AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2016GL070868

River-discharge dynamics in the Southern Central Andes and the 1976–77 global climate shift

F. Castino[1], B. Bookhagen[1], and M. R. Strecker[1]

[1]Institut für Erd- und Umweltwissenschaften, Universität Potsdam, Potsdam, Germany

Key Points:

- Change point for increase in discharge between 1971 and 1977 linked to the 1976–77 climate shift
- Most pronounced discharge increase observed in high percentiles for the Southern Central Andes across the change point
- Discharge increase of 40% in the NW Argentine Andes between 1971 and 1977

Supporting Information:

- Supporting Information S1

Correspondence to:
F. Castino,
castino@geo.uni-potsdam.de

Citation:
Castino, F., B. Bookhagen, and M. R. Strecker (2016), River-discharge dynamics in the Southern Central Andes and the 1976–77 global climate shift, *Geophys. Res. Lett.*, *43*, 11,679–11,687, doi:10.1002/2016GL070868.

Received 16 AUG 2016
Accepted 9 NOV 2016
Accepted article online 12 NOV 2016
Published online 26 NOV 2016

Abstract Recent studies have shown that the 1976–77 global climate shift strongly affected the South American climate. In our study, we observed a link between this climate shift and river-discharge variability in the subtropical Southern Central Andes. We analyzed the daily river-discharge time series between 1940 and 1999 from small to medium mountain drainage basins (10^2–10^4 km^2) across a steep climatic and topographic gradient. We document that the discharge frequency distribution changed significantly, with higher percentiles exhibiting more pronounced trends. A change point between 1971 and 1977 marked an intensification of the hydrological cycle, which resulted in increased river discharge. In the upper Rio Bermejo basin of the northernmost Argentine Andes, the mean annual discharge increased by 40% over 7 years. Our findings are important for flood risk management in areas impacted by the 1976–77 climate shift; discharge frequency distribution analysis provides important insights into the variability of the hydrological cycle in the Andean realm.

1. Introduction

There is increasing evidence that the global climate shift occurred between 1976 and 1977, associated with sea surface temperature variability in the North Pacific Ocean [*Graham*, 1994; *Miller et al.*, 1994], strongly affected the South American climate [*Marengo*, 2004; *Agosta and Compagnucci*, 2008; *Kayano et al.*, 2009; *Carvalho et al.*, 2011; *Jacques-Coper and Garreaud*, 2015]. *Marengo* [2004] suggested that an intensification of moisture advection from the Tropical Atlantic into the Amazon basin may have increased rainfall in southern Amazonia starting from 1975–1976. Modifications to the low-level atmospheric circulation occurred during the mid-1970s and were documented in southern South America, resulting in lower midlatitude cyclonic activity [*Agosta and Compagnucci*, 2008]. During the same period, rapid changes in temperature and rainfall patterns were observed throughout South America [*Kayano et al.*, 2009; *Jacques-Coper and Garreaud*, 2015].

The spatiotemporal rainfall pattern in tropical and subtropical South America is controlled by the South American Monsoon System (SAMS). On average, southward moisture transport by the SAMS occurs between late October and late April [*Zhou and Lau*, 1998; *Vera et al.*, 2006; *Marengo et al.*, 2012]. *Carvalho et al.* [2011] showed that, starting from 1971–1972, the onset (demise) of the SAMS has been occurring earlier (delayed). This has resulted in a prolongation of the wet season (approximately 25 days) related to the 1976–77 climate shift. Furthermore, the acceleration of glacial retreat in tropical South America between the mid-1970s and early 1980s was linked with Pacific Ocean warming associated with this climate shift [*Francou*, 2003; *Rabatel et al.*, 2013; *Hanshaw and Bookhagen*, 2014].

Several studies have documented a rapid increase in mean river discharge in large South American rivers (i.e., the Amazon, Negro, Orinoco, La Plata, Paraná, and Paraguay) during the 1970s [*García and Vargas*, 1998; *Genta et al.*, 1998; *Robertson and Mechoso*, 1998; *Labat et al.*, 2004; *Marengo*, 2004; *García and Mechoso*, 2005; *Pasquini and Depetris*, 2010]. These studies mostly linked river-discharge variability to the El Niño–Southern Oscillation, whereas *Marengo* [2004] and *Labat et al.* [2004] ascribed the observed changes to the 1976–77 climate shift. To our knowledge, no study has analyzed how the magnitude frequency distribution of river discharge changed in response to the climate shift. This information would be necessary, however, to better understand pronounced changes in sediment flux and fluvial behavior in the Andean foreland and intermontane basins.

In this study, we examined how the frequency distribution of river discharge evolved between 1940 and 1999 in the Southern Central Andes, using standard and quantile regression [*Koenker and Bassett*, 1978] combined with change-point analysis [*Taylor*, 2000]. Our study area encompassed the eastern flank of the Central Andes between 21°S and 28°S, in the transition between the tropics and subtropics (Figure 1). Strong contrasts in topography, rainfall, and vegetation cover characterize this area, with low elevation in the east at about

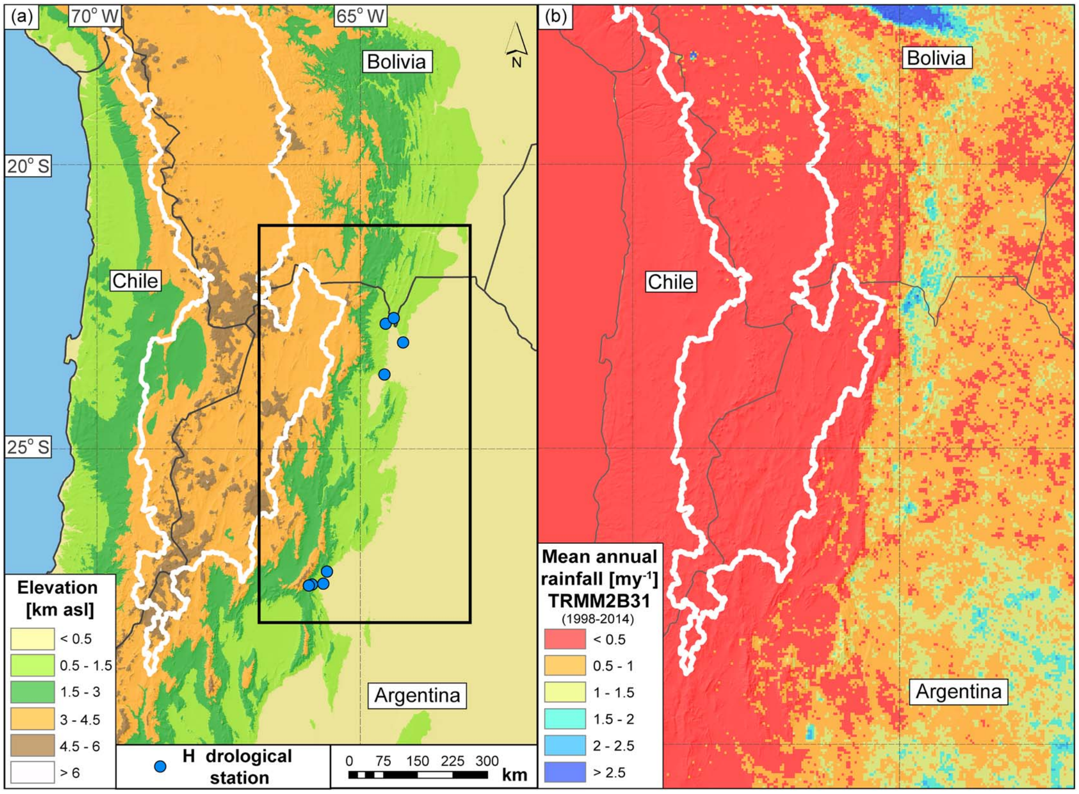

Figure 1. (a) Topography (SRTM) of the Southern Central Andes. The boundary of the internally drained central Andean Plateau is outlined in white; the thin dark grey line denotes international borders. The black rectangle delineates the study area in NW Argentina where discharge time series ($n = 8$; blue dots) are available (cf. Figure S1). (b) Mean annual rainfall data derived from TRMM 2B31 V7 (1998–2014) [*Bookhagen and Strecker*, 2008; *Bookhagen and Burbank*, 2010]. Rainfall is characterized by a pronounced gradient between low-elevation frontal areas and arid, high-elevation areas of the internally drained plateau in the orogen interior.

0.5 km above sea level (asl) and high elevations in the west with peaks in excess of 6 km [*Bookhagen and Strecker*, 2012]. We relied on daily river-discharge time series from small to medium-size drainage basins (10^2–10^4 km^2) for the period 1940–1999 (Figure 1). These catchment sizes are more sensitive to climate change than large drainage basins such as the Amazon or La Plata basins, which contain large floodplains that dampen discharge trends [*Dunne and Mertes*, 2007; *Melack et al.*, 2009].

In a previous study, we documented a trend reversal in 1979 toward decreasing mean annual rainfall at the topographic transition between low regions in the east and intermediate elevations (0.5–3 km asl) [*Castino et al.*, 2016]. At the same time, an increasing magnitude of extreme rainfall events (>90th percentile) at high elevations (>3 km asl) was detected. However, no statistically significant link between the trend reversal in 1979 and the 1976–77 climate shift was observed, most likely because of the high stochasticity and intermittency of rainfall-related processes. In this study, we used river discharge to decipher the impact of the 1970s climate shift on the hydrological cycle. This is paramount not only for improving water resources and flood-risk management but also for understanding sediment-transport processes that impact infrastructure and landscape development in different compartments of the Andean orogen.

2. Data and Methods

We relied on eight daily discharge time series derived from hydrological stations at the eastern flanks and foreland of the Southern Central Andes in NW Argentina (Figure 1). The time series, starting in 1914, were made available to us by the National Department of Water Resources (Subsecretaría de Recursos Hídricos de la Nación, Banco Nacional Hídrico). The gauged drainage basins differ in basin size (10^2–10^4 km^2) and climatic conditions (from predominantly humid to semiarid environments; cf. Figure S1 and Text S1 in the supporting information [*World Meteorological Organization*, 2008]). Data density is higher, and data are more reliable for the period of 1940–1999, so we focused our analysis on this time period. The investigation was

Table 1. Main Hydrologic Indices Used in This Analysis: Normalized Discharge anomaly (NAQ_y) and Percentiles of Normalized Daily Discharge ($PINQ_d$)

Index	Definition	Expression
NAQ_y^{season}	Normalized (*N*) annual (ANN) or seasonal (DJF and MAM) discharge anomaly with respect to the mean discharge of the reference period 1970–1999	$NAQ_y^{season}(i) = \frac{Q_y^{season}(i) - \overline{Q_{ref}^{season}}}{\overline{Q_{ref}^{season}}}$ $Q_y^{season}(i)$: mean annual (ANN) or seasonal (DJF and MAM) discharge of the *i*th year, $i = 1, \dots, Ny$; Ny: length of the time series in years; $\overline{Q_{ref}^{season}}$: mean annual (ANN) or seasonal (DJF and MAM) discharge for the reference period 1970–1999
$PINQ_d^{season}$	Ith percentile (I = 5, 10, …, 90, 95) of the normalized (*N*) daily discharge Q_d^{season} with respect to the 50th percentile of the reference period 1970–1999	$Q_d^{season}(j) = \frac{Q_d(j)}{\left(P50Q_d^{season}\right)_{ref}}$ $Q_d(j)$: daily discharge of the *j*th day, $j = 1, \dots, n$; *n*: the length of the annual (ANN) or seasonal (DJF and MAM) time series in days; $\left(P50Q_d^{season}\right)_{ref}$: annual (ANN) or seasonal (DJF and MAM) median (50th percentile) of daily discharge for the reference period 1970–1999
	season = ANN, DJF, MAM	

performed on annual and seasonal scales (December through February (DJF) and March through May (MAM)), because the wet season contributes up to 90% to the total annual discharge on average (Figure S1).

We used several statistical indices (Table 1) to characterize discharge dynamics and trends (cf. Text S2 [*Compagnucci et al.*, 2000]). We primarily focused on NAQ_y^{season}, which is the normalized annual (ANN) or seasonal (DJF and MAM) discharge anomaly with respect to the mean discharge of the reference period 1970–1999, and the $PINQ_d^{season}$, which is the Ith percentile (I = 5, 10, …, 90, 95) of the normalized daily discharge Q_d^{season} with respect to the 50th percentile of the reference period 1970–1999.

The spatial variability of discharge in the study area between 1940 and 1999 was analyzed by cross correlating the time series. The high values of cross correlation for each station pair (rho > 0.5, $p < 0.001$) reveal a high, spatially coherent discharge pattern, with a maximum time lag of one day (Figure S2). Because of the high correlation between the time series, we stacked the eight normalized time series (i.e., the spatial mean of the eight time series of normalized daily discharge), and in the following sections we refer to the stacked mean time series as the *multistation mean*. Single-station results are available in the supporting information.

We used the multistation mean time series to identify discharge trends, taking a two-tiered approach:

1. To test for a linear trend, we applied both linear and quantile regression analyses [*Koenker and Bassett*, 1978; *Cade and Noon*, 2003; *Yu et al.*, 2003] to normalized discharge anomaly and to normalized daily discharge, respectively. Trend values were expressed in per year of the normalizing factor (for linear regression: $\overline{Q_{ref}^{season}}$; for quantile regression: $\left(P50Q_d^{season}\right)_{ref}$, season = ANN, DJF, MAM). Student's *t* test and Mann-Kendall test at 5% significance level were used to determine whether each time series had a statistically significant trend [*Mann*, 1945; *Kendall*, 1948].
2. To test for nonlinear trends, we used change-point analysis [*Taylor*, 2000], applied to both normalized discharge anomaly and the percentiles of normalized daily discharge. Statistical significance of the identified change points was verified by using a bootstrapping technique at the 5% significance level (Text S3). Uncertainties associated with change-point timing were estimated by combining change-point analysis and bootstrapping within the percentile errors ($\pm 1\sigma$) (percentile standard error estimated following *Evans* [1942]), resulting in nonsymmetric uncertainties. We emphasize that the change-point timing is independent of the normalization reference period (Figure S5).

3. Results

Linear regression analysis applied to NAQ_y^{ANN} revealed statistically significant ($p < 0.05$) positive trends on the annual scale for the period of 1940–1999 for the multistation mean time series (+0.008 ± 0.002 per year) (Table 1 and Figure 2a). Similar results were obtained for the wet season. Quantile regression also showed a statistically significant trend for the multistation mean time series: The trend of the median normalized discharge ($P50NQ_d^{ANN}$: +0.008 ± 0.001 per year) and the trend for the 90th percentile of normalized discharge ($P90NQ_d^{ANN}$: +0.053 ± 0.003 per year) indicate a higher trend magnitude for the higher percentile (Table 1 and Figure 2b).

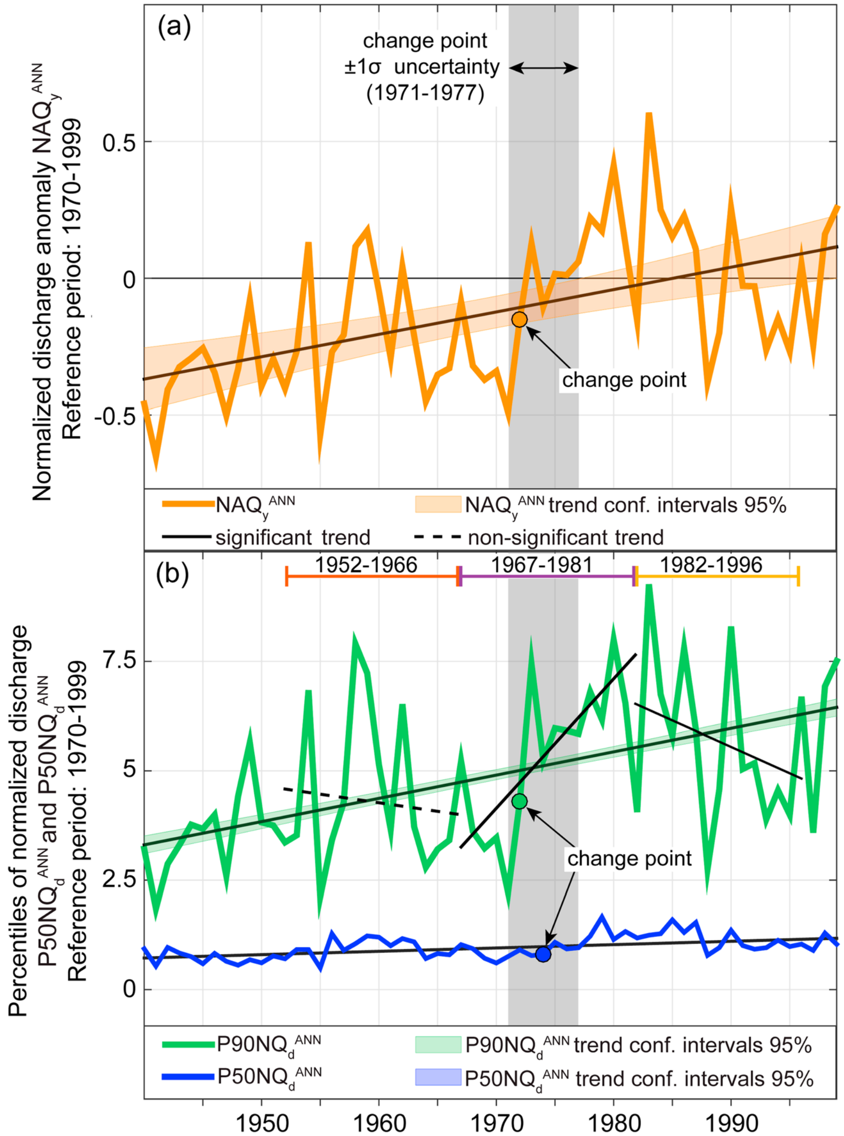

Figure 2. Results of linear regression and change-point analysis for the annual multi-station time series. (a) Annual normalized discharge anomaly NAQ_y^{ANN} (orange): statistically significant change point ($p < 0.05$) results in 1972 (orange circle); statistically significant trends were observed for the complete time series (1940–1999, positive; black solid line; shading: confidence intervals at 95%; cf. Table S8). (b) Daily normalized discharge at the 50th percentile ($P50NQ_d^{ANN}$; blue) and at the 90th percentile ($P90NQ_d^{ANN}$; green): Statistically significant change points were found in 1974 (blue circle) and 1972 (green circle), respectively; $P50NQ_d^{ANN}$ and $P90NQ_d^{ANN}$ also exhibited a statistically significant positive trend for the complete time series (1940–1999; black solid line). The horizontal color bars indicate the 15 year periods before (1952–1966), across (1967–1981), and after (1982–1996) the change point; trend analysis was also conducted for these as well (cf. Figure 3). The light grey polygons represent the $\pm1\sigma$ uncertainty of change-point timing (1971–77) based on a bootstrap analysis (Figure S10).

We detected a statistically significant ($p < 0.05$) change point during the period of 1940–1999 for the annual and seasonal multistation mean time series of NAQ_y^{season} (season = ANN, DJF, MAM), indicating a rapid increase in mean discharge in 1972 (Figures 2a and S6). Similar results were obtained for the percentiles of normalized daily discharge $PINQ_d^{season}$, with change points between 1972 and 1977 ($\pm1\sigma$ uncertainty: 1971–77) (Figures 2b and S10). In the following, we will refer to this as the *1971–77 change point*.

Changes to the discharge frequency distribution were evaluated within three 15 year periods: before (1952–1966), across (1967–1981), and after (1982–1996) the change point. The linear trend analysis of NAQ_y^{ANN} before (1952–1966) and after (1982–1996) the change point revealed no statistically significant trends when Student's *t* tests were used, whereas significant results were found by using the Mann-Kendall test. Statistically significant positive trends were found across the change point (1967–1996) (+0.045 ± 0.009 per year). Results from quantile regression applied to Q_d^{ANN} for the 90th percentile ($P90NQ_d^{ANN}$) suggest a statistically significant positive (+0.296 ± 0.029 per year) trend across and a statistically significant negative (−0.122 ± 0.023 per year) trend after the change point (Figure 2b). The complete results are shown in Table S8 in the supporting information.

The number of events exceeding the 90th percentile of normalized daily discharge $\left(P90NQ_d^{ANN}\right)$ and the fraction of total discharge accounted for by the 10 largest discharge events also revealed a statistically significant change point during the early 1970s that yielded higher values (Figure S9). The detailed results of the trend and change-point analyses are shown in Text S4.

4. Discussion

Over the past 20 years, several studies have addressed streamflow variability in South America, documenting a spatially and temporally heterogeneous pattern [*Marengo*, 1995, 2009; *Compagnucci and Vargas*, 1998; *Robertson and Mechoso*, 1998; *García and Vargas*, 1998; *Genta et al.*, 1998; *Compagnucci et al.*, 2000; *Piovano et al.*, 2002; *Callede et al.*, 2004; *Labat et al.*, 2004; *García and Mechoso*, 2005; *Pasquini and Depetris*, 2007]. *Marengo* [1995] did not observe a clear trend pattern in streamflow during the period between 1903 and 1992 in some of the largest river basins of tropical South America (in Peru, Brazil, Argentina, and Venezuela) and attributed long-term variations in the Amazon river to decadal and multidecadal modes of climate variability [*Marengo*, 2009]. In the subtropics and extratropics, both *Genta et al.* [1998] and *Robertson and Mechoso* [1998] found relatively low mean discharge values until 1940 and increased values after 1970 for the main drainage basins in southeastern South America. Increased discharge after 1970 was also reported by *García and Mechoso* [2005], associated with rapid changes in the mean values between 1970 and 1972 in the largest drainage basins of South America. These trends had been previously observed in the Rio de La Plata by *García and Vargas* [1998]. Similar results were also found for rivers in the Cuyo region in the Argentine Andes between 30°S and 40°S [e.g., *Compagnucci et al.*, 2000], suggesting a change from decreasing to increasing discharge trends around 1977. An increase in the water level of the Laguna Mar Chiquita, a saline lake located in the Pampean plains of central Argentina (30.5°S, 62.7°W), was also observed starting in 1972, documenting a change toward wetter conditions [*Piovano et al.*, 2002]. *Pasquini and Depetris* [2007] analyzed trends based on the monthly mean discharge time series of Andean rivers between 15 and 50°S, including the Rio Bermejo, which was also considered in our study for approximately the same period. Pasquini and Depetris [2007] documented a shift from a decreasing to an increasing trend in ~1950.

One of the most prominent results of the above studies is a discharge trend change during the 1970s [*García and Vargas*, 1998; *Genta et al.*, 1998; *Robertson and Mechoso*, 1998; *Compagnucci et al.*, 2000; *García and Mechoso*, 2005]. This finding is in agreement with our analysis, which showed a rapid change in the Southern Central Andes during 1971–77 (Figures 2 and S10). We documented a long-term increasing trend at all percentiles of daily discharge; this change was most pronounced for the uppermost percentiles (>70th; Figure 3a). This implies that the upper end of the discharge frequency distribution became heavier during 1940–1999 and suggests a general intensification of the hydrologic cycle.

The change point documented in the river discharge is statistically significant, temporally coherent, and documented at every percentile value and time scale (annual and seasonal) from 1971 to 1977 (Figure 3). This finding is also confirmed by the number of events exceeding the annual 90th percentile of normalized daily discharge $\left(P90NQ_d^{ANN}\right)$ and the fraction of total discharge accounted for by the 10 largest discharge events. Both exhibit a statistically significant change point toward higher values during 1971–1972 (Figure S9). This result is not only revealed by the multistation mean but also supported by single-station analysis (Text S4), confirming that a rapid change toward higher discharge occurred during the period of 1971–77.

We noted that the identified change point precedes the 1976–77 climate shift (Figure 2). Previous studies suggested that the duration of the SAMS changed during 1971–1972 and impacted the annual flow in the Parana River [*Carvalho et al.*, 2011]. Given the change-point uncertainty of 7 years, we could not distinguish the drivers of the hydrologic changes, but our analysis supports the timing of the 1976–77 climate shift

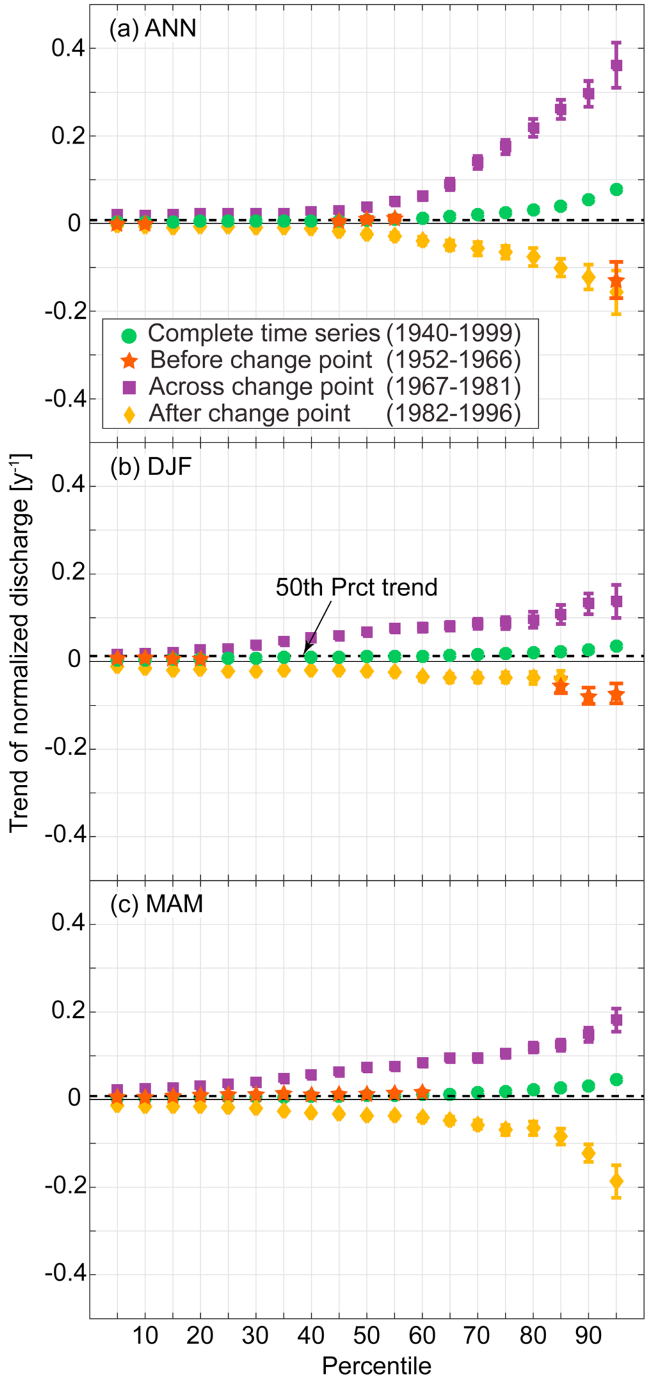

Figure 3. Discharge trends (±1 standard error [*Evans*, 1942]) in the normalized daily discharge Q_d^{season} for different percentiles of the frequency distribution of the multistation mean time series on (a) annual and (b and c) seasonal scales for the period of 1940–1999, obtained through quantile regression. Trend values for the complete time series (green circles) and the periods before (1952–1966; red stars), across (1967–1981; purple squares), and after (1982–1996; yellow diamonds) the change point are shown. Absolute percentile trend magnitudes strongly dependent on the time scale of normalization: The values of the 50th percentile used for the seasonal scale (DJF and MAM) are approximately 2–3 times larger than those used for the annual scale.

affecting South America [*Agosta and Compagnucci*, 2008; *Kayano et al.*, 2009; *Carvalho et al.*, 2011; *Jacques-Coper and Garreaud*, 2015]. Importantly, our analysis clearly reveals a coeval intensification of the hydrologic cycle during 1971–77.

To further investigate the link between the 1976–77 climate shift and discharge variability in the Southern Central Andes, we applied linear and quantile regression analyses to the multistation mean time series for the periods before (1952–1966), across (1967–1981), and after (1982–1996) the change point. For the normalized annual discharge anomaly $\left(NAQ_y^{ANN}\right)$, we observed mostly nonsignificant trends for the periods before and after the change point, whereas for the period across the change point (1967–1981), we documented statistically significant increasing trends (Table S8). Quantile regression showed a temporally coherent trend pattern with statistically significant positive (negative) trends across (after) the change point for all considered percentiles, with nonsignificant trends before the change point (Figure 3). Quantile regression of the single-station analysis suggested similar timing and therefore emphasized the coherent spatial pattern of this trend reversal across and after the change point (Table S8). This observation suggests that (normalized) mean discharge is not an adequate metric for deriving trends for these distributions over the considered time period; because of this we relied on quantile regression instead.

A potential explanation for the trend reversal across and after the 1971–77 change point (from positive to negative) is attributable to large-scale climate oscillations. Several studies have addressed the link between discharge in major South American rivers and large-scale modes of variability, often linking discharge in tropical as well as subtropical South American rivers to El Niño–Southern Oscillation cycles [*Marengo*, 1995; *Robertson and Mechoso*, 1998; *Compagnucci et al.*, 2000; *Pasquini and Depetris*, 2007; *Bookhagen and Strecker*, 2011]. Additional factors include solar activity [*Compagnucci et al.*, 2014; *Antico and Torres*, 2015] and Pacific Decadal Oscillation phase transitions [*Marengo*, 2004; *Jacques-Coper and Garreaud*, 2015], which is also interpreted as a possible controlling factor of the climate shift in extratropical South America [*Jacques-Coper and Garreaud*, 2015].

Our quantile regression analysis documented that the uppermost percentiles of normalized daily discharge presented the most pronounced trends, independent of the considered period (Figure 3). In a previous study analyzing rainfall-trend patterns in the Southern Central Andes for the period of 1950–2014, *Castino et al.* [2016] documented significant trends for the uppermost percentile of daily rainfall, which were particularly pronounced in the wet season (DJF), whereas the median values showed low or no significant trends. Interestingly, the frequency of events exceeding high percentiles did not show any statistically significant trends. These results were interpreted to be indicative of significant changes, particularly in the magnitude of rainstorms affecting the Southern Central Andes. Furthermore, two main results that are relevant for our analysis were shown [*Castino et al.*, 2016]. First, a pronounced increase in total rainfall amount during the period of 1950–2014 confirmed the intensification of the hydrological cycle during this period. Second, a rainfall trend reversal toward decreasing rainfall amounts in the topographic transition zone between the low ($<$0.5 km) and the intermediate (0.5–3 km) elevations to the west was observed after 1979. The drainage basins considered here are located at this topographic transition zone, and river-discharge analysis shows a similar trend reversal. The rainfall trend analysis did not reveal a spatiotemporally coherent change [*Castino et al.*, 2016], in contrast to the river-discharge trend during 1971–77 presented in this study. We attribute this limitation to the high spatiotemporal stochasticity and intermittency of rainfall-related processes, associated with sparse and disparately distributed rainfall stations. The rainfall network therefore does not fully capture the small spatiotemporal scale of convective cells that partially control the rainfall pattern at the topographic transition zone at intermediate elevations during the wet season [*Romatschke and Houze*, 2010; *Rasmussen and Houze*, 2011; *Rohrmann et al.*, 2014]. Thus, the rainfall network does not capture the storm distribution, whereas the hydrologic stations do. In this context, it is conceivable that despite the fact that the trend reversal is also observed in the rainfall pattern [*Castino et al.*, 2016], the timing and magnitude of the 1971–77 change point are not properly detected by rainfall time series analysis (Figure S13 and Text S5).

To provide a quantitative evaluation of the changes in water volumes across the change point, we used the upper Rio Bermejo catchment (the largest catchment with a discharge for the reference period of 1970–1999: $13 \cdot 10^9\ m^3\ yr^{-1}$; Table S2 and Figure S1) as an example. The mean annual discharge for this drainage basin increased by 40% (confidence interval 95%: $\pm$15%) across the change point, corresponding to an increase of $5.2 \pm 2.0 \cdot 10^9\ m^3\ yr^{-1}$ in 7 years (1971−77). A considerable fraction of this increase in water volume was derived from the 10 largest events per year. During the 10 years prior to the change point (1961–1970), these events contributed 12% of the total discharge on average, whereas after the change point (1978–1987), the mean annual contribution increased to 25% of the total, confirming that the uppermost percentiles underwent a pronounced increase. Since river discharge has a direct control on sediment transport capacity, a pronounced increase in discharge has a prominent impact on erosional hillslope processes, as well as on the remobilization of transiently stored coarse river sediments. Over the last decade, field observations in NW Argentina have shown that the downstream areas at elevations between 500 and 1000 m have been affected by aggradation processes [*Marcato et al.*, 2009; *Comisión Binacional para el Desarrollo de la Alta Cuenca del Río Bermejo y el Río Grande de Tarija (COBINABE)*, 2010]. We hypothesize that the increase in discharge in the intermediate elevation zone has resulted in increased sediment transfer, which ultimately caused aggradation in lower lying areas, as the fluvial system was overwhelmed by the sustained influx of coarse sediment, causing infrastructural damage and the loss of agricultural land [*Rivelli*, 1999; *Cencetti and Rivelli*, 2011; *Marcato et al.*, 2012].

5. Conclusion

We analyzed the dynamical evolution and the trends of river discharge in the Southern Central Andes during 1940–1999. We used a daily multistation mean time series obtained by stacking eight river-discharge time series from catchments (10^2–10^4 km^2) located on the eastern flank of the Southern Central Andes along a steep topographic and climatic gradient. We estimated different indices on annual and seasonal scales, focusing our analysis on the wet season (DJF and MAM), and applied a two-tiered approach of standard and quantile regressions followed by change-point analysis to evaluate runoff trends between 1940 and 1999. We obtained two key results: First, quantile regression analysis revealed a spatially coherent and statistically significant positive increase in discharge for the period of 1940–1999, with higher trends for the uppermost percentiles, suggesting an intensification of the hydrological cycle in this area; second, change-point analysis presented a rapid increase in discharge during the period 1971–77, most likely linked to the 1976–77 climate shift. We also observed positive (negative) trends across (after) the change point at most percentiles of daily discharge in every season. Our study provides evidence to support a link between hydro-meteorological drivers and sediment transport processes in semiarid mountain environments. The decadal-scale increase in discharge at the higher percentiles has resulted in massive sediment transport, which continues to affect downstream infrastructure and agricultural areas.

Acknowledgments
Our study was supported by the Leibniz Fund of the German Science foundation (DFG) to M.S. (STR373/19-1) and the Germany Ministry of Education and Research project PROGRESS (Climate Change, Georisk and Sustainability initiative at Potsdam University) to M.S. and B.B. The authors thank the Subsecretaría de Recursos Hídricos (BDHI), Argentina, for providing rain gauge and discharge time series. We thank in particular D. Cielak (BDHI), Ricardo N. Alonso (UN Salta), Arturo Villanueva (UN Tucumán), and E. Marigliano (EVARSA, Argentina) for their valuable support during this study. We also thank two anonymous reviewers for their valuable comments.

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