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Evidence of ENSO and IOD Interplay in Continental Climatic Records from Southern Himalaya (Renuka Lake), India

Narendra Kumar Meena[1], Pranaya Diwate*[1, 2] and Sundeep Pandita[3]

[1]*Wadia Institute of Himalayan Geology, Dehra Dun - 248001(UK), India*
[2]*Centre for Climate Change and Water Research, Suresh Gyan Vihar University, Jaipur- 302011 (RJ), India*
[3]*Department of Geology, University of Jammu, Jammu -180006 (JK), India*
*(*Corresponding author, E-mail: pranayadiwate7@gmail.com)*

Abstract

We studied the ^{210}Pb and ^{137}Cs isotope dated shallow sediment core taken from the Renuka Lake (India), using the multiproxy approach, *e.g.* clay minerals (illite, chlorite and kaolinite), Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW). In overall distribution, illite (65%) dominates throughout the sequence, followed by chlorite (19%) and kaolinite (16%). The average value of CIA and CIW in the Renuka Lake was estimated 76 and 93, respectively. Based on these proxies, two major wet and warm (*ca.*1839-1890 AD and *ca.*1929-1959 and two arid (*ca.*1890-1929 AD and *ca.*1959-2003 AD) phases of the climate were observed in the Renuka Lake. The climatic phases of the Renuka Lake area seem to be influenced significantly by the sea surface temperature (SST) anomalies *e.g.* Indian Ocean Dipole (IOD) and El Nino Southern Oscillation (ENSO). The more positive value of the Dipole Mode Index (DMI) since 1920 AD and onward affected the monsoon-dominated climate in the foothill region of the Himalaya. It has also been observed that the relationship between ENSO-ISM was weakened and the influence of Indian Ocean Dipole (IOD) increased on ISMR despite the strong El-Nino year (1997), the ISMR remained above the normal. The present study gives strong evidences of the multiple factors that have been controlling the monsoon in the region.

Keywords: Monsoon, ENSO, IOD, Clay Minerals, Sediment Core, Renuka Lake, Southern Himalaya, India

Introduction

The Indian Summer Monsoon (ISM) is a macro scale phenomenon, directly affected by the forcing factors, and internal and external boundary conditions such as solar insolation, Eurasian and Himalayan snow cover and contrasting Sea Surface Temperature (SST) (Kucharski *et al.*, 2006; Cherchi *et al.*, 2007). The SST affects ISM with two profound systems, *i.e.* El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) over time and space (Kutzbach, 1987). The ENSO is an ocean-atmosphere interaction phenomenoncharacterized by surface warming of the tropical Pacific Ocean and weakening of equatorial trade winds that occur after every few years (Bjerknes, 1966, 1969; Allan *et al.,* 1996; Kumar *et al.*, 1999; Timmermann *et al.*, 2018). In other means, the Southern Oscillation is characterized by irregular strengthening and weakening of the trade winds induced by the changes in the surface pressure (Webster and Yang, 1992; Yang *et al.,* 1998; Lau and Nath, 2000). The ENSO affects ISM directly by large-scale circulation change over the Indo-western Pacific Ocean which further increases or decreases the ISM intensity (Chen and Yen, 1994). The negative phase of ENSO (El-Nino) results in less ISM precipitation, whereas positive (LA Nino) brings strong ISM (Sikka and Gadgil, 1980; Angell, 1981; Rasmusson and Carpenter, 1982; Ropelewski and Halpert, 1986, 1989). Therefore, ENSO events are also associated with extreme events of droughts and floods (Power *et al.*, 1999) in the Indian subcontinent.

IOD is known as anomalous SST difference between western (50E-70E and 10S-10N) and southeastern equatorial Indian Ocean (90E-110E and 10S-0N), and characterized by Dipole Mode Index (DMI) (Saji *et al.*, 1999; Webster *et al.*, 1999). A positive (negative) IOD is identified when DMI is positive (negative). In normal conditions, positive IOD increases the rainfall over the Indian subcontinent. There are so many studies that have been carried out to develop an understanding of the relationship and mechanism between ENSO and IOD and its profound effects on the monsoon and other global circulation. The study on the relationship between ENSO-ISM and IOD-ISM during 1958-1997 revealed that the ENSO and ISM are weakly related, whereas the IOD and ISM

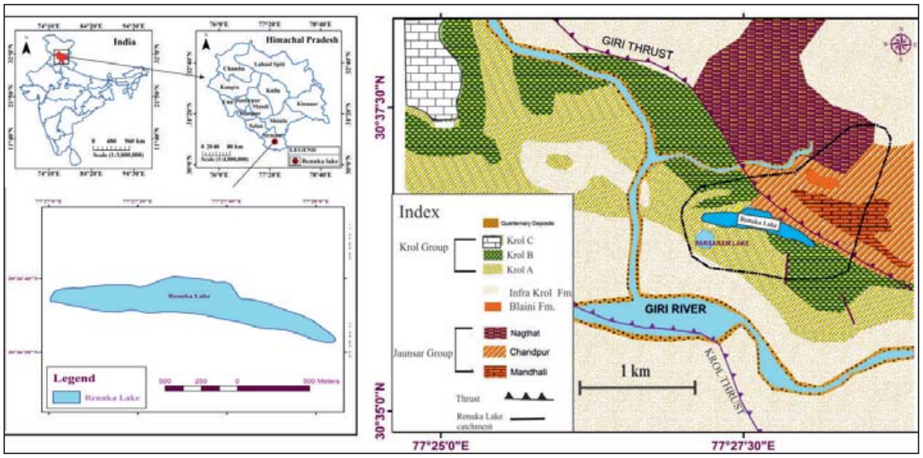

Fig. 1. Map showing the location of Renuka Lake and coring site (red dot) (Source- Google earth). Geological map of Renuka Lake and the Catchment area (*modified after* Das and Kaur, 2008), (Fm.-Formation)

have strong relationship (Ashok *et al.*, 2004). The instrumental records of the ENSO and IOD are available for the past ~150 years (Meyers *et al.*, 2007) in which the IOD and positive ENSO (El Nino) merely coupled, except during 1967 and 2007 (Behera *et al.*, 2008). However, the coupling of two systems may not be possible annually but can be detected at inter-annual time (decadal to sub-decadal) scale because of the response of the ENSO and IOD to each other. Such records sometimes cannot be retrieved from the instrumental correlation but can be observed from the continental proxy records such as the Renuka Lake, which is situated at foothill region of the Lesser Himalaya and proved to be an excellent site to study this variability. Moreover, high sedimentation in the Renuka Lake provides a unique opportunity to study decadal to sub-decadal records from the foothills of the Himalayas (Borgaonkar *et al.*, 1996, 2011: Yadav and Singh, 2002, Yadav, 2009; Yadav and Bhutiyani, 2013). Therefore, the proposed study is aimed to reconstruct palaeoclimatic records for the past 170 years through extreme events such as drought and floods from a lake sediment core and correlate that with the interplay of ENSO and IOD. Therefore, the objective of the present study is to find out evidence of ENSO and IOD interplay records from southern Himalaya (Renuka Lake), India.

Study Area

The Renuka Lake (30° 36' 36"N; 77° 27' 45"E) is located about 35 km east of Nahan in the Sirmour district, Himachal Pradesh, India, at an elevation of 645 m ASL in the low subtropical zone in the Lesser Himalaya (Fig.1; Das and Kaur, 2001). The lake is believed to have been formed by an abandoned channel of the Giri River, which presently flows by the west of the lake (Virdi and Philip, 2006). This oblong-shaped lake is oriented in the east-west direction covering an area of 0.182 km^2. The maximum depth of the lake basin is 13 m (Diwate *et al.*, 2020) and has water spread over 0.2 km^2. The maximum width and length of the lake is 0.2 km and 1.05 km, respectively (Singh and Sharma, 2012). The lake received 1500-2000 mm/year out of around 80% of the rainfall is received from July to September every year. The lake is fed by streams, internal springs (open due to fractures and fault), and monsoon. The outlet of the lake opens toward the Parashuram Tal and then outflows towards the Giri River in the west. The gradient of the northern slopes is gentle, whereas thesouthern slope is steep. In the northern side, Jammu ka Tibba is the highest altitude point (1591 m) in the catchment area.

Geologically, the catchment rocks of the Renuka Lake belong to the Blaini, Infra Krol, Krol, and Jaunsar groups of the Proterozoic age. Major rock types are carbonaceous shale, slate, siltstone, purple dolomite,and limestone. Renuka area is tectonically active and overlying the Main Boundary Thrust zone (Auden, 1934; Singh and Mahajan, 1987; Das and Kaur, 2001; Das and Kaur, 2008; Singh and Sharma, 2012; Kumar *et al.,* 2019a and b). The composition of the soil of the area shows a diverse combination of siltstone, shale,and sandstone in different proportions (Srikanta and Bhargava, 1998). The formations like the Nagthat, the Chandpur and the Krol B are exposed in the northern boundary of the Renuka Lake (Fig.1) while the southern part comprises rocks such as shale and limestone belonging to the Krol-A, Krol-B, and Infra Krol formations. The north-eastern part of the lake is made up of rocks of the Mandhali Formation. The western part is made up of Krol-A Formation whereas, the Krol-B and the Chandpur Formations are present in the eastern part.

Material and Methods

Sampling

The sediment core was retrieved from the central part of the Renuka Lake in the year 2011 using a piston corer (Fig.1) and its top 2 m part was used for the current study. The core was linearly bisected into two halves (U-channels) and one 'U' channel was sub-sampled by slicing at 1 cm resolution using a blade. Sliced samples were prepared for radionuclide dating using ^{210}Pb, ^{137}Cs isotope, and in addition for clay minerals and geochemical analysis as per the following process.

Chronology

The age of the sediments core was known using ^{210}Pb radionuclide isotope analyses which were further cross-checked by ^{137}Cs isotope. The ^{210}Pb and ^{137}Cs activities were determined according to the standard protocol (Somayajulu *et al.*, 1999; Sarkar *et al.*, 2016; Meena *et al.*, 2017; Kumar *et al.*, 2019c)**.** The measurement was performed at Physical Research Laboratory (PRL), Ahmadabad, India.

The ^{137}Cs vertical profiles were used to validate the chronologies established with the ^{210}Pb dating method. The ^{137}Cs vertical profile in the Renuka Lake showed a clear maximum value in the 37.5 cm (7dpm/g) layer. The inventory of ^{137}Cs exhibited minimum values of 0 dpm/g to a maximum 7dpm/g with an average of 4.55 dpm/g. The minimum and maximum ^{210}Pb excess values are ranging from 0.5 to 9 dpm/g, respectively. The ^{210}Pb ex (on a logarithmic scale) in sediment cores from the Renuka Lake was also determined. Excess ^{210}Pb (^{210}Pb ex) activity shows an exponential decrease with depth in the Renuka Lake core profile. The top sample at a depth of 2 cm shows the value of 9 dpm/g followed by 4 dpm/g at the 19 cm. The sample at 37.5 cm possesses 0.5 dpm/g and exhibits exponential decay. The sample below 37.5 cm does not show any ^{210}Pb ex activity.

The sedimentation rate for the Renuka Lake was estimated using ^{210}Pb and ^{137}Cs radioactive isotope techniques (Table 1). According to ^{210}Pb the lake indicated two different sedimentation rates, *i.e.*, 0.51 cm/year upper part (0-19cm depth) for the period of *ca.* 2011 to 1974 AD and 0.78 cm/year lower part (19-40cm depth) from 1974 to 1950 AD, whereas the average sedimentation of the lake was measured to be 0.64 cm/year .^{137}Cs profile shows a distinctive peak at 37.5 cm and was considered as ^{137}Cs fallout in the atmosphere, which is referred to as maximum ^{137}Cs fallout due to 1963 nuclear weapon test. The average sedimentation rate of the lake was estimated to be 0.78 cm/year, considering 1963-64 AD as a time marker at 37.5 cm depth that has a reasonable agreement with the ^{210}Pb based sedimentation rate (0.64 cm/year) (Table 1).

Clay Mineralogy

Clay minerals analysis was performed using 15 samples from various depths. Clay was separated from the bulk sample following the protocol of Brindley and Brown (1980). A 05 gm from each sediment sample was taken in a glass beaker and inorganic carbon content was removed by adding 1N hydrochloric acid (HCl). The organic carbon was also removed by adding 30% Hydrogen peroxide (H_2O_2). Clay particles <2 µm were extracted using the Stokes' settling velocity principle. The extracted particles of <2 µm were centrifuged and smeared on a glass slide. Clay mineralogical analysis was carried out using X-ray Diffractometer (PANalytical X' Pert PRO) at the XRD lab of Wadia Institute of Himalayan Geology, Dehradun, India. Clay mineralogical analysis was carried out from 4 to 60° 2θ range with a step size of 0.02°. The XRD run was carried out after treatments such as air-dried, ethylene glycol saturation (for 12 hours),and heated at 500^0 C. Glycolation and heating of the slides were done toidentify clay minerals shifting or destroying peak values after this treatments. To verify the presence of kaolinite and chlorite, a 6N HCl treatment of the clay fraction was carried out in a boiling water bath and after 1 hour of treatment with acid, chlorite was easily decomposed which further confirmed by slide run (Oinuma and Kobayashi, 1966).

The clay minerals were identified using X-Ray diffractogram peaks and intensity results. The Illite was identified by basal spacing at 9.90-10 Å and 4.97-5.04 Å (001), the confirmation of illite was done by glycolation and heating treatment (Bradley and Grim, 1961). Kaolinite was detected on basis of its basal (001) peak that corresponds to the 7.02-7.10 Å and 14.05-14.30 Å (001) that destroyed at 550^{0}C but unaffected after glycolation treatment. The chloritewas detected at 14.05-14.30 Å (001) with reflection at 4.69-4.73 Å (003). The 7.02-7.10 Å (001) and 3.52-3.54 Å (002) are identical in both kaolinite and chlorite hence, the confirmation of chlorite was done by the hydrochloric acid test (Kodama and Oinuma 1962)**.** The disappearance 14 Å peak after acid treatment confirmed the presence of chlorite.

Table 1: Depth and corresponding Age based on Constant Rate Sedimentation (CRS) in the Renuka Lake used for Geochemical (*) and Clay mineralogical (**) analysis.

Sr. No.	Depth (in cm) (*)	Age (AD)	Depth (in cm) (**)	Age (AD)
1	4	2003	2	2007
2	10	1990	6	1999
3	18	1974	12	1987
4	28	1962	30	1959
5	40	1946	36	1952
6	46	1939	38	1949
7	54	1928	54	1928
8	64	1916	56	1926
9	72	1905	66	1914
10	78	1898	72	1908
11	84	1890	84	1890
12	90	1882	90	1885
13	94	1877	96	1880
14	96	1875	102	1867
15	102	1867	124	1839
16	106	1862	-	-
17	112	1854	-	-
18	118	1846	-	-
19	120	1844	-	-
20	124	1839	-	-

Geochemistry

For the analysis of majorelements, 05 gm from each sediment sample was oven-dried at about 60-80^{o}C. The dried samples were powdered up to 88 µm size using the Tima Mill crushing machine. The powdered samples were further mixed with 3-4 drops of polyvinyl alcohol and pressed under hydrologic pressure (2000 kg cm^{-2}) to make pellet using (INSMART XRF 40 pellet machine). The pellets were exposed directly for X-rayfluorescence (XRF) measurement in the XRF machine (Model: Brucker S8 Tiger). The X-ray intensities of the different elements of each sample were matched with reference intensity to obtain intensity and further quantified using the intensity correction model (Saini *et al.*, 2000). The CIA and CIW were calculated as per the standard method (Nesbit and Young, 1982; Harnois, 1988).

Instrumental Data

In the present study, to compare the Renuka Lake data to regional and local climate, we have correlated the present data with the other established database. The data used in this study were sourced from the work of different authors such as the Dipole Mode Index Reconstruction (Saji *et al.*, 1999), the Total Solar Irradiance (Bard *et al.*, 2000) and ENSO data (Moy *et al.,* 2002).

Results and Discussion

Palaeoclimate Reconstruction Using Clay Mineral Variations

The Himalaya has one of the highest weathering (physical and chemical weathering) and erosion rates in the world (Milliman and Meade, 1983; Sarin *et al.*, 1992; Galy and France, 2001) that regulated by the tectonics forces and climate at the millennium time scale (Colin *et al.*, 1999). The weathering and erosion produce various clay minerals, *e.g.* kaolinite that formed during intense chemical weathering of various rocks under humid climate (Chamley, 1989; Tripathi and Rajmani, 2007). It remained unaffected by post-depositional changes and is preserved as a paleoclimatic record (Singer, 1980). Thus, the higher percentage of kaolinite in lakes sediments indicates warm and wet climatic conditions. The Illite and Chlorite are primary clay minerals that are derived from physical weathering of low grade metamorphic and granitic parent rocks because illite and other micaceous minerals are commonly inherited from parent rocks or other materials, where they were formed under different pressure/temperature conditions existing on Earth's surface (Chamley, 1989). The higher percentage of these minerals reflects the decrease of hydrolytic processes and the dominance of the physical weathering that usually occurred in cold and dry climatic conditions (Colin *et al.*, 1999). Particularly, Chlorite is more susceptible to chemical weathering compared to illite (Biscay, 1965). So, the production of chlorite suggests mixedweathering influenced by both chemical and physical weathering and perhaps shows a moderate phase (involvement of both physical and chemical weathering) of climate.

The semi-quantitative calculation was carried out to determine the percentage of each clay mineral present in the sample using an X-pert high score plus program (Fig.2; Biscay, 1965**.** As per abundance in the core, we considered three main clay minerals such as illite, chlorite and kaolinite (Table 2). In overall distribution, illite (65%) dominates throughout the sequence, followed by chlorite (19%) and kaolinite (16%). As per temporal distribution, the lowest percentage of illite (58%) logged during ca.1839 to 1890 AD, whereas chlorite shows 23% and kaolinite 19%. During ca.1890-1929 AD, the Illite increased to 74% while kaolinite and chlorite decreased to 10%, and 16%, respectively. The illite again slightly decreased (70%) while kaolinite increased 14% between ca.1929-1959 AD and chlorite remained constant during this phase. Between *ca.*1959 to 2007 AD, Illite again decreased to 63%, while kaolinite and chlorite fluctuated between 15-23% and 13-17%, respectively (Table 2).

The kaolinite and illite ratio (K/I) of the core ranges between 0.07 - 0.8. During *ca.*1839 to 1890 AD, the K/I ratio exhibited 0.38 that decreased to 0.14 during 1890-1929 AD. The K/I ratio again increased up to 0.30 during *ca.*1959 to 2007 AD that again decreased to moderate (0.21) during *ca.*1929-1959 AD.

Based on the clay mineral distribution, various phases of the wet and dry climate have been observed. The period between ca.1839-1890 AD showed a wet phase that could be inferred by the relatively higher values of kaolinite, chlorite and depleted value of illite under the influence of high precipitation. The Kaolinite/Illite ratio (K/I ratio) may indicate the humidity indices of an area (Das *et al.*, 2013). In the period between *ca.*1839-1890 AD shows a wet and warm phase, inferred by relatively higher values of kaolinite, K/I, chlorite

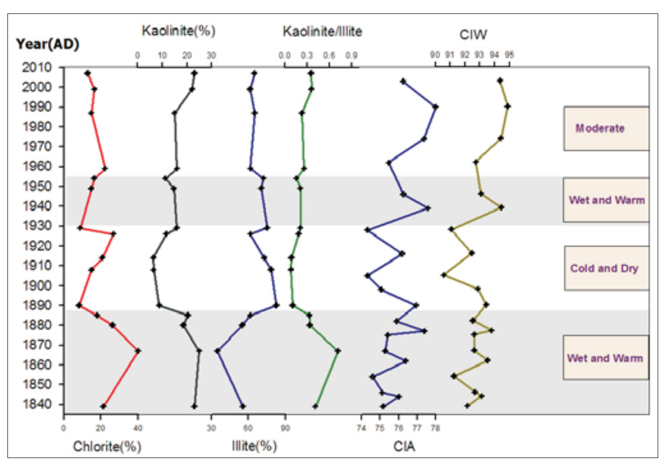

Fig..2. Clay mineralogy and Geochemistry of 126cm Core of Renuka Lake

Table 2: Clay mineralogical data from Renuka Lake with Age-Depth.

Sr. No.	Year	Depth	Chlorite %	Illite %	Kaolinite %
1	2007	2	12.7945	65	23
2	1999	6	16.486	61.4401	22.074
3	1987	12	14.87	65.13	15
4	1959	30	22.231	61.7705	15.9984
5	1954	36	16.4359	72.2828	11.2813
6	1949	38	14.8562	70.4569	14.687
7	1929	54	8.7879	75.3636	15.8485
8	1926	56	26.7361	61.6793	11.5846
9	1914	66	20.7975	72.8004	6.402
10	1908	72	15	78.5	6.5
11	1890	84	8.3114	82.8299	8.8587
12	1885	90	17.9359	61.637	20.427
13	1880	96	26.2626	55.2189	18.5185
14	1867	102	40	35	25
15	1839	124	21.2967	55.7321	22.9712

and depleted value of illite under the influence of high precipitation. During ca.1890-1929 AD, the sediments were characterized by enrichment of illite and depleted values of kaolinite, chlorite and K/I depicting as cold and dry period. The period during *ca.*1929-1959 AD was interpreted a wet and warm phase characterized by relatively high kaolinite and low illite values. The recent period *ca.* 1962-2010AD showed a mixed signal because chlorite and illite were decreased with increasing kaolinite content and therefore, this period witnessed a moderate climatic phase. In the monsoon-dominated Himalayas, the ISM governed a major part of weathering and erosion (Derry and France–Lanord, 1996; Bookhagen *et al.*, 2005)**.** Thus, the wet and warm phase of the climate can be interpreted as an intensification of ISM, whereas the opposite trend as a weak ISM phase.

Paleoclimatic Reconstruction by CIA and CIW

The Chemical Index of Alteration (CIA) and Chemical index of weathering (CIW) have been used to quantify the chemical weathering intensity (Nesbit and Young, 1982). The average values of CIA and CIW in the Renuka Lake were estimated 76 and 93, respectively. The values of CIA, CIW and found to be changed with time, *i.e.* during *ca.*1839-1890 AD as 76 and 93, respectively. During *ca.* 1890-1929 the values of CIA and CIW slightly decreased to 75 and 92, respectively. The CIA and CIW and slightly increased (77 and 93) from *ca.*1929-1959 AD, during this period. At the top of the core (1959-2003 AD) the CIA and CIW exhibited the highest values, *i.e.* 77 and 94, respectively. The CIA and CIW are robust indicators of chemical weathering intensities (Nesbit and Young, 1982). The values of both indexes below 60 indicate lower weathering, 60 to 80 moderate and above 80 shows extreme weathering (Fedo *et al.*, 1995; Fig. 2). The validity of CIA as a paleoclimatic proxy has been tested well and found a direct relation with annual precipitation and temperature in marine and Lake Paleoclimatic records (Sheldon *et al.*, 2002). The higher CIA value (78) of the Renuka Lake suggests a moderate to high chemical weathering and that falls within the tropical and sub-tropical range (Selvaraj and Chen, 2006). The higher values of CIA during *ca.*1839-1890 AD suggest that higher chemical alteration/weathering and lower physical weathering under warm and wet climate in the Renuka Lake. During *ca.*1890-1929 AD, the sediments are characterized by slightly decreased values of CIA and CIW that indicated less chemical and more physical weathering possible due to a cold and dry climate. The period between *ca.*1929-1959 AD was interpreted as a wet phase, which characterized higher values of the CIA and CIW. The period from ca.1959-2003 AD showed an increase in chemical alteration/weathering and decreasing physical weathering due to cold and dry climate.

ISM, ENSO and IOD Interplay

It has been well established that various phase (positive, negative) of the IOD and ENSO has a profound effect on the ISM and winter rain in Himalaya and peninsular India. Both the SST-driven phenomenon can have their impact due to the following possible modes, *i.e.* when both ENSO and IOD are positive, both negative, ENSO positive and IOD negative and IOD positive and ENSO negative. These effects may exist at meteorological (annual scale) and decadal to sub-decadal time scale. However, at an annual scale, the co-occurrence of positive IOD and La Nina is an infrequent phenomenon due to the associated phase of Walker Circulation that can be detected in meteorological data, whereas decadal and sub-decadal variations can be seen on the proxy-based climatic records due to feedback related mechanism.

The positive IOD and La-Nina at the annual scale were observed only during 1967 and 2007, similarly the IOD events were also rare in two consecutive years as observed in 1913-14 and 2006-07 (Behera *et al.*, 2008; Fig.3). For instance, the wet and warm climate in the Renuka Lake records during 1877, 1946, and 1974 suggested the result of La- Nina and IOD coupling that brought excess monsoon in foothill Himalaya. However, the presence of LA-Nina and IOD may also result in the dry climate (decreased monsoon) and such events as observed in the year 1962 are rare (Fig.3).

The extremely El Nino and Negative IOD during 1990 and 1882 seem severe drought years as both ISM and WD failed to bring the moisture. The positive phase of the ENSO (El-Nino) affects the ISMR by east-west displacement of Walker Circulation which leads to deficit ISMR (Ropelewski and Halpert, 1987). Several workers have suggested that during the El Nino phase, the surface pressure gets increased, which further suppresses atmospheric convection in the Indian Ocean and western equatorial Pacific (Shukla and Paolino, 1983; Kumar *et al.*, 1999). These anomalies affect the ISM by

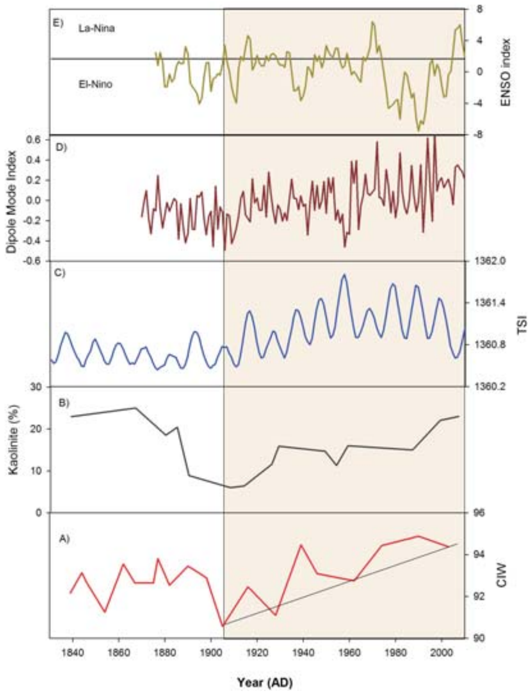

Fig. 3. Comparison of the present study with ENSO, Dipole Mode Index and TSI.

weakening Southwest monsoon wind that causes a large deficit in ISM. The negative ENSO and IOD years during the 1990 and 1882 bring wet and the warm climate over the Renuka Lake region might be possible by March–April–May–June (MAMJ) precipitation and directly associated with the interplay ENSO (positive) and North Atlantic Oscillation (NAO). Yadav (2011) reported such a situation in 1990 from Tree-ring-width data of Himalayan cedar. However, the dominance of the westerlies can also be ruled out. The winter precipitation over Northwest India has also been found linked with the ENSO variability (Yadav, 2009).

Several earlier studies (Allan, 1994; Kachi and Nitta, 1997) have shown that ENSO is a part of inter-decadal variability. In the warm pacific inter-decadal SST variation, the regional Hadley circulation related toElNino reinforces, while that is associated with La-Nina opposed the inter-decadal Hadley Circulation (Krishnamurthy and Goswami, 2000). During the warm (cold) phase of the inter-decadal oscillation, El-Nino (La-Nina) expected strongly related to droughts (flood), and La-Nina (El-Nino) have not significant correlation. These will cause a strong correlation between El-Nino and droughts.

These climatic behaviors are comparable with the tree-ring record from Kumaun Himalaya (Yadav *et al.*, 2014), which shows a drought condition in the region during 1919-1924 AD. Cook *et al.* (2010) also suggested several drought years during this time as may also be inferred for *ca.* 1838AD, 1845AD, and 1855AD. The present data also show a significant correlation with IOD data. The DMI value from *ca.* 1920AD onward shows the higher numbers of positive IOD events, which are considered to be responsible for high rainfall.

The positive IOD mode supports the high monsoon year, while negative IOD is responsible for the weakening of the rainfall in NW India (Nair *et al.*, 2018). Taking this interpretation in consideration, the more positive value of DMI since 1920 AD onward suggests the effect of dipole mode in the foothill of the Himalayan region which is seen from the present study. It is noticed that in recent years the relationship between ENSO-ISM was weak and the influence of IOD was increased on ISMR, *e.g.* despite the strong El-Nino year (1997), the ISMR was above the normal (Pai *et al.*, 2004).

Kumar *et al.* (2020) in their study had inferred that there is no relationship exit that can describe the reason of the excess and deficit rainfall in the changing pattern of Nino-3 index. Such a condition was also observed during 1997 and despite the strongest El-Nino of the century, no drought occurred.Yadav (2011) suggested that some of the other forcing factors also play a role in modulating the monsoon system, which possibly influences the ENSO-MAMJ precipitation pattern during 1930-1960.

Conclusions

Based on the clay minerals variation, CIA and CIW, we conclude that the Renuka Lake faced two major wet and warm phase of the climate in the recent past. The two wet and warm phases (*ca.*1839-1890 AD and *ca.*1929-1959) and two arid phases (*ca.*1890-1929 AD and *ca.*1959-2003 AD) were evident in the region. It has also been observed that the relationship between ENSO-ISM was weakened and the influence of Indian Ocean Dipole (IOD) got increased on ISMR *e.g.* despite the strong El-Nino year (1997), the ISMR remained above normal. The present study gives the strong evidences for the multiple factors that have been controlling the monsoon in the region.

Authors' Contributions

Narendra Kumar Meena: Conceptualization, Methodology, Investigation, Writing - Original Draft. **Pranaya Diwate:** Investigation, Reviewing and Editing. **Sundeep Kumar Pandita**: Conceptualization, Supervision.

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