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# The Holocene floods and their affinity to climatic variability in the western Himalaya, India

Shubhra Sharma[a,b,c,*], A.D. Shukla[a], S.K. Bartarya[b], B.S. Marh[c], Navin Juyal[a]

[a] Physical Research Laboratory, Ahmedabad, India
[b] Wadia Institute of Himalayan Geology, Dehradun, India
[c] Department of Geography, Himachal Pradesh University, Shimla, India

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ABSTRACT

The present study in the middle Satluj valley explores the sedimentary records of past floods with an objective to understand the climatic processes responsible for their genesis. Based on lithostratigraphy, sedimentology, and grain size variability, 25 flood events are identified. The geochemical data indicate that the flood sediments were mostly generated and transported from the higher Himalayan crystalline and the trans-Himalaya. Our study suggests that the floods were generated by Landslide Lake Outburst Floods (LLOFs) during extreme precipitation events. However, the existing database does not allow us to negate the contribution from Glacial Lake Outburst Floods (GLOFs). Field stratigraphy supported by optical chronology indicates four major flood phases that are dated to 13.4–10.4, 8.3–3.6, 2.2–1.4, and < 1.4 ka (kilo-annum). These phases correspond to the cooler and less wet conditions and broadly correlate with the phases of negative Arctic Oscillation (− AO) and negative North Atlantic Oscillation (− NAO). Thus, implying coupling between the moisture-laden monsoon circulation and southward penetrating mid-latitude westerly troughs for extreme precipitation events and consequent LLOFs. Additionally, a broad synchronicity in Holocene floods between the western Himalaya and across the mid-latitudinal region (30°N–40°N) suggests a synoptic scale Arctic and Atlantic climate variability.

## 1. Introduction

The floods in the Himalaya are ascribed to multiple processes such as mesoscale atmospheric circulations, synoptic scale interrelated atmospheric anomalies, cloud bursts, torrential rains, Landslide-induced Lake Outburst Floods (LLOFs), Glacial Lake Outburst Floods (GLOFs), and coupling of Indian Summer Monsoon (ISM) and westerlies (Houze et al., 2011; Lau and Kim, 2012; Rasmussen and Houze, 2012; Dimri et al., 2016). The fragmentary sedimentary records of the Himalayan floods extend back from historical periods (Rana et al., 2013; Wasson et al., 2013; Sundriyal et al., 2015) to the Holocene (Coxon et al., 1996; Srivastava et al., 2008; Wasson et al., 2008). Although studies ascribe ISM for the subrecent and Holocene Himalayan floods (Srivastava et al., 2008, 2016; Wasson et al., 2008, 2013), the recent meteorological studies from the western Himalaya (Vellore et al., 2015) and other mid-latitude regions indicate that the North Atlantic Oscillations (NAO) and Arctic Oscillation (AO) play a significant role (Knox, 2000; Huang et al., 2007; Benito et al., 2015). Considering that the future projections predict more variability in ISM and NAO along with increased frequency and/or magnitude of floods (IPCC, 2001, 2007, 2014); therefore, expanding the current understanding of the role of the climate systems is pertinent in generating unusual extreme hydrological (catastrophic flood) events in the Himalayan region.

Evidence is growing to suggest that extreme hydrological events are associated with the synoptic atmospheric circulation patterns and storm tracks that result from global climate change (Knox, 2000; Huang et al., 2007; Liu et al., 2014). In recent times, the occurrence of such events in response to climate variability and their synchronicity at the regional, continental, and global scales has become a major area of interest in climate change science (Benito et al., 2015). Studies indicate that subtle shifts in climate can result in dramatic changes in the magnitude and frequencies of floods (Knox, 2000; Liu et al., 2015). The historical records of extreme hydrological events indicate temporal changes in the strength of meridional and zonal atmospheric flow for the cause of floods in the mid-latitudes (Knox, 2000; Francis and Vavrus, 2012; Francis, 2015; Francis and Vavrus, 2015; Vellore et al., 2015).

The semiarid and subhumid monsoon-influenced fluvial systems across the mid-latitude regions are differentially sensitive in their response to climate variability (Knox, 2000; Saint-Laurent, 2004;

* Corresponding author at: Physical Research Laboratory, Ahmedabad, India.
*E-mail address:* shubhra@prl.res.in (S. Sharma).

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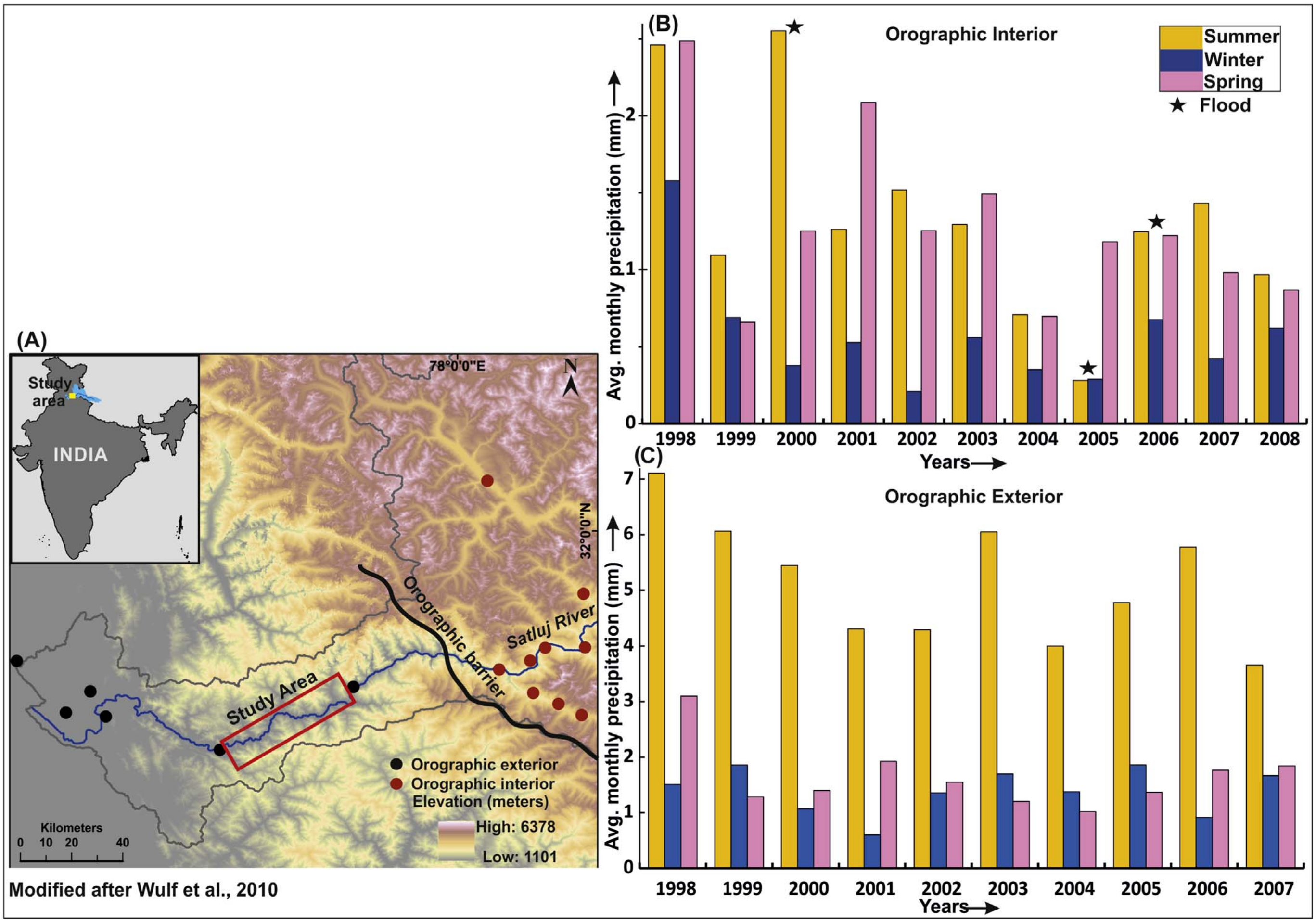


**Fig. 1.** (A) Map showing the location of weather stations in the middle Satluj valley. Red dots mark the orographic interior, whereas the black dots represent the orographic exterior. Relief around MCT marks the orographic barrier (thick black line) and divides the river catchment into the orographic interior and orographic exterior. (B) and (C) are the bar diagrams showing the summer (June–September), winter (December–February), and spring (March–May) precipitation for years 1998 to 2008 from orographic interior and orographic exterior respectively (compiled from Wulf et al., 2010). As it can be seen in the orographic interior, the winter (21%) and the spring (31%) precipitation dominates; while in the orographic exterior, summer rainfall dictates the precipitation budget (~68%). Black stars in (B) mark the years when Satluj valley was flooded in recent times (Gupta and Sah, 2008a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Huang et al., 2010; Benito et al., 2015). Such climate variations were known to be frequent during the Holocene (Mayewski et al., 2004); however, coupling between the Holocene climate and floods is still poorly understood (Knox, 1985, 2000; Ely et al., 1993; Ely, 1997; Huang et al., 2013). In view of this, reconstruction of extreme flood events based on the geological archive of flood records becomes essential toward building a better understanding of how regional/global flood patterns evolve in response to regional/global climate change (Knox, 2000; Wilhelm et al., 2012). Although the sediment records of past floods are prone to erosion and are often sporadically distributed (Knox, 2000; Benito et al., 2003b), nevertheless the deposits provide valuable information about estimating peak discharge and, thus, flood risk assessment (Ely et al., 1993; Benito et al., 2004, 2015; Thorndycraft et al., 2005).

In the last decade, the Satluj River witnessed devastating floods that adversely affected people across the border in India and Pakistan (Table S1). These floods are ascribed to extreme precipitation events and consequential LLOFs (Gupta and Sah, 2008a, 2008b; Jain et al., 2013). However, a comprehensive understanding of the causes and processes is yet to be ascertained. The present study reconstructs the flood records in the middle Satluj River valley of the western Himalaya and attempts to explore the causes of Holocene floods. Specifically, the study tries to ascertain the possible mechanisms responsible for the Holocene floods and their temporal distribution in response to climate variability at regional and global scales. Further, to understand the coupling between regional and global climate processes (if any) and sensitivity of fluvial systems to synoptic-scale atmospheric circulation, the results from the study area are compared with the flood records of the mid-latitude regions.

## 2. Study area

The Satluj River is the largest tributary of the Indus River and has the third largest catchment area in the Himalaya (Wulf et al., 2010). > 80% of its catchment lies in the rain shadow zone of the trans-Himalaya. Precipitation data compiled from the meteorological stations located in the Satluj River catchment (Wulf et al., 2010) show that the ISM dominates (~68%) to the south of the Main Central Thrust (MCT) where the higher Himalayan ranges act as an orographic barrier; whereas in the north of the MCT (the orographic interiors) the winter and spring precipitation (October–May), brought by the mid-latitude westerlies account for ~51% of the total precipitation (Fig. 1).

The Satluj River drains through three major litho-tectonic units. From the north to south these are the Tethyan Sedimentary Sequences (TSS), the Higher Himalayan Crystalline (HHC) and the Lesser Himalayan (LH) meta-sedimentary rocks. The above lithological units are demarcated by major structures such as the South Tibetan Detachment System (STDS), the Main Central Thrust zone (MCT), and the Main Boundary Thrust (MBT). The present study is undertaken in the middle Satluj valley (31.45°N, 77.63°E; 31.27°N, 77.02°E) located to