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Multi-decadal Hydrological Retrospective: Case study of Amazon floods and droughts

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ABSTRACT

Recently developed methodologies such as climate reanalysis make it possible to create a historical record of climate systems. This paper proposes a methodology called Hydrological Retrospective (HR), which essentially simulates large rainfall datasets, using this as input into hydrological models to develop a record of past hydrology, making it possible to analyze past floods and droughts. We developed a methodology for the Amazon basin, where studies have shown an increase in the intensity and frequency of hydrological extreme events in recent decades. We used eight large precipitation datasets (more than 30 years) as input for a large scale hydrological and hydrodynamic model (MGB-IPH). HR products were then validated against several in situ discharge gauges controlling the main Amazon sub-basins, focusing on maximum and minimum events. For the most accurate HR, based on performance metrics, we performed a forecast skill of HR to detect floods and droughts, comparing the results with in-situ observations. A statistical temporal series trend was performed for intensity of seasonal floods and droughts in the entire Amazon basin. Results indicate that HR could represent most past extreme events well, compared with in-situ observed data, and was consistent with many events reported in literature. Because of their flow duration, some minor regional events were not reported in literature but were captured by HR. To represent past regional hydrology and seasonal hydrological extreme events, we believe it is feasible to use some large precipitation datasets such as i) climate reanalysis, which is mainly based on a land surface component, and ii) datasets based on merged products. A significant upward trend in intensity was seen in maximum annual discharge (related to floods) in western and northwestern regions and for minimum annual discharge (related to droughts) in south and central-south regions of the Amazon basin. Because of the global coverage of rainfall datasets, this methodology can be transferred to other regions for better estimation of future hydrological behavior and its impact on society.

1. Introduction

The development of detailed and consistent hydrological records of past extreme events, such as floods and droughts, is key for better assessment of future hydrological risks and to understand the effects of climate variability and change. Reports of increased floods and droughts in the Amazon in recent years, for example, indicate a need for tools to better access past hydrological databases to understand how frequent or extreme the recent events have been (e.g. Marengo and Espinoza, 2016; Swierczynski and Ionita, 2017). Regional-scale hydrological models and climate reanalysis have improved in recent years, creating opportunities for development of a multi-decadal Hydrological Retrospective to characterize past floods and droughts.

The Amazon basin is the world largest basin; it drains about 6 million km^2 and discharges ~15% of the freshwater that reaches the world's oceans. It is also an important large biome with a major influence on the carbon cycle and global climate (Junk, 1993; Dirzo and Raven, 2003; Phillips et al., 2009), and its water resources meet many human needs, such as fluvial transportation, agriculture, fisheries and energy production.

Hydrological extreme events have been reported in the Amazon basin with increased frequency since the 1980s (Espinoza et al., 2009b, 2011; Sena et al., 2012; Satyamurty et al., 2013; Gloor et al., 2013; Marengo et al., 2013). Amazon droughts generally have been associated with positive sea surface temperature (SST) anomalies in the tropical Atlantic and with El Niño events, while floods have been linked mainly to La Niña events (Aragão et al.,

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2007; Zeng et al., 2008; de Linage et al., 2014; Marengo and Espinoza, 2016).

Recent floods, such as those in in 1989, 1999 and 2009, mainly in the central and eastern regions (Marengo et al., 2012), and in 1986, 1993, 1999, 2009, 2012 and 2014 in the western regions (Espinoza et al., 2013, 2014), caused high impacts on ecosystems, the local population and socioeconomic activities such as fishing, farming, transportation and human health (Schöngart and Junk, 2007; Marengo et al., 2013; Satyamurty et al., 2013; Espinoza et al., 2014; Castello et al., 2015; Alho et al., 2015; Ovando et al., 2016). Droughts in 1964, 1980, 2005 and 2010 (Zeng et al., 2008; Marengo et al., 2008, 2011; Espinoza et al., 2011; Saatchi et al., 2013) caused persistent disturbances in forest and difficulties in river transportation, farming and fishing, which disrupted the food supply to residents, interrupted hydroelectric power generation and affected human health, especially because of smoke from forest fires (Saleska et al., 2007; Aragão et al., 2008; Phillips et al., 2009; Asner and Alencar, 2010; Lewis et al., 2011; Frolking et al., 2011; Xu et al., 2011; Fernandes et al., 2011). Recent studies have detected an increase in maximum discharge over the last century in the main river (e.g. Callède et al., 2004; Gloor et al., 2013), while a decrease in dry-season rainfall and discharge has been detected since the 1970s (Espinoza et al., 2009a,2011; Marengo et al., 2011). Projections to the end of 21st century show a probable increase in maximum discharge in the west (main river) and a persistent decrease in the east (e.g. Guimberteau et al., 2013; Boisier et al., 2015; Sorribas et al., 2016).

It is difficult to characterize past hydrological extremes because in situ observation records generally are available only for recent decades and only for a few river locations. Improvements have been made, however, in hydrological models capable of simulating surface hydrological and hydraulic processes and variability and changes related to land use and climate (Nijssen et al., 2001; Coe et al., 2008; Beighley et al., 2009; Neal et al., 2012; Yamazaki et al., 2012; Alfieri et al., 2013; Paiva et al., 2013; Sorribas et al., 2016; Karlsson et al., 2016). Hydrologic remote sensing observations (Lettenmaier et al., 2015) and climate reanalysis have also evolved in recent years. Merging hydrological models with these new datasets could provide information with better spatio-temporal coverage to explore past hydrological behavior (Nogués-Paegle et al., 2002).

These datasets could be coupled with distributed hydrological models to create a hydrological retrospective representing historical hydrological fields (e.g. discharge, soil moisture, water levels) to study past floods and droughts. Several studies using climate reanalysis of hydrology have focused on validation and analysis of rainfall fields, but few were aimed at validation of hydrological modeling (e.g. Reichle and Liu, 2015; Xu et al., 2016), and this method still is not commonly used to explore past extreme events.

In this study, the fusion of hydrological modeling and climate reanalysis or large rainfall datasets is called Hydrological Retrospective (HR), a methodology developed to better understand past hydrological processes, in this case given focus on extreme events. Studying these events is critical for implementing sustainable water management policies and mitigating negative impacts. Understanding past extreme events is also important for estimating likely future patterns, because of close correlations (Knox and Kundzewicz, 1997; Scaife et al., 2008; Bovolo et al., 2012; Smith and Lawson, 2012; Phipps et al., 2013; Lee et al., 2016).

The aims of this study are: i) to develop a Hydrological Retrospective methodology for representing past floods and droughts ii) to validate several precipitation datasets with extensive data series, from both climate reanalysis and merged products, using them as input for hydrological and hydrodynamic modeling in the Amazon basin and comparing the results with in situ discharge observation, using by statistical metrics, iii) to determine whether these datasets and modeling can capture seasonal flood and drought events registered by in-situ discharge and reported in literature, and iv) to estimate the trend of maximum, mean and minimum annual values for historical simulated discharge time series in Amazon basin, using a statistical trend test.

2. Data and methods

2.1. Hydrological Retrospective (HR)

To understand the concept of HR, it is essential to describe similar efforts in other scientific areas such as oceanography or meteorology, where reanalysis has a longer history of use (Gibson and Medium Range Weather Forecasts, 1997; Kistler et al., 2001). According to Saha et al. (2010) and Dee et al. (2014), climate reanalysis is the constant reprocessing of climatic observations using weather forecasting systems and data assimilation methods. The goal is to describe the climate using as much information as possible. Information is estimated for several atmosphere, ocean and land surface parameters, then a state of the art is created for each parameter, usually on a global scale. Climate reanalysis is now being done by research institutions such as ECMWF (European Centre for Medium-Range Weather Forecasts), NCEP-NCAR (National Center for Environmental Prediction – National Center for Atmospheric Research) and the NASA (National Aeronautics and Space Administration)Goddard Space Flight Center (GSFC).

There are three types of climate reanalysis: atmospheric, ocean-atmospheric, and reanalysis based on land surface models (Reichle and Liu, 2015). Early reanalysis of precipitation variables was generated using atmospheric models; currently some reanalysis (e.g. MERRA-Land, ERA-Interim Land) uses a land surface component through data assimilation of satellite observation and/or in-situ gauges, which could result in better prediction systems, especially in areas such as continental hydrology (Koster et al., 2011; Dee et al., 2014; Reichle and Liu, 2015). Reanalysis datasets differ mainly in places with low coverage of in situ observations (e.g. Asia, North Africa and South America) (Adler et al., 2001; Pohlmann and Greatbatch, 2006; Garreaud et al., 2009; Bovolo et al., 2012), although products of reanalysis have improved over South America since the 1980s because of availability of satellite data (Kalnay et al., 1996). It is therefore important to evaluate the different datasets available for each study area.

Some examples of evaluation of the performance of precipitation reanalysis at a global scale and for South America and Amazon basin are presented below:

Several studies has been conducted around the world. Betts et al. (2009), Shah and Mishra (2014), Prakash et al. (2015) and Gao et al. (2016) evaluated precipitation reanalysis datasets such as MERRA, ERA-Interim, CFSR, ERA-40, NCEP1, NCEP2, GLDAS and ERA-20CM, finding that performance differed depending on factors such as location, catchment area size, and topographic and climate characteristics. Many precipitation datasets for the South American Monsoon System (SAMS) have also been evaluated, including, in the Bolivian Andes and the Amazon basin, CFSR, MERRA, ERA-40 (Betts et al., 2005; Carvalho et al., 2012; Bovolo et al., 2012; Blacutt et al., 2015). These studies generally concluded that these datasets are skillful for representing the average annual cycle of precipitation, although they underestimate the observed record in rainy seasons and overestimate it in the dry season. Because previous studies show that many rainfall reanalyses based only on atmospheric models do not provide a robust representation of precipitation, including the land surface component in the reanalysis could be expected to improve performance. Details of various climate reanalyses that are currently available can be found at <reanalyses.org>. Other available sources of rainfall data include