ENSO's Role in Improving an Interannual Model for Summer Rainfall over Pakistan

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Abstract

The present study investigates ENSO's role in summer rainfall over Pakistan and employs the relevant indices in developing a statistical interannual model (IAM) for predicting the rainfall. Correlation based cross-validation stepwise regression (C_CVSR) method is utilized to find the robust predictors. For reconfirmation of robustness for the selected predictors, the K-folds test samples approach has been used. It is revealed that Walker circulations induced by negative (positive) sea surface temperature anomaly (SSTa) over the eastern tropical Pacific are responsible for producing convection (subsidence) over the south Asian region that accordingly modulates the summer monsoon. Besides, over the study area, the summer heating, strong convection induced by the upper tropospheric high over the west central Asia and moisture feeding through the Bay of Bengal play active roles in producing stronger monsoon. Addition of ENSO based secondary predictor has significantly improved the performance of the model. It is revealed that in addition to upper tropospheric zonal wind over the northeastern Atlantic during June, SSTa over the eastern equatorial Pacific also holds a significant relationship with the rainfall. Accordingly, the IAM is established based on a joint impact of the upper tropospheric westerly (from northeast Atlantic) as well as the tropical easterly currents (from east equatorial Pacific). Besides considerable improvement in RMSE and variance values, the correlation coefficient has been upgraded from 0.71 to 0.75 for calibration and 0.71 to 0.83 for the validation period. Accordingly, it has been developed into a useful tool for seasonal prediction of summer rainfall over Pakistan.

Keywords: Interannual variability, ENSO, summer monsoon, velocity potential, Walker circulation.

Introduction

At interannual time scales, the summer monsoon over Pakistan and northwestern India is mainly affected by the mid-latitude circumglobal teleconnection 'CGT' (Syed et al. 2011). It has been revealed that the positive phase of CGT is significantly associated with the South Asian Monsoon (SAM). Also, the tropospheric anomalous high over the west central Asia has been proved for holding a close interaction with the SAM (Ding and Wang 2005). Besides, the summer monsoon only covers some particular parts of the country, north-northwestern and the southwestern regions remain unaffected (Kazmi et al. 2016). The summer monsoon over Pakistan and northwestern India is mainly concentrated during the Jul-Aug season (Ding and Ke 2013; Syed 2011).

Apart from the local effect of sea surface temperature (SST) through neighboring tropical-extratropical oceans on the Asian monsoon, a remote impact of SSTs through the central-eastern tropical Pacific is also present (Wang 2006). In a recent study by Ding et al. (2010) it is explored that the SAM and other regional monsoons in the northern hemisphere (NH), are modulated by the zonally oriented El Niño Southern Oscillation (ENSO) forcing in the tropics and extratropics. ENSO remained a major factor in modulating the summer monsoon over the south Asia at interannual level (e.g., Webster and Yang 1992; Wang et al. 2000; Goswami 1998; Hu et al. 2005).

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The Walker circulation may be utilized to describe the negative correlation of the eastern equatorial Pacific SST anomaly 'SSTa' or Niño-3 with the SAM (Palmer et al. 1992; Soman and Slingo 1997). Anomalous warming over the central-eastern Pacific causes the shift of ascending Walker cell towards the east that results in fading the warming (and corresponding convection) over the western Pacific up to Indian Ocean. Accordingly, the Indo-west pacific regions would come under the subsidence that leads to reduction in summer rainfalls over the neighboring areas including south Asia (Lau and Wang 2006). Besides, ENSO impose negative impact on the SAM by reducing the length of rainy season (Goswami and Xavier 2005). On the other hand Webster and Yang (1992) states that there exists association between ENSO and the Asian monsoon but based on their lag lead varying correlation, ENSO may not be considered as an independent predictor (Webster and Yang 1992). Whereas, a persistent thermal low develops during early summer over the study area is mainly responsible for modulating the surface winds that accordingly supply moisture content for the summer monsoon (Saeed et al. 2011).

Pakistan is an agrarian country but based on the climate change consequences, adequate water has not been available throughout the cropping season. Reliable data information for atmospheric and hydrological parameters is obligatory for more realistic and comprehensive agrometeorological research in the region. Accordingly, in addition to relatively coarse resolution GCM projections, sub-regional data is required to project local climates (Kazmi et al. 2015). Investigation of climate projections on smaller scales in future perspective may not be practicable through simulations of the global models (Guo et al. 2012). In this context, the application of downscaling approach has been a recommended option (Li et al. 2013).

In comparison to dynamic approach, statistical downscaling is quite suitable to conduct localized climate impact studies, particularly in developing countries with insufficient resources (e.g., Wilby and Dawson 2007; Kazmi et al. 2016). In statistical downscaling, it is assumed that the conditions prevailed in the past period may also be valid for the future (Wilby 1997). Predictor selection and relevant domain play vital roles in statistical downscaling, especially for future projections (Frias et al. 2006; Schmidli et al. 2007). Several research projects based on the statistical downscaling have been conducted by employing different approaches like linear regression (e.g., Lang and Wang 2010; Liu et al. 2011), singular value decomposition (Bretherton et al. 1992; Widmann and Bretherton 2003) and correlation based cross-validation stepwise regression 'C_CVSR' (Guo et al. 2012). In the present study, C_CVSR approach has been adopted.

This study is an extension of our recently published work (Kazmi et al. 2016) on developing a statistical interannual model (IAM) for predicting the summer rainfall over Pakistan. Formerly, only Zonal Wind at 200 hPa over Northeast Atlantic for June (U2JNEA) has been selected as a robust predictor. Later, based on the importance of ENSO in modulating summer monsoon over south Asia, it has been decided to engage SST (over Pacific/Indian Ocean) and relevant Niño indices to further improve the model. Accordingly, the present study aims to improve the IAM by employing recommended predictors in the ENSO-monsoon context. The remainder of the manuscript is organized as follows. Section 2 describes the data and methods utilized to run and validate the model. Section 3 outlines the main features of establishing the statistical model and its cross-validation. Section 4 describes the physical verification of the secondary ENSO based predictor by employing Walker circulation in the core rainy season, and finally, a summarized discussion is presented in section 5.

Data and Methodology

We have incorporated observed data of monthly rainfall for the core rainy season Jul-Aug 'JA' (for the period of 55 years, 1960-2014) for all the available stations of Pakistan provided by Pakistan Meteorological Department. However, to establish the statistical IAM for downscaling the summer rainfall over Pakistan, only the data for the monsoon zone of the country (Figure 1) is employed. This zone covers the major parts of the country excluding the areas located in north-northwest and the southwest. Besides, for validation of the observed rainfall data set, JA monthly rainfall data for Global Precipitation Climatology Center (GPCC) on a 0.5° latitude/longitude grid has been taken from National Centre for Environmental Prediction (NCEP).

Monthly data for zonal & meridional wind (200, 850 hPa), HGT at 200 hPa and SLP is extracted from NCEP for the mentioned 55 years for Apr-Aug on a 2.5°x2.5° grid. Also, the data of monthly SST (2.5°x2.5°) and all the important Niño indices for the whole study period has been utilized for Dec-Aug period. The Niño indices include ONI, TNI, MEI, Niño-(1+2), Niño-3 and Niño-3.4. Moreover, monthly data of South Asian Summer Monsoon Indices (SASMI) which includes SASMI, SASMI1 and SASMI2 is used for Jun-Aug, available at: http://ljp.gcess.cn/dct/page/65576.

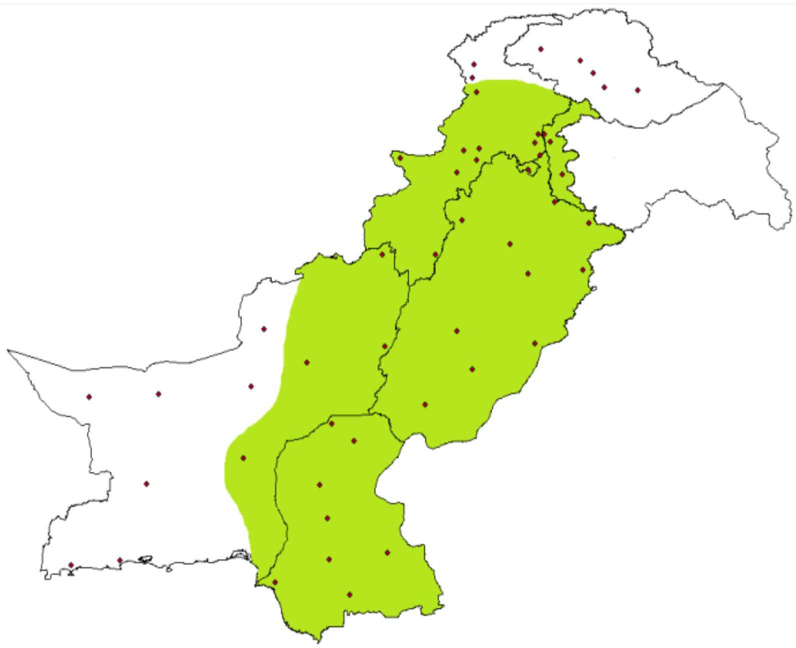

Figure 1: Monsoon zone of Pakistan (green shading), dots represent the data points available for the study period.

Primarily, the predictand and predictors data sets are transformed into interannual components through Fourier filtering. For model processing, the whole study period is distributed into training and independent test periods. Out of whole data period, the first 40 years (1960-99) have been taken as training and the rest (15 years, 2000-14) as test period. Following Guo et al. (2012, 2014) and Kazmi et al. (2016), all the candidate predictors listed earlier are utilized to find potential predictors through C_CVSR approach. It selects the robust predictors from the set of potential predictors through leave-one-out cross validation method by reducing the false possibility. The reliability of the predictors is presented by the root-mean-square-error (RMSE) produced between the observation and the estimation based on the cross validation.

To verify the reliability of the robust predictors and supporting factors, Empirical Orthogonal Function (EOF) analysis has been applied on SST (over the specific region) for the spring/pre-monsoon (Apr-May) to summer/monsoon (Jun-Aug) period. Though C_CVSR method has very strict criteria of predictor selection but reconfirmation of the model's outcome is processed prior to physical verification. Following Gutiérrez et al. (2013) and Kazmi et al. (2016) the K-folds approach has been adopted to revalidate the IAM. Following the statistical studies format, the whole study period has been reorganized as 80% as training/validation period and 20% as independent test period. The whole study period of 55 years is fragmented into five distinct test samples, each holding eleven years. To proceed, taking any four of these segments as calibration period, the fifth one is set to be forecasted. The robust predictors as well as the relevant atmospheric circulations are correlated based on the K-folds approach. After the confirmation made, physical verification of the robust predictors is processed. In the present study, Walker circulation has been engaged to prove the robustness of secondary ENSO based predictor.

Establishment of IAM

To investigate interannual correlation, all the specified Niño indices have been incorporated as model's input for the duration of December till June. But only three of them have shown significant association with JA-rainfall over the study region during June, for training as well as validation periods. Besides, global SSTs are also tested to investigate possible correlation with the rainfall in the ENSO perspective. Accordingly, SST over eastern equatorial Pacific for June (EEP-SSTJ) has shown considerable association for a region (150°-100°W, 5°S-5.5°N) which is quite similar to Niño-3 area (150°-90°W, 5°S-5°N). Table 1 depicts the correlation related statistics between the targeted rainfall and the Niño based potential predictors. It is important to mention here that for examining the effect of ENSO on summer rainfall over the study region, smaller correlation coefficients have also been considered, based on their significance throughout the study period.

Table 1: Interannual correlation between the Niño indices, EEP-SSTJ for June and JA-rainfall, over the study area.

Period	ONI	Niño-3.4	Niño-3	EEP-SST$_J$
Training (1960-99)	-.49**	-.47**	-.46**	-.47**
Validation (2000-14)	-.68**	-.76**	-.74**	-.77**

** Correlation is significant at .01 level, * Correlation is significant at .05 level.

Afterwards, the rest of predictors including U2JNEA have also been added as input for the IAM. Similar to our recent study Kazmi et al. (2016), U2JNEA has been selected as the primary predictor followed by EEP-SSTJ. Although the other predictors listed in table 1 also hold the equivalent correlations with the rainfall but are finally neglected by the model based on failure in F & t-tests. The relevant mathematical equation may be written as

$$Y_A(t) = 29.74 \times U2J_{NEA}(t) - 24.81 \times EEP - SST_J(t) \qquad (1)$$

Where, Y_A *(t)* is the interannual component of rainfall for 'tth' year (t = 1, 2… 40) over the period 1960–1999, $U2J_{NEA}$ is the 'tth' value of zonal wind at 200 hPa over northeast Atlantic during June and $EEP\text{-}SST_J$ is the 'tth' value of SST over the east equatorial Pacific ocean for June.

The corresponding locations of the robust predictors are depicted in Figure 2. These correlations are validated by employing GPCC data for JA-rainfall in comparison with the observed (maps not included). Important statistics related to the IAM output like correlation coefficient, RMSE and variance are listed in table 2. It has been noticed that after taking the second predictor, either Niño-3 for Jun or $EEP\text{-}SST_J$ to run the IAM, the performance of the model has been improved in all aspects (table 2). Values for both RMSE and variance have been enhanced for calibration as well as for the validation period. Besides, the correlation coefficient has well been improved for the test period and considerably during the training period. It confirms the effect of ENSO on the summer monsoon over the study region. Moreover, the comparison between the modeled and the observed rainfall shows that throughout the study period, the IAM model performed well (Figure 3). There are quantitative discrepancies for some particular years but during most of the period both the data series have shown quite similar patterns of wet and dry episodes.

Table 2: Downscaled results obtained for the IAM in training (1960–99) and independent test periods (2000–14) are shown. Corr is correlation between observation and prediction; Var (Coefficient of Variance) is the ratio of RMSE (mm) to the climatology July–August rainfall during 1960–2014.

	Training Period			Test Period		
IAM	Corr	RMSE	Var (%)	Corr	RMSE	Var (%)
Present Run	0.75	34.09	13.3	0.83	33.63	13.1
Former Run (Single Predictor)	0.71	36.25	14.1	0.71	36.91	14.4

Cross-Validation of IAM

Prior to physical verification of ENSO based secondary predictor, cross-validation of the model's outcome is processed. For that purpose, the K-folds approach is adopted as briefed earlier in the methodology. Table 3 shows the correlation based statistics for both of the robust predictors. It can be observed that overall the secondary predictor remained significantly associated with the rainfall, except in case of K2 & K3. It is to be noted that EEP-SSTJ has been taken as a secondary predictor and may not be dependable for all such discrete test samples. However, based on our former distribution of the study period (1960-99, 2000-14), the secondary predictor has shown significant affiliation with the rainfall for both the calibration as well as the validation periods (table 1). On the other hand, throughout the study period, the mutual relationship between the selected predictors has not been significant. It depicts that the final predictors for the IAM are absolutely independent of each other and not being originated or influenced by a single factor.

Table 3: Correlation of the robust predictor with JA- rainfall and between each other, based on K-fold distribution.

Period	U2JNEA & Rain	EEP-SST$_J$ & Rain	U2JNEA EEP-SST$_J$
K1	0.76**	-0.73*	-.50
K2	0.68*	0.09	-0.19
K3	0.66*	-0.47	-0.32
K4	0.82**	-0.60*	-0.34
K5	0.84**	-0.62*	-0.45

** Correlation is significant at .01 level, * Correlation is significant at .05 level.

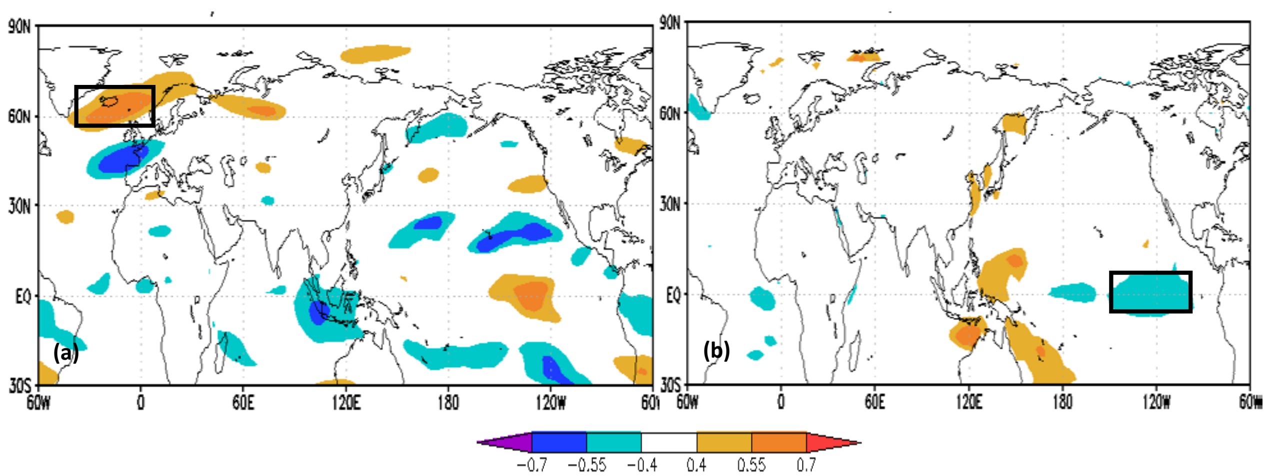

Figure 2: Correlation between detrended JA-rainfall (observed) for study area with Zonal Wind- 200 hPa (a), and SST (b) during June, for the training period of 40 years (1960-99). Rectangles show the areas with comparatively higher correlation and lower RMSE (se lected as robust predictors).

Physical Verification of ENSO based Secondary Predictor

For physical verification, primarily EOF analysis is applied on equatorial Pacific SST for spring/pre-monsoon to summer/monsoon seasons and spatial maps of leading modes are being presented for discussion. Figure 4 depicts that the leading modes are holding positive loadings over the eastern equatorial Pacific with major contribution in the total variance. Relatively same situation prevailed over the particular region since spring up to the summer/monsoon season. Data analysis projects that in case of La Niña conditions or negative SSTa (during the spring-summer season), the surface winds over the central-eastern Pacific blow easterly (Figure 5). But with the warming of the SSTs the corresponding winds start moving in the reverse direction. Subsequently, the anomalous warming and the resulting convection over the western Pacific to eastern Indian Ocean get disappeared. Some recent studies (e.g., Lau and Nath 2000; Shinoda et al. 2004) proposed that the ENSO-induced circulation anomalies may help produce SSTa in the Indian Ocean through cloud-radiation and wind-evaporation mechanisms which ultimately modulate summer rainfall over the Indian monsoon region.

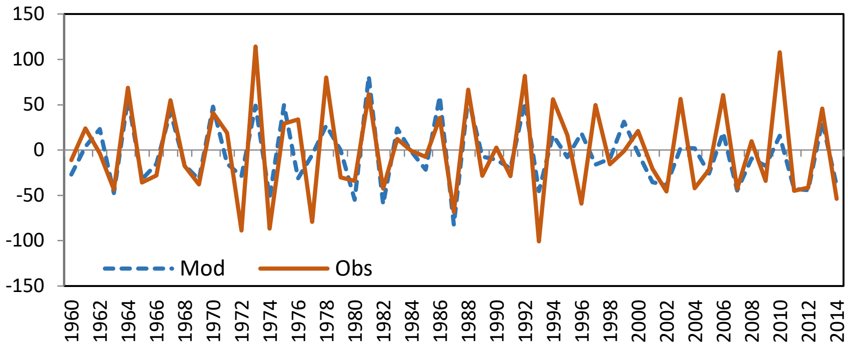

Figure 3: Detrended JA-rainfall observed and the modeled are plotted for the whole study period. A vertical line separates the training and the validation period.

A similar mechanism is elaborated in a study by Meehl et al. (2002) that cooler SSTs in the eastern equatorial Pacific are favorable for strong monsoon in south Asia. Also, Figure 6 shows a comparable pattern for summer winds originated during Non-El Niño (El Niño) conditions over the east equatorial Pacific and during stronger (weaker) monsoon over the study region. The described wind patterns are developed as a result of ENSO dependent anomalies in the surface pressure over the maritime continent (Achuthavarier et al. 2011). Besides, over the study area, the surface winds during summer are modulated by the differential heating between the land and sea (Webster 1987; Meehl 1994).

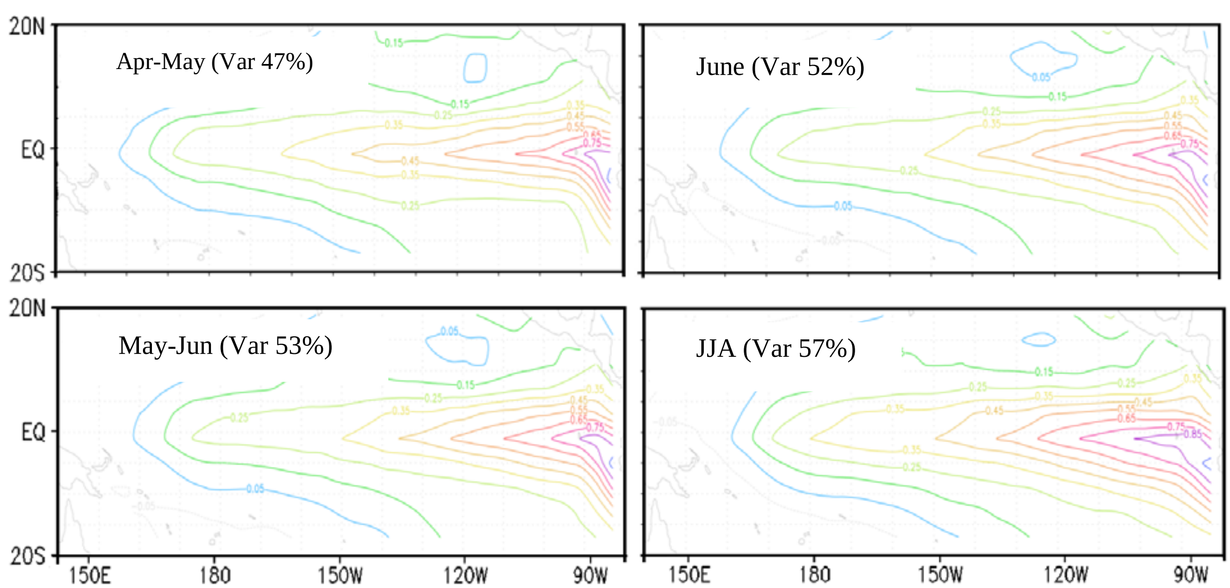

Figure 4: Leading EOF modes of SST over the equatorial Pacific during spring/pre-monsoon and summer seasons, for the study period 1960-2014.

The conventional ENSO-induced teleconnection response during the monsoon is caused by the large-scale east west shifts in the tropical Walker circulation (Krishna Kumar et al. 1999). Velocity Potential (VP) 200 hPa is considered a good surrogate for the Walker circulations. Accordingly, it is incorporated to see the relevant behavior in different modes of summer rainfall as well as ENSO conditions. Fan et al. (2016) stated that the Walker Circulation is modified by negative (positive) SSTa (over the eastern tropical Pacific) through triggering convection (subsidence) over the SAM region that accordingly cause increase (decrease) in the rainfall. Figures 7 (a, b) illustrate the organization of VP 200 hPa during summer (JJA) for wet and dry episodes of summer monsoon over the study area. Besides, Figure 7 (a, c and b, d) depict the similarity between the relevant circulations during strong (weak) monsoons and Non-El Niño (El Niño) episodes. It can be observed from these figures that ENSO modulates Walker circulation that in turn impacts the summer monsoon over the study area.

It is well evident from Figure 7(a and c) that during the period of strong monsoon (over the study area) there will be anomalous cyclonic circulation over the region of western Pacific up to eastern Indian Ocean and Indian subcontinent. But the situation becomes entirely opposite in case of El Niño especially the Cold Tongue (CT) El Niño. Moreover, we have plotted the significant correlation maps between VP 200 hPa-JJA verses the targeted rainfall and Niño-3-Jun in Figure 8 (a, b). It confirms that throughout the study period of 55 years (1960-2014) the ENSO-monsoon relationship has remained consistent.

However, in a few studies (e.g., Krishna Kumar et al. 1999; Kinter et al. 2002) it has been shown that the impact of ENSO on the summer monsoon over the Indian region has been reduced after 1980 and not remained reliable any more. But in the present study it is explored through data analysis that the specified association remained significant throughout the study period of 55 years (1960-2014), however, its polarity has been changed (from negative to positive) for a short period during 1990s (Figures not shown). For more elaboration, summer rainfall over the study area has been correlated with VP (200 hPa) for JJA and SST (Jun) for the post 1980 period (Figure 9a-b). Significant correlation between SST over the eastern equatorial Pacific and the rainfall is well evident from Figure 9b. Hence, based on strong affiliation of VP 200-hPa (Walker circulation) and SSTa over the particular region with the targeted rainfall, it may be concluded that ENSO-Monsoon association is still valid and reliable.

Through data analysis and based on insights of recent studies in the region (Meehl 1987, 2002; Krishna Kumar et al. 1999), it has been revealed that in ordinary conditions (La Niña, in particular) the SSTa over the east equatorial Pacific remains negative and may produce anomalous warming and corresponding convection over the western Pacific up to the eastern Indian Ocean. But in case of CT El Niño, the said conditions are transferred towards the central and eastern equatorial Pacific. Accordingly, an anomalous high pressure is likely to appear over the western Pacific up to the Indian subcontinent (the region comprising Pakistan, India and Bangladesh). Accordingly, the convection disappears and the consequent rainfall will be suppressed over both of the specified regions including our study area. Whereas, an anomalous cyclonic condition would be developed over the central to eastern equatorial Pacific. The surface wind pattern over the specified region (Figure 6c, d) has further confirmed that negative (positive) SSTa or Non-El Niño (El Niño) conditions over the eastern equatorial Pacific play favorable role in producing stronger (weaker) monsoon over the study area.

Based on insights of the recent studies and through our data analysis (Figures. 5-9), we have proposed a possible mechanism to describe the impact of the secondary ENSO based predictor on the summer rainfall over Pakistan in Figure 10. Notably, the present work is particularly focused on the summer monsoon over Pakistan. Also, we have shown the role of anticyclone over the eastern Indian/western equatorial Pacific Ocean and temperature gradient between the land and water mass modulates the surface winds in feeding moisture to the Indo-Pak region. Moreover, we have described that collective impact by strong heating during summer, enhanced convection established through the west central Asian high and continuous moisture feeding from the Bay of Bengal play important roles in intensifying the condensation and producing stronger monsoon over the study area.

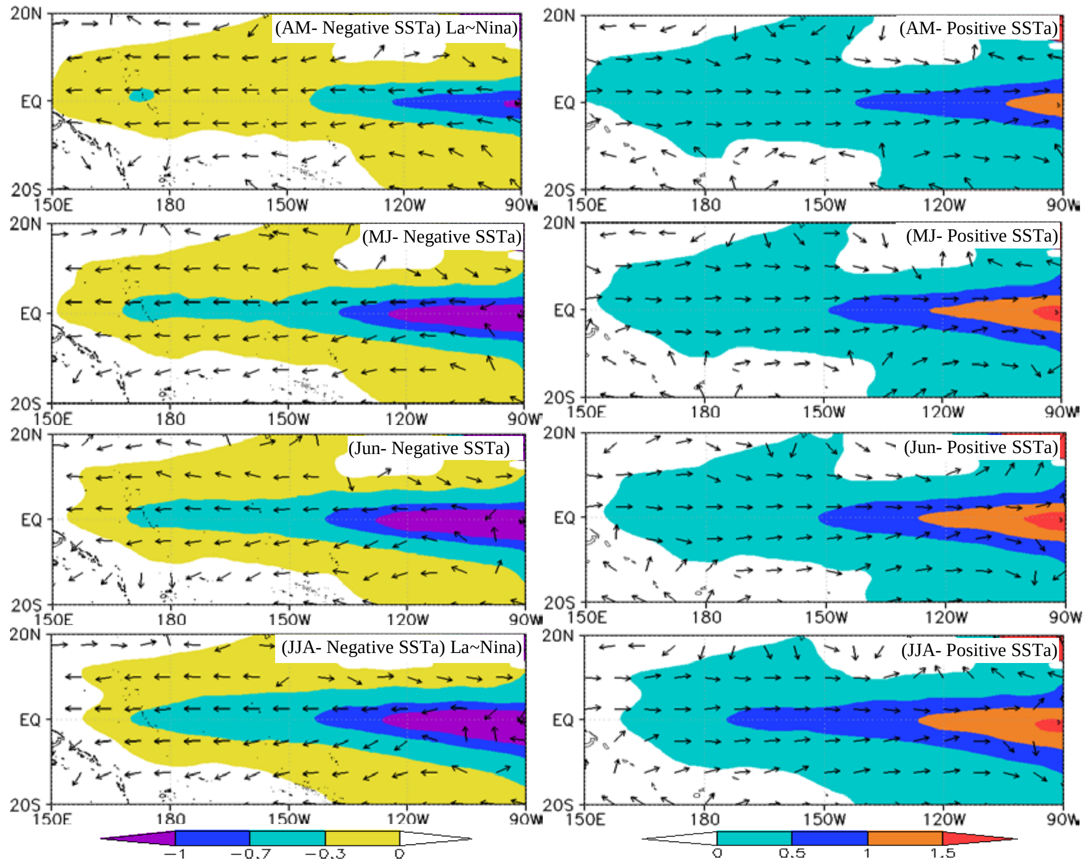

Figure 5: Detrended SST (eastern equatorial Pacific) & wind 850 hPa for La Niña (negative SSTa) and CT El Niño conditions (positive SSTa) during spring/pre-monsoon and summer seasons, in the study period 1960-2014.

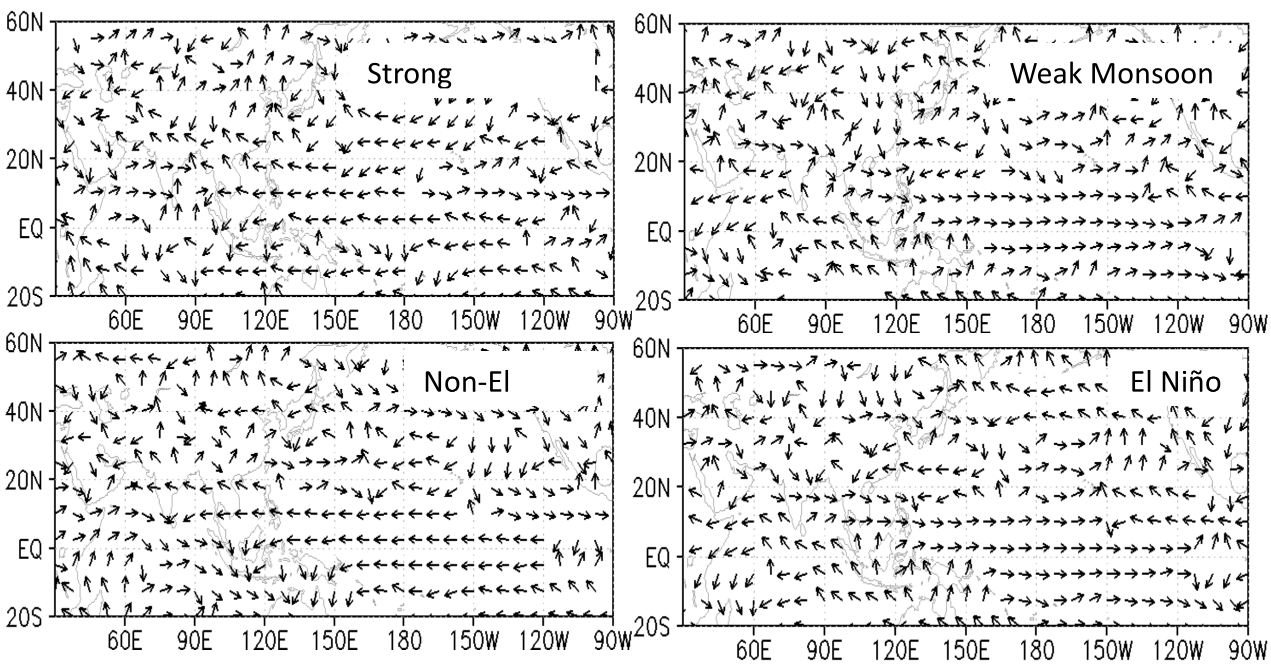

Figure 6: Winds at 850 hPa for the summer season JJA, during different conditions, for the whole study period of 55 years, 1960-20014.

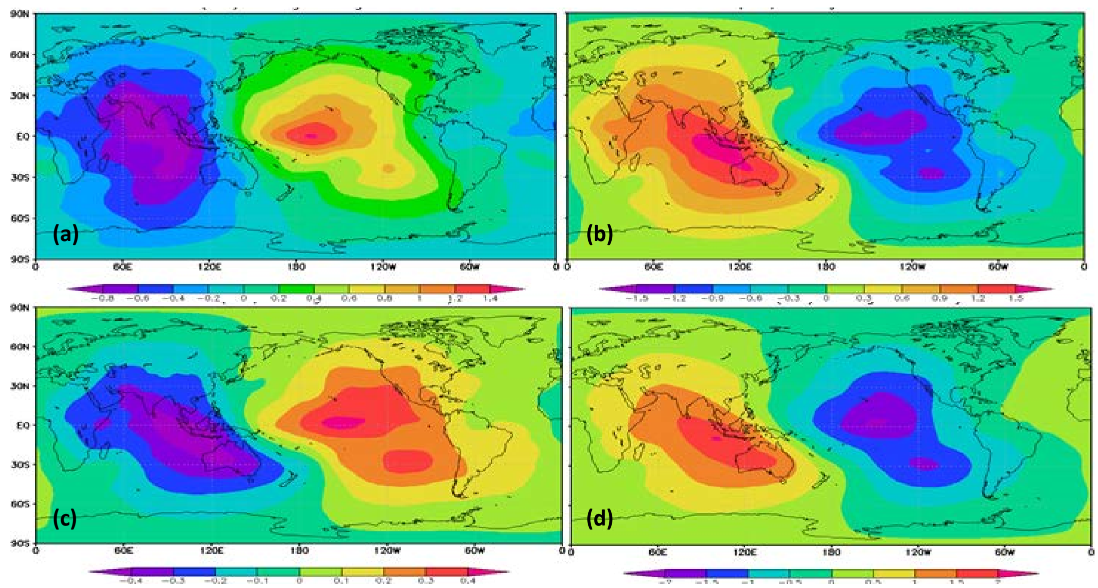

Figure 7: Detrended Velocity Potential at 200 hPa (106 m2 s-1) for JJA are shown for Strong (a) and the Weak Monsoon (b), Non-El Niño (c) and El Niño periods (d).

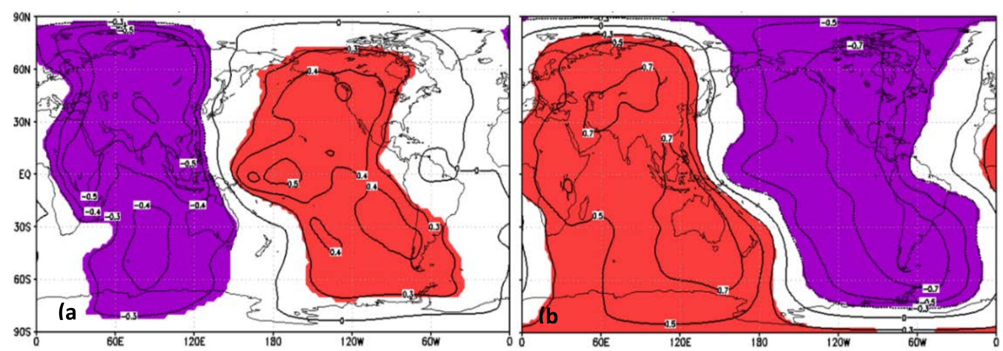

Figure 8: Interannual correlation between detrended Velocity Potential at 200 hPa for JJA with Jul–Aug rainfall (a) and Niño-3 for June (b), shading shows the significance at 0.05 level.

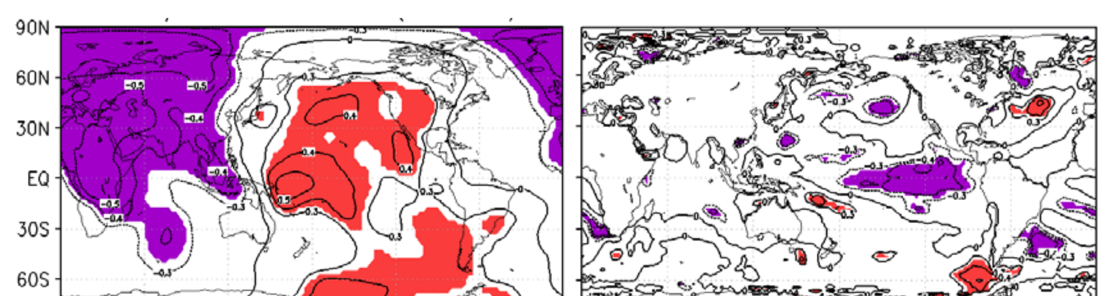

Figure 9: Interannual correlation between detrended Jul–Aug rainfall with Velocity Potential at 200 hPa for JJA (a) and SST for June (b) during the period 1981-2014, shading shows the significance at 0.05 level.

Summary

To further improve the statistical IAM for summer monsoon over Pakistan, SSTa over the tropical Pacific may be utilized as candidate predictors (Kazmi et al. 2016). After employing SST for Dec-Jun period, EEP-SSTJ has been selected as the secondary robust predictor besides U2JNEA, for the statistical IAM for summer rainfall over Pakistan. Accordingly, the overall performance of the model has been improved. In this study, the IAM has been established by considering the combined impact of upper tropospheric westerly from northeast Atlantic and the tropical easterly currents from the east equatorial Pacific. We have employed VP 200 hPa to engage the Walker circulations for different modes of summer rainfall as well as ENSO. Accordingly, in addition to considerable upgradation in RMSE & variance, the correlation coefficient has also been improved from 0.71 to 0.75 for calibration and 0.71 to 0.83 for the validation period. Besides utilization of strict C_CVSR criteria for predictor selection, a reconfirmation has also been processed through the application of the K-folds discrete test samples approach. Data analysis has shown that SSTa over the eastern equatorial Pacific holds a reliable negative correlation with the summer rainfall over the core region which has been gradually increased in the recent years. However, during 1990s the stated relationship has got reversed (in polarity) for a short period, which needs to be addressed in a separate study. Moreover, it is revealed that besides enhanced convection induced by the west central Asian high (HGT-200 hPa), strong heating during summer and continuous moisture feeding from the Bay of Bengal also take active part in producing stronger monsoon over the study area. The output of the statistical model for interannual variability of the targeted rainfall has been confirmed on physical grounds. Accordingly, it has become a practical model for seasonal prediction of summer rainfall over Pakistan. The outcome of the present study would be useful for future research work on the relevant issues.

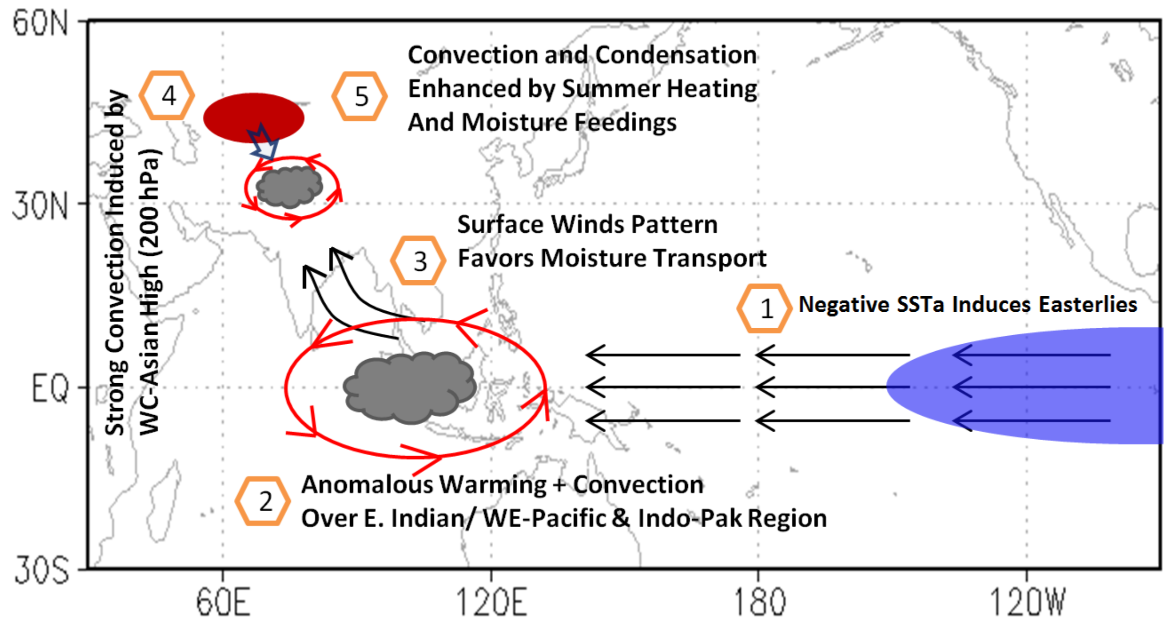

Figure 10: This diagram highlights the major processes involved in the proposed mechanism behind effect of secondary ENSO based predictor 'EEP-SSTJ' on the summer monsoon over Pakistan. Primarily, over the eastern equatorial Pacific, easterlies are triggered through negative SSTa during Spring-Summer season (1). Also the modified Walker Circulation induces anomalous warming and consequent convection over the Eastern (E) Indian & Western Equatorial (WP) Pacific up to Indo-Pak (India & Pakistan) region (2). Moreover, surface winds move towards the landmasses (due to temperature & pressure gradient) favoring the moisture transport to the study area (3). On the other hand, upper tropospheric high over the West Central (WC) Asia induces strong convection over the particular region (4). Finally, the enhanced convection through the WC-Asian high, strong heating during summer and continuous moisture feeding through the Bay of Bengal collectively play important roles in strengthening condensation process over the study area and produce stronger monsoon (5).

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