River flow reconstruction of the Lohit River Basin, North-east India based on tree-rings of *Pinus merkusii* (Merkus pine)

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ABSTRACT

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Dendrochronological analysis of *Pinus merkusii* (Merkus pine) collected from Mishmi Hills, Arunachal Pradesh, North–east India shows its potential to provide continuous and long–term information about changes in river flow of Lohit River Basin (LRB). A 170 years (1830–1999 C.E.) long regional tree-ring width chronology of Merkus pine was prepared using 80 tree cores. Based on the correlation analysis between tree-ring chronology and river discharge data, the river flow was reconstructed for the month of May from 1846 to 1999 C.E. The reconstruction showed long term low and high flow periods along with extreme drought and pluvial years. Past river flow reconstruction for hydro–climatic variability in this southwest monsoon-dominated region of North–east India requires further notice. Longer tree–ring records along with wider spatio-temporal network of discharge data from Arunachal Pradesh will help to develop better records of river flow reconstructions of the region.

Key–words—*Pinus merkusii*, Lohit River, Drought, Hydro-climate, Water management.

पाइनस मर्कुसयाई (मर्कस चीड़) के वृक्ष–वलयों पर आधारित लोहित नदी द्रोणी, पूर्वोत्तर भारत की नदी प्रवाह पुनर्रचना

संतोष के. शाह, रोहिणी सिंह, निवेदिता मेहरोत्रा एवं लेक्गिनसंग थॉम्टे

सारांश

मिशमी पहाड़ियां, अरूणाचल प्रदेश, पूर्वोत्तर भारत से संगृहीत *पाइनस मर्कुसयाई* (मर्कस चीड़) का वृक्षकालानुक्रमणीय विश्लेषण लोहित नदी घाटी (एल आर बी) के नदी प्रवाह में परिवर्तनों के बारे में अनवरत और दीर्घवधि सूचना प्रदान करने की इसकी संभावना दर्शाता है। 80 वृक्ष क्रोड प्रयुक्त करते हुए मर्कस चीड़ का 170 वर्ष (1830–1999 सीई) दीर्घ आंचलिक वृक्ष वलय चौड़ाई वृक्षकालानुक्रमण बनाया गया था। वृक्ष वलय कालानुक्रमण एवं नदी निस्सरण आंकड़ा के बीच सहसंबंध विश्लेषण पर आधारित 1846 से 1999 सीई से मई माह का नदी प्रवाह पुनर्रचित किया गया। पुनर्रचना ने अत्यधिक सूखा एवं वृष्टीय वर्षों के साथ–साथ दीर्घवधि अल्प एवं उच्च प्रवाह अवधियां दर्शायीं। पूर्वोत्तर भारत के इस दक्षिण–पश्चिम मानसून प्रभावित अंचल में जल–जलवायु संबंधी परिवर्तनीयता हेतु गत नदी प्रवाह पुनर्रचना पर और ध्यान देने की ज़रूरत है। अरूणाचल प्रदेश से प्राप्त निस्सरण आंकड़ा के व्यापक अनुपात–कालिक नेटवर्क के साथ दीर्घतर वृक्ष–वलय अभिलेख अंचल में सरिता प्रवाह पुनर्रचनाओं के बेहतर अभिलेख विकसित करने में सहायक होंगे।

सूचक शब्द— *पाइनस मर्कुसयाई*, लोहित नदी, सूखा, जल–जलवायु, जल प्रबंधन।

INTRODUCTION

THE Eastern Himalaya Rivers have a major contribution in the water supply of the populous area of northeastern India. The rivers are under enormous pressure due to the persistent environmental changes and human impact along their course and the watershed regions. The research on river runoff in the context of global climate change (ACIA, 2005; Serreze *et al.,* 2006; Harding *et al.,* 2011; IPCC, 2013) has been coming under much prominence. The influence of the river run–off in the hydrological cycle is significant and is one of the main components that contribute to the hydro–climate systems (Fig. 1). Such hydrological regions are expected to have been impacted by the global warming which might cause subsequent increase of the weathered products in the river along with that of rainfall (Barry & Chorley, 2003). Heavy rainfall in a short period shall cause large volumes of run–off that leads to flood and may complicate the conjunctive use of surface water and groundwater (Hiscock, 2005). The glaciers also influence the hydrology regime of the Himalayan Rivers and they strikingly increase their control over the stream flow at higher altitudes in the river basin (Verghese & Iyer, 1994). The glaciers in Western Himalaya are contributing up to two–third of the annual water discharge in the Sutlej and other rivers of the region. But the input of the glacial melt in rivers of Sikkim and northeastern India is relatively less with intense Monsoon rainfall in the region adding to a greater part of the run–off. One of the major river basins in the northeastern India is the river Brahamaputra Basin.

The eastern most river basin of India forming a part of the Brahamputra River Basin is the Lohit River Basin (henceforth LRB). The Lohit river catchment spreads across international borders covering part of Tibet. The Lohit River is a tributary of river Brahmaputra and originates at an elevation of 6190 m above mean sea level from the snow–clad peaks in Eastern Tibet. The Lohit River is perennial in nature, with its main source being snowmelt of the Eastern Himalayan glaciers and other small streams. The melting mostly takes place between February and October in the Eastern Himalaya where the winter snow at lower altitudes melts first and ice melting begins when the rising snowline reaches the glacier. This subsequently synchronizes with the onset of the Monsoon. During lean season, i.e. from November to March every year there is a drop in discharge (Lohit Basin Report, 2016).

The demand and supply ratios of the water in the world's river basins is one of the limiting factor for global agriculture, industry, hydropower and municipal development due to the extreme climate fluctuations occurring. The available
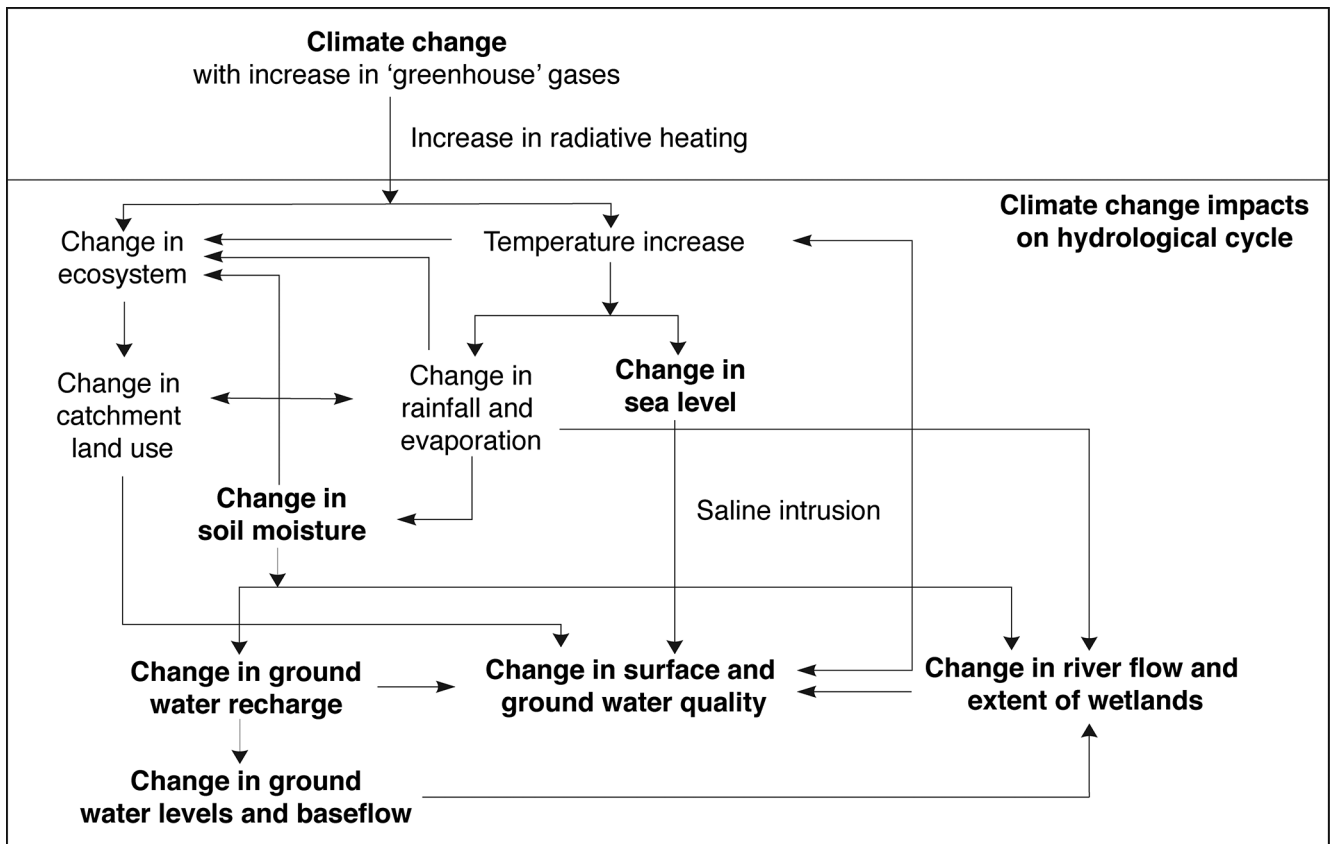

Fig. 1—Diagrammatic representation of impacts of various factors on the natural hydrological cycles and their linkages with changes in the hydrological conditions (after Hiscock, 2005).

water resource records are not necessarily capturing all the modes of variability significant to the resource management and planning. The hydrologist are more so convinced on this aspect by the Palaeoclimatic data which record various signals of the variability in the available water resources in the past. The palaeo–records contributed by dendrochronology in augmentation of hydrologic records–precipitation and streamflow has thus helped in the planning of various water resources globally over the past few decades. The statistical expansion of streamflow time series using tree–ring data, i.e. Streamflow reconstruction, has been increasingly functional as a planning and research tool in water resources studies. Tree growth and natural runoff respond similarly to changes in the precipitation budget of the river basin and/or watershed making tree–rings ideally suited for this purpose. Large areas of these watersheds are occupied by moisture–sensitive tree, especially in the high elevations of the temperate latitudes, from where originates most of the runoff in semiarid watersheds (Meko & Woodhouse, 2011).

Merkus pine (*Pinus merkusii* Jungh. & de Vriese*)* trees are selected for the present study. This is a two–needle pine and it extends from the southern Shan States of Myanmar, southwards through the hills of the Salween and Thaungin drainage. This pine crosses the equator to be also found in Thailand, Cochinchina, Sumatra, Java, Borneo and the Philippines (Sahni, 1990). In India it is only growing in the Mishmi Hills of Arunachal Pradesh, North–east India. The dendroclimatic potentiality of Merkus pine has been established earlier from India (Buckley *et al.,* 2005, Shah & Bhattacharyya, 2012), Thailand (Buckley *et al.,* 1995; D'Arrigo *et al.,* 1997; Pumijumnong & Wanyaphet, 2006; Pumijumnong & Eckstein, 2011) and Lao (Buckley *et al.,* 2007).

The main objectives of the present study are (1) to understand the relationship between Merkus pine (*Pinus merkusii)* and the river discharge from LRB and (2) to reconstruct past river flow using ring width chronology of Merkus pine and its long term assessments.
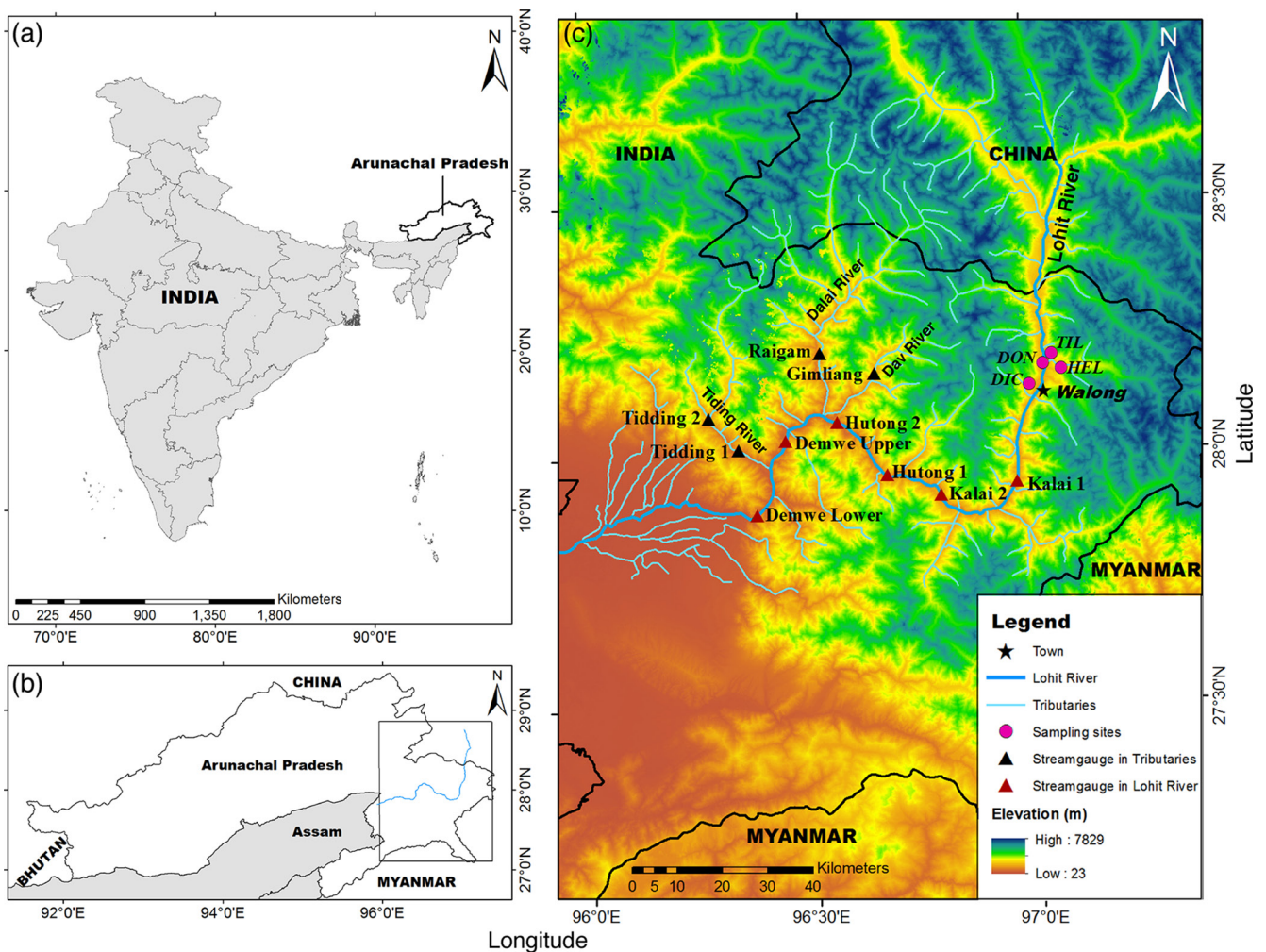

Fig. 2—Map showing study area of Lohit River Basin (a) Map of India showing Arunachal Pradesh, (b) Arunachal Pradesh showing boundary of study area and (c) Lohit River Basin with tree-ring sampling sites, river gauge station and other details.

Study site

The present study area of LRB is located in Anzaw District of Arunachal Pradesh, North–east India. This district covers an area of 6190 km² and is bounded by China on the north, by Myanmar in the east. The study site lies between latitudes 27°34'N and 29°36'N and longitudes 95°38'E and 97°44'E where we aim to carry out the hydrological reconstruction of the watershed with tree cores as a proxy archive collected from the Mishmi hills (Fig. 2). The drainage network in the LRB is complex being controlled by the structural features where the dendritic and rectangular drainage patterns are conspicuous. Both LRB and Mishmi hills falls into Mishmi Block, a geological domain of Arunachal Pradesh. The Mishmi block lies adjacent to the Naga–Patkai ranges of Arkan–Youma Mountains to the south along another tectonic plate, the Mishmi thrust.

Climatically, LRB is characterized as cool and highly humid at lower elevations and in the valleys whereas intensively cold weather prevails at higher elevations. The winter season commences from late November and continues up to March followed by monsoon season from May to September. The hydro–meteorological data for this area of the basin is not available. However, the average annual rainfall recorded in the catchment area at Chaglongam station is 2554 mm, 2165 mm at Hawai, 3790 mm at Hayuliang, 1204 mm at Kibithoo, 4654 mm at Salangam, 4230 mm at Tidding and 1167 mm at Walong stations. The temperature in the region varies generally from a maximum of 25°C to 35°C in summer to a minimum of 1° to 10°C in winter (Lohit Basin Report, 2016).

MATERIAL AND METHODS

Tree–ring data

For the collection of tree cores, the eastern Himalayan sub–tropical pine forest of Mishmi hills, which is dominated by Merkus pine occurring at an elevation range of 1200–1400 masl, was considered. Two cores per tree were sampled (total 130 cores from 67 trees), from four localities of Mishmi hills, i.e. Dichu, Dong, Helmet top and Tilam top (Fig. 2) using Swedish Increment borer. In the Laboratory, samples were air dried at room temperature and processed further using standard method of Dendrochronology (Stokes & Smiley, 1968; Speer, 2010). The samples were mounted and surface was polished manually with different grades of sand paper to make the ring boundaries clearly visible under stereo–zoom microscope. The rings of the polished sample were examined and counted from pith to bark, to accurately assign the calendar date to each rings in which year they are formed. This was done through the method of cross dating using skeleton plotting technique (Stokes & Smiley, 1968). Each dated series were measured using Velmex Tree–ring measurement system incorporate with linear encoders with 0.001 mm precision. Later cross dating and measurements were checked with program COFECHA (Holmes, 1983; Grissino–Mayer, 2001) to identify possible dating and measurement problems in the samples.

The tree–ring chronology (henceforth TRC) was developed using signal–free standardization approach (Melvin & Briffa, 2008) in computer program RCSsigFree (www.ldeo.columbia.edu/tree–ring–laboratory/resources/software). The signal–free technique of standardization improves the
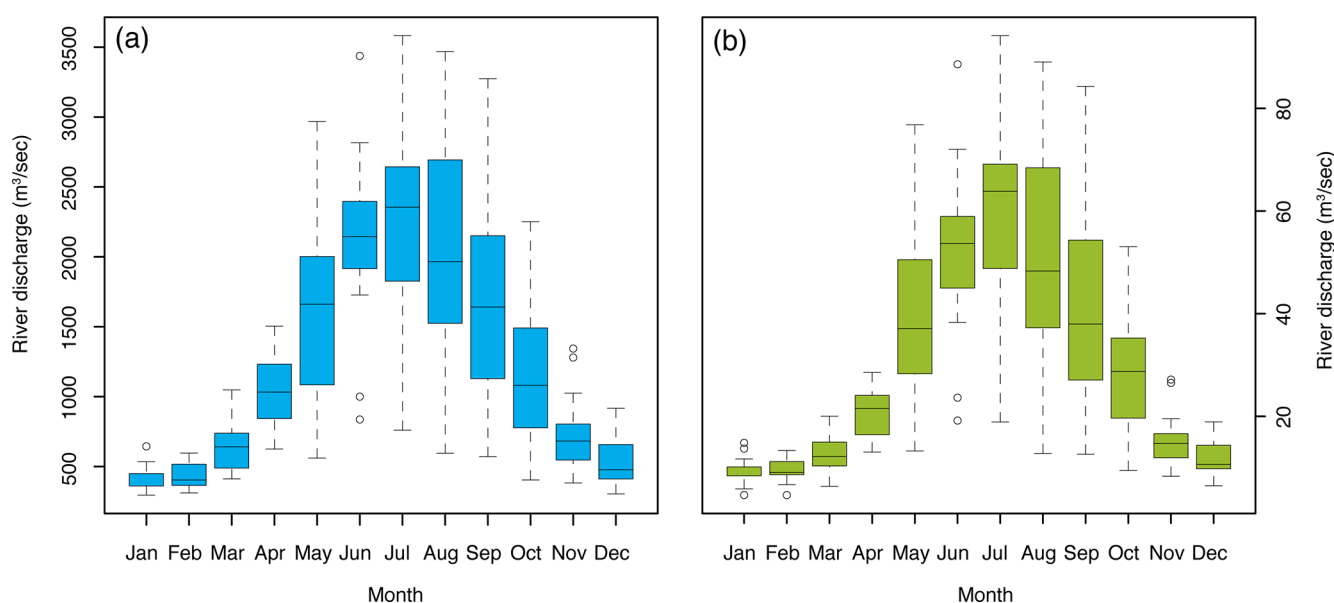

Fig. 3—Hydrographs of gauge stations (a) Demwe Lower and (b) Gimliang based on the 1986–1999 period.

preservation of low frequency in TRC and minimizes the effect of the varying segment lengths (Cook *et al.,* 1995). The standardization was done by fitting smoothing spline with 50% frequency–response cutoff of 67% of the length of each series. The final stabilized, signal–free TRC was produced using bi–weight robust means (Cook, 1985; Cook & Kairiukstis, 1990). The various statistics, which are used to assess the dendroclimatic potentiality of TRC (Fritts, 1976), were calculated for both full and common period. The common period covers highest number of tree cores in the datasets. The expressed population signal (EPS), a value of 0.85 accepted as a reasonable threshold (Wigley *et al.,* 1984), was used to assess the adequacy of sample replication for acceptance of TRC quality.

River discharge data

River discharge data were procured for 10 river gauge stations of the LRB. Among these six–gauge stations, i.e. Kalai 1, Kalai 2, Hutung 1, Hutung 2, Demwe Upper and Demwe Lower are on main Lohit River (Lohit Basin Report, 2016). The other four, viz. Gimliang, Raigam, Tiding 1 and Tiding 2 are on right bank tributaries of Lohit River (Fig. 2). The gauge stations Gimliang and Raigam are located on the Dav River and Dalai River respectively. And other two, i.e. Tiding 1 and Tiding 2 are located on Tiding River which is another right bank tributary of Lohit River. The details of each gauge station along with river discharge information are given in Table 1. The common time period covered by river discharge data in all ten stations is from 1986–2002 C.E.

A Box–and–Wishker plot was used to prepare the hydrograph of the monthly discharge data of the gauge records

from LRB. The analysis was carried out in R version 3.5.1 (R Core Team, 2018). All the 10 gauge records showed similar seasonality behaviour and here hydrographs of only two gauge records–one from the main Lohit River, i.e. Demwe Lower and another from the tributary of Lohit River, i.e. Gimliang are represented in Fig. 3. The hydrograph showed maximum seasonality flow recorded during the months of May–September constituting maximum percentage of mean annual discharge. During lean season, i.e. from November to March every year there is a drop in discharge (Fig. 3). This seasonality observed during the months of May–September is the representation of the monsoon rainfall, which accounts for most of the annual precipitation. The sudden increase in the flow of May month might be associated with input from snowmelt. The initiation of the summer month during April months with increase of temperature, perennial snow in higher elevation starts melting which contributes higher flows during May.

River flow reconstruction methodology

Simple correlation was calculated between TRC and monthly river discharge records of LRB. We considered a dendroclimatic window starting from June of the prior year to growth and ending in the following December. This dendroclimatic window covers the water year period for both previous and current year. The significance of the correlation coefficient was judged at p <0.05. Among the ten gauge stations from LRB, only two gauge stations i.e., Demwe Lower and Gimliang are considered for correlation analysis as the reference stations for the hydrological budget of the watershed. The time period considered for the correlation
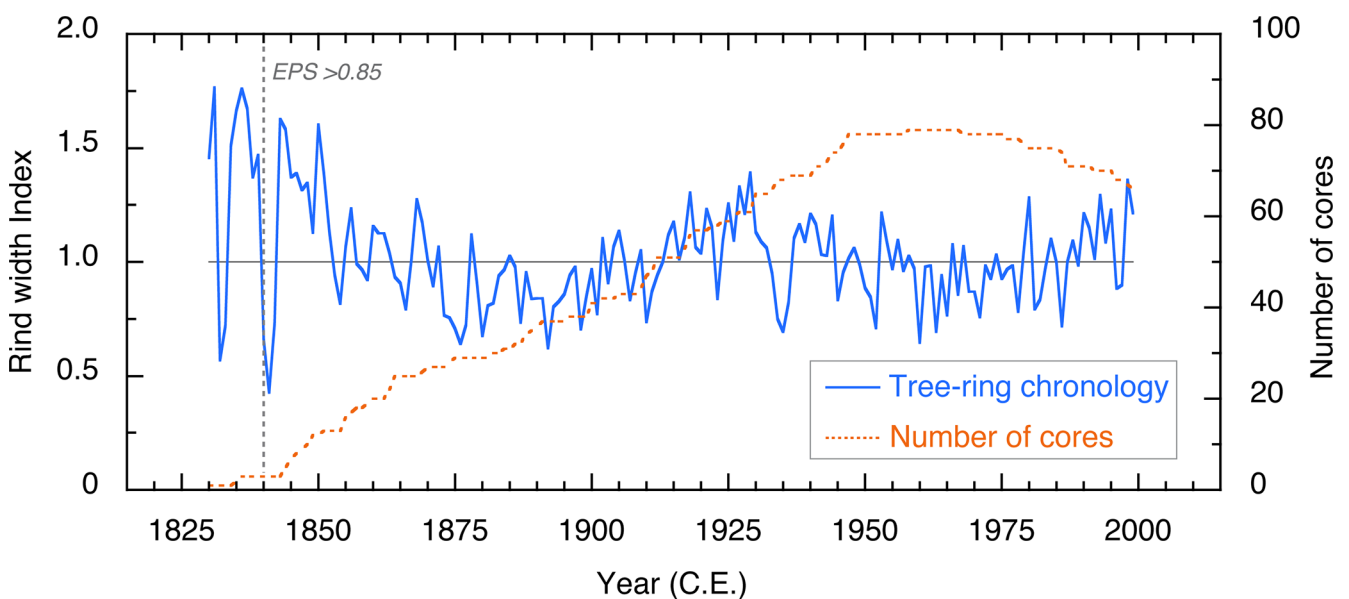

Fig. 4—Regional tree–ring chronology (RTRC) of *Pinus merkusii* (Merkus pine) extending from 1830 to 1999 C.E. along with number of tree cores.

Table 1—Details of gauge stations of Lohit River Basin (LRB) in North–east India.

GAUGE STATIONS	CA	LAT	LONG	AWY	MAX	MIN
Kalai 1 [†]	16610	27.91	96.96	11854.6	1933.4	351.5
Kalai 2 [††]	15654	27.91	96.96	12837.4	2077.2	377.4
Hutong 1[††]	17968	27.96	96.73	12958.2	2110.9	379.8
Hutong 2 [††]	18450	27.92	96.96	13613.2	2161.6	390.0
Demwe Upper [†††]	440	28.03	96.45	13959.8	2167.2	393.1
Demwe Lower [†††]	20174	27.88	96.38	14703.3	2271.5	413.3
Gimliang [††††]	371.4	28.14	96.63	353.8	59.8	9.5
Raigam [††††]	1697.45	28.18	96.52	1574.9	266.2	41.9
Tidding 1 [††††]	614.5	28.99	96.39	739.6	123.6	20.4
Tidding 2 [††††]	525.6	28.08	96.28	832.2	224.6	19.8

[†] time span–from May, 1984 to April, 2003   [††] time span–from June, 1984 to May, 2003
[†††] time span–from May, 1984 to April, 2004   [††††] time span–from May, 1985 to May, 2004
CA – catchment area   LAT – latitude in degree north
LONG – longitude in degree east   AWY – annual water yield in m³/sec
MAX – maximum discharge per month in m³/sec   MIN – minimum discharge per month in m³/sec

analysis using both these gauge stations was 1984–1999 C.E. The Demwe Lower is the lower most gauge station on the main Lohit River, which might represent the volume of upper part of the catchment. Gimliang is the closest gauge station from our tree–ring sampling site and records the discharge of the Dav River a tributary of the Lohit River. Thus these two gauge stations shall provide the overall perspective of the Lohit River watershed in the study area and its relationship with TRC of the Mishmi hills.

The river discharge variable significantly correlated with the TRC for the time period of 1984–1999 C.E. was considered for the reconstruction of the past river flow. For this transfer function model (Fritts, 1976) was developed based on simple linear regression. The simple linear regression model, the TRC and monthly river discharge are entered as the predictor and predictand respectively. The time series of reconstruction was truncated based on the EPS threshold value dropping below 0.85. The river discharge data is available for a relatively short period. Thus to test the reliability of the reconstructed river discharge parameter, we used the leave–one–out cross validation technique (Michaelsen, 1987). With this approach, the cross–validation steps are repeated iteratively and in each step, one observation is removed from the calibration set and the model is applied to predict the omitted observation. In this cross validation, calibration statistics such variance explained by the model or r–square (RSQ), adjusted r–square (RSQadj) are calculated between the estimated and actual values generated in the regression model. The statistical significance of the regression equation was estimated using an F–ratio. The reduction of error (RE) (Fritts, 1976) and root mean square

error of validation (RMSEv) (Weisberg, 1985) were calculated as a validation statistics. Among these, a positive RE and the lowest RMSE are taken as a basis for validity and reliability of the model (Cook & Kairiukstis, 1990). The Durban Watson (DW) statistics was computed to determine the autocorrelation (lag–1 autocorrelation) of the residual, persistence in the reconstruction. The final river flow reconstruction was then analyzed to understand long–term variation in low and high flow events. The reconstruction analysis was carried out in R version 3.5.1 (R Core Team, 2018).

RESULTS

Tree–ring chronology

Based on the result of cross dating and further evaluated through COFECHA (Holmes, 1983; Grissino–Mayer, 2001), we found 80 series which are belongs to four sites are well correlated with mean series correlation of 0.46. The mean length series of these combined dated samples is 101 years. Based on these set of ring–width measurements from four sites of Mishmi hills, we developed a 170–years long regional tree–ring chronology (henceforth RTRC) of Merkus pine, which extends from 1830 to 1999 C.E. (Fig. 4). The RTRC statistics, i.e. mean sensitivity, standard deviation and first order auto–correlation calculated for full time period is 0.183, 0.264 and 0.470 respectively. The RTRC statistics calculated for the common period 1958–1999 C.E., showed various mean series correlations such as correlation within trees (0.457), between trees (0.237) and among all radii (0.239). In addition,
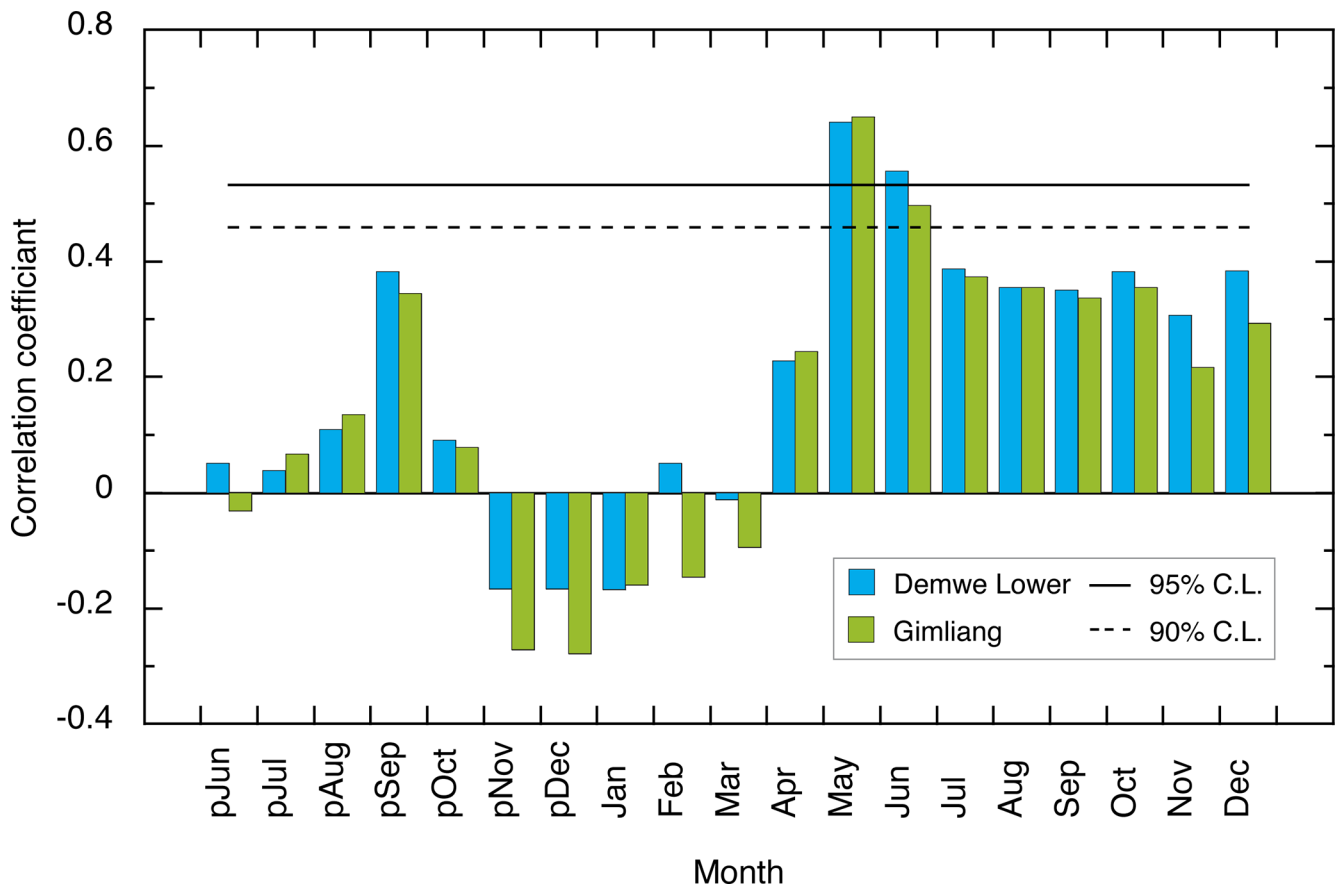
Fig. 5—Correlation between regional tree–ring width chronology (RTRC) of *Pinus merkusii* (Merkus pine) and river discharge data of Demwe Lower and Gimliang for the time period of 1986–1999 C.E.

the signal to noise ratio (SNR) and variance explained in the first principal component is 20.8% and 28.1% respectively. The EPS value had crossed the threshold limit of 0.85 (Wigley *et al.,* 1984) from the 1846 onward (Fig. 4).

Palaeohydrologic reconstruction

The correlation analysis showed that the RTRC of Merkus pine exhibits statistically significant (p<0.05) correlation with log–transformed May month's river discharge records of both the gauge stations, i.e. Demwe Lower and Gimliang having correlation coefficient of 0.64 and 0.65 respectively (Fig. 5). In the simple linear regression model developed for 1986–1999 C.E., we estimated the May month river discharge using RTRC of Merkus pine (Fig. 6). The leave–one–out cross validation statistics for the calibration–verification period of 1986–1999 C.E. showed reliability of the estimated May river discharge and passed all the statistical criterion (Table 2). The reconstruction accounts for 41% (for Demwe Lower) and 42% (for Gimliang) of the total variance of the instrumental gauge discharge from 1986 to 1999 C.E. The RE value is found positive for both the gauge stations but is higher for the Gimliang station (+0.113) than compared to

Demwe Lower station (+0.104). But the positive RE showed the robustness of the linear regression model for both the gauge stations. The verification RMSE for Demwe lower and Gimliang is 0.165 and 0.167 m³/sec respectively. The verification RMSE is considerably smaller than the standard deviation of the observed river discharge. Finally, the May month's river flow was reconstructed for both Demwe Lower and Gimliang from 1846 to 1999 C.E. and it captured distinct high and low flows variability (Fig. 6). This time period was selected based on the EPS threshold value dropping below 0.85 before 1846 (Fig. 6).

The low flow and high flow periods in the reconstructions was determined by the mean value calculated for the entire period of reconstructed river flow. Similarly, the extreme low and high flow periods are noted on the basis of 25th quartile and 75th quartile respectively (Fig. 6). However, the reconstructions of the river flow developed for the May month for both the gauge stations, i.e. Demwe Lower and Gimliang showed similar variability and differences are seen only in their discharge volume (Fig. 6). This showed that there are no differences in the records of gauge stations and both main Lohit River and its tributaries and these gauge records can be utilized individually to represent the entire Lohit

Table 2—Leave–one–out–cross–validation statistics for May river flow reconstruction for the Lohit River Basin using two gauge stations.

	RSQ	RSQadj	F value	RE	RMSEc	RMSEv	DW
Demwe Lower	0.41	0.36	8.33 (p–value = 0.014)	0.104	0.14	0.17	1.85
Gimliang	0.42	0.37	8.79 (p–value = 0.012)	0.113	0.15	0.17	1.86

RSQ – r–square   RSQadj – adjusted r–square   RE – reduction of error
RMSEc – root mean square for calibration   RMSEv – root mean square for verification   DW – durbin–watson statistics

catchment. In the reconstruction, the longest decadal low flow periods recorded are 1871–1913 C.E. and 1957–1987 C.E. Similarly, the longest decadal high flow period recorded in the reconstruction is during 1914–1932 C.E. The longest extreme low flow periods based on the 25th quartile are 1889–1895 C.E. and 1873–1877 C.E. Two longest high flow periods are observed on the basis of 75th quartile and these are 1846–1852 C.E. and 1927–1930 C.E. The reconstruction also captured the widely know drought, i.e. the late Vatican Great drought of 1876–1878 C.E. (Davis, 2001; Cook *et al.*, 2010). These drought years are also captured in the drought atlas MADA (Cook *et al.*, 2010) that is developed for Monsoon Asia using wide Asian tree–rings network.

The atmospheric anomaly of 500 mb geo–potential heights in dry and wet years (dry minus wet) in May were studied based on the maps. The analysis was carried out in web portal of NOAA Earth System Research Laboratory (www.esrl.noaa.gov/psd/cgi–bin/data/getpage.pl). A subset of three common dry/low flow (1986, 1987 and 1997) and wet/ high flow (1991, 1995 and 1998) years observed in both actual and estimated river flow record of the six driest and wettest years in 1986–1999. Two maps one for wet years and another composite difference (dry minus wet) 500 mb anomaly was prepared for these subsets of years. The atmospheric circulation patterns over the time period in the region was influenced by the Siberian high and the El Niño Southern Oscillations (ENSO) patterns originating in the Pacific Ocean (Fig. 7).

DISCUSSION

Tree–ring data are a widely used as a reliable proxy for river flow reconstructions from various parts of world (Meko & Woodhouse, 2011 and references there within) and Asia, viz. China (Gou *et al.*, 2007; 2010; Yuan *et al.*, 2007; Liu *et al.*, 2010; Yang *et al.*, 2012; Sun *et al.*, 2013); Indonesia (D'Arrigo *et al.*, 2011); Mongolia (Pederson *et al.*, 2001, 2013; Davi *et al.*, 2006, 2013; Guang *et al.*, 2012; Leland *et al.*, 2013); Pakistan (Cook *et al.*, 2013; Rao *et al.*, 2018); Turkey (Akkemik *et al.*, 2008) and India (Shah *et al.*, 2013, 2014; Singh & Yadav, 2013; Misra *et al.*, 2015). Earlier Shah

et al. (2014) reconstructed river flow of Lachen River from north Sikkim, eastern Himalaya. However, study on river flow reconstruction using tree–ring data has not been taken up earlier from this extreme northeast corner of North–east India. Thus the present study from the LRB adds new database of river flow reconstruction from this southwest monsoon–dominated region of northeastern India.

The RTRC of Merkus pine developed from Mishmi hills has moderate to high mean sensitivity and standard deviation. This showed that the Merkus pine from this region of North–east India has year–to–year moderate high–frequency variance in its tree–ring sequence. The moderate value of the first order auto–correlation showed previous year climate is also contributing in the radial growth of Merkus pine. The correlation within trees is higher as compared to the correlation between trees and among all radii, which might be due to anthropogenic activities and tectonic sensitivity of the study area. The percentage of variance explained in first principal component and signal to noise ratio showed moderate degree of commonality in growth variance in the tree–ring sites exists but can explain some common hydro–climatic factors. The EPS criterion showed that, major length of time series successfully capture the reliability of the chronology and crossed the EPS threshold criteria.

We observe a positive relationship between ring width and river discharge during May of the current year. During this time summer temperature accelerates the snowmelt and glacial melt, which contributes the increase in river discharge. This sudden increase in river discharge after prolonged winter season, recharge the soil moisture content and enhance tree growth during the growing season, as supported by the positive response to May river flow. Thus the significant correlation of RTRC with river discharge during May month of current year seems to be mainly contributed by snowmelt and glacial melt.

The transfer function models for the reconstruction with calibration–validation statistics indicate that the fidelity of the model towards reconstruction of river flow for both the gauge stations of LRB. Both gauge stations, i.e. Demwe Lower and Gimliang, captures higher variance in the model, which due to a high degree of spatial homogeneity of the river discharge

records for both main Lohit River and its tributaries (Fig. 3). The present study region of LRB is in a highly variable mountainous terrain but the hydrologic signals recorded in tree–rings of Merkus pine suggest that river flow is governed by similar characteristics in this region. The future studies should target to develop longer tree–ring chronologies than the present study, which shall help to extend such hydro–climate reconstruction further back in time.

There is a clear similarity between the wet years and the atmospheric circulation over the Pacific Ocean, which has the strongest impact over the ENSO. The ENSO is one of the key regulating factors of the Indian Summer Monsoon (ISM) and overall precipitation over the northeastern India.

The precipitation in the LRB during the month of May is influenced by the early ISM and the net river flow in the LRB during May has contribution of the glacial melt and overall precipitation. Hence the composite map shows the relationship recorded in the tree–ring indices, the highest river flow for the month of May and the height anomaly are linked with the ISM and its interplay with the atmospheric circulation patterns over the Pacific Ocean. Also the dry years indicate the strong impact of Pacific Ocean when the deficit in the river flow in May month is probably created by the decrease in the strength of ISM and the circulation pattern changes over the Siberian High region. Nevertheless the interplay of all these environmental factors and change in the strength
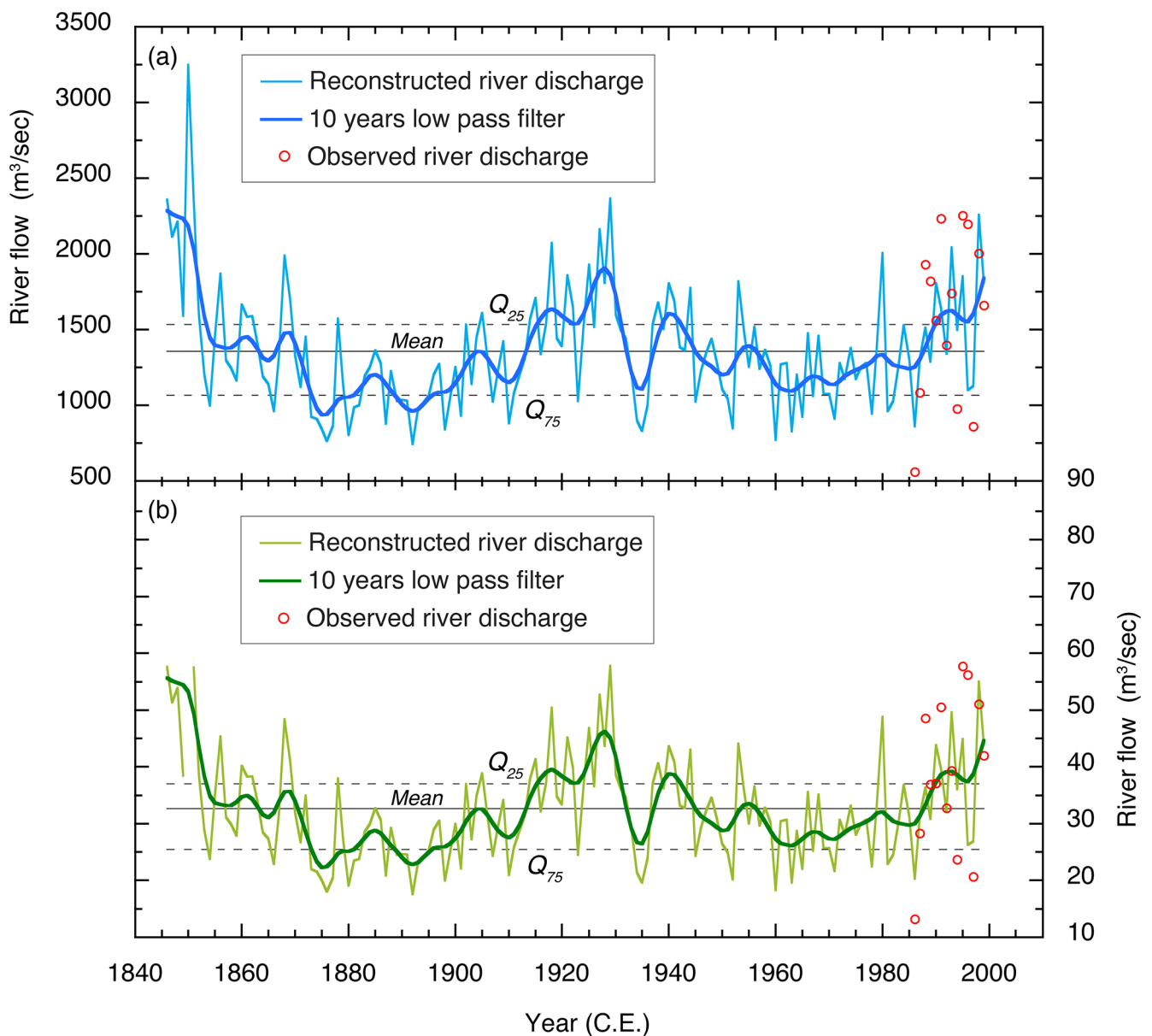

Fig. 6—The reconstructed May river flow, spanning 1846–1999 C.E. along with 10 years low pass filtered smooth and actual May river flow, spanning 1986–1999 C.E. for (a) Demwe Lower gauge station and (b) Gimliang gauge station. Q_{25} and Q_{75} are 25th quartile and 75th quartile respectively.
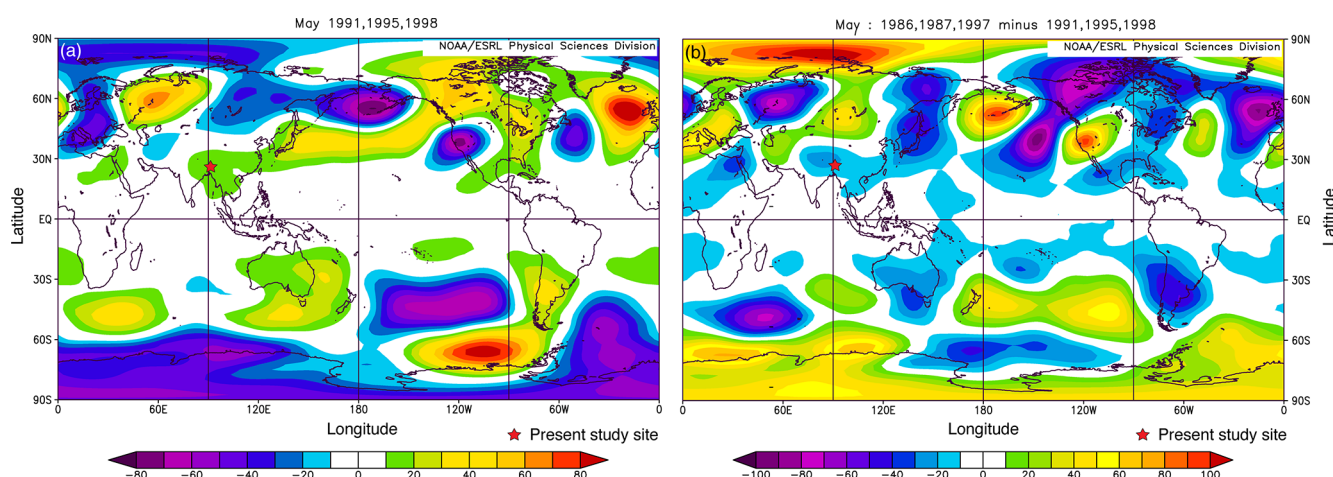
Fig. 7—Composite map of difference in May 500 mb height anomalies in (a) wet years and composite of dry minus wet years. Anomalies (colour bar) are departures from 1981–2010 climatology.

of the river flow in the LRB and water availability in the LRB watershed region. These observation need to be further studied and extended on the basis of longer and widespread tree–ring data sets for this Monsoon dominated region of the northeastern India.

The longest decadal high flow period recorded in the reconstruction is during 1914–1932 C.E. Two longest high flow periods, i.e. 1846–1852 C.E. and 1927–1930 C.E. are observed in the present reconstruction on the basis of 75th quartile. The period of high flow between 1846–1852 C.E. and 1927–1930 C.E. in the LBR was the time period when low flow was recorded in the Yeruu River flow reconstruction of Mongolia region (Pederson *et al.,* 2013). This inverse relationship is understandably similar to the relationship observed in the composite maps during the dry years in LRB and atmospheric circulation pattern at Siberian high (Fig. 7). Another river flow reconstruction record from the Mississippi river one of the largest river in North America based on tree–ring data showed extreme flooding in 1927 during the late winter and early spring (Therrell & Bialecki, 2015). The river flow recorded in the Mississippi Basin is influenced several potential factors operating at different scales within the basin including the Atlantic Multi–decadal Oscillation (AMO), ENSO, and the Pacific Decadal Oscillation (PDO) (Therrell & Bialecki, 2015 and references there in). This stream flow record during the spring flood years and its comparison to the atmospheric circulation patterns indicated a relationship with the atmospheric circulation over the Northern Pacific Ocean. Thus one of the largest rivers of the world also witnessed largest spring flood event in 1927 also recorded the high flow period in the LRB. Both these regions are showing a strong influence of the atmospheric circulation over the North Pacific region thus impacting large–scale climate forcing mechanisms over the river basins. However more robust tree–ring chronologies from northeastern India and better spatio–temporal coverage of river flow reconstructions from

major river basins shall help to establish this tele–connections of spring flood events and atmospheric–ocean oscillations such as ENSO, PDO and AMO.

CONCLUSIONS

In the present study, river flow reconstruction for the Lohit River Basin, based on tree–ring data of Merkus pine (*Pinus merkusii*) was carried out based on the regional tree–ring chronology. The reconstruction showed long–term low flow, high flow periods, extreme drought years, and extreme pluvial years. The study revealed the potential of Merkus pine to provide continuous and long–term information about variability in river flow. However, based on the analysis, there is a need for past river flow reconstructions of the hydroclimatic variability in this monsoon dominated region of the North–east India. Moreover, longer tree–ring records along with wider spatio–temporal network of discharge data from Arunachal Pradesh will help to develop better records of river flow reconstructions of the region.

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