Climate-driven acceleration in forest evapotranspiration fuelling extreme rainfall events in the Himalaya

Nilendu Singh 1, Jayendra Singh 1, Anil K Gupta 2, Achim Bräuning 3, A P Dimri 4, A L Ramanathan 5, Vikram Sharma 6, Reet Kamal Tiwari 1*, Joyceeta Singh Chakraborty 1, Pankaj Chauhan 6, Tanuj Shukla 7, Mohit Singhal 8, Suman Rawat 9, Shefali Agarwal 9 and P Raja 10

1 Wadia Institute of Himalayan Geology, Dehradun 248001, India
2 Department of Geology and Geophysics, IIT Kharagpur, Kharagpur 721302, India
3 Institute of Geography, University of Erlangen-Nuremberg, Erlangen 91058, Germany
4 School of Environmental Sciences, Jawaharlal Nehru University, New Delhi 110067, India
5 Department of Geography, Institute of Science, Banaras Hindu University, Varanasi 221005, India
6 Department of Civil Engineering, IIT Ropar, Ropar 140001, India
7 Forest Research Institute, Dehradun 248006, India
8 Department of Earth Sciences, IIT Kanpur, Kanpur 208016, India
9 Indian Institute of Remote Sensing, Dehradun 248001, India
10 ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Udhamamandalam 643004, India
* Author to whom any correspondence should be addressed.

E-mail: reetkamal@gmail.com

Keywords: extreme rainfall event, forest evapotranspiration, greening-thermophilization, tree-ring cellulose isotopes, ecophysiology, Himalaya

Supplementary material for this article is available online

Abstract

Warming-induced expansion in vegetation coverage and activity can accelerate the montane hydrological regimes. However, the climate impacts on ecohydrology of forested valleys of the Himalaya are uncertain. In this study, utilizing results of about three centuries of cellulose isotope chronologies (δ13C and δ18O) of dominant tree species, geo-chronological proxies, bio-geophysical dataset and simulations including satellite observations, we show an activation in the ecophysiological processes including evapotranspiration (ET) since the 1950s. Observation suggests rapid greening, while isotopic records indicate enhanced assimilation and transpiration in deciduous species vis-à-vis conifers post 1950s. Given strong vegetation-precipitation feedback and superimposed on the increasing trends of conducive atmospheric factors affecting valley-scale convective processes, intensification in forest ET is manifesting in a progressive enhancement in extreme rainfall events (EREs) since the last few decades. Results suggest that representation of ecophysiological processes and dynamics of seasonal moisture loading in observational and modelling framework is critical for understanding EREs under climate change.

1. Introduction

The terrestrial carbon and water cycles are strongly coupled (Lemordant et al 2018, Gentine et al 2019). The Earth’s greening has caused acceleration in these cycles with enhanced control of vegetation on the terrestrial energy fluxes in recent decades. It has been shown to be largely modulated by plant functional types (PFTs) and background climate conditions (Graven et al 2013, Zhang et al 2015, 2016, Forkel et al 2016, Forzieri et al 2020).

In the past few decades, energy-water cycle over the Tibetan Plateau (TP) has changed significantly than rest of the globe (Yao et al 2019, Liu et al 2020, Wu 2020). Climate change-induced increase in evaporative surface is expected to influence the distribution of heat and moisture (Zhu et al 2016). The TP is a region of strong land–atmosphere coupling, which is susceptible to hydrological impacts with the increase in evaporative surface (Yao et al 2019, Liu et al 2020, Wu 2020). It is an isolated region of atmospheric moisture and a significant moisture source in the summer. Its southern boundary rim (the Himalayan arc) due to abundant water vapour convergence during summer and driven by ‘elevated heat pump’ effect, correspond to a region of high cloud
frequency and extreme rainfall events (EREs) (Yao et al 2019, Liu et al 2020). Regional studies generally suggest an overestimation in precipitation, which is centrally attributable to evaporative surfaces and local latent heat flux (Liu et al 2020). Large modelling biases arising out of local evapotranspiration (ET) thus, also affect the estimates on flooding, landslide risk and water resources. Increase in the evaporative surface through a positive feedback loop could enhance the frequency of EREs and floods particularly during the summer-monsoon season. Indeed, studies indicate a rapid increase in EREs in the past few decades (Shukla and Sen 2021).

Increase in ET, mainly from the valley forest enhances the total amount of precipitation, and may further increase the frequency of EREs in future. Forests act as a massive biotic pump of water vapour to the atmosphere that drives continental-scale hydrological cycle (Makarieva and Gorshkov 2007, Sheil and Murdiyarso 2009, Spracklen et al 2012, Makarieva et al 2014, Wright et al 2017). Besides, the enhanced control of vegetation on terrestrial energy fluxes, recent evidence shows the emerging role of forest ecophysiology in global hydrological cycle (Guerrieri et al 2019, Mathias and Thomas 2021). Over the forested mountains, climate change can reduce runoff water availability by enhancing forest ET, given the central role of physiological response of CO$_2$ in ET and evaporative fraction changes (compared to radiative, albedo or precipitation changes due to increased atmospheric CO$_2$) (Lemordant et al 2018, Mastrotheodoros et al 2020). Stable isotopes ($\delta^{13}$C, $\delta^{18}$O) in tree-rings are such an important tool to decipher this physiological forcing, which permit the examination of long-term plant physiological responses to environmental changes. Tree-ring $\delta^{18}$O values are regarded as a sensitive proxy of regional scale physical climate, while $\delta^{13}$C values are strong predictor of local ecohydrology (Zeng et al 2017, Singh et al 2021).

Valley forests, through regional-local transpiration-condensation cycle are known to sustain the convective system for a longer period (Makarieva and Gorshkov 2007, Sheil and Murdiyarso 2009, Makarieva et al 2014, Wright et al 2017). Thus, it is likely that increase in forest ET could augment frequent development of deep convections during convective season. In fact, the Himalaya is one of the largest global sources of vegetation-regulated moisture recycling (Keys et al 2016). Modelling efforts certainly suggest a high recycling ratio of precipitation and a high moisture memory, indicating dominance of ET and recycled precipitation in local-regional precipitation climatology. For example, local ET could contribute up to 60%–90% of the precipitated moisture (Tuinenburg et al 2012, Harding et al 2013, Martius et al 2013, Bohlinger et al 2017).

The Himalayan arc is increasingly becoming prone to EREs (Shukla and Sen 2021). We compiled all published and government records expressing the occurrence of EREs in the Himalaya (including cloudbursts, floods, flash floods, heavy rain-induced landslides, debris flows, and paleoflood events) since the 1800 CE (figure 1; table S1 (available online at stacks.iop.org/ERL/16/084042/mmedia)). We observed that summer monsoon-dominated central Himalayan valleys are emerging as a hot-spot region, which includes western Nepal, and the Indian central Himalaya (Uttarakhand and eastern Himachal Pradesh) (Dimri et al 2016, 2017, Bohlinger et al 2017, Karki et al 2017, 2018, Bohlinger and Sorteberg 2018, Talchabhadel et al 2018) (figure 1). A record from Uttarakhand indicates nearly fivefold increase in EREs since the 1950s (figure S1, table S1). The isotope dendroclimatological studies from this hotspot central Himalayan region suggest climate homogeneity and thus a high coherence in the hydroclimatic signal. Regional tree-ring $\delta^{18}$O chronologies indicate a high annual to multi-decadal coherence in the climatic response (Xu et al 2018, Singh et al 2019, 2021).

Coincidently, these valley recesses have the world’s most intense and tallest convective storms (Houze et al 2007, Rasmussen and Houze 2012). The thermo-orographic lifting and consequent augmentations in the flows as air passes through adjacent valley folds initiate convection (Shrestha et al 2015, Dimri et al 2016, 2017, Karki et al 2018, Kirshbaum 2018). Steep valley slopes regulate this formation of valley-scale (20–30 km$^2$) convective cells, which is diurnally regenerated and facilitates orographic locking. Moreover, because of strong influence of topography on precipitation, the influence of land surface flux feedback on generation of convective system is strong (Houze et al 2007, Medina et al 2010, Rasmussen and Houze 2012, Martius et al 2013). Therefore, superimposed on the increasing trends in summertime mean convective available potential energy (CAPE) (Singh et al 2017), amplification in local mountain circulation (Norris et al 2020) and pre-monsoon heating (Gautam et al 2009, 2010); land surface flux feedbacks would play an increasingly important role in determining the intensity of convective systems and generation of EREs in these valley recesses (Rotunno and Ferretti 2001, Kirshbaum et al 2018). In addition, the facets of land-climate interactions such as vegetation-precipitation feedback loop, moisture recycling, and surface flux feedbacks are strong at this transitional climate zone at the interface between eastern and western Himalaya. Both isotopic and modelling studies indicate high moisture recycling rates and an enhancement in positive trend in recent decades (An et al 2017). Moreover, the region is characterized by a strong ecohydrological
Figure 1. Extreme rainfall events (EREs) in the Himalaya. To explore facets of land-climate interactions in the Himalaya, it has been classified into three distinct climatic regions: Western Himalaya (WH), Central Himalaya (CH) and Eastern Himalaya (EH; with sub-regions: EH I, EH II and EH III). The increasing trend in EREs in recent decades is most prominent in the valleys of the central Himalaya, which includes western Nepal, Uttarakhand (UK) and eastern Himachal Pradesh (HP). Yellow dots indicate geographical location of EREs since the 1800s (table S1). Blue box denotes the sampling area (DOK valley) for tree-ring cores and geo-chronological proxies. Red dots indicate surface meteorological observatories. Inset figure illustrates the sensitivity of ET to LAI ($\Delta$ET/$\Delta$LAI) for the Himalaya and its regions. Indicating unimodal behaviour for the central regions (CH, EH I & II) that remain high during monsoon season, while the sensitivity is different for WH and EH III.

memory (Chauhan and Ghosh 2020), carbon and water cycle coupling (Singh et al 2014), seasonal land-atmosphere feedbacks (Singh et al 2020), and a high interspecies and spatiotemporal coherence between tree-ring $\delta^{13}$C and $\delta^{18}$O (Singh et al 2021). Thus, studies confirm the dominance of ET and vegetation-mediated moisture recycling in local-regional precipitation climatology.

In this work, we investigated stimulation in forest ecophysiological processes through century-scale tree-ring cellulose isotope ($\delta^{18}$O and $\delta^{13}$C) chronologies of dominant and diverse PFTs (broadleaf deciduous and evergreen conifers). Decadal-scale dynamics of greening, changes in vegetation, and increment in primary production were assessed through $^{14}$C dated pollen and geochemical soil profile analyses. Recent 50 years of satellite remote sensing data were utilized for analysing regional trends in vegetation and seasonal greening at the valley-scale. Greening-induced acceleration in ET across the Himalaya and facets of land-climate interactions such as regional sensitivity of ET to leaf area index (LAI), moisture memory, precipitation efficiency are computed by utilizing in-situ meteorological data, satellite and reanalysis datasets, and Weather Research and Forecasting (WRF) simulations at valley and regional scales.

2. Materials and methods

2.1. Tree-ring stable isotope chronologies

Due to the combined effects of climate warming and CO$_2$ fertilization, stimulation in ecophysiological processes (photosynthesis, transpiration and stomatal conductance) were investigated in three regionally dominant tree species of diverse PFTs, growing in the central Himalayan valley (figure 1). Tree-ring cellulose of a broad-leaf deciduous species (*Aesculus indica*) and two evergreen conifer species (*Abies pindrow* and *Picea smithiana*) were analysed for annual $\delta^{18}$O, $\delta^{13}$C, assimilatory $^{13}$C discrimination ($\Delta^{13}$C), and trends in their correlations (stomatal conductance: dual-isotope ratio of $\delta^{13}$C and $\delta^{18}$O) encompassing the last 273 years (1743–2015). Sampling of tree-ring cores was carried out from a representative glacier valley of the Indian central Himalaya (Uttarakhand, Dokriani glacier valley (DOK), figure 1) covering altitudinal range from mid-valley (2400 m asl) to tree-line (3400 m asl). Here (DOK valley), we run one of the permanent field stations since 2000 CE, from where 300 tree-ring cores were extracted from 150 dominant trees comprising four broadleaf deciduous and two evergreen conifer species (table S2). Two core samples per tree were collected at breast height using 5.15 mm diameter
increment borers. Increment cores from 20 to 35 trees of sampled PFTs were further processed. Dendrochronological procedures such as mounting, surface smoothing, tree-ring widths measurement, cross dating, quality control was conducted as per the standard methodology (Holmes 1983, Singh et al 2019, 2021). Labour-intensive isolation of cellulose from whole wood and stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) were carried out at the Institute of Geography, Erlangen, Germany. For detailed dendro-isotopic procedure one may refer to Singh et al 2019 (for $\delta^{18}O$) and Singh et al 2021 (for $\delta^{13}C$). The analytical precision was equal or better than 0.2‰ for both the isotopes. The isotope ratios are presented in the common $\delta$-notation against PDB and VSMOW respectively as:

$$\delta^{13}C = \left[ \frac{\left( \frac{^{13}C}{^{12}C} \right)_{\text{sample}}}{\left( \frac{^{13}C}{^{12}C} \right)_{\text{PDB}}} - 1 \right] \times 1000 \text{ (‰)}$$

$$\delta^{18}O = \left[ \frac{\left( \frac{^{18}O}{^{16}O} \right)_{\text{sample}}}{\left( \frac{^{18}O}{^{16}O} \right)_{\text{VSMOW}}} - 1 \right] \times 1000 \text{ (‰)}.$$ 

Discrimination against $^{13}C$ ($^{13}C$) during carbon fixation by trees was computed as:

$$\Delta^{13}C = \frac{\delta^{13}C_{\text{Atm}} - \delta^{13}C_{\text{plant}}}{1 + \delta^{13}C_{\text{plant}}}.$$ 

Widely accepted correction procedure to correct tree-ring isotope chronology for the incorporation of isotopically light carbon released by the burning of fossil fuels and increasing CO$_2$ concentration was adopted (McCarroll and Loader 2004). The correction procedure has the advantage of being an objective one as it effectively removes any declining trend in the $\delta^{13}C$ series post AD 1850, which is attributed to physiological response to increased atmospheric CO$_2$ concentrations (McCarroll and Loader 2004).

### 2.2. Geo-chronological analyses and phytosociological survey

To have an estimate on the timing and magnitude of warming-induced greening and consequent change in the primary production, a phytosociological survey was conducted in the DOK valley (2015) covering the altitudinal range from mid-valley (2400 m asl) to treeline (3400 m asl) to understand community structure in terms of dominance and proportional abundance of evergreen conifers and thermophilic deciduous members. We assessed decadal changes in soil organic carbon stock of a glacio-lacustrine deposit from sub-alpine ecotone zone (3400 m asl, DOK valley). The response and extent of thermophilization in the lower part of this glaciated valley (2500 m asl) were assessed by analysing pollen from forest surface-layer profile.

#### 2.2.1. Phytosociological survey

Sixty sampling points (based on species-area curve) were randomly chosen, where 10 m × 10 m quadrats were laid for sampling of the tree layer. Total number of tree species, number of individuals under each species and their diameter at breast height were recorded to obtain corresponding frequency, density and basal cover (Ellenberg and Mueller-Dombois 1974). Overall community composition was characterized by proportional abundance of deciduous and evergreen members, their size structure (as indicated by girth class distribution), importance value index (IVI) of each species and dominance-diversity plot (table S2).

#### 2.2.2. Soil organic carbon profile

Decadal-scale changes in soil organic carbon stock (loss-on-ignition (LoI): wt%) was derived from accelerator mass spectrometry (AMS) $^{14}$C-dated glacio-lacustrine deposit (90 cm) from sub-alpine ecotone zone (3400 m asl), where shrubs and deciduous vegetation are coming up while glaciers recede. The percentage of organic carbon in each 2 cm section was determined by LoI. Overall, a standard and sequential LoI method was followed (Bali et al 2017). Moisture content was removed at 105 °C and residues were burned at 550 °C for 4 h. Weight for LoI was calculated as a percentage of dry weight. The mean percentage deviation between the repeated runs was 0.73 ± 0.55%. A major oxide (P$_2$O$_5$) concentration estimation of the sediment samples was also performed with x-ray fluorescence analysis through sequential spectrometer (Bruker S8 Tiger), following standard procedure (ref). The accuracy of measurement was better than 2% with a precision of <2%.

#### 2.2.3. Pollen analyses

Pollen analyses of a dated forest surface-layer profile (10 cm) (~2500 m asl) ascertained recent changes in the floristic forest composition. Pollen extraction was carried out at 1 cm intervals. About ~2 g dry weights of sediments were treated with KOH, HCl, and HF to remove humic acid, carbonate, and silicates, respectively. Before chemical treatment, one Lycopodium spore tablet with known number of spores (~10 680 spores) was added in each sample in order to estimate pollen concentration. The chemical treatment was followed by sieving with 10 and 120 μm mesh clothes for removal of fine and coarser fractions. Finally, residues were mounted in DPX mountant for preparation of permanent slides. Pollen identification and counting was conducted under light microscope (Olympus BX 61) at 400× and 1000× magnifications and a minimum of 300 terrestrial pollen grains were counted from each sample (Phadtare and Pant 2006).

#### 2.2.4. Radiocarbon dating

The radiocarbon dates for the bulk organic rich forest-soil profile (2500 m asl) and alpine strata
(3400 m asl) were obtained from AMS Laboratory in Poznán, equipped with the 1.5 SDH-Pelletron Model ‘Compact Carbon AMS’ ser. no. 003, following standard procedures for AMS radiocarbon dating. The age calibration of the radiocarbon ages to calendar years BP (BP = AD 1950) has been done according to the age calibration program of OxCal ver 4.3.2; IntCal 13 atmospheric curve. Age extrapolation on the stratigraphy has been done by calculating average sedimentation rate between top (0 cm; 0 year BP) to dated surface (7 cm; 106 year BP). Although, we have also applied another dating technique (Pb-210), on the upper surface layers; however, there was no excess high 210Pb excess (210Pb–226Ra) in the surface sample to be used for dating purpose (R. Rengarajan, PRL; Per. Comm.). Thus, in case of unavailability of any other dates we simply applied the age extrapolation by assuming uniform sedimentation rate. In case of glacio-lacustrine deposit, sampling year (2014) has been taken as reference to present day, represented as 0 year BP.

2.3. Valley-scale changes in the vegetation

2.3.1. LANDSAT

Given the repetitive nature of EREs over a particular catchment/valley (Dimri et al 2016, 2017), we identified eight ERE-prone valleys in the Uttarakhand Himalaya (Garhwal and Kumaun Himalaya) (table S3). To derive seasonal and valley-scale changes in Normalized Difference Vegetation Index (NDVI)-based vegetation area during summer (April–October: when both evergreen conifer and deciduous canopy are green) and during winter (November–March: when only evergreen species including conifers remain green), we utilized all available LIT Landsat data (a total of 766 images) of different sensors onboard (MSS, TM, ETM+, OLI) since 1972. Images were downloaded (https://glovis.usgs.gov), processed and analysed for vegetation trends in summer and winter months. Landsat time-series since 1972 for eight ERE-prone valleys (table S3) of the Uttarakhand Himalaya (Garhwal Himalaya: DOK, BHI, MAN and CHA; Kumaun Himalaya: NAN, SUN, NAM and KAL) were downloaded (https://glovis.usgs.gov) (for details see table S4). Watershed boundaries in each of the eight glacier valley were delineated utilizing mosaicked and re-projected tiles of 30 m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model v2 (downloaded from http://gdx.cr.usgs.gov/gdex/). Available LIT Landsat data with less than 10% cloud cover were selected and referenced to the Geographic Coordinate system Universal Transverse Mercator (UTM) Zone 44° N. In order to bring time-series data to a common scale and remove the atmospheric contribution, all the images were converted to reflectance value using the ENVI™ FLAASH module (Saini et al 2016). NDVI is a commonly used indicator to observe vegetation growth and dynamics; hence the selected Landsat images were transformed into NDVI time series using following equation:

\[ \text{NDVI} = \frac{\text{NIR} - \text{red}}{\text{NIR} + \text{red}} \]

To analyse changes in vegetation area in each valley during summer and during winter, we calculated five year seasonal image composites using the maximum value composite procedure, except for the period from 1972 to 1980, for which a nine-year composite was generated due to lower availability of cloud free images. The compositing process strongly reduces the effect of clouds, snow and other sources of noise, as well as seasonal differences caused by solar angle differences and vegetation phenological changes are minimized. A threshold of NDVI greater than 0.35 was considered, to extract significant vegetation cover. Finally, we generated time-series for the extracted green area for each valley (table S3).

2.3.2. MODIS

To quantify regional changes in vegetation for the Uttarakhand Himalaya (Garhwal and Kumaun Himalaya), we utilized MODIS MOD13Q1 250 m NDVI product, which was downloaded from Land Processes Distributed Active Archive Center (LPDAAC: www.reverb.echo.nasa.gov) (table S4). MOD13Q1 is a composite product developed by selecting the highest quality pixels within a temporal window of 16 days of atmospherically corrected bi-directional surface reflectance and had been masked for water, clouds, heavy aerosols and cloud shadows. Images were mosaicked and re-projected to UTM Projection zone 44° N and study area was sub-setted. The scale factor was multiplied by the valid range of image to calculate NDVI value and by using a threshold value of 0.3. The procedure to extract green areas was similar to that applied for the Landsat images. We then merged NDVI time series seasonally to compute green area during summer and winter seasons, respectively. Finally, we computed area coverage by deciduous broadleaf vegetation as difference between green area during summer and winter.

2.4. Vegetation index and ET rate in the Himalayan region

The LAI, enhanced vegetation index (EVI) and ET since 2000 CE for different regions of the Himalaya (figure 1) had been deduced using 500 m resolution 8-day composite MODIS products (LAI: MOD15A2H; EVI: MYD13A1; ET: MOD16A2) (table S4). EVI product (MYD13A1) was downloaded from Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) (https://lpdaacsvc.cr.usgs.gov/appEears/). For data generation, products were clipped using a shapefile for the respective Himalayan region. Pixel values were then exported using ERDAS imagine to ASCII format. A MATLAB code was prepared to calculate average
value for each data. Overall, we followed the processing manual for the MODIS products.

2.5. Climate dataset and simulations
Observed climatic records are scarce in the Himalaya and mostly available for few stations situated at the lower elevations. Hence, utilizing rainfall data from six rain gauge stations since 1979 (figure 1), we prepared a regional rainfall data series (Singh et al. 2019). Rainfall data of each month were normalized with respect to common period (1979–2015) before averaging to create a regional climate series. Then, averaged regional series were converted to original absolute values using average means and standard deviations of all individual months of all the stations (Singh et al. 2019). District-wise monthly rainfall datasets (www.imd.gov.in/section/hydro/districtrain/districtrain.html) provided by the India Meteorological Department (IMD) were used as an auxiliary parameter. Moreover, Tropical Rainfall Measuring Mission (TRMM) monthly rainfall datasets (TRMM 3B43 v7) were assessed for Garhwal as an auxiliary parameter. Tropical Rainfall Measuring Mission provided data from WRF derived CWV and observed precipitation. CWV can be removed from the atmosphere at a given location and time. Linkage between ET and precipitation was deduced based on autocorrelation analysis of PET, P-Efficiency at regional and valley-scale, and MODIS-based sensitivity analysis of ET to LAI (ΔET/ΔLAI) for the Himalaya and its sectors (figure 1). Finally, a statistical Lagged Covariance Ratio method based on positive feedback between PET and later rainfall (P), such that the lagged covariance of PET and P divided by the lagged autocovariance of PET was employed to quantify regional and valley-scale land-atmosphere coupling.

2.6. Statistical analyses
The linear trends in the biophysical time series were estimated using ordinary least squares regression. Its statistical significance level (P) was assessed by the two-tailed Student’s t-test to verify whether the trend was statistically significant rather than random noise. To detect significant monotonic increasing or decreasing trend, non-parametric Mann–Kendall trend test and Sen’s slope were applied, and P value were calculated by the two-tailed Student’s t-test. The Mann–Kendall test provides additional verification for the robustness of the linear regression trend analysis, as it is less sensitive to the beginning and end of the analysis period. All statistical lead-lag, break-point analyses, cross- and auto-correlations were performed in MATLAB (2012) environment.

3. Results and discussion

3.1. Activation of ecophysiological processes
3.1.1. Photosynthesis
The mean δ13C value of *Aesculus indica* (broadleaf deciduous species: 1820–2015) was −24.31 ± 0.82‰, while for conifer species it was −2.0‰ higher (*Abies pindrow*, 1743–2015: −22.17 ± 0.71‰; *Picea smithiana*, 1830–2015: −22.21 ± 0.76‰). The difference (−2.05 ± 0.61‰) between δ13C time-series of two PFTs indicates a higher level of isotope discrimination in broadleaf species relative to the conifers. A significant and positive inter-species correlation exists between them, which indicate influence of common and coherent climatic factors on assimilation process (table 1). Break-point analysis indicated 1954 as a year of change in the isotopic composition. For broadleaf species, slopes of trends for the periods prior and after 1954 are −0.001% yr−1 and −0.032% yr−1, respectively. For conifers, they are −0.0007% yr−1 and −0.025% yr−1, respectively (P < 0.001). Irrespective of the PFTs, a mean ∼5% (4.45%–5.63%) decline in isotopic composition was noted after 1954 relative to the pre-1950s levels (figure 2).

Worldwide studies on tree-ring δ13C records usually do not provide a general support for a CO2 fertilization effect on the forest biomes under soil
nutrient limiting conditions. However, a warming-induced increase in water and nutrient availability from melting glaciers and thawing permafrost with concurrent rising CO$_2$ levels in the mountain ecosystems have been shown to enhance productivity, forest expansion, and thermophilization (Gottfried et al. 2012, Shen et al. 2015, Silva et al. 2016, Zeng et al. 2017, Panthi et al. 2020). Consistent with the mechanism, our PFTs’ $\delta^{13}$C chronologies indicate a significant stimulation in photosynthetic assimilation rate since the 1950s (figure 2). Changes in species tree-ring $\delta^{13}$C over time are consistent with CO$_2$ stimulation of photosynthesis, which indicated 7.3% (6.9%–7.5%) enhancement in photosynthesis rate relative to the pre-industrial period. When considering the changes in atmosphere-to-plant $^{13}$CO$_2$ discrimination ($\Delta^{13}$C), we found that $\Delta^{13}$C in broadleaf species was 11.7%–14.0% higher relative to the conifers. $\Delta^{13}$C time-series of broadleaf species showed an increasing trend since 1954, with an average rate of 0.15% yr$^{-1}$, while it remained stable for the conifers (0.003‰ yr$^{-1}$) (figure 2). Thus, CO$_2$ stimulation in photosynthetic assimilation might have resulted in corresponding increase in transpiration (figure 2), indicating an anthropogenic climate change impact on acceleration in valley forest ET. Besides, greening-induced increase in global transpiration (Zhang et al. 2015, Zeng et al. 2016), our results are in agreement with those reported from other mountain environments (Goulden and Bales 2014, Mastrotheodoros et al. 2020), and the TP (Shen et al. 2015, Sun et al. 2016).

3.1.2. Transpiration
Tree-ring $\delta^{18}$O preserves hydroclimatic signals that are essentially coherent over a very large area (Baker et al. 2016, Zeng et al. 2017, Xu et al. 2018, Singh et al. 2021). Our $\delta^{18}$O chronologies (table 1) bears a high annual to multi-decadal coherencies with other central Himalayan $\delta^{18}$O chronologies, indicating a common coherent controlling factor, primarily related to regional climate (Xu et al. 2018, Singh et al. 2019, 2021). The mean $\delta^{18}$O value of Aesculus indica was 25.74 ± 2.2‰, while for the conifers, it was found higher (Abies pindrow: 29.44 ± 1.77‰; Picea smithiana: 28.07 ± 1.67‰) (table 1). Relative to pre-1950s level, mean increment in $^{18}$O enrichment was found higher in broadleaf deciduous species (5%) in comparison to the conifers (3%). Higher transpiration rates of broadleaf species and differences in the stomatal conductance can create $^{18}$O enrichment offset, given similar rooting-depths. At the same vapour pressure deficit, leaves with low transpiration rates become isotopically enriched in heavy isotope as compared to leaves having high transpiration (Cuntz et al. 2007, Farquhar et al. 2007). The Péclet effect (water enrichment by the backward diffusion at the site of evaporation) also reduces the contribution of enriched water in broadleaf species with greater transpiration and hydraulic conductivity. Nearly three centuries of PFTs’ $\delta^{18}$O records indicate a consistent increase in ET since the 1950s (figure 3). ET remains directly proportional to $\delta^{18}$O, when its variability is controlled by evaporative demand and inverse when stomatal conductance is the dominant factor (Cuntz et al. 2007, Farquhar et al. 2007). In a warm-moist environment, as in the monsoon-dominated central Himalaya, where evaporative demand prevails, increasing $^{18}$O enrichment of water is associated with increasing ET. We found a strong correlation of $\delta^{18}$O values against ET ($R^2 = 0.48$, $P < 0.001$, $n = 15$: 2000–2015) as compared to regional soil moisture ($R^2 = 0.13$, $P < 0.05$, $n = 34$: 1982–2015). These relationships point towards a dominant role of valley forest ecophysiology in regulating atmospheric moisture (Kahmen et al. 2011, Singh et al. 2014). In a warm-moist environment, $\delta^{18}$O values are mainly controlled by basin-intrinsic ecophysiological

| Aesculus indica (Ai) | Abies pindrow (Ap) | Picea smithiana (Ps) | Aesculus indica (Ai) | Abies pindrow (Ap) | Picea smithiana (Ps) |
|---------------------|------------------|---------------------|---------------------|------------------|---------------------|
| 1820–2015 (196 years) | 1743–2015 (273 years) | 1830–2015 (174 years) | 1820–2015 (196 years) | 1743–2015 (273 years) | 1830–2015 (174 years) |
| Mean ± std. deviation (%) | -24.31 ± 0.05 | -22.17 ± 0.04 | -22.21 ± 0.05 | 25.74 ± 0.15 | 29.44 ± 0.11 | 28.07 ± 0.12 |
| Std. deviation (‰) | 0.82 | 0.71 | 0.76 | 2.20 | 1.77 | 1.67 |
| Coefficient of variation (%) | 3.4 | 3.2 | 3.4 | 8.5 | 5.2 | 5.9 |
| First-order autocorrelation (1976–2015) | 0.50–0.83 | 0.60–0.87 | 0.62–0.83 | 0.80–0.96 | 0.76–0.89 | 0.85–0.90 |
| Inter-tree correlation (1976–2015) | 0.73 | 0.71 | 0.58 | 0.75 | 0.84 | 0.76 |
| Inter-species correlation (Ai–Ap) (Ap–Ps) (Ps–Ai) | | | | | | |
Figure 2. (a) $\delta^{13}C$ chronologies of PFTs indicating enhanced (4.45%–5.63%) assimilation rates after 1950s in a record of 273 years (1743–2015 CE). Dark lines indicate 21 year running average. Error margins are based on five individual isotope series in each species from 1976 to 2015. (b) Atmosphere-to-plant $^{13}CO_2$ discrimination ($\Delta^{13}C$) and CO$_2$ fertilization effect on species’ $\delta^{13}C$ chronologies. Magnitude of $\Delta^{13}C$ in deciduous species is 2.08‰–2.23‰ higher relative to the conifers, indicating higher rates of assimilation, transpiration and shows an increasing trend (0.15‰ yr$^{-1}$) since 1954. In contrast, conifer species do not show any trend (0.003‰ yr$^{-1}$). (c)–(e) Comparison of raw $\delta^{13}C$ series (dark lines), $\delta^{13}C$ series corrected for post-industrial changes in isotopic composition of atmospheric CO$_2$ (dotted lines), and $\delta^{13}C$ series after additional correction for physiological responses to increasing concentrations of atmospheric CO$_2$ (bright lines) in deciduous species ($A. indica$) (c), and in conifer $P. smithiana$ (d) and $A. pindrow$ (e).
Figure 2. (Continued.)

Figure 3. (a) $\delta^{18}O$ isotope chronologies of PFTs indicating increase in transpiration since the 1950s. (A. indica: 1820–2015 CE; A. pindrow: 1743–2015 CE; and P. smithiana: 1830–2015 CE). (b) z-scores of $\delta^{18}O$ time series of PFTs indicate a coherent response of climate. Dark lines indicate 21 year running average.
processes (Baker et al. 2016). Above results underscore an increase in species’ ET rate, and signify increasingly higher contributions from broadleaf species since the 1950s.

3.1.3. Stomatal conductance
We utilized simultaneous analyses of $\delta^{13}$C and $\delta^{18}$O in both PFT tree-ring chronologies to investigate the relative importance of stomatal limitations versus photosynthesis. The 51 year running correlation suggests a current phase of declining stomatal limitation in both PFTs (Figure 4). During wetter periods, stomatal conductance is high and photosynthetic capacity is limiting, so the two isotopes are either negatively correlated or show no relationship (Cullen et al. 2008, Liu et al. 2014). A high positive correlation exists between $\delta^{13}$C and $\delta^{18}$O during drier periods in a normally humid environment. Low correlation characterizes phases of high stomatal conductance, ensuring enhanced (less regulated) release of water vapour to the atmosphere (Figure 4). Moreover, stomatal conductance is not assumed to be a limiting factor in energy-limited (moist) environments of the Himalaya especially during the warm-wet growing season (April–October), which coincides with the summer monsoon period. In this context, we also observed the stem water forcibly flowing out when trees (irrespective of PFT) were punctured during coring (Young-Robertson et al. 2016). Moreover, as wood density of A. indica is comparable to all other dominant deciduous species (table S2), stomatal conductance and consequent transpiration are also supposed to be comparable (Lin et al. 2015), having a direct implication on enhancement in forest transpiration.

3.2. Elevation-dependent warming and widespread greening
LoI analyses of glacio-lacustrine deposit (3400 m asl, DOK valley) indicate that since the 1900s, burial of soil organic carbon (and consequent increment in the primary productivity) is unprecedented in a 6000 radiocarbon-year record (figures S2(a) and (b)). During the last 100 years, increase in organic carbon stock was about 40% (figure S2(a)). Result also indicates a concurrent increase in the availability of essential micronutrient phosphorus, which greatly accelerates the rates of primary production following glacier recession (Darcy et al. 2018). We also ascertained this response and extent of thermophilization in lower part of this valley (2500 m asl) by analysing pollen in a forest surface-layer profile. Pollen record indicated an increasing trend in thermophilic broadleaf deciduous species relative to the conifers (figures S2(c) and (d)). These results, thus, suggest a widespread impact of warming and consequent intensification in ET through the vegetation that has been taking place at least for a century. The timing of observed impacts in the region notably corroborates with that reported from TP (Silva et al. 2016). Besides, a phytosociological survey made across the mid-altitudinal forest to alpine zone also suggests an expansion of broadleaf vegetation (figure S3, table S2). Corresponding analysis on girth-class distribution indicates a dominant and emerging status of broadleaf species within the young tree population (figure S3). The dominant member in forest community was A. indica (broadleaf deciduous vegetation, Log IVI: 1.75). However, a log–normal pattern of dominance-diversity curve implies near-equal resource sharing and competence of deciduous and conifer species in
the forest (figure S3, table S2). Thermophilization and enhanced growth of mountain plant communities (Gottfried et al. 2012, Shen et al. 2015, Silva et al. 2016, Sigdel et al. 2020), increment in soil organic carbon stock (Ding et al. 2017), pollen composition (Phadtare and Pant 2006), geochemical indices (Bali et al. 2017), provide a certain and long-term evidence of regional greening, expansion of thermophilic vegetation, and consequent enhancement in primary production (Nan et al. 2017) favoured by concurrent permafrost thawing and glacier recession. Regional decline in albedo due to greening, expansion of thermophilic vegetation, growing season length, and treeline advancement (Bhattacharya et al. 2011, Bharti et al. 2012, Shrestha et al. 2012, Telwala et al. 2013, Yang et al. 2017) would act as a self-reinforcing feedback to atmospheric warming; hence further accelerate the rate of vegetation expansion and greening.

3.3. Valley-scale greening

Five decades of high resolution Landsat imageries were utilized to ascertain greening trends at the valley-scale (table S3). Results indicate a substantial increase in deciduous vegetation fraction in eight ERE-prone valleys (Uttarakhand Himalaya since the 1972 CE (figures S4(a) and (b)). Across the valleys, deci- duous fraction increased on an average of 24% (15%–35%), relative to pre-1994 level, while the evergreen vegetation also increased but steadily. Increase in the deciduous fraction is relatively more towards the humid eastern side (i.e. Kumaun Himalaya and adjacent Nepal Himalaya). Current mean deciduous area coverage in the valleys is 36%, which varies from 22%–49% in different valleys. Seasonal green-area coverage analyses indicate that with the advent of spring season approximately 41% (range: 31%–51%) of the valley area turns-up green with deciduous canopy development (figure S4(d)). Moreover, we derived green-area for the entire region (all eight valleys together) from a high resolution (250 m) MODIS NDVI (>0.3). Results show that deciduous vegetation coverage has been expanding more rapidly (at the rate of 37.2 km² yr⁻¹) relative to the evergreen vegetation including conifers (13.7 km² yr⁻¹) (figure S4(c)). While, current extent of regional greening indicates that with pre-monsoon flush of new foliage, approximately 50% of the area rapidly turns-up green (figure S4).

Several observations have indicated extensive greening in the mid-altitudinal ranges, and some workers have anecdotally even reported browning in evergreen conifer forests in the Himalaya (Mishra and Chaudhuri 2015, Mishra and Mainali 2017). Decadal-scale environmental changes resulting from climate warming, augmentation in regional pre-monsoon rainfall (Singh et al. 2006, Karki et al. 2017, Bohlinger and Sorteberg 2018, Talchhabadel et al. 2018, Shrestha et al. 2019), enhanced glacier-snowmelt and nutrient flow (Silva et al. 2016), and disturbances such as forest fires (Zobel and Singh 1997) might have favoured deciduous broadleaf species over the conifers.

Alterations in vegetation type and area play key roles in controlling terrestrial hydrologic response because of central role of physiological response of CO₂ and vegetation-induced acceleration in ET (Lemondant et al. 2018, Mastrotheodoros et al. 2020). The broadleaf deciduous species are a ‘strong sink as well as source’ of moisture relative to the conifers, which maintain relatively high stomatal conductance even when the risk of cavitation of water conductive element is high (Carnicer et al. 2013, Siddiq et al. 2017). They play a significant role in water and carbon cycle coupling, attributable to their higher water consumption, stomatal conductance, storage, and lower water use efficiency (Graven et al. 2013, Welp et al. 2013, Frank et al. 2015, Forkel et al. 2016, Young-Robertson et al. 2016). For example, transpiration from broadleaf deciduous trees just during the canopy development period (few weeks) can contribute to about 5% of the Yukon River’s annual discharge (Young-Robertson et al. 2016).

The provision of adequate water availability during deciduous canopy expansion period and pre-monsoon convective season (MAMJ) largely coincides in the region. During canopy development, leaves of deciduous species expand faster (1.42 cm² d⁻¹) than those of conifers (0.97 cm² d⁻¹) (Zobel and Singh 1997). Warm-moist environmental condition, and fast and vigorous canopy development during pre-monsoon season is supposed to be mediated by a less strict stomatal control, allowing them to release water and assimilate carbon at a faster rate as compared to the conifers (Swann et al. 2010). Consequently, enhanced water vapour release during convective season could strengthen the convective cells because of orographic locking that may further increase the convergence and frequency of summer-time EREs (Dimri et al. 2016, 2017). Interestingly, the deciduous trees have a shorter (April–October) but more intense period of water release and CO₂ uptake (Graven et al. 2013, Welp et al. 2013, Forkel et al. 2016) compared to conifer counterpart in the valleys, as their ET rates are higher (50%–80%) (Swann et al. 2010, Frank et al. 2015, Siddiq et al. 2017). If the conductance of deciduous canopy is enhanced by 50% with flush of new foliage (Richardson et al. 2013); substantial atmospheric water availability during convective season cannot be over-rulled.

The relative importance of deciduous and conifer species can also be abdicated from a remarkable synchrony that exists between phase of high stomatal conductance (low δ¹³C and δ¹⁸O correlation in A. indica) and increased incidences of EREs in the valleys since the last seven decades (figure S5(a)). A comparison of 21 year running δ¹³C–δ¹⁸O correlation in a deciduous species and a conifer species (of similar length chronology) indicated a higher stomatal conductance in deciduous species
(figure S5(a)). Despite similar inter-annual variations between PFTs (indicating a common climatic forcing), the inter-species isotopic incoherency became pronounced around 1900 CE. Prior to the 1900 CE, the coherency in PFTs were similar (A. Indica: 0.28 ± 0.15; P. smithiana: 0.23 ± 0.13). The $^{13}$C–$^{18}$O correlation sharply increased in the deciduous species (0.4 ± 0.16) after the 1900 CE, while for the conifer, it reduced to 0.03 ± 0.18 (figure S5(b)). Interestingly, the timing is consistent with reported observed increase in vegetation productivity and conifer–deciduous divergence (section 3.2).

### 3.4. Greening-induced acceleration in ET across the Himalaya

Our compiled ERE record since 1800 CE from the Himalaya (table S1, figure 1), indicates central Himalaya as a ERE hotspot region in recent decades, which include the valleys of western Nepal, and the Indian central Himalaya (Uttarakhand and eastern Himachal Pradesh) (figure 1). Therefore, across its different climatic and biogeographical regions, we derived correlations between EVI and ET, regional sensitivity of ET to LAI ($\Delta$ET/$\Delta$LAI) (Zeng et al. 2016) and the annual to seasonal-scale changes in EVI, LAI and ET. Overall, these results confirm that the pre-monsoon season is a critical phase with respect to land-atmosphere interaction, with the central Himalaya being a hotspot region (figures 5 and S6, table S6).

For the Himalaya, LAI and ET have increased by 16.7% and 12.5% respectively (P < 0.05), while, their rates vary regionally (figure 5(a)). Among the regions, CH and WH showed strongest increase in ET as well as LAI (P < 0.001). In contrast, increase in eastern Himalayan regions was minimal and non-significant (figure 5(a)). For regional correlation analyses between greening and ET, we utilized an independent EVI dataset, as LAI is an input variable in Modis-derived ET (figure S6). Results indicate that for the Himalaya a high correlation exists between EVI and ET ($r = 0.82, P < 0.001$). The correlation was high for CH ($r = 0.77, P < 0.001$) and WH ($r = 0.79, P < 0.001$). EVI-ET correlation was found moderate for EH I ($r = 0.59, P < 0.05$). However, the correlation declined beyond EH I (figure S6). Based on positive response of ET to greening and constrained by inversely proportional relation between $\Delta$ET/$\Delta$LAI and observed trend of LAI ($\Delta$LAI/$\Delta$t), Himalaya's sensitivity of ET to LAI was estimated at 1.26 mm d$^{-1}$ per m$^2$ m$^{-2}$, which is almost four times higher than global average $\Delta$ET/$\Delta$LAI (Zeng et al. 2016). With this sensitivity, observed greening of the Himalaya can be translated into acceleration of ET by a rate of $\sim$35.3 mm yr$^{-1}$ (figure 5(b)). Concerning the Himalayan sub-regions, the rate of acceleration of ET was lowest for WH (26.5 mm yr$^{-1}$) and highest for the EH II & III (>40 mm yr$^{-1}$), while for CH and adjacent EH I it remained between 32 mm yr$^{-1}$ and 36 mm yr$^{-1}$ respectively. Further, monthly sensitivity analyses revealed a unimodal behaviour in the central regions (CH, EH I & II), which remained highest with concurrent monsoon season (figure 5(b)). Interestingly, the sensitivity of WH was opposite to that of the other regions; it remained highest during winter, concurrent with the influence of the westerlies. Sensitivity behaviour of EH III was slightly different, possibly due to an asynchronous nature of seasonal phenology (Kikim and Yadava 2001). While for the central regions, the synchronous pattern of vegetation phenology having coherent and concentrated leaf-fall to canopy development (Zobel and Singh 1997) makes it a distinct and a sensitive region (table S6). Seasonal increase in LAI and ET in different sub-regions indicated that the pre-monsoon season is a critical phase with respect to land-atmosphere interaction (figure 5(c)). Because of biophysical feedback induced by the response of ET and a higher greening rate, stronger evaporative cooling and faster moisture recycling can be expected particularly in the central regions.

Here it is pertinent to mention about the underestimation of Modis-derived ET. Modis estimates transpiration as only 24% of land ET (Miralles et al. 2016), whereas the global water-isotope based observations indicate it over 60%, and even higher for the tropics to sub-tropics (Lian et al. 2018). Thus, Modis-derived underestimation of transpiration to ET ratio for the central Himalaya (particularly for the Uttarakhand Himalaya) suggest underestimated climate feedbacks triggered by vegetation greening due to underestimating the sensitivity of ET to LAI ($\Delta$ET/$\Delta$LAI). Under given atmospheric conditions, ET partitioning is highly dependent on vegetation type, density and structure (Lian et al. 2018). Thus, given widespread greening and thermophilization (a favoured expansion of broadleaf vegetation over needle-leaf conifers), we contend a comprehensive change in ET partitioning behaviour and a gross-scale alteration in surface–atmosphere interactions having a direct implication on the atmospheric branch of the hydrological cycle (Guerrieri et al. 2019, Mastrotheodoros et al. 2020).

### 3.5. Valley ET as additional source of atmospheric moisture

Both valley-scale (Landsat) and regional (Modis) greening estimates (section 3.3) suggest that 40%–50% of the area rapidly turns-up green with pre-monsoon flush of new foliage and canopy development (figure S4). Superimposed on the increasing trends of vegetation, particularly of deciduous species, water vapour loading to the atmosphere could be substantial. For example, according to an estimate of coverage area of deciduous species (in DOK valley), with pre-monsoon canopy development, Aesculus indica released 68% more moisture to the atmosphere relative to concomitant conifers.
Figure 5. (a) MODIS (500 m) LAI and ET product since 2000 CE indicates that both LAI and ET in the Himalaya have increased (* * \( P < 0.05 \)). Among the regions, greatest increase in ET as well as LAI has been observed for WH and CH (* * * \( P < 0.001 \)); while for the eastern Himalaya increase is minimal and non-significant (* \( P > 0.05; \) ns \( P > 0.1 \)). Sen's slope for ET and LAI has been indicated as inset. (b) Monthly sensitivity analysis indicates a unimodal behaviour for the central regions (CH, EH I & II) that remained highest during ISM season, while the behaviour is different for WH and EH III. Inset plot indicates regional sensitivity of ET to LAI (ET/LAI). (c) Multi-year averaged LAI and ET indicate that growing season increase in LAI and ET is prominent in the central Himalayan region. Red dots indicate highly significant (\( P < 0.001 \)) trend (Sens’s slope). Particularly, pre-monsoon season (MAMJ) increase in both ET and LAI is prominent.
Additionally, given comparable wood density of dominant deciduous species in the valley (table S2), the transpiration rates also stand comparable (Lin et al 2015). Therefore, the impact of enhancement in forest ET driven by physiological activation (section 3.1) and rapid seasonal expansion could be profound in development of convective clouds and local rainfall enhancement (Swann et al 2010, Richardson et al 2013). Enhancement in ET with onset of growing season causes an increase in moisture content and condensation in the vertical air column. Increased vertical pressure gradient resulting from condensation helps to maintain the convective systems and set the stage for the development of deep convection by drawing moist air from adjacent valleys. This would support a gradual increase in the moist static energy over the valleys, which would enhance convection and cumulus cloud development (Makarieva and Gorshkov 2007, Sheil and Mursiyanarso 2009, Makariwva et al 2014, Ellison et al 2015, Wright et al 2017).

Besides enhancement in local precipitation, increase in the evaporative surface and abrupt changes in water-energy fluxes that occur with the onset of growing season could cause important feedbacks to regional climate such as changes in humidity and temperature (Richardson et al 2013). Accordingly, the reported decline in pre-monsoon surface temperature since the 1960s (Thapa et al 2015, Yadav et al 2004) and concurrent increasing trends in the pre-monsoon rainfall (Singh et al 2006, Karki et al 2017, Bohlinger and Sorteberg 2018, Talchabhadel et al 2018, Shrestha et al 2019), appears to be associated with evaporative cooling with seasonal broadleaf vegetation expansion and increased transpiration that follows leaf-out (Shen et al 2015).

The vegetation-precipitation feedback loop is expected to be strong where precipitation and radiation primarily determine the vegetation growth (Panthi et al 2020). Our results, particularly $\Delta ET/\Delta LAI$, which indicates the sensitivity of central Himalayan region, may be a qualitative aspect, as MODIS ET algorithm uses LAI as an input. Therefore, to have another estimate on vegetation-precipitation feedback loop for the central Himalaya, we analysed decadal-scale (2000–2015) feedback parameter as lagged covariance ratio between reanalysis dataset of monthly ET and rainfall. Results indicate a high coupling ratio for both at the regional (CH: 0.58 ± 0.15) and valley-scale (0.53 ± 0.14) (through observed in-situ data of monthly potential ET (PET) and rainfall in DOK valley). Vegetation-regulated moisture recycling studies have indicated a high recycling ratio (~80%) that assert a strong land-atmosphere feedback (Dirmeyer et al 2009, Tuinenburg et al 2012, Harding et al 2013, Keys et al 2016). In fact, the Himalaya is one of the largest global sources of vegetation-regulated moisture recycling (Dirmeyer et al 2009, Keys et al 2016). Such modelling and isotopic studies (An et al 2017, Verma et al 2018) certainly suggest a high recycling ratio of precipitation and a high moisture memory, indicating the dominance of ET and recycled precipitation in local-regional precipitation climatology.

Weather Research and Forecasting (WRF) model was employed in same eight ERE-prone valleys distributed across the Uttarakhand Himalaya (figure S4(d)) to estimate existing contribution of valley ET to precipitable CWV. WRF model with single domain convection permitting configuration (table S5) from year 2005 to 2010 (except 2007) was applied covering the months from June to September. Fine-scale (3 km) simulation results suggest an average of 35% (24%–41%) contribution of ET to CWV. Mean ET/CWV ratio is 0.47, which varied in the range between 0.34 and 0.57 across different valleys. Though, we were not able to include all the pre-monsoon months (MAMJ (March to June)), but results based on the month of June suggest that valley ET remains about five times the level during monsoon season (figure S7(a)).

Our results on P-Efficiency at the valley-scale indicate a high efficiency (61%). As expected, the highest (94%) and the lowest (20%) P-Efficiency were observed during a strong (2010) and a weak (2009) monsoon year, respectively (figure S7(b)). A higher P-Efficiency indicates an effective local dynamic mechanism that facilitates condensation process leading to precipitation. Further, our results on P-Efficiency for the region (derived from total precipitable water from reanalysis dataset and observed regional precipitation since 1979), indicate a significantly increasing trend (figure S7(c)). An increasing P-Efficiency probably indicates strengthening of the convective system.

Analyses further indicate a high autocorrelation in PET from pre-monsoon to monsoon convective season with respect to relatively dry winter (figure S8(c)). A high autocorrelation indicates strong local moisture recycling and high moisture memory. Analysis of our daily PET also indicated an increasing trend, where pre-monsoonal increase in PET is most prominent (figure S8(d)). Besides, reanalysis data also suggest statistically significant increasing trends in pre-monsoon AWV and latent heat flux (figures S8(a) and (b)). Trends in AWV also indicate that prior to new leaf flush and canopy development (during winter), the atmosphere tends to be relatively dry.

Therefore, a significant increase in ET from valley forests and combined effects of prevailing high pre-monsoon lapse rate (Kattel et al 2013, Yadav et al 2019), elevated pre-monsoon heating (Gautam et al 2009), and CAPE (Singh et al 2017) may facilitate higher vertical velocities, which trigger new and intense convective cells and thus a higher frequency of EREs. Besides, the seasonality in surface roughness plays an important role in valley-scale convection. Evergreen conifer forests usually dominate north-facing slopes where surface roughness is less...
variable. In contrast, southern slopes show a higher seasonality in surface roughness, as deciduous vegetation dominates. During convective season, differential heating and difference in ET between northern and southern slopes could lead to the development of forest breeze that may augment the convective cells.

The southern slopes of the Himalaya act as an elevated heat source starting pre-monsoon, which, in combination with local orography, primarily determines the convective strength (Gautam et al 2009, 2010, Dimri et al 2016, 2017). Consistent with the ‘elevated heat pump’ hypothesis, progressive decline in snow cover extent and enhanced pre-monsoon heating over the southern slopes (Gautam et al 2009) lead to the strengthening of meridional tropospheric temperature gradient, and consequently, convection over the valleys (Gautam et al 2010). Superimposed on the consistently increasing trend of tropospheric warming, mean summertime CAPE (Singh et al 2017), and pre-monsoon heating, convection is likely to intensify over forested valleys, where the vegetation-precipitation feedback loop and local moisture recycling is strong. Additionally, increasing pre-monsoon rainfall, increase in glacier-snowmelt, as well as extensive formations of glacial lakes are making even more water available for evaporation. It is, thus, highly possible that significant enhancement in ET driven by physiological activation and seasonal expansion in the green area could enhance the total amount of precipitation, and further increase the frequency of EREs in future. It will have a great bearing on human well-being and economic condition of the Indian sub-continent.

4. Conclusion

Warming-induced acceleration in the hydrological cycle could have an immediate implication on regions with strong land-atmosphere coupling such as the Himalaya. Utilizing tree-ring stable isotope (δ13C, δ18O) chronologies of forest tree species, we show a combined warming and CO2 fertilization effect on the activation of vegetation ecophysiological processes. Isotope records indicate an enhancement in the processes like assimilation, stomatal conductance and ET since the 1950s at its highest levels in the past about three centuries (1743–2015 CE). Dated geochronological proxies (pollen and organic carbon) suggest climate change-induced thermophilization (a favoured expansion of broadleaf vegetation over needle-leaf conifers) and enhancement in the primary production (consequent ET) since the twentieth century. Satellite observations suggest increasing trends in the greening and ~40% seasonal expansion in the evaporative surface at the valley-scales. These additional amounts of water vapour would enhance the total amount of precipitation and magnitude and/or frequency of EREs based on the trends of conducive atmospheric conditions and biophysical factors, which tends to strengthen the convective system. Augmentation in orographic flows is likely to continue with increased forest ET and subsequent increase in recycled component of precipitation. It seems plausible that nearly fivefold increase in the frequency of EREs since the 1950s is a consequence of CO2-induced physiological activation, greening, and expansion of deciduous broadleaf vegetation on the valley slopes. Decadal-scale coherence between stomatal conductance and ERE record also corroborates this view point. This work provides a multi-decadal assessment of ecophysiological behaviour of forest tree species and could be a step towards tracking water cycle in the high mountain Asia to understand how much water passes between solid, liquid and vapour phases, affecting regional hydrology with vegetation changes. Generated dataset provide immediate support to study land surface processes tied to stomatal conductance and build a framework of observations to construe hitherto poorly understood land surface processes regulating sudden valley rainstorms. We contend that further investigation on actual contribution of forest ET to EREs (seasonal moisture loading dynamics through valley vegetation) could lead to the development of early warning system, and help modelling community on realistic land surface coupling.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Data and materials availability

Data needed to evaluate the conclusions are present in the paper and/or the supplementary materials. Additional data/code requirement (if any) may be requested from the authors.

Acknowledgments

This work was supported by the Department of Science and Technology (DST) through the ‘Centre for Glaciology (CFG) at Wadia Institute of Himalayan Geology (WIHG)’. We thank anonymous reviewers for significant and constructive comments that greatly improved the quality of this work. We thank C Mayr, I Burchardt, A Beyer, and R Höfner-Stich for assistance with isotope analyses at FAU Erlangen-Nuremberg. We are grateful to Dr R Rengaswamy (PRL) for 210Pb dating of our soil samples. Dr Praveen Kumar and Dr R R Yadav are sincerely acknowledged for reviewing this manuscript. N S and A K G acknowledge DST for support under Fast-track young scientist fellowship (SR/FTP/ES-166/2014) and J C Bose fellowship (SR/S2/JCB-80/2011) respectively.
Author’s contributions

N S and R K T conceived initial research, N S analysed final dataset and wrote first draft of the manuscript. N S and J S designed this study with inputs from co-authors. Synthesis, respective analysis, interpretations and discussion related to tree-ring width isotopes, meteorological/remote sensing analyses, WRF simulations, ecological, geochemical, palynological and space-based observations were performed by J S, A B, N S, A P D, J S C, T S, S R, V S, and R K T. P C assisted in tree core collection. Authors contributed equally to interpretation, discussion, and drafting of the manuscript.

Conflict of interest

Authors declare no competing interests.

ORCID iDs

Nilendu Singh https://orcid.org/0000-0001-8061-0180
Joyeeta Singh Chakraborty https://orcid.org/0000-0002-3867-6036
Pankaj Chauhan https://orcid.org/0000-0002-7757-4825

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