Journal of South American Earth Sciences 77 (2017) 218–246

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Glacier monitoring and glacier-climate interactions in the tropical Andes: A review

Bijeesh Kozhikkodan Veettil [a,*], Shanshan Wang [b], Sergio Florêncio de Souza [a], Ulisses Franz Bremer [a,c], Jefferson Cardia Simões [c]

[a] Centro Estadual de Pesquisas em Sensoriamento Remoto e Meteorologia, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil
[b] Key Laboratory of Arid Climate Change and Reducing Disaster of Gansu Province & Key Open Laboratory of Arid Climate Change and Disaster Reduction of CMA, Institute of Arid Meteorology CMA, Lanzhou 730020, China
[c] Centro Polar e Climático, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil

A R T I C L E I N F O

Article history:
Received 12 May 2016
Received in revised form
18 March 2017
Accepted 17 April 2017
Available online 22 April 2017

Keywords:
Dry outer tropics
ENSO
Equilibrium line
Inner tropics
ITCZ
PDO
Tropical glaciers
Wet outer tropics

A B S T R A C T

In this review, we summarized the evolution of glacier monitoring in the tropical Andes during the last few decades, particularly after the development of remote sensing and photogrammetry. Advantages and limitations of glacier mapping, applied so far, in Venezuela, Colombia, Ecuador, Peru and Bolivia are discussed in detail. Glacier parameters such as the equilibrium line altitude, snowline and mass balance were given special attention in understanding the complex cryosphere-climate interactions, particularly using remote sensing techniques. Glaciers in the inner and the outer tropics were considered separately based on the precipitation and temperature conditions within a new framework. The applicability of various methods to use glacier records to understand and reconstruct the tropical Andean climate between the Last Glacial Maximum (11,700 years ago) and the present is also explored in this paper. Results from various studies published recently were analyzed and we tried to understand the differences in the magnitudes of glacier responses towards the climatic perturbations in the inner tropics and the outer tropics. Inner tropical glaciers, particularly those in Venezuela and Colombia near the January Intertropical Convergence Zone (ITCZ), are more vulnerable to increase in temperature. Surface energy balance experiments show that outer tropical glaciers respond to precipitation variability very rapidly in comparison with the temperature variability, particularly when moving towards the subtropics. We also analyzed the gradients in glacier response to climate change from the Pacific coast towards the Amazon Basin as well as with the elevation. Based on the current trends synthesised from recent studies, it is hypothesized that the glaciers in the inner tropics and the southern wet outer tropics will disappear first as a response to global warming whereas glaciers in the northern wet outer tropics and dry outer tropics show resistance to warming trends due to the occurrence of cold phases of El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) together. Mountain glaciers in Ecuador show less retreat in response to the warming trend, probably due to high altitudes (above 5750 m), in comparison to glaciers in Colombia and Venezuela. However, elevation-dependent warming (EDW) is a major concern in the tropical Andes. In a nutshell, smaller glaciers at lower altitudes in the inner tropics and the southern wet outer tropics near the Amazon Basin are disappearing faster than other glaciers in the tropical Andes.

Contents

* Corresponding author.
E-mail address: bijeesh.veettil@ufrgs.br (B.K. Veettil).

http://dx.doi.org/10.1016/j.jsames.2017.04.009
0895-9811/

1. Introduction

Glacier records such as moraine chronology or mass balance time series contain valuable information about the climate of the past (Leclercq and Oerlemans, 2012). Tropical glaciers are one of the most visible indicators of climate change due to their fast response time (Vuille et al., 2008a), sensitivity to climate variations (Hastenrath, 1994), proximity of melting conditions (Kaser and Osmaston, 2002), and clear visibility of their reaction (loss or gain of mass balance) (Lemke et al., 2007; Vuille et al., 2008a). Tropical glaciers differ from other glaciers due to their geometry of the incoming solar radiation as well as the seasonal regime of ablation/accumulation. The accumulation of snow occurs at high altitudes (where the air temperature is low) while ablation continues at the terminus (lower altitude and higher temperature) (Chevallier et al., 2011). The definition “tropical” is applied only if glaciers are situated within the three boundaries; i.e. within the tropics of Cancer and Capricorn (i.e. between 23.43°N and 23.43°S), Intertropical Convergence Zone (ITCZ), and where diurnal temperature range equals annual temperature range (Kaser and Osmaston, 2002).

Glacier-climate interactions in the tropics can be influenced by external forcings such as solar irradiance modulation (Jomelli et al., 2009; Rabatel et al., 2006, 2008), volcanic activities (Angelis et al., 2003; Veettil et al., 2016a, 2016b), and the presence of light-absorbing particles such as black carbon on glacier surfaces (Schmitt et al., 2015). An increase in the incoming solar radiation during less cloudy days can influence glacier mass balance sensitivity towards a change in other meteorological variables such as air temperature (Rabatel et al., 2006). Glacial maximum in Peru and Bolivia occurred during the Maunder Solar Minimum (1645–1725) and glacier retreat in the tropics was observed to be slowed down during the Dalton Solar Minimum (1783–1830) (Rabatel et al., 2005a), even though many glaciers in the Alps retreated or no advances were reported during the Maunder Minimum (Luterbacher et al., 2001; Zasadni, 2007). Volcanic activities influence mass balance changes both directly (Ginot et al., 2010) and indirectly (Rabatel et al., 2013; Veettil et al., 2016a, 2016b), and may be able to mask the influence of climate change on glaciers. Direct influence can be due to glaciochemical activities of ions (Ginot et al., 2010) by altering refreezing temperature levels or reduction in the surface albedo due to particulate materials. Indirect influence includes reduction in the solar irradiance due to volcanic aerosols such as sulphates in the stratosphere. A well-known example for the second type of complex phenomenon is the eruption of Mount Pinatubo in Philippines (even though this volcano is far from the tropical Andes) which suppressed the prevailing warming conditions during 1992–1995 due to a cooling effect of volcanic aerosols in the stratosphere (Angelis et al., 2003; Rabatel et al., 2013; Veettil et al., 2016a, 2016b, 2016e). The presence of light-absorbing particles such as black carbon from human population centres also causes increased surface melting by absorbing energy from solar radiation due to reduced surface albedo (Schmitt et al., 2015).

Based on the new Randolph Glacier Inventory (RGI) (Arendt et al., 2012; Pfeffer et al., 2014), more than 95% of all tropical glaciers on the earth are situated in the Andes of South America and the remaining are distributed in Africa and Asia. The Andes extend over varying temperature and precipitation zones and are influenced (mainly) by the Atlantic circulation patterns in the north and influenced highly by the Pacific circulation in the south (Kaser, 2001; Favier et al., 2004a; Rodbell et al., 2009; Sagredo and Lowell, 2012; Veettil et al., 2016a). The mean maximum height of the Andes is more than 4000 m above sea level (a.s.l.) along the tropical and subtropical region. This physical barrier disrupts the atmospheric circulation resulting in contrasting climatic conditions on the western and eastern slopes of the Andes. Tropical Andes can be classified into inner and outer tropics based on the seasonality of precipitation, humidity, and accumulation-ablation conditions. Climatic conditions in this region favour year round ablation towards the terminus (Francou et al., 2004).

More than 80% of the freshwater supply in the arid and semi-arid areas in the mountain regions of the tropics and the subtropics originates from glaciers (Messerli, 2001; Vuille et al., 2008a). The balance between accumulation and ablation of these water buffers can disrupt at any time by perturbations in climate thereby causing an imbalance in the river flow regimes in the nearby basins. Tropical Andean glaciers are important contributors of water resources in many high elevation basins, particularly in Bolivia and Peru, during the dry season (Ribstein et al., 1995; Mark and Seltzer, 2003; Villacis, 2008; Soruco et al., 2009; Chevallier et al., 2011; Gascoin et al., 2011). Many of the catchments of the Cordillera Blanca are glacially fed (Juen et al., 2007; Baraer et al., 2015). Runoff from basins near the rapidly retreating glaciers