Scientific Research Publishing

International Journal of Geosciences, 2019, 10, 29-38
http://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Impact of Seasonal Low on Sea Level Rise

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How to cite this paper: Baig, M.J., Iqbal, M.J. and Naz, S. (2019) Impact of Seasonal Low on Sea Level Rise. *International Journal of Geosciences*, **10**, 29-38.
https://doi.org/10.4236/ijg.2019.101003

Received: December 21, 2018
Accepted: January 25, 2019
Published: January 28, 2019

Abstract

Every region around the globe has its unique climatic conditions which are set based on different orographic constant and atmospheric dynamic features. These features posses' variability on different time scales. Determining the local sea level change based on terrestrial non-tidal, short-term variability is complicated. Some internal mechanisms of ocean are also taking place along with the external physical ones. We show that variability at Sindh-Baluchistan coastal belt can be greatly explained via dimensional indices of the position and intensity of the atmospheric center of action (COAs). This technique has already proved its usefulness at number of location especially in Northern Atlantic. It takes into account the changes in the atmospheric pressure which is exerted on the sea surface influencing the variability in sea level on seasonal scale and on inter-annual basis. As warming causes thermal expansion of water it also causes changes in atmospheric circulation. Both of these processes affect the sea level variability on their respective time scales. Atmospheric being the quicker one of the two to pass on the effect is also more influential to explain the variability in local sea level. In this attempt the COA approach is used to assess the impact of low pressure on local sea levels.

Keywords

Sea Level, South Asia Low pressure, Indian Ocean

1. Introduction

During the last 3 millennium, the mean sea level has been below today's observed values. Furthermore, variations occurred gradually. For instance, the change in sea level during the period from year 1000 to year 1800 was in the range of a few centimeters. The rate of sea-level rise increased between the nineteenth and twentieth century's, and now satellite measurements show sea level rising by 3.4 millimeters (mm) per year from 1993 to 2008 [1], which is almost twice the average rate for the twentieth century.

The global sea level rise is a multifaceted phenomenon in its own. Sea level rises due to a thermal expansion of the ocean which contributes about 40% in current sea levels changes while the 60% [2] [3] is due to melting of glaciers and ice sheets as the global warming continues. This also calls for the coastal flooding which disturbs the socio-economic structure of the society [4]. The coastal geomorphology is directly applicable to human livelihood. United Nations estimates suggest that about 66 percent of the world's population lives within a few kilometers of the coast; consequently food production, communications, settlement, even recreation, are concentrated here. This rise has local dependence as well as global. In western hemisphere's high latitudes sea level rise is affected by uplift (submergence) of the land due to ice unloading (rebound) phase, since last glaciations. The Maldives Island (Northern Indian Ocean) sea level is rising due to rising temperature, and thus, puts this place at the highest risk of inundation due to global warming.

In months from April to August, the south Asia low pressure (SALP) is created along the monsoon trough from northeast India extending towards Arabian Sea and into Saudi Arabia (**Figure 1(a)**). This low pressure system is caused

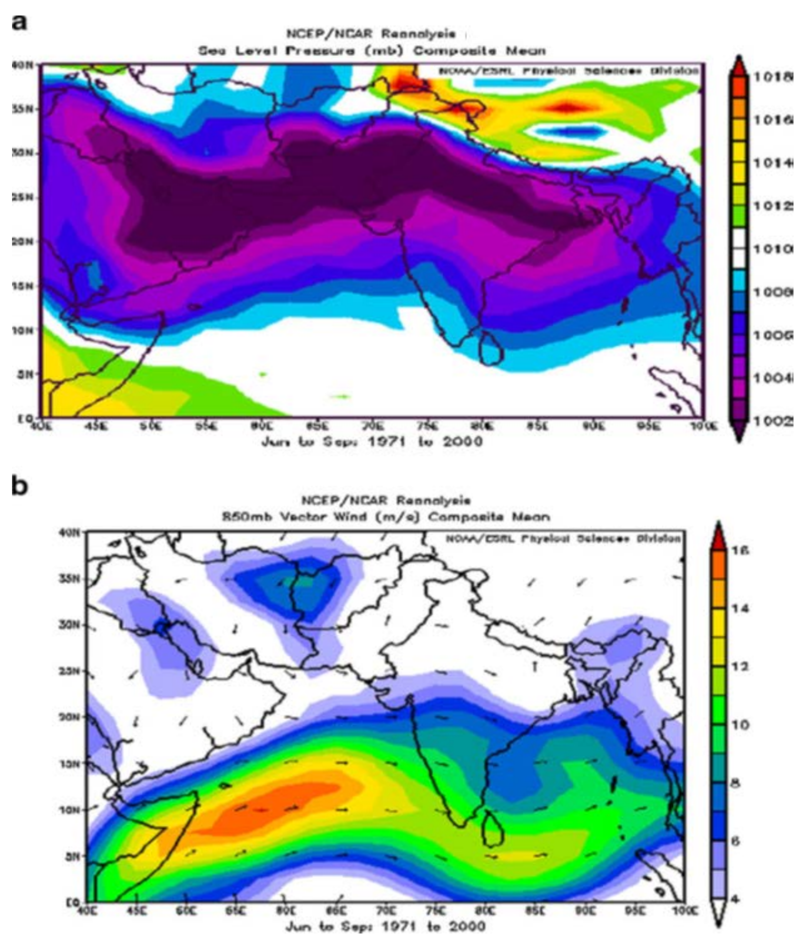

Figure 1. Note that pressures less than 1002 mb in the South Asia low extends from north India to Saudi Arabia (a). The cyclonic flow around the low brings the moisture laden winds from the Arabian Sea into the Central Indian region (b) (Source: NCEP/NCAR Reanalysis data).

by the heating of the surface. The pressure and the distribution of the South Asia low pressure fluctuate from year to year with changes in the global and regional circulations. Thus, this study is an attempt for investigating the possible impact of South Asian low heat on the variability of local sea level for Karachi coast using the centers of action (COA) approach [5]. The large-scale semi-permanent high and low pressure centers which are prominent on a global map of monthly averaged sea level pressure were called the centers of action by Rossby [6]. Rossby noted a key point that the changes not only in the pressure but also the position of a center of action impact's regional circulation. According to the scheme applied here, a COA is characterized by three indices representing its area averaged longitude, latitude, and pressure. Numerous studies have illustrated the advantages of the COA approach [5] [7]-[12].

In the following section, the sea level data pre-processing is discussed with reference to GIA and IB. In methodology section the COA approach is described. In following sections the regression and correlation of data is discussed. Before conclusion, an attempt is made to explain the physical mechanisms to establish the relationships between the South Asian low heat and sea level variability by examining the composite maps of large-scale circulation fields using NCEP/NCAR Reanalysis data. In the end, on the basis of previous results and possible physical mechanism the conclusion is made.

2. Preprocessing of Data

There are number of natural mechanisms (internal and external to the ocean) working in harmony with each other and affecting the sea level rise. As glacier isostatic adjustment (GIA) (also called post glacial rebound) takes place with start of an ice age and slows down to the next ice age (19,000 - 21,000 year cycle). The rebound phase doesn't stop with ice vanished, it continues long after the ice, this depends upon the nature of earth's mantle viscosity [13] [14]. It affects the sea level by coastal uplift at some places and other by submerging of coastal areas. Then there is atmospheric loading/unloading effect on sea level called Inverted barometric effect (IB). In this the sea level increases in low pressure and decreases in high pressure. This effect need to be corrected when analyzing the climatological changes is to be observed in sea level change.

The sea level is influenced by vertical motion of the earth crests happening globally, with variable degree. It varies from a fraction of millimeters per 250 year to tens of centimeters per decades, and it goes in both directions, somewhere the earth crust is moving upwards and on the other sites it's going the other way. One has to do the adjustments for the tectonic movement and other anthropogenic causes, so that the true change due to atmospheric variability can be assessed.

On preliminary analysis of the respective sea level data obtained from tide gauges (**Figure 2**), the Arabian Sea coasts found to have affected significantly. As discussed above regarding the IB, that its signal are not significant for this part

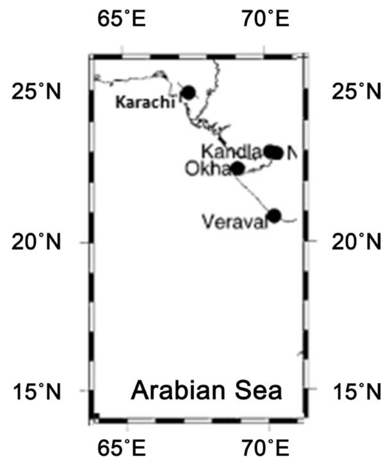

Figure 2. Location of Tide Gauge station (Top left) Karachi [15].

of the world, therefore we considered raw sea level data and the GIA corrected sea level data along with detrended sea level data for our analysis.

We use monthly sea level data obtained from Permanent Service for Mean Sea Level (www.PSMSL.org/data/) for the period from 1948 to 2008. For the same period, the monthly averaged gridded sea level pressure (SLP) data were also used for calculating objective COA indices for the monthly pressure, latitude, and longitude of the Indian Ocean low pressure as described by Bakalian [5], obtained from Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/cru/data/hrg/cru_ts_2.10).

3. Methodology

We can determine the impact of atmospheric pressure fluctuations on sea level variability in Arabian Sea and it can be attained through a quantitative assessment of the fluctuation in the pressure and locations of the South Asia low pressure. The pressure index I_p of a low pressure system (SALP) is defined as an area-weighted pressure departure from a threshold value over the domain (I, J):

$$I_{p,\Delta t} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t} - P_t\right)\cos\varphi_{ij}\left(-1\right)^{M}\delta_{ij,\Delta t}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\cos\varphi_{ij}\delta_{ij,\Delta t}} \tag{1}$$

where P_{ij}, Δt is the SLP value at grid point(i, j) averaged over a time interval Δt. In this case, monthly SLP values are taken from NCEP reanalysis, P_t is the threshold SLP value, and ϕ_{ij} is the latitude of the grid point (i, j). $M = 0$ for the high and 1 for the low. $\delta=1$ if $(P_{ij,\Delta t} - P_t) > 0$ and $\delta = 0$ if $(P_{ij,\Delta t} - P_t) < 0$. This ensures that the pressure difference is due to the low pressure system. The intensity is thus a measure of the anomaly of the atmospheric mass over the section (I, J) [5]. The domain of the South Asia low was chosen as 10˚N to 35˚N and 35˚E to 95˚E. The domain of the low and their threshold values P_t (1013 mb) were chosen by examining their geographical ranges in NCEP Reanalysis data over the period 1948-2008. Similarly, the latitudinal index $I_{\phi,\Delta t}$ (SALT) is defined as:

$$I_{\varphi,\Delta t} = \frac{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t} - P_t\right)\varphi_{ij}\cos\varphi_{ij}\left(-1\right)^M \delta_{ij,\Delta t}}{\sum_{i=1}^{I}\sum_{j=1}^{J}\left(P_{ij,\Delta t} - P_t\right)\cos\varphi_{ij}\left(-1\right)^M \delta_{ij,\Delta t}} \tag{2}$$

and the longitudinal index $I_{\lambda,\Delta t}$ (SALN) is defined in an analogous manner. The COA approach examines not only the impact of the intensity of South Asia low pressure on climate variability but also determines the influence of its meridional and zonal movement on the same.

4. Regressions and Correlations Results

We have used the center of action (COA) approach for South Asia low pressure (SALP), which develops in summer time (starts developing in the end of April and stays till August). The Sindh coastal (Karachi coastal area) region shows significant increase in sea level as temperature and SALP (found in the Arabian Sea region) shows high correlation in the area, so the low pressure also influence the wind (Figure 3) from Arabian Sea into central India. This coupled action of enhanced SST with southwestern wind causes the sea level to increase on the Sindh coast. The negative values of correlation (Table 1) suggest the increase in sea level with strength of low pressure which is consistent with the earlier studies. Karachi and some other West Indian coasts show a significant ($p < 0.05$) variation

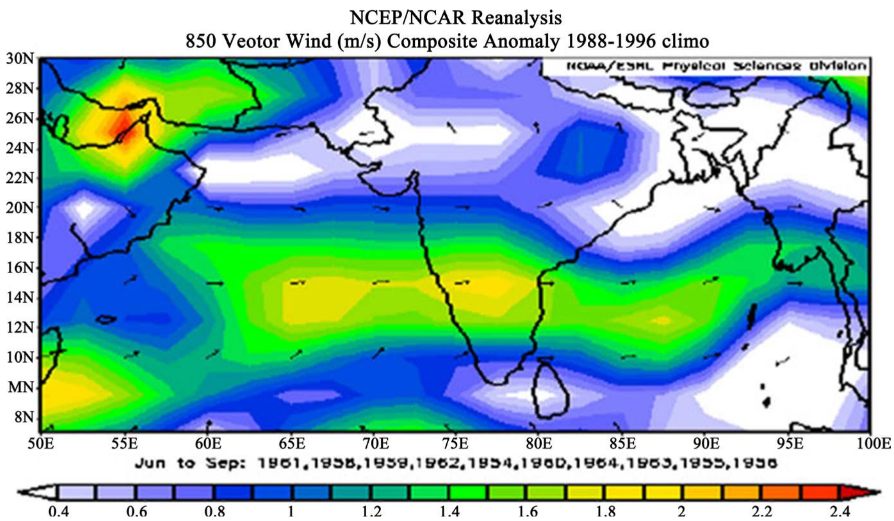

Figure 3. When the SE low is deeper than normal, there is a strengthening of monsoon winds entering Central India. (Source: NCEP/NCAR Reanalysis data).

Table 1. Correlation matrix of intensity of SALP with sea levels.

		SALPS	Detrend_SALPS
Karachi	RAW-SL	–	−0.52
	DETREND-SL	−0.40	−0.51
	GIA-SL	–	−0.51
Average number of years			57.00
Significant probabilities at 5%			0.28

due to prevailing low heat. To further assess the impact of SALP on controlling the sea level variability as it is a complex process involving some internal and external factor the control this inter-seasonal to decadal scale variation, two round of calculations are run to arrive at a viable conclusion. In first, some linear and cross correlation are calculated between modes of sea level (raw and GIA corrected) and three pressure indices (area averaged pressure, latitude and longitude component), to figure out any possible association amongst the meteorological and sea level rise factors. In the second, a multiple regressions are performed for sea level using the contributing components of the predictors suggested in the first round of analysis.

5. Mechanisms for the Relationships between COA and Sea Level Variability

On preliminary analysis of the respective sea level data obtained from tide gauges, the Arabian Sea coast found to have affected significantly by the low heat (SALP) (**Table 1**). As discussed above regarding the IB, that its signal are not significant for this part of the world, therefore we considered raw sea level data and the GIA corrected sea level data for our analysis.

The long term changes are also part and parcel of this low heat. As represented in **Figure 4**, the equator ward movement of the SALP is evident as the concentration of heat is also found toward the equator. Along with the pressure gradient the wind speed yields an anomaly of 2 - 4 m/s along the tropic of cancer (**Figure 1(b)**). This wind is hypothesized to affect the wind driven coastal setup and wind driven Rossby waves which can have impact upon coastal sea level. The prominent association of low pressures and temperature (**Figure 5**) also affect the thermosteric sea level. The other possible mechanism is the resultant bulge of water due to temperature increase also experiences the gravitational force due to coriolis force, which moves this temperate water toward the coasts and at the coasts the same prevailing wind causes the coastal upwelling. Both of these mechanisms supplement each other and results in a rise in sea level.

Sea level does not only depend on external factors, there are internal mechanisms as well. So, while working on the multiple factor, the autoregressive nature of the sea level is also taken into account to adjust for all the internal processes taking place in sea level fluctuation. It is also found that at Karachi coast sea level data is found to depend on its last year value in both modes of data (Raw and GIA corrected sea level). The single hypothesis relating the impact of global warming on the climate of South Asia is its active response to any temperature change. For example, having a comprehensive look at the correlation structure of the sea level and COAs, a maximum lag of two years is found which is much shorter travel time for heat flux to sea level then found in northern Atlantic of six-years at Bermuda (Curry *et al.*, 1998). The multiple regressions are performed until a significant level is achieved (**Table 2**). The longitudinal component of COA is found to have more influence on sea level compare to the

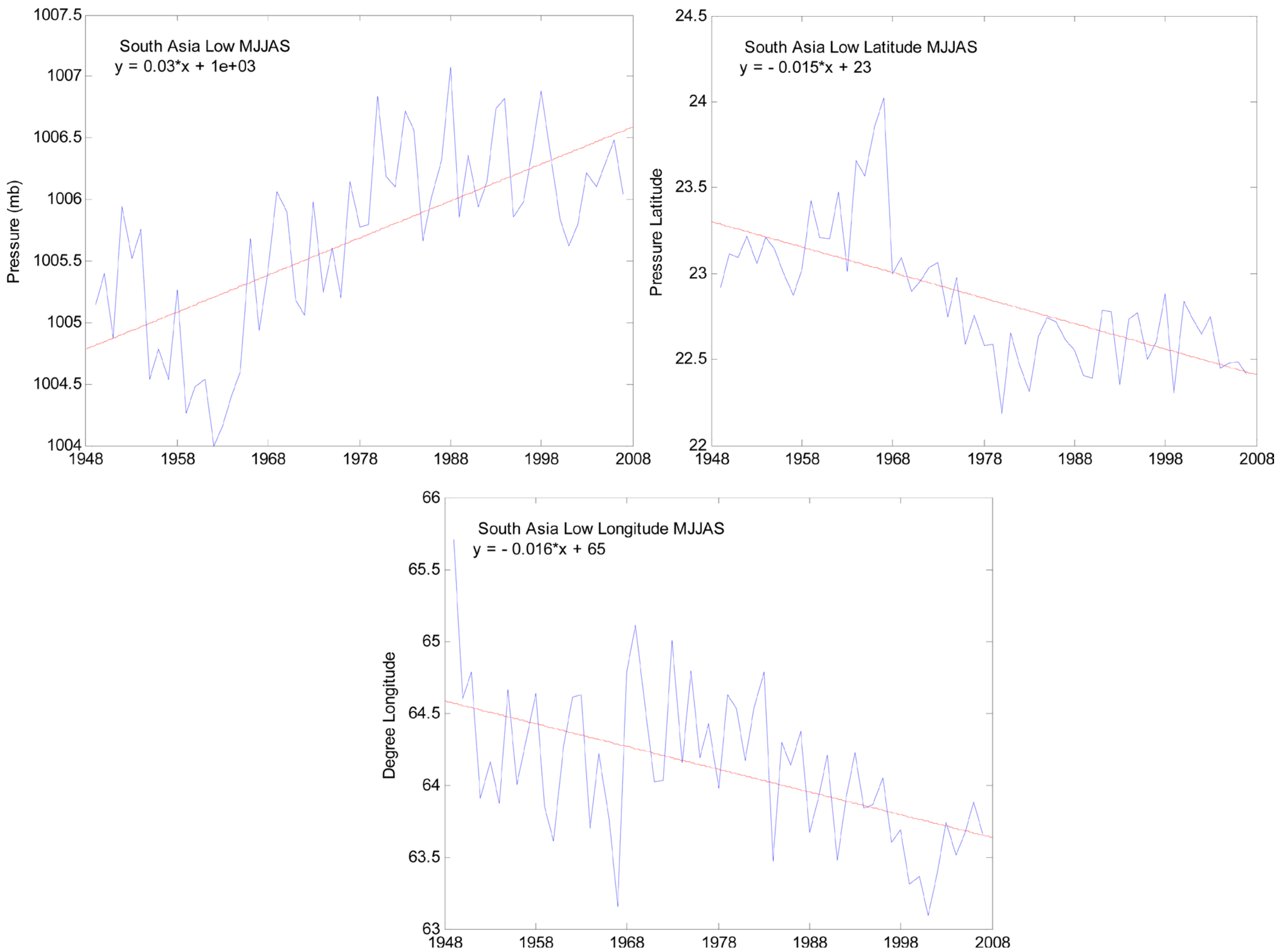

Figure 4. long term changes in the state of the COAs for months May through September. Long-term changes are significant in South Asia low, latitude and longitude.

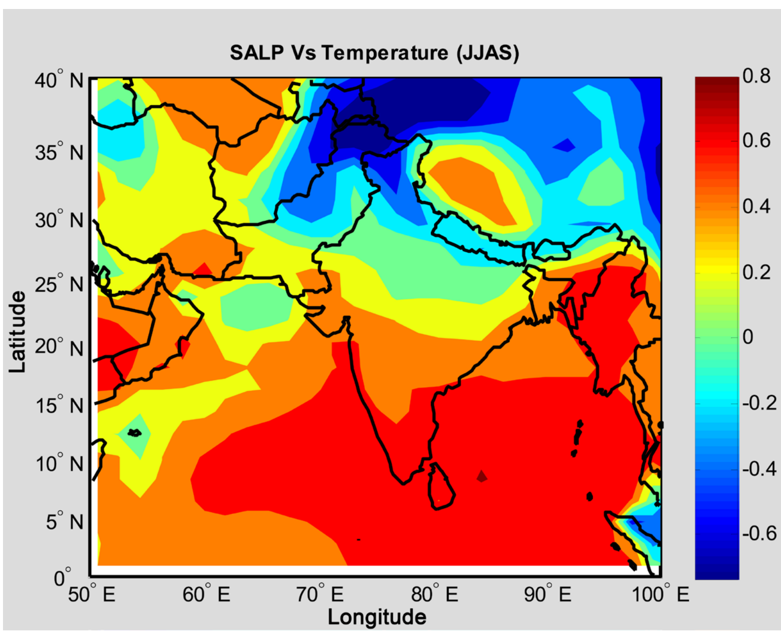

Figure 5. Correlation between regional temperature and low pressure. (Source: NCEP/NCAR Reanalysis data).

Table 2. Summary of Sea Level Rise Rates and Regression Output.

	Karachi
Period analyzed	(1958-2008)
SLR (Raw)[a]	0.52
R^2 of Regression	0.6
Regression Slope[a]	0.81
% of Raw Trend	155.8
Residual SLR[a]	-0.29
SLP (GIA Adjusted)[a]	1.1
R^2 of Regression	0.6
Regression Slope[a]	1.4
% of Raw Trend	127.3
Residual SLR[a]	-0.3

[a]Rates are in mm/yr.

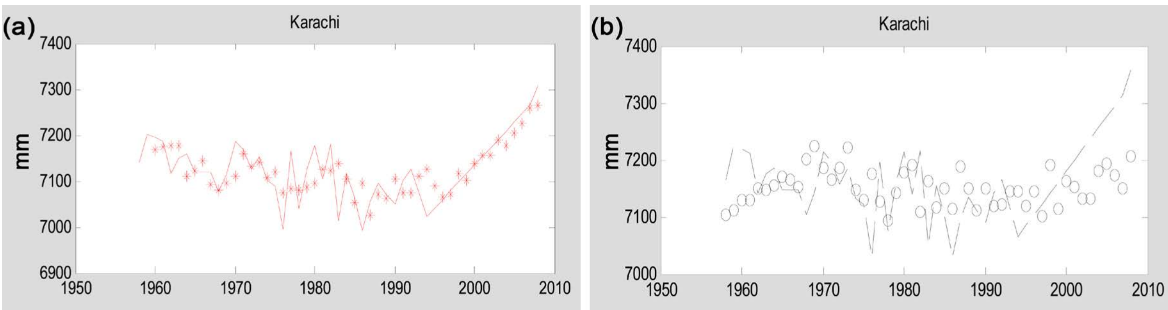

Figure 6. (a) Scatter is the multiple regression model output against raw sea level (b) Scatter is the multiple regression output for GIA corrected against the virgin GIA corrected sea level data.

latitudinal component, which is also consistent with the SALP longitudinal westward movement (**Figure 4**).

The location of the coast make a big difference, *i.e.*, Karachi coast experience a sea level rise (0.61 - 0.52 mm/yr), but our regression models accounts for 23% - 60% of the variability in the raw sea level data and 19.5% - 60% for the GIA corrected data (**Table 2**). For the unbiased comparison our multiple regressions explains 61% - 83% of the variability in the raw sea level and 70+% in GIA corrected sea level, strengths the linkage between COAs and the ocean. The ocean's internal mechanisms' causing the sea level variability are accommodated by keeping a lagged sea level term on the predictor side of the regression in both modes of sea level data *i.e.* raw and GIA corrected. Our averaged sea level rise is around 0.91 mm/year and GIA corrected is around 1.05 mm/yr which closer to Wadhams and Munk's [16] 1.1 mm/year than Miller and Douglas's [17] 1.5 - 2.0 mm/yr.

6. Conclusion

These results suggest that a large fraction of annual mean sea level variability at this Northern Indian Ocean coast is correlated with shifts in the position and intensity of COAs. The overall multiple regressions account for 23 - 60% of the variability in raw sea level and 19.5 - 60% in GIA corrected sea level. These results strongly suggest that meteorological processes do contribute to the ocean processes by redistributing water, heat and respond to the atmospheric pressure across the ocean basin (**Figure 5** and **Figure 6**). The low pressure system seems to have profound effect on sea level rise in pre-monsoon months (April to August).

Acknowledgements

I am thankful to Dean Faculty of Science (University of Karachi) for the research grant provided and to the National Centre for Environment and Prediction (NCEP) for providing the necessary climatic data. And I am also thankful of the Permanent Service for Mean Sea Level (PSMSL) site for necessary sea level data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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