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Freshwater discharge into the Caribbean Sea from the rivers of Northwestern South America (Colombia): Magnitude, variability and recent changes

Juan Camilo Restrepo [a,b,*], Juan Carlos Ortíz [a], Jorge Pierini [c], Kerstin Schrottke [d], Mauro Maza [a], Luís Otero [a], Julián Aguirre [e]

[a] Grupo de Física Aplicada, Océano y Atmósfera, Departamento de Fisica, Universidad del Norte, km 5 via Puerto Colombia, Barranquilla, Colombia
[b] Instituto de Estudios Hidráulicos y Ambientales (IDEHA), Universidad del Norte, km 5 via Puerto Colombia, Barranquilla, Colombia
[c] Universidad Nacional del Sur, Departamento de Física (UNS-CIC-CCT) CC 804 Florida 7500, Complejo CRIBABB, Edificio E1, B8000FWB Bahía Blanca, Argentina
[d] Institute of Geosciences, JRG Sea-Level Rise and Coastal Erosion, Christian Albrechts University of Kiel, Otto Hahn Platz 1, 24118 Kiel, Germany
[e] Grupo de Investigaciones Ambientales – GIA, Instituto de Energía, Materiales y Medio Ambiente, Escuela de Ingenierías, Universidad Pontificia Bolivariana, Medellin, Colombia

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S U M M A R Y

The monthly averaged freshwater discharge data from ten rivers in northern Colombia (Caribbean alluvial plain) draining into the Caribbean Sea were analysed to quantify the magnitudes, to estimate long-term trends, and to evaluate the variability of discharge patterns. These rivers deliver ~340.9 $km^3\ yr^{-1}$ of freshwater to the Caribbean Sea. The largest freshwater supply is provided by the Magdalena River, with a mean discharge of 205.1 $km^3\ yr^{-1}$ at Calamar, which is 26% of the total fluvial discharge into this basin. From 2000 to 2010, the annual streamflow of these rivers increased as high as 65%, and upward trends in statistical significance were found for the Mulatos, Canal del Dique, Magdalena, and Fundación Rivers. The concurrence of major oscillation processes and the maximum power of the 3–7 year band fluctuation defined a period of intense hydrological activity from approximately 1998–2002. The wavelet spectrum highlighted a change in the variability patterns of fluvial systems between 2000 and 2010 characterised by a shift towards a quasi-decadal process (8–12 years) domain. The Intertropical Convergence Zone (ITCZ), El Niño – Southern Oscillation (ENSO) events, and quasi-decadal climate processes are the main factors controlling the fluvial discharge variability of these fluvial systems.

1. Introduction

Fluvial discharges play a major role in the hydrological cycle, the thermodynamic stability of the oceans, and biogeochemical processes. Therefore, the quantification of the magnitude and variability of fluvial discharges is fundamental when dealing with coastal and continental shelf oceanography. Dramatic changes in hydrological patterns, high seasonal variability, and a growing anthropogenic intervention have been reported for several major rivers of the world during the last two decades (e.g., Huntington, 2006; Pinter et al., 2006; Varis et al., 2012; Walling and Fang, 2003). The streamflow of a river can be used as an integral of the annual or interannual climatic fluctuations that characterise its basin. Thus, streamflow changes have been repeatedly analysed to detect significant trends, identify major oscillation periods, and determine the relationships between climatic forcing and hydrological responses. In this context, river flows have been used as a type of climatic indicator, as have long-period streamflow fluctuations, to identify and characterise different climatic periods (e.g., Dai et al., 2009; Labat et al., 2004, 2005; Labat, 2008; Milliman et al., 2008; Pasquini and Depetris, 2007; Pekarova et al., 2003; Probst and Tardy, 1987; Walling and Fang, 2003).

In recent years, some studies have reported contrasting results regarding streamflow trends, but there are some agreements regarding the major oscillatory components that control streamflow fluctuations. Based on a time series analysis of the annual streamflow data of fifty major rivers distributed throughout the world, Probst and Tardy (1987) observed that during the first half of the last century, Europe and Asia were affected by a significant humid regime. In contrast, Africa, North and South America were exposed to a humid regime throughout the last half of that century. Furthermore, it was concluded that in a given relatively

* Corresponding author. Address: Departamento de Física, Universidad del Norte, km 5 vía Puerto Colombia, Bloque L – Oficina 2-24, Barranquilla, Colombia. Tel.: +57 5 3509509x3487; fax: +57 5 3598852.

E-mail addresses: restrepocj@uninorte.edu.co (J.C. Restrepo), jortiz@uninorte.edu.co (J.C. Ortíz), jpierini@criba.edu.ar (J. Pierini), ks@gpi.uni-kiel.de (K. Schrottke), julian.aguirre@upb.edu.co (J. Aguirre).

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small region, the streamflow fluctuations are generally synchronous and closely related to pressure oscillations of different scales (Probst and Tardy, 1987). According to Pekarova et al. (2003), there was no evidence of significant trends (neither increasing nor decreasing) in the annual streamflow of the 24 major rivers of the world, but they identified the alternation of wet and dry periods and of extreme cycles of high-low discharge almost every 3.6, 7, 13–14, 20–22, and 28–32 years. In addition, Pekarova et al. (2003) identified a geographical control in these hydrological shifts, consequently the extreme cycles do not occur simultaneously around the world. Milliman et al. (2008) indicated that the cumulative discharge of 137 rivers, representative of regions of the entire world, remained statistically unchanged between 1951 and 2000, thus offering little support to a global intensification of the hydrological cycle. However, the authors noted significant changes in individual rivers and at regional levels. For example, streamflow from large South American rivers (Amazon, Orinoco and Magdalena) remained relatively constant, with the noteworthy exception of the Parana River, whose discharges rose to 45% throughout 1950–2000. However, the streamflow of most rivers draining into the Mediterranean Sea and Indian Ocean declined considerably (Milliman et al., 2008).

Thus far, the streamflow of the main rivers of South America have been analysed to identify historical trends, regional hydrological patterns, variability cycles or relationships with climatic forcings (i.e., Amarasekera et al.,1997; García and Mechoso, 2005; Genta et al., 1998; Labat et al., 2005; Pasquini and Depetris, 2007; Robertson and Mechoso, 1998; Restrepo and Kjerfve, 2000). Amarasekera et al. (1997) identified a weak correlation between Pacific surface sea temperature anomalies and the annual discharge of the Amazon River, with the ENSO (El Niño – Southern Oscillation) explaining less than 10% of the annual streamflow variability. In contrast, a wavelet spectrum analysis of the annual streamflow from the Amazon River indicates a 3–6 year oscillation, typical of ENSO variability, and a nearly permanent 2-year coherence between the Southern Oscillation Index (SOI) and Amazon discharge (Labat et al., 2005). An analysis of the hydrological data (1930–2000) in the main rivers draining the southeastern areas of South America also displayed contrasting historical trends. The Parana basin experienced a steady increase in its streamflow during the second half of the last century, whereas the Patagonia basins underwent a sharp discharge decrease (Genta et al., 1998; Pasquini and Depetris, 2007; Robertson and Mechoso, 1998). Spectral analyses of streamflow time series indicated that the ENSO phenomenon and pressure anomalies over the South Atlantic Ocean control the shifts and oscillations of the hydrologic regimes in southeastern South America (Pasquini and Depetris, 2007).

Streamflow variability has a direct effect on the littoral morphodynamic and coastal circulation processes, as found for the Caribbean Rivers of Colombia, especially the Magdalena River (Fig. 1), thus regulating coastal and estuarine processes at the regional scale (Restrepo and Kjerfve, 2004; Restrepo and Lopez, 2008). Based on a statistical analysis of annual streamflow data and SOI anomalies, the ENSO might be responsible for up to 65% of streamflow interannual variability in rivers such as the Magdalena, Cauca, Cesar, Rancheria, and Sinú (Gutiérrez and Dracup, 2001; Mesa et al., 1997; Restrepo and Kjerfve, 2000). However, until now, there has only been sparse information available on recent hydrological changes and other oscillation periods and their relationship to known climatic forcing and the corresponding hydrological responses of the rivers draining the Caribbean plain of northern Colombia (Fig. 1). What are the dominant time scales in the hydrological signal of these rivers given the atmospheric circulation/air mass dynamics and setting of drainage basins (i.e. buffering capacity)? Are there regional patterns of hydrological change, especially during the last decades? How important is the co-occurrence of oscillations of different period for generating extreme streamflow events? The lack of data on these subjects has hampered the effective implementation of water resource management plans oriented towards prevention or mitigation of the adverse effects of hydrologic events. In recent years, such plans have gained importance due to an increase in the number, duration and intensity of hydrological events such as floods and droughts (Hoyos et al., 2013). Therefore, new analyses are made in this study on hydrological data (monthly mean streamflow) from ten rivers draining the Caribbean plain of Colombia to (1) quantify recent fluvial discharges into the Caribbean Sea, (2) to estimate long-term streamflow trends, and (3) to identify patterns of freshwater discharge variability at different time scales.

2. Study area

The Caribbean plain of Colombia is located in the northernmost region of South America. It extends from the *Darien* tropical rainforest, in the Colombia-Panamá border, to the *Península de La Guajira* in the east and the slopes of the *Cordillera de los Andes* in the south (Fig. 1). Compressional stresses generated at the collision between the South American plate, the Nazca oceanic plate, the Panamá volcanic arc, and the western part of the Caribbean oceanic plate fractured the continental crust, promoting large-scale horizontal and vertical movements of blocks. Thus, the blocks of the South American crust emerged and horizontally displaced along major thrust and strike-slip faults, conforming the ranges of the North Andean Block (Kellog, 1984). Hence, the Caribbean plain of Colombia comprises extensive lowlands with heights below 100 m, ranges and plateaus with heights between 200 and 1000 m in the southwest (*Serranías de Abibe*, *San Jerónimo* and *Ayapel*) and northeast (*Serranía de Macuira*), and one of the highest coastal mountain ranges in the world, the *Sierra Nevada de Santa Marta*, with heights up to 5000 m (Fig. 1). The lowlands are dominated by savannah ecosystem used for agriculture and grazing. According to temperature/rainfall conditions tropical dry/rain forest can also be found in the lowlands and plateaus. The mountainous zones are characterised by a progressive transition from basal forest (1000–1200 m.a.s.l.) to Andean forest (1000–4000 m.a.s.l.), Paramos (3000–4800 m.a.s.l.) and permanent glaciers (>4700 m.a.s.l.). The latter in the Sierra Nevada de Santa Marta (IDEAM, 1998). By the 1990's almost 30% of the Caribbean lowland forest had been converted into agricultural crops and extensive grazing lands. Consequently, the Caribbean plain of Colombia was identified as a hot spot of deforestation within the country. In the last years, however, deforestation rates in this zone have diminished significantly (Etter et al., 2006).

The rivers examined in this study originate from headwaters in the *Cordillera de los Andes* (Sucío, Mulatos, Sinú and Magdalena Rivers) and the *Sierra Nevada de Santa Marta* (Aracataca, Fundación, Frío, Palomino and Rancheria Rivers) (Fig. 1). The headwaters of the Sucío, Mulatos and Sinú Rivers are located in the *Nudo de Paramillo*, where the Cordillera Occidental bifurcates into the *Serranías de Abibe*, *San Jerónimo* and *Ayapel*. The Sucío River runs northwestward from its headwater at a height of 4080 m before it joins the Atrato River, where it turns to the north until it empties into the *Uraba* gulf. The Mulatos River drains a plateau in the *Serranía de Abibe* over ∼115 km from south to north, before discharging directly into the Caribbean Sea. The Sinú River has a drainage basin of 14.7×10^3 km^2, which comprises a steep mountainous zone in the headwater, an alluvial valley formed by the *Serranías de Abibe* and *San Jerónimo*, and extensive alluvial flood plains where significant water storage occurs (i.e., lagoon systems). The Sinú River measures 415 km from its headwater at a height 3960 m to its mouth in the Caribbean Sea. The Magdalena