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Influence of Pacific Ocean multidecadal variability on the distributional properties of hydrological variables in north-central Chile

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SUMMARY

This paper addresses the relationship between multitemporal variability and regime shifts in the Pacific Decadal Oscillation and El Niño Southern Oscillation, with precipitation and streamflows in Andean watersheds of the north-central region of Chile. In addition, an analysis of the effect of a regime shift displayed by annual streamflow records on their distributional properties is performed. By applying empirical fluctuation processes to monthly standardized PDO, Niño 3.4, precipitation and streamflow time series, the occurrence of a regime shift in the streamflow series, consistent with that for PDO, but highly dependent on the latitude of particular watersheds, is shown. No regime shift is detected for the precipitation time series. Using the ensemble Empirical Mode Decomposition procedure on all series, a relationship between climatic indices and hydrological variables in two main modes is determined: the former associated with a mean period of quasi 1.5–3 years related to interannual variability, and the latter with a mean period of quasi 30–35 years, related to decadal low frequency variability. Using the regional frequency analysis based on the L-moments procedure, it is found that the distributional properties of streamflow records are influenced by the phases of the PDO, with changes that affect the mean, L-CV, L-skewness and L-kurtosis in three identified homogeneous regions. The importance of incorporating low-frequency climate variability for distributional analysis and the implications of these results for water resources management and planning in north-central Chile and similar areas is discussed.

1. Introduction

One of the main concerns related to climate studies, along with natural disasters, is the impact of climate variability and change on the availability of water resources and activities that depend on them (Alavian et al., 2009; UNESCO-WWAP, 2009). Traditionally, water resources management and planning have mainly relied on understanding of the water supply at the watershed scale. Estimations of this supply, as well as the climatic variables it determines, have been ruled by the paradigm of stability, related to the so-called "climate normals" (Arguez et al., 2012). This approach, based on hydrological stability (Paturel et al., 2003), has been widely used, for example, in the development of water balances at the basin level in Latin America, whose components are estimated, traditionally, from 30-year reference period mean values (UNESCO, 2007). In Chile, this approach has been well accepted in national water balance studies, as well as in water availability forecast estimations of snowmelt-driven streamflows (DGA, 2012).

However, despite its importance, the paradigm of stability is being increasingly challenged in the context of climate variability and change (Arguez and Vose, 2011). In fact, in the last few decades, there has been a growing interest in the scientific community in studying departures from these patterns of stability, which in the case of rivers, is known as river flow regime (Yang et al., 2012). The concepts of regime and regime shift have been widely discussed, particularly in association with the study of climate and interdecadal variability in the North Pacific, where there is no consensus on whether changes are best characterized as a stationary random process, or as a sequence of distinct "regimes" with different statistics (Rudnick and Davis, 2006). Regardless of its nature, there is a growing interest in the study of the relationship between regime shifts of large oceanic-atmosphere modulators and their expression in hydroclimatic variables and subsequent impact on the availability of water resources for society and the environment. In fact, several authors argue that climate and human activities are the main change forces in hydrological variables and patterns of stability, with ocean–atmosphere drivers

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being the main long-term drivers of change in water regimes, water availability and river ecosystems (Balaji et al., 2012; Edmonds et al., 2003; Gangopadhyay and McCabe, 2010; Lucio et al., 2012; Seager et al., 2010; Yang et al., 2012). It is widely recognized that a major ocean–atmosphere driver that determines, on a global scale, the interannual variability of hydrological variables is the El Niño Southern Oscillation (ENSO) (Haddad et al., 2004). Its effects worldwide (Vecchi and Wittenberg, 2010), in South America (Garreaud et al., 2008), the Southern Andes (González and Vera, 2010), and in Chile (Montecinos and Aceituno, 2003) have been discussed. However, there is a growing consensus on the existence of other sea surface temperature patterns, such as the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO), acting as forcings of variability of the hydrological system in decadal or even larger time scales (Balaji et al., 2012). The PDO is one of these low-frequency patterns that has been studied considerably in recent years and could be even more important than ENSO in predicting decadal scale hydrological variability (Kirby et al., 2010). Recent research has identified a significant association between changes in PDO phase (occurrence of positive and negative phases) with changes in atmospheric variables and hydrologic regimes worldwide (Andreoli and Kayano, 2005; Lucio et al., 2012; McCabe et al., 2004; Mendez et al., 2011; Rui and Yaping, 2010).

In particular in Chile, recent studies indicate that both snowpack and river streamflows of Andean watersheds, between 30° S and 37° S, exhibit regime shifts consistent with that shown by the PDO in late 1970s (Masiokas et al., 2006, 2010). A similar association is suggested by Schulz et al. (2012) regarding precipitation in northern Chile, between 18°S and 20°S latitude, and by Quintana and Aceituno (2012) for that between 30°S and 43°S latitude, associated with an increase in the South East Pacific Subtropical Anticyclone during the cold phase of the PDO. Similarly, Rubio-Álvarez and McPhee (2010) reported a low, but statistically significant correlation between annual PDO and winter streamflows in the period 1952–2003, for a cluster of rivers located between 35°S and 37°S latitude.

Although these studies suggest an association between changes in PDO regime and multidecadal variability of the main hydrological variables in north-central Chile, there are relevant aspects which have not yet been thoroughly considered, such as: (a) the PDO, expressed in the hydrology of the north-central region in terms of an abrupt change, both in precipitation and streamflow; (b) the relationship between climate indices and hydrological variables at multiple time scales; (c) the relative importance of ENSO and PDO in the long-term hydrological regime and (d) the potential relationship between the streamflow regime shift and its distributional properties. The last issue is considered highly relevant, because Andean watershed streamflows are the main source of water for the economic, social and environmental development of north-central Chile (Rubio-Álvarez and McPhee, 2010). Also, there is an urgent need to incorporate climate variability in hydrologic frequency analysis, information from which has been traditionally used to support water management and planning, not only in Chile, but worldwide as well (Griffis and Stedinger, 2007). Accordingly, this study proposes the following objectives: (a) to assess the existence of regime shifts in precipitation and streamflow monthly time series in north-central Chile, and, if present, to analyze the relationship between these shifts and those experienced by the ocean–atmosphere drivers ENSO and PDO, (b) to determine the relative importance of both drivers in the variability of the hydrological regime in the study area at multiple time scales and (c) to analyze the effect of PDO regime shift in the distributional properties of the streamflow records. It is expected that, based on this work, the agencies that make decisions regarding water resources in areas prone to low-frequency pacific climate influences, like north-central Chile, will be able to incorporate aspects of multidecadal hydroclimatic variability to improve their decision-making procedures for water resources monitoring, management and planning.

2. Methodology

2.1. Study area

The study area spans a territory in north-central Chile between latitudes 29.4°S and 36.4°S and between longitudes 69.8°W and 72.8°W (Fig. 1), covering an area of ca. 120,500 km^2. This zone includes part of the Chilean arid region at its northern boundary, characterized by 9–10 dry months per year, and the semi-arid to sub-humid regions on the southern boundary, with 5–6 dry months per year (Verbist et al., 2006).

Mean annual precipitation (MAP) shows both a North–South and an East–West gradient, with a minimum of 50.6 mm in the northernmost rain gage station (El Trapiche) and a maximum of 2152.1 mm at the southernmost one (Bullileo Embalse). The extra-tropical frontal disturbances associated with the winter rains and the windward orographic rainfall formation due to the Andes explain the increase in the MAP from north to south and from the sea to the Andes (Rutllant, 2004). This spatial pattern and temporal dynamics are linked to the general circulation of the atmosphere in this area, and may be adversely affected by conditions of negative anomaly in sea surface temperatures associated with La Niña-ENSO phenomenon events, causing reductions of more than 60% in annual precipitation (Montecinos and Aceituno, 2003; Rutllant, 2004).

2.2. Climate records and data preparation

For this study, monthly mean streamflows and monthly accumulated precipitation time series were used (Table 1). For precipitation records, 14 stations with record lengths greater than 55 years and less than 5% missing data were selected. With these, a database of monthly precipitation records in a concurrent period from January 1943 to December 2003 was generated. For streamflow records, 6 stream gauge stations with record lengths greater than 80 years and less than 5% missing data were selected. As was done with the precipitation records, a database of monthly streamflows for a concurrent period from January 1914 to December 2006 was generated. When necessary, data filling was performed using K-Nearest Neighbor (Troyanskaya et al., 2001) for $k = 5$ using the VIM R package (Templ et al., 2012).

All precipitation and streamflow time series were transformed into standardized anomalies, facilitating simultaneous analysis and comparison, as:

$$X_t = \frac{(x_t - \overline{X})}{\sigma} \quad (1)$$

where X_t is the standardized anomaly, x_t is the observed time series and $\overline{X}$ and σ are precipitation (streamflow) time series concurrent period mean and standard deviation, respectively (Wilks, 2011).

2.3. ENSO and PDO indices

Correlation analysis between ENSO and PDO indices with precipitation and streamflow records was performed using the following indices:

(i) Pacific Decadal Oscillation: PDO is defined as the leading eigenvector of the mean monthly SSTs occurring in the Pacific Ocean north of 20°N. According to this definition, monthly PDO index values (Mantua et al., 1997) were obtained from the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) PDO index, available at [http://jisao.washington.edu/pdo/PDO.latest].