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Trends in the hydrologic regime of Alpine rivers

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SUMMARY

This paper describes a trend analysis performed on 177 streamflow time series collected over the Alps in Central Europe. The analysis covers several facets of the Alpine hydrologic regimes, including winter droughts and spring snowmelt flows, both in terms of severity and timing of occurrence. Statistical trend tests are applied at a local scale (i.e. on a site-by-site basis) and at a regional scale (seeking a common trend for sites within the same hydro-climatic region). The overall results indicate a trend toward less severe winter droughts, and consistent changes in the timing of snowmelt flows. However, a more in-depth analysis at the scale of hydro-climatic regimes reveals more contrasted changes. While most glacial- and snowmelt-dominated regimes show a decreasing trend in the severity of winter droughts, contrasted trends are found for mixed snowmelt–rainfall regimes in the Southeastern Alps. Changes in the timing of snowmelt flows (earlier start and increased duration of the snowmelt season) mostly affect glacial- and snowmelt-dominated regimes. Lastly, glacial regimes show an increase in the volume and the peak of snowmelt flows.

1. Introduction

1.1. Detecting trends in hydrologic series

Trend analyses have received widespread attention in the hydrologic and climate communities (see e.g. Kundzewicz et al., 2005; Moberg and Jones, 2005; Svensson et al., 2005; Pujol et al., 2007; Hannaford and Marsh, 2008; Stahl et al., 2010; Hodgkins and Dudley, 2011; Giuntoli et al., 2013 for recent examples). Trend analysis is indeed a useful preliminary step to assess the existence of significant changes in hydro-climatic series, before attempting to understand their possible causes (Merz et al., 2012). The detection of trends within hydrologic series raises several challenges. Firstly, the inter-annual variability of hydrologic series is generally very large, especially in the extreme domain, hence restricting the power of statistical tests to detect trends based on relatively short series. Secondly, many catchments are impacted by direct anthropogenic influences, such as water withdrawal or hydro-electricity production, which may create artificial trends in addition to climate trends. Lastly, ensuring the homogeneity of streamflow measurements over several decades is difficult: rating curves may change or gauging stations may be relocated, thus creating spurious trends in the time series (Lang et al., 2010). Specific testing procedures (Kundzewicz and Robson, 2000; Parey et al., 2007; Renard et al., 2008) and thoroughly-reviewed datasets of undisturbed catchments (Hannah et al., 2011; Burn et al., 2012; Whitfield et al., 2012) are required to face these challenges.

1.2. Observed trends in hydro-climatic variables in the Alps

Many studies have investigated the existence of trends in cryospheric variables over the world. Chapter 4 of the IPCC report (2013) provides an overview of these studies. We focus here on reviewing trend analyses for hydro-climatic variables in the Alpine region.

Stewart (2009) presents an overview of the changes in snowpack and snowmelt-related flows in the Alps and in other moun-

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tainous areas of the world. Focusing on the Alps, an overall decrease in snow cover is observed during the 20th century for low- and mid-elevations. Trends are less significant at higher elevations, and snowpack even increased due to higher precipitation totals. Auer et al. (2007) and Brunetti et al. (2006, 2009) describe an analysis of several climate variables over the Alpine region based on the HISTALP dataset. A general increase in annual temperature and air pressure is observed during the 20th century. Trends in precipitation are spatially more variable: for instance, annual totals increase in the northwest but decrease in the southeast. Other studies have focused on national scales and specific variables. In one such study, Frei and Schär (2001) analyzed 133 raingauges in Switzerland and found an increase in the frequency of intense events in winter and autumn during the 20th century.

Trend analyses on streamflow variables have often been performed at a relatively small spatial scale, for specific sub-regions within the Alpine area (see Viviroli et al., 2011 for an overview). Birsan et al. (2005) analyzed 48 gauging stations in Switzerland, and found increases in winter, spring and autumn streamflow. Castellarin and Pistocchi (2012) used 17 stations in the Swiss Alps observing upward trends in annual streamflow maxima. In the French Alps, Giuntoli et al. (2012) observed decreasing high flow volumes from high-elevation catchments. In the same region, Renard et al. (2008) also observed an earlier timing of snowmelt-related flows, less severe winter droughts and an increase in annual flow for highly glacierized catchments. For the latter catchments, Pellicciotti et al. (2010) found similar results in Switzerland (see also Casassa et al., 2009 for other mountainous areas of the world). The results for highly glacierized catchments seem consistent with what is expected in a warming climate, as described by Huss et al. (2008).

The study of Bard et al. (2012) is one of the few analyses covering the whole Alpine region for streamflow variables, but was restricted to high flows. Results showed an increase in the volume and peak of snowmelt flow for glacial regimes, and an earlier start of snowmelt flow. Lastly, the European-wide study of Stahl et al. (2010), based on 441 small undisturbed catchments, encompassed about 110 catchments in the Alpine region; trends toward less severe winter droughts were detected in most of them.

1.3. Objectives

The objective of this paper is to assess the existence of trends affecting hydrologic regimes in the Alps. The analysis described herein is unique in several respects. Firstly, it uses an extended and thoroughly-reviewed dataset of daily streamflow series covering most of the Alpine region. Secondly, it uses hydrologic indices adapted to the peculiarities of snowmelt-influenced catchments, and describing low, medium and high flows. Lastly, it operates at both local and regional scales, enabling a comprehensive assessment of the detected trends consistency.

The paper is organized as follows. Section 2 describes the dataset of daily streamflow series and its properties. Section 3 describes the methods used to analyze the evolution of hydrologic regimes, and more precisely the definition of hydrologic indices and the statistical setup for trend detection. The results are presented in Section 4 and discussed in Section 5. In Section 6 the main outcomes of this work are summarized.

2. The AdaptAlp dataset

2.1. Daily streamflow series and associated catchments

The dataset used in this paper was gathered within the EU Alpine Space Programme project AdaptAlp, and is therefore named after it. The AdaptAlp dataset contains daily streamflow series for snowmelt-influenced catchments located in the Alps. As described in Bard et al. (2012), the strategy used to gather these series involves extensive quality checks in order to meet the following requirements: (a) the gauging station has been active over a period of at least 40 years; (b) the station controls a largely "undisturbed" catchment where direct anthropogenic influences can be neglected; (c) the daily streamflow series is free from any major non-homogeneity due to measurement issues.

Data quality has been assessed through a first round of analysis investigating changes affecting low, medium and high flows over the whole available period for each gauging station. In particular, step-change tests (Pettitt, 1979) were used to highlight suspicious stations. For example a significant step change occurring on the same date for many hydrologic indices may be indicative of a measurement inhomogeneity (e.g. due to station relocation, change in the measurement sensor or method, etc.). The results from this first round of analysis were discussed with the data producers. Following this discussion, stations were excluded from the dataset whenever a specific cause for the detected change could be identified (typically, station relocation, building of some hydraulic structure influencing the river flow, etc.). Some of the stations were judged appropriate only for a specific flow range. As an example, some stations are only usable for high flow analyses because measurement issues and/or minor direct influences compromise their suitability for low flows.

This selection strategy yields a total of 177 series from six countries[1] (Austria, France, Germany, Italy, Slovenia and Switzerland, see Fig. 1a). Among these 177 series, 140 are suitable for high flow analyses, 134 for low flow analyses and 126 for all flow ranges. Fig. 1b shows the effective record length (i.e. after the removal of missing values), with most stations providing between 40 and 50 years of daily data. A few series are effectively shorter than 40 years (due to missing data), while a few others are very long, with more than 80 years of data. Note that the series may appear quite short compared to other meteorological variables. For instance, in the HISTALP project (Auer et al., 2007), many series span the whole 20th century for variables such as air pressure, temperature or precipitation. Such long series are unfortunately scarcely available for streamflow data: while long series of water stages do exist, the same is not true for rating curves that estimate the stage–discharge relationship, thereby reducing the availability of reliable streamflow data. At the time of writing of this paper, 169 time series from the AdaptAlp dataset have been made available through the Global Runoff Database Center.[2]

The station elevations range mostly between 400 and 1200 m.a.s.l. (Fig. 1c). The dataset comprises catchments of varied size, the majority of which have an area between 100 and 1000 km^2 (Fig. 1d). Around twenty catchments have a significant part of their area covered by glacier, however precise quantification was not available for all of them. Lastly, Fig. 1f shows the data availability, and suggests that the period 1961–2005 provides the best trade-off for analyzing as many stations as possible over a 40 years long common period.

2.2. Hydrologic regimes and hydro-climatic regions

Although all catchments in the AdaptAlp dataset are influenced by snowmelt, they still span a significant diversity of hydrologic regimes. The catchments are clustered into homogeneous hydrologic regimes to allow regime-specific analyses. Nine regimes are defined as presented in Fig. 2; they range from pure glacial and snowmelt regimes to mixed snowmelt–rainfall regimes. The

[1] The names of the 177 gauging stations are given in the online material.

[2] (GRDC: http://www.bafg.de/GRDC/EN/Home/homepage_node.html)