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Tracing isotopic signatures (δD and $\delta^{18}O$) in precipitation and glacier melt over Chorabari Glacier–Hydroclimatic inferences for the Upper Ganga Basin (UGB), Garhwal Himalaya

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ABSTRACT

Study region: Chorabari Glacier in Upper Ganga Basin, Garhwal Himalaya.
Study focus: Authors attempt to characterize the isotopic signatures in different components of the hydrological cycle and decipher the role of summer and winter precipitation on glacier melt using stable isotopes (δD, $\delta^{18}O$) coupled with existing hydrometeorological observations during the glacier ablation season (June–September) for the years 2011–2012.
New hydrological insights: The isotopic composition of various components of hydrological cycle i.e., precipitation (rainfall and snowfall), glacier surface ice and glacier melt have partly overlapping isotopic ranges. $\delta^{18}O$, δD and d–excess compositon indicates that precipitation during pre-monsoon (May/June) and post-monsoon (September/October) season have mixing of local moisture with that from westerlies. While during monsoon (June–September) rainfall-runoff contributes to the streamflow with snow and glacier melt. The depletion pattern of snow covered area (SCA) reflected by snow depletion curves (SDC) imply that most of the solid precipitation in the region results from westerlies, while during summers the precipitation from the Indian Summer Monsoon (ISM) is in the form of rainfall over higher altitudes. The isotopic depletion curve (IDC) of meltwater follows the trend of SDC's. The backward wind trajectories for the precipitation events also indicate that the source of winter precipitation is from westerlies while summer precipitation is from ISM. Present day $\delta^{18}O$, δD and d–excess composition and their climatic interpretation are site and time specific.

1. Introduction

The application of isotopes in hydrology and climate sciences is based on the general concept of "tracing", in which either artificially introduced isotopes or naturally occurring (environmental) isotopes are employed, which can be used for a wide range of applications. Owing to their abundances and natural fractionation (phase change) in nature these isotopes have been applied to understand the hydrological cycle (Behrens et al., 1975; Ramesh and Sarin, 1992; Ladouche et al., 2001; Burns, 2002; Carey and Quinton, 2005; Rai et al., 2016; Cable et al., 2011; Klaus and McDonnell, 2013; Dahlke et al., 2014; Wang et al., 2015), atmospheric processes (Schmidt et al., 2005; Tian et al., 2007; Risi et al., 2008; Vimeux et al., 2011; Gao et al., 2011), and paleoclimate reconstruction based on proxy archives of ice cores, tree rings, lake sediments, ocean cores, speleotherms, etc. (Thompson, 2000; Kang

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et al., 2002; Gupta et al., 2003; Ramirez et al., 2003; Yao et al., 2008; Liang and Eckstein, 2009; Cai et al., 2010; Jones et al., 2016; Dutt et al., 2015).

Another important development is the use of $\delta^{17}O$ and $\delta^{17}O$–excess for paleoclimatic reconstructions and its association with relative humidity (Barkan and Luz, 2005, 2007; Landais et al., 2008; Risi et al., 2010; Winkler, 2012). Thus, environmental isotopes are unique for regional studies of water resources to obtain time and space integrated characteristics. Generally, isotope tracers are not used as independent tools but to supplement hydrometeorological, geophysical and geochemical information and for a better understanding of the processes taking place in a hydrological system (Lambs, 2000).

In recent times, the use of stable water isotopes has been ubiquitous in catchment hydrology that has led to major advancements in understanding the processes involved in the global hydrological cycle as well as the local hydrometeorological phenomenon (Gat, 1996; Diefendorf and Patterson, 2005; Jonsson et al., 2009; Meredith et al., 2009; Henderson and Shuman, 2010). Specifically, isotopes can be used for tracing the source, movement, and pollution of ground and surface waters.

The distribution of $\delta^{18}O$ and δD in modern precipitation has been documented under programmes of International Atomic Energy Agency (IAEA), World Meteorological Organisation (WMO), Global Network of Isotopes in Precipitation (GNIP), Global Network of Isotopes in Rivers (GNIR), Moisture Isotopes in the Biosphere and Atmosphere (MIBA), as well as independent programmes in several countries like National programme on "Isotopic fingerprinting of Waters of India (IWIN), China Network of Isotope in River and Precipitation (CNIRP), etc. with the main focus on systematic collection of basic spatial data on the isotope content of precipitation across the globe to determine temporal and spatial variations of both environmental stable isotopes and tritium in precipitation (Jouzel et al., 1997; Rozanski et al., 1993; Yao et al., 2013). It is well established that $\delta^{18}O$ and δD in precipitation have a linear relationship (Dansgaard, 1953, 1954, 1964; Craig, 1961) known as the Meteoric Water Line, which is useful in hydrometeorology indicating the source/origin of the moisture. Craig (1961) proposed a Global Meteoric Water Line (GMWL), which was later modified by Rozanski et al. (1993). The equation $\delta D = (8.2 \pm 0.1)\ \delta^{18}O + (11.3 \pm 0.6)$ for the GMWL on the basis of exhaustive isotope data collected through the IAEA/WMO worldwide network is given by Rozanski et al., 1993. The GMWL represents a global normal of numerous Local Meteoric Water Lines (LMWL). LMWL is controlled by the local climatic conditions and the source of the vapour mass, particularly the slope of the line is influenced by the secondary evaporation. The knowledge of LMWL is essential for regional or local hydrological studies. $\delta^{18}O$ and δD are well correlated with surface air temperature and precipitation amount at the precipitation site, while d–excess is correlated with the physical conditions (humidity, air temperature and sea surface temperature) of the oceanic source area of precipitation (Merlivat and Jouzel, 1979; Yu et al., 2008). It also reveals the conditions existing during development and interaction or mixing of air masses during transportation to the precipitation site (Froehlich et al., 2002). Jouzel et al. (1994), Ciais et al. (1995), Hoffmann et al. (2000) exhibits the utility of d–excess for calibration of general circulation models (GCM's).

In spite of the integrated efforts of IAEA and WMO along with efforts from various countries to develop a global baseline data of isotopes in precipitation, there still remains a large gap in the Himalayan region. The Himalayan region is influenced by mid-latitude Western Disturbance (WD) or Westerlies as well as the Indian Summer Monsoon (ISM) that is sensitive to climate change and anthropogenic forcing. Thus, the study of stable isotopes in the Himalayan region is imperative for understanding the large scale atmospheric circulation and hydrological systems (Lyon et al., 2009; Sinclair and Marshall, 2009; Dahlke and Lyon, 2013). Though a large number of studies have been carried out on the northern slopes of the Himalaya (Aizen et al., 1996; Kang et al., 2002; Aizen et al., 2009; Yu et al., 2009; Hren et al., 2009; Lyon et al., 2009; Yao et al., 2009; Liu et al., 2010; Yao et al., 2013; Yang et al., 2011; Wu et al., 2015; He and Richards, 2015), only a handful of studies are available on the southern slope and that to in the lower reaches (Ramesh and Sarin, 1992; Nijampurkar and Rao, 1992, 1993; Bartarya et al., 1995; Pande et al., 2000; Rai et al., 2009; Kumar et al., 2010a,b; Wen et al., 2012; Rai et al., 2016).

The high altitude regions (above 3000 m asl) of the Himalaya have a very sparse network of hydrometeorological stations and even fewer stations for collection of precipitation samples (rain and snow) for isotopic studies. Thus, the isotopic signature of precipitation (rain and snow), ice, proglacial streams at high altitude regions of the Indian Himalaya is not available. Furthermore, the relationships of isotopic signature of precipitation with meteorological parameters is absent for correct interpretation of time series data generated from archives such as Himalayan ice cores, high altitude lake sediment cores, tree rings, etc. In this paper, we attempt to report the analysis of hydrometeorological data, event based and monthly isotopic composition of precipitation (rain and snow), glacial ice and glacier melt from Chorabari Glacier. Monthly and seasonal Local Meteoric Water Lines have been developed; moisture source has been identified using backward air mass trajectories and d-excess. An attempt to develop isotopic signature to categorize the hydrograph into its components i.e. rain, snow, glacier/ice and runoff has been made. The isotopic evolution of meltwater discharge in relation to depletion of snow covered area in the selected basin has also been investigated.

2. Study basin

The present investigations were conducted over a medium sized Chorabari Glacier (30°46′ 20.58″ N–79°2′ 59.381″ E) situated in the Mandakini sub-basin of the upper Ganga basin, Uttarakhand, India (Fig. 1). The basin ranges between an elevation of 3800 m a.s.l from the glacier terminus up to the glacier head at an elevation of 6420 m a.s.l (Kumar et al., 2016). Proglacial stream emerging from Chorabari Glacier (Fig. 2e) is the main source of Mandakini River, a tributary of Alaknanda River. Geological Survey of India (GSI) characterised Chorabari Glacier with an identification number (IN 5O132 02 003), according to the Glacier Inventory of India (Sangewar and Shukla, 2009). The glacier is compound valley type glacier oriented in a south facing direction with an accumulation area of 2.99 km^2 and ablation area of 3.67 km^2 (Fig. 2c, d). The glacier length is ~7.5 km covering an area of ~6.6 km^2. The discharge gauging site (~3800 m a.s.l.) was established ~200 m downstream of glacier termini (Kumar et al., 2016), defining a catchment of ~15.4 km^2 (Fig. 1).