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Ice core records of climate variability on the Third Pole with emphasis on the Guliya ice cap, western Kunlun Mountains

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A R T I C L E I N F O

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A B S T R A C T

Records of recent climate from ice cores drilled in 2015 on the Guliya ice cap in the western Kunlun Mountains of the Tibetan Plateau, which with the Himalaya comprises the Third Pole (TP), demonstrate that this region has become warmer and moister since at least the middle of the 19th century. Decadal-scale linkages are suggested between ice core temperature and snowfall proxies, North Atlantic oceanic and atmospheric processes, Arctic temperatures, and Indian summer monsoon intensity. Correlations between annual-scale oxygen isotopic ratios ($\delta^{18}O$) and tropical western Pacific and Indian Ocean sea surface temperatures are also demonstrated. Comparisons of climate records during the last millennium from ice cores acquired throughout the TP illustrate centennial-scale differences between monsoon and westerlies dominated regions. Among these records, Guliya shows the highest rate of warming since the end of the Little Ice Age, but $\delta^{18}O$ data over the last millennium from TP ice cores support findings that elevation-dependent warming is most pronounced in the Himalaya. This, along with the decreasing precipitation rates in the Himalaya region, is having detrimental effects on the cryosphere. Although satellite monitoring of glaciers on the TP indicates changes in surface area, only a few have been directly monitored for mass balance and ablation from the surface. This type of ground-based study is essential to obtain a better understanding of the rate of ice shrinkage on the TP.

1. Introduction

The Third Pole (TP), which is composed of the Tibetan Plateau and the Himalaya, is the core of High Asia, a region that contains an ice cover of over 100,000 km^2 (Dyurgerov et al., 2002; Yao et al., 2012). Within western China, ~46,000 glaciers have a total area of ~59,000 km^2 (Ding et al., 2006), which constitutes one of Earth's largest stores of ice. The TP, especially the Himalaya, is also referred to as "Asia's water tower" (Immerzeel et al., 2010) as its cryosphere is a major contributor to the continent's rivers which sustain ~1.5 billion people in 10 countries. Because it is the highest and largest (5 million km^2) of Earth's elevated regions, the TP has a significant role in regional and global environmental change and in Earth's climate system.

The climate of the TP is influenced by several air masses and moisture sources (Fig. 1A), including the Southeast Asian monsoon and the Southwest or Indian summer monsoon (ISM) systems and the continental westerlies (Tian et al., 2001, 2003; Yao et al., 2013). The mountain systems along the southern periphery are impacted primarily by the summer monsoons and the northwestern and northern regions are influenced by the westerlies throughout the year (Tian et al., 2007). However, some of the precipitation in the arid interior is derived from continental moisture recycled from the monsoons (Dong et al., 2016; Yao et al., 2013). This tends to complicate the interpretation of precipitation chemistry such as

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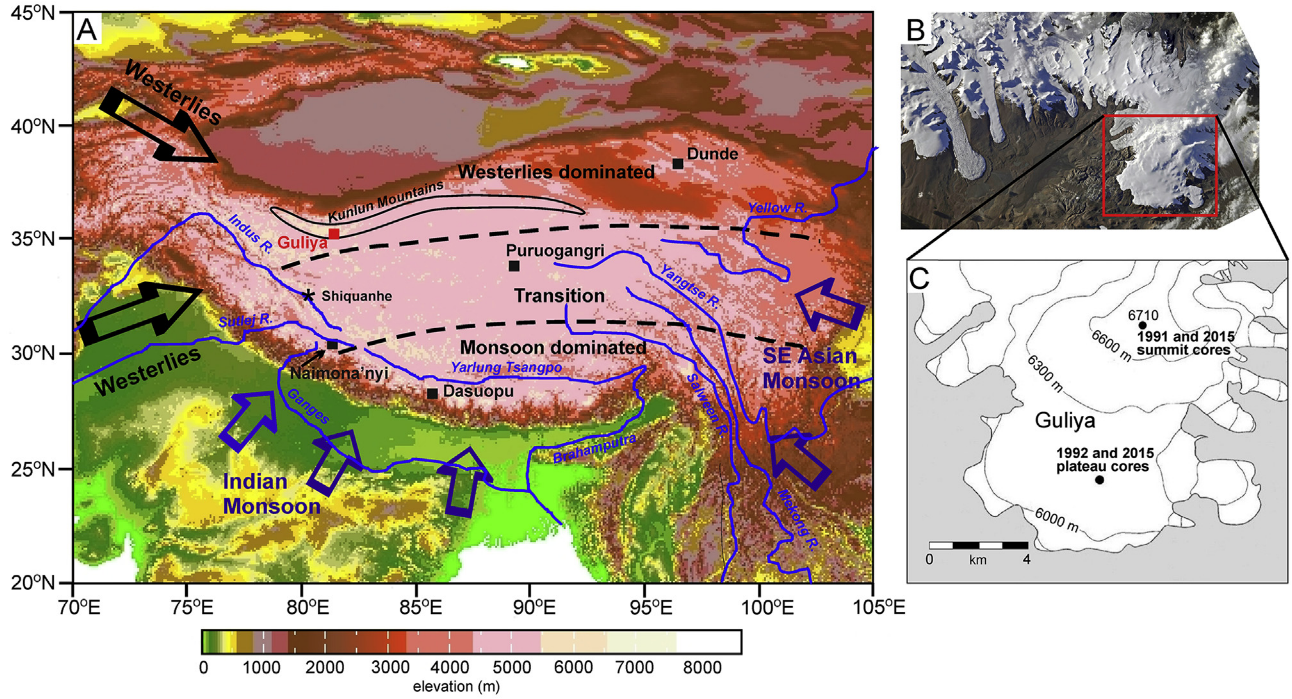

Fig. 1. Regional setting of Third Pole and Guliya ice cap. (A) Third Pole region and northern India showing major river systems, locations of ice core sites marked with black squares (the Guliya site is identified with a red square) and dominant air masses. The three major climate regimes (monsoon dominated in the south, westerlies dominated in the north, and the transition between westerlies and monsoon dominated) are based on Yao et al. (2013). (B) Satellite photos show the ice sheet in the western Kunlun Mountains with Guliya bordered by the red box. (C) Topographic map of the Guliya ice cap shows locations of drill sites in the early 1990s and in 2015. Relief map source: NOAA NGDC GLOBE (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NGDC/.GLOBE/.topo/).

stable isotopes of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) and their derivative d-excess, which together can provide information on temperature and on moisture sources and transport. Stable isotopes from ice cores drilled throughout the TP have been used to reconstruct climate histories extending back several thousands of years (Thompson et al., 2005); however, the interpretation of these isotopes is not yet fully resolved.

Since 1984 ice cores have been recovered from five ice fields across the TP (Fig. 1A) by The Ohio State University's Byrd Polar and Climate Research Center (OSU-BPCRC), in collaboration with the Lanzhou Institute of Glaciology and Geocryology (LIGG) and the Chinese Academy of Science's Institute of Tibetan Plateau Research (ITP-CAS). Each core has provided new information about climatic and environmental changes on regional to hemispheric scales (e.g., Beaudon et al., 2017; Duan et al., 2007; Sierra-Hernández et al., 2018; Thompson et al., 1989, 1990, 1997, 2000, 2005, 2006a,b, 2011; Tian et al., 2006; Yao et al., 1997, 2006). Taken together, these records demonstrate the TP's climatic complexity and diversity. One of the ice fields, the Guliya ice cap (35.13°N; 81.38°E; 6710 masl), covers 200 km^2 and is located in the western Kunlun Mountains (Fig. 1B), one of the longest mountain chains in Asia which extends from the Karakorum Range in the west to near the Qaidam Basin in the east. Guliya lies in the driest region of the TP above the highest equilibrium line altitude (Yao et al., 2012), and the current maximum accumulation (~230 mm water equivalent (w.e.)/year (a^{-1})) is the lowest of all the ice fields that have been drilled jointly by OSU-BPCRC and ITP-CAS. Reconnaissance field programs were conducted in 1990 and 1991, and a drilling program in 1992 resulted in the retrieval of a core to the bedrock on the Guliya Plateau (GP) (Fig. 1C). Twenty-three years passed before the site was revisited for another deep-drilling program.

Here we present and discuss recent climate records from ice cores drilled in 2015 on Guliya and changes in temperature proxies and ice accumulation that have occurred across the ice cap since the mid-19th century. The cores have been analyzed at annual to subannual resolution for chemical and physical parameters, and the climate records from these analyses will be used to describe teleconnections among the western interior of the TP, the North Atlantic, the Arctic, and tropical oceans. The last 1000 years of the Guliya $\delta^{18}O$ record from both the 1992 and 2015 GP cores, along with other ice core $\delta^{18}O$ time series from around the TP (Fig. 1A), will be used to illustrate similarities and variations in the climate history of this region. Finally, the recent warming trend across the TP will be evaluated using stable isotopic time series from the ice cores.

2. Materials and methods

In 1990 and 1991, a cooperative team from the OSU-BPCRC and the LIGG recovered several short cores from the Guliya ice cap, including a 16 m firn core in April 1991 from the Guliya Summit (GS) at 6710 m above sea level (masl) (Fig. 1C), along with samples from a 1.5 m pit (Fig. S1). Temperatures were measured in the shallow summit borehole (Fig. 2). The pit and shallow core samples were analyzed for $\delta^{18}O$ and concentrations of mineral dust, and beta activity (β) from ^{90}Sr and ^{137}Cs decay was measured in the top 5 m of the core to identify the 1962/63 Arctic thermonuclear test. The $\delta^{18}O$ stratigraphy of the pit (^{18}O depletion in winter and enrichment in summer) is consistent with polar cores and opposite to that in the Dasuopu glacier in the central Himalaya (28°N; 85°E) which is located directly within the ISM influence (Thompson et al., 2000). However, seasonal dust concentrations in the pit are consistent with Dasuopu (i.e., high in the winter and early spring and low in summer). The sample handling of the Guliya 1991 pit