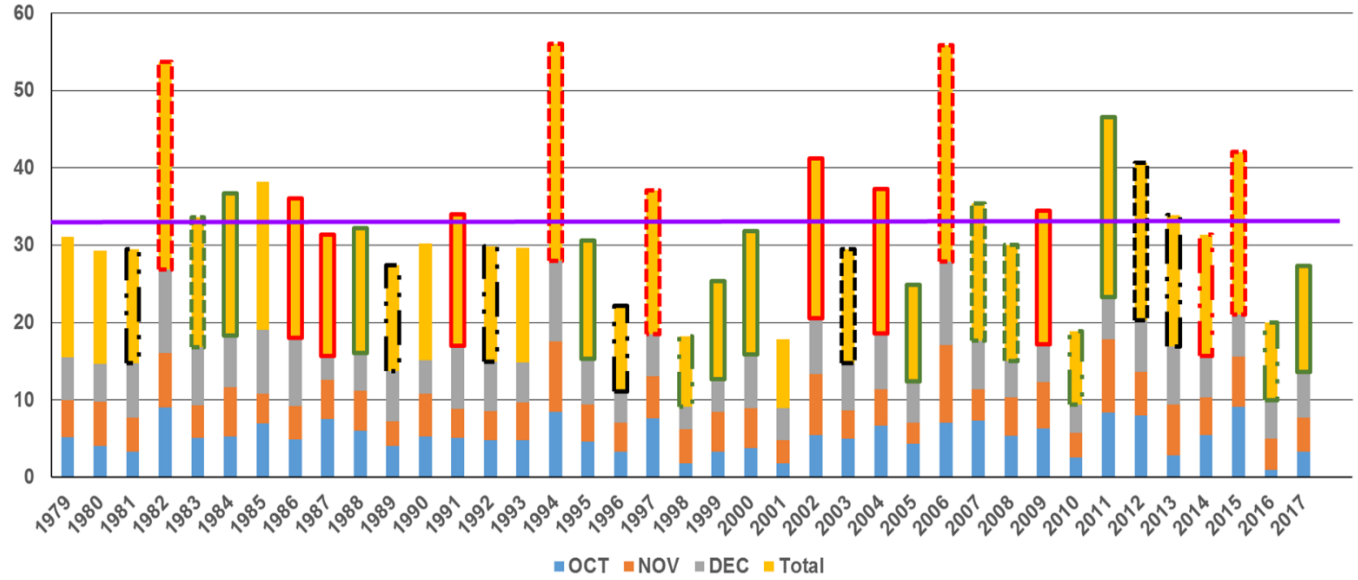


Figure- 4 Inter-annual variation of average monthly rate of precipitation (mm/day) from CPC Merged Analysis of Precipitation (CMAP) averaged between 50°-70°E and 0-10°S

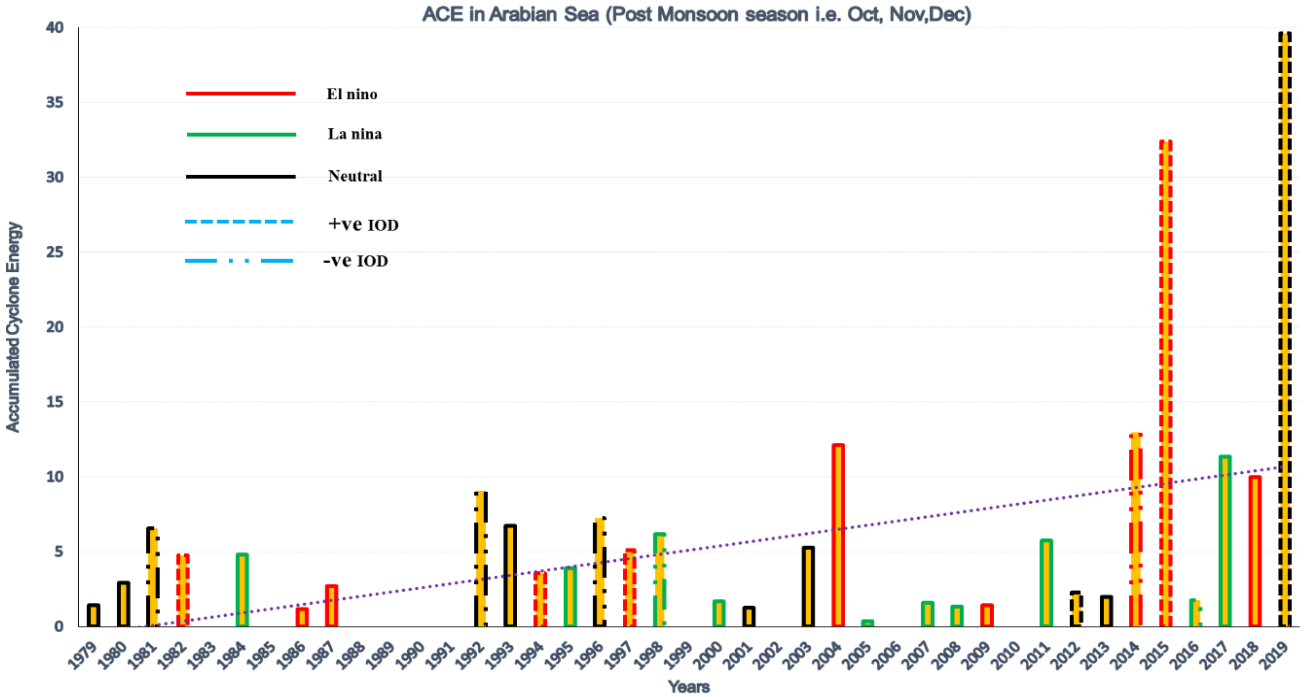
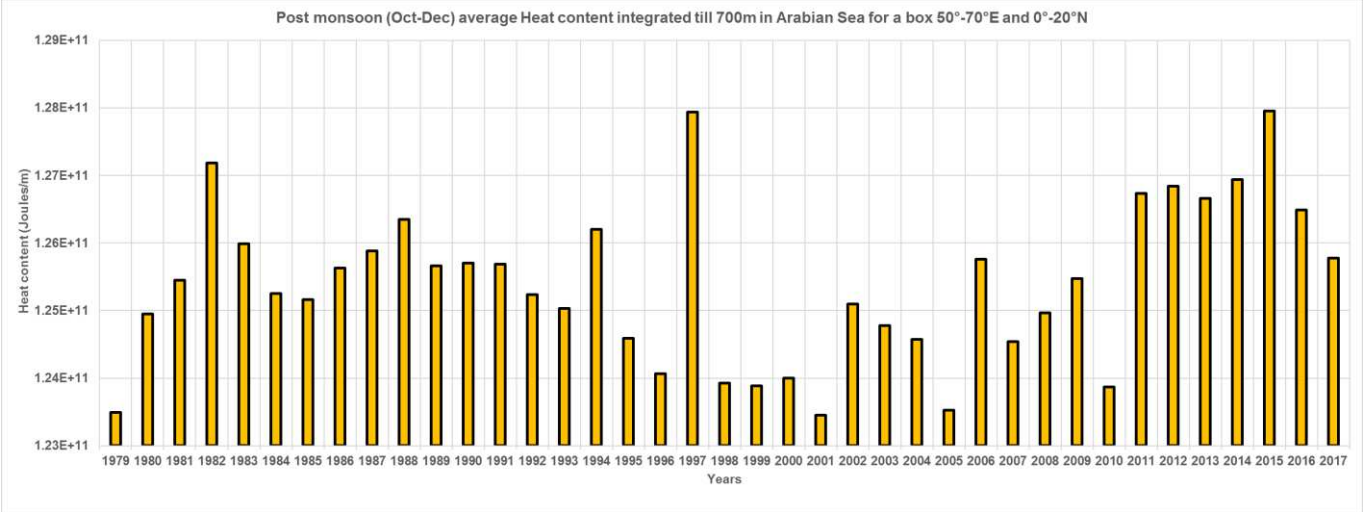


Figure-5 Accumulated cyclone energy from 1979-2019. Years are classified into the El-Niño, La-Niña, positive and negative IOD years.



489 Figure-6a Inter-annual variation of post-monsoon average heat content over AS integrated up
490 to 700m for a box between 50-70ºE and 0-20º N

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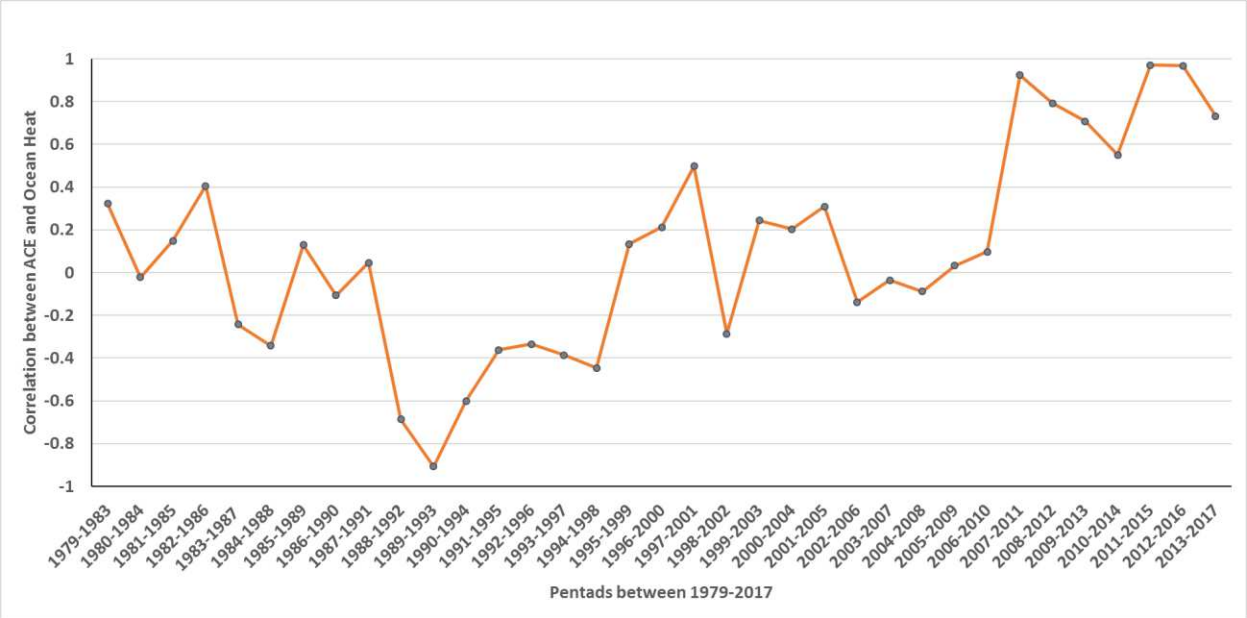

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494 Figure-6b Variation of correlation coefficient between OHC over AS integrated up to 700m
495 for a box between 50-70ºE and 0-20º N and ACE.

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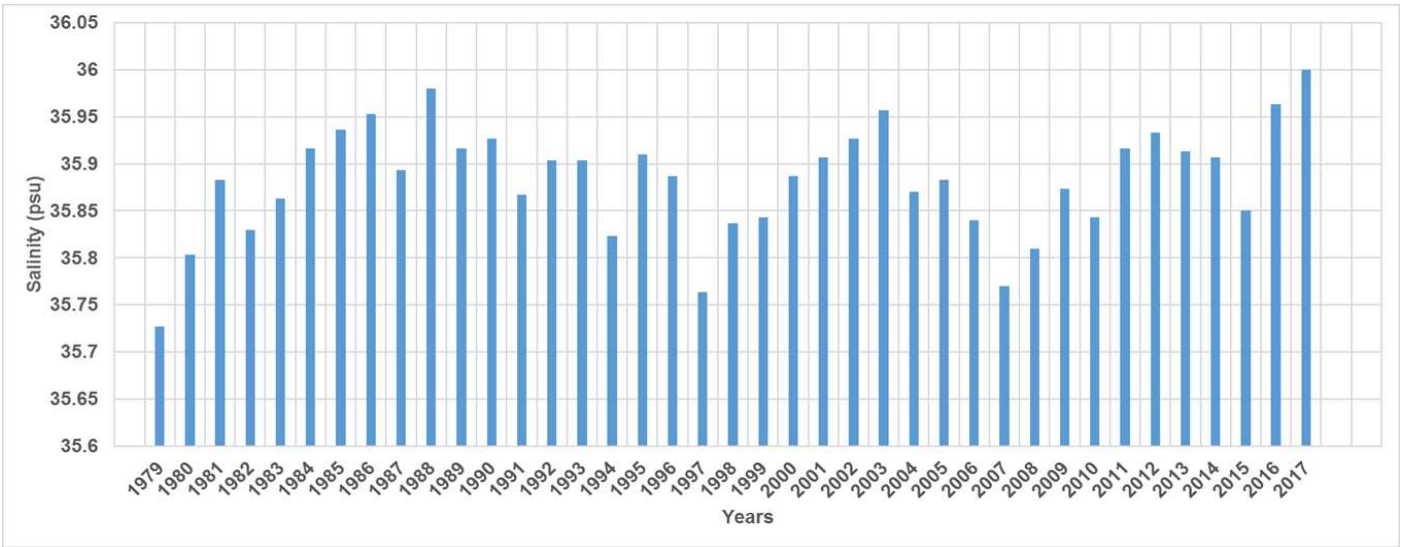


Figure 7 The variation of salinity averaged up to 100m for the same box.

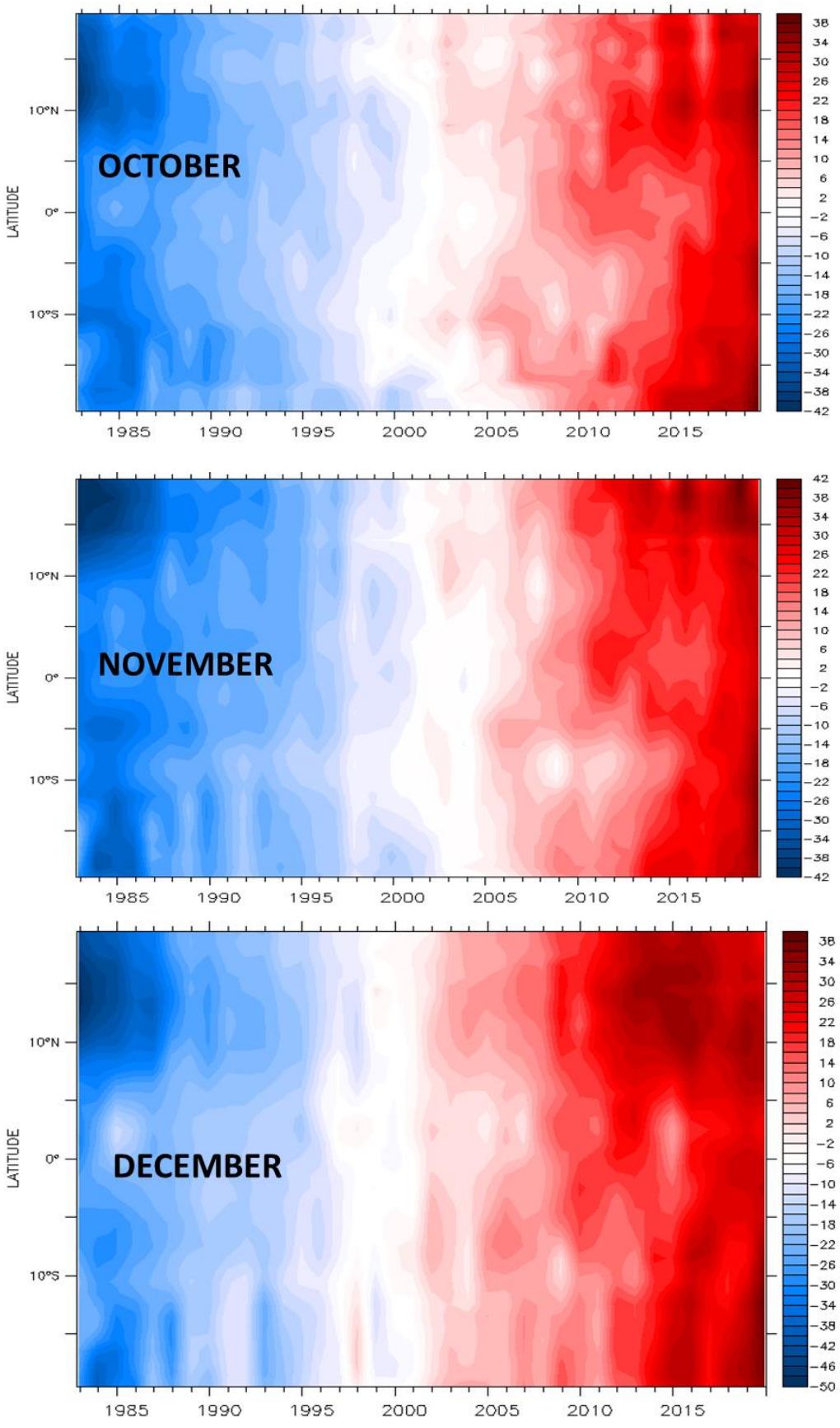
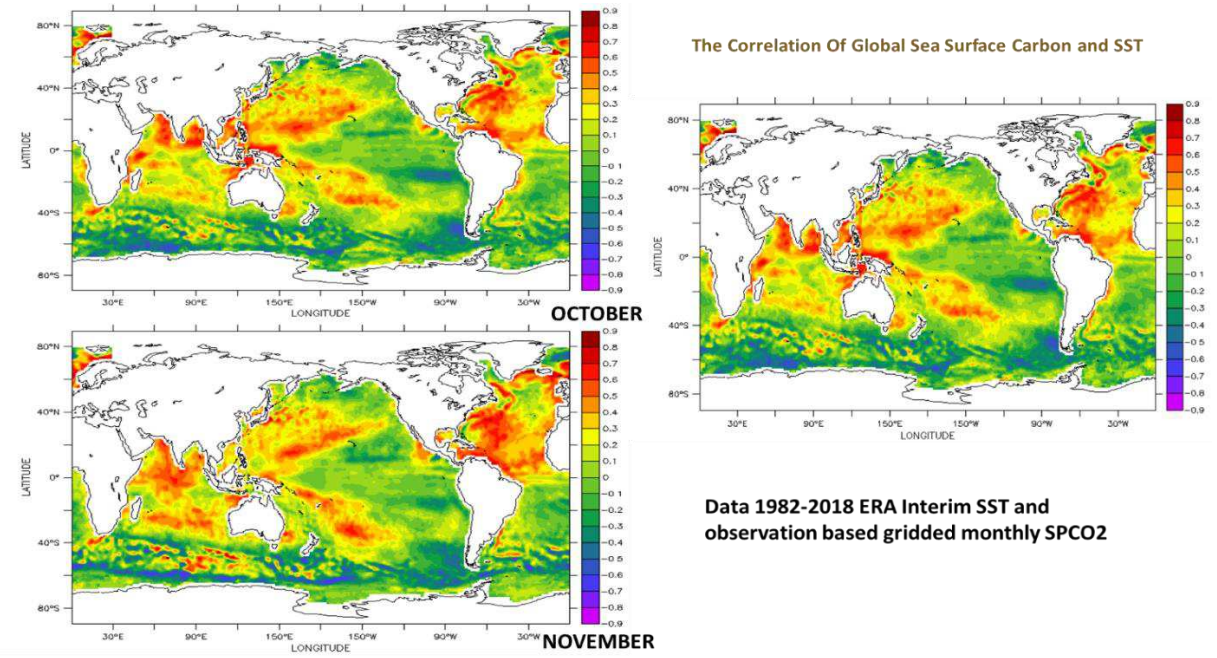


Figure 8 The variation of anomaly in partial pressure of carbon at surface between 50-70E from 1982-2019.



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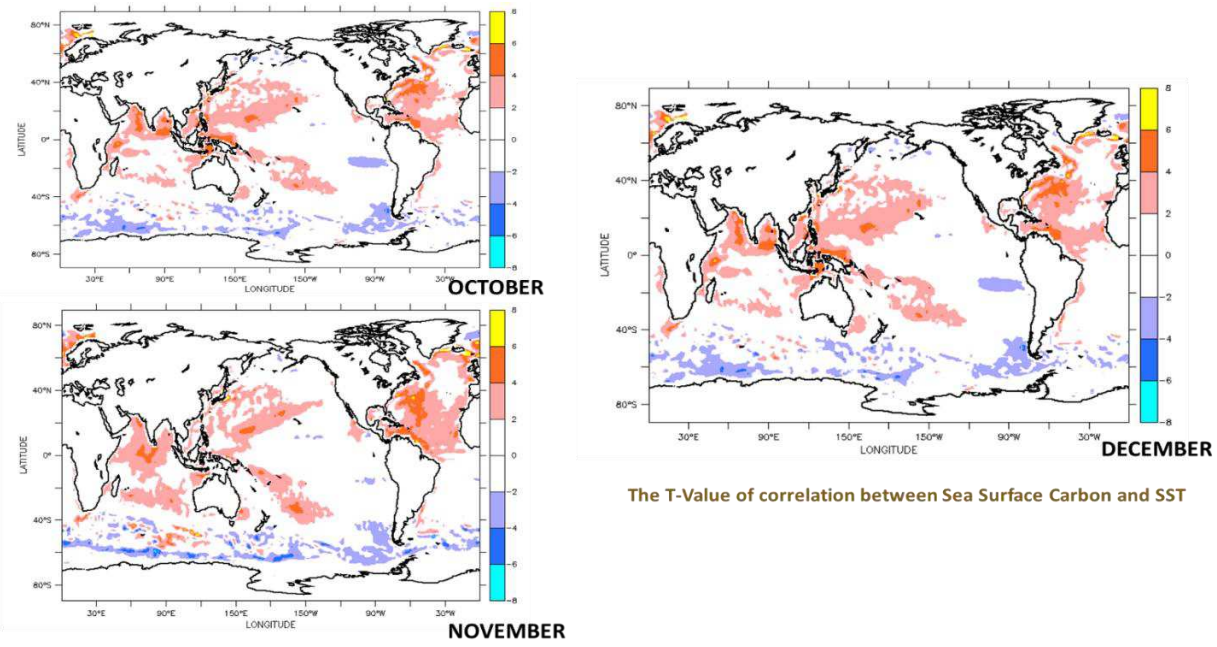

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526 Figure 9 (a) Correlation coefficient between partial pressure of carbon at surface and SST for
527 global ocean 1982-2019 (b) Statistical significance of the correlation (T value).

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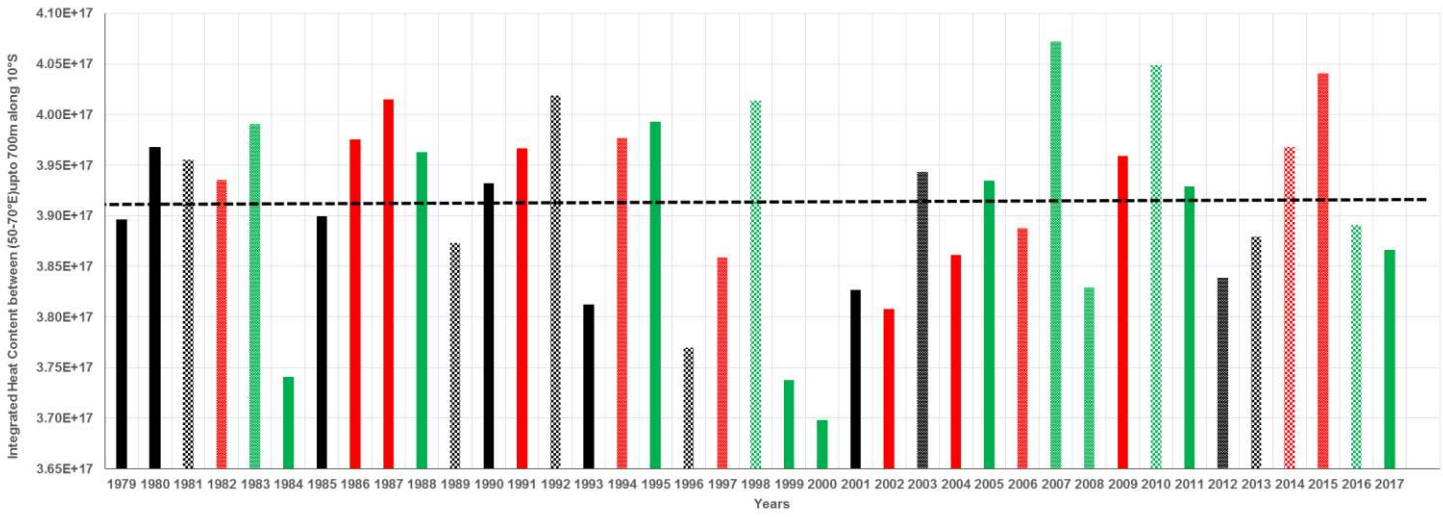

531 Figure-10 The integrated heat content between 50-70E integrated up to 700m along 10S

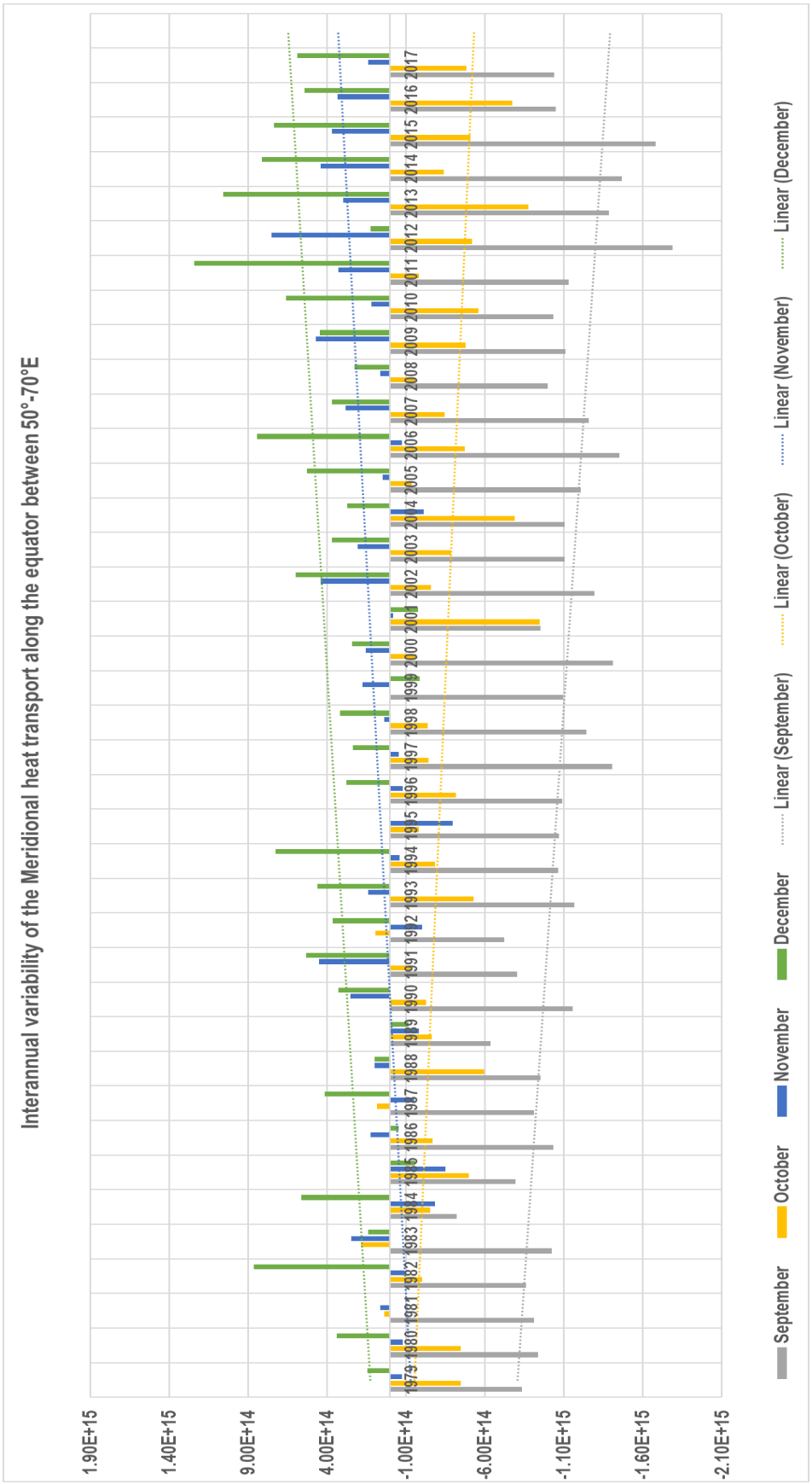

Figure-11 the inter-annual variability of the meridional heat transport along equator integrated up to 700 m

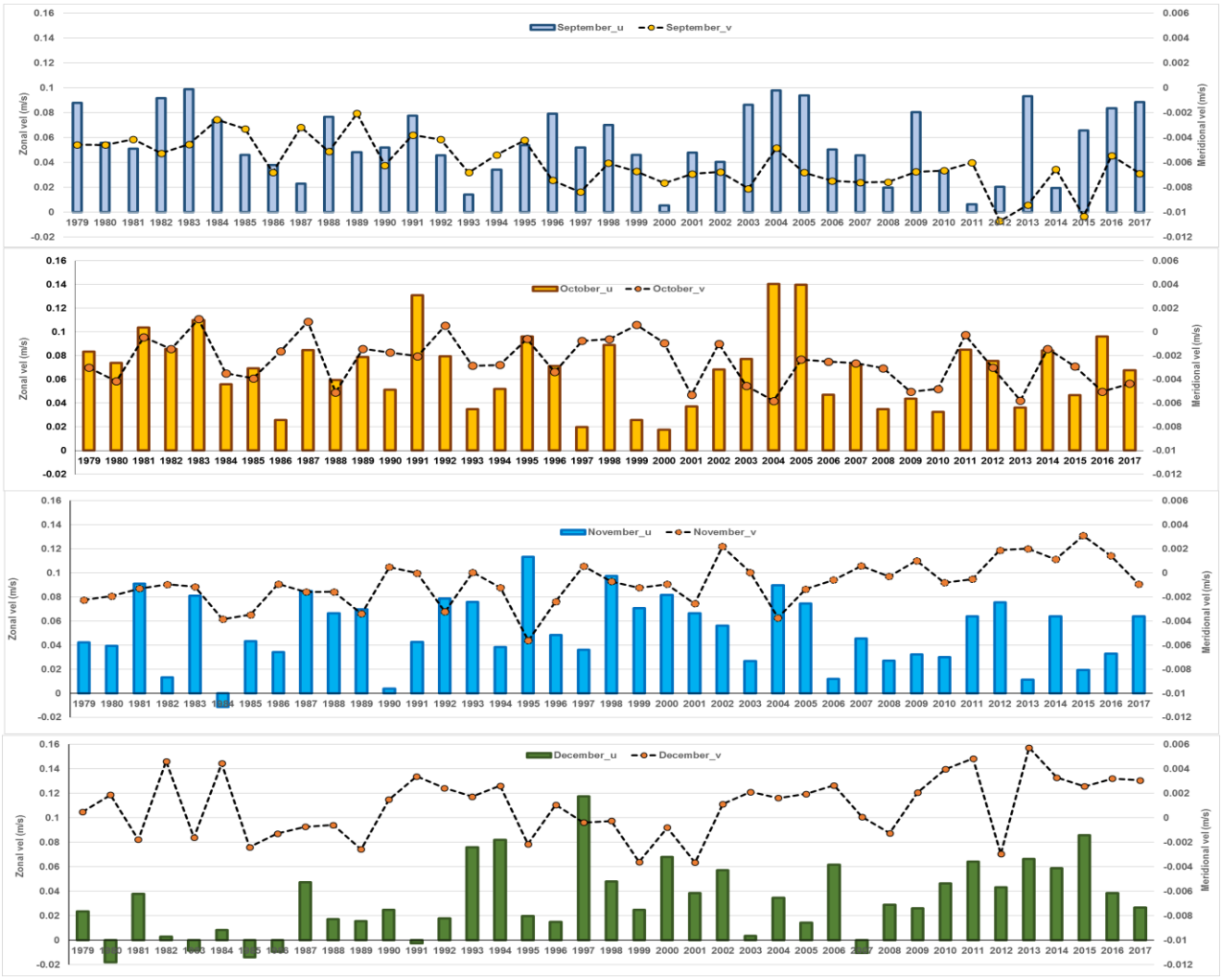

Figure-12 the inter-annual variability of the zonal (bar)/meridional(line) currents at equator up to 700 m