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Invited review

A review of Glacial and Holocene paleoclimate records from southernmost Patagonia (49–55°S)

Rolf Kilian [a,*], Frank Lamy [b]

[a] Geologie, FBVI, Universität Trier, Behringstr. 16, 54826 Trier, Germany
[b] Alfred Wegener Institut für Polar- und Meeresforschung, Am Alten Hafen 26, 27568 Bremerhaven, Germany

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ABSTRACT

Southern South America is the only landmass intersecting the southern westerly wind belt (SWW) that influences the large-scale oceanography and controls for example the outgassing of CO_2 in the Southern Ocean. Therefore, paleo-reconstructions from southernmost Patagonia are of global interest and an increasing number of paleoclimate records have been published during the last decades. We provide an overview on the different records mostly covering the Holocene but partly extending into the Late Glacial based on a large variety of archives and proxies. We particularly discuss possible reasons for regionally diverging palaeoclimatic interpretations and summarize potential climate forcing mechanisms. The Deglacial and Holocene temperature evolution of the region including the adjacent Pacific Ocean indicates "Antarctic" pattern and timing consistent with glacier re-advances during the Antarctic Cold Reversal. Some records indicate a significant accumulation control on the glacier fluctuations related to changes in SWW strength and/or position. Reconstructions of Holocene changes in the SWW behaviour provide partly inconsistent and controversially discussed pattern. While records from the hyperhumid side point to a stronger or southward displaced SWW core during the Early Holocene thermal maximum, records from the lee-side of the Andes show either no long term trend or the opposite, suggesting enhanced westerlies during the late Holocene "Neoglacial". Likewise, centennial-scale global or hemispheric cold intervals, such as the Little Ice Age, have been interpreted in terms of enhanced and reduced SWW strength. Some SWW variations can be linked to changes in the El Niño-Southern Oscillation (ENSO) consistent with instrumental climate data-sets and might be ultimately forced by solar variability. Resolving these inconsistencies in southernmost Patagonian SWW records is a prerequisite for improving hemispheric comparisons and links to atmospheric CO_2 changes.

1. Introduction

The southernmost tip of South America is of particular interest for paleoclimate reconstruction, since it is the only land-mass intersecting the core of the southern westerly wind belt (SWW) at latitudes between 49 and 53°S (Fig. 1). On a hemispheric scale, SWW changes substantially contribute to the forcing of the deep and vigorous Antarctic Circumpolar Current (ACC). Wind-induced upwelling within the ACC in the Southern Ocean raises large amounts of deep water to the ocean's surface in this circumpolar belt affecting the global thermohaline circulation (e.g. Marshall and Speer, 2012) and atmospheric CO_2 contents (e.g. Toggweiler et al., 2006). Therefore, the SWW exerts a strong control on global climate and oceanography.

The first paleoclimate records from Patagonia were based on glacier advance reconstructions (Caldenius, 1932; Mercer, 1965) and on pollen records from soil and peat records (Auer, 1933, 1958, 1960, 1974; Heusser, 1971). Multi-proxy reconstructions based on lake and fjord sediment cores as well as stalagmites initiated only during the past 10 years and constitute now a growing number of partially high resolution records. The number of paleoclimate-related publications particularly increased since ca 2005 (to more than 25 publications/year; Fig. 2). Despite this large number of publications and the global implications of the Patagonian paleoclimate, reconstructions of Glacial and Holocene SSW changes are partly inconsistent and discussed controversially. Contrasting inferences have been derived from proxy records in southern Patagonia for example on multi-millennial time-scales during the Holocene (e.g. Mayr et al., 2007a,b; Lamy et al., 2010; Moreno et al., 2010; Waldmann et al., 2010; Fletcher and Moreno, 2011) but also regarding shorter term climate variations on centennial time-

* Corresponding author.
E-mail address: kilian@uni-trier.de (R. Kilian).

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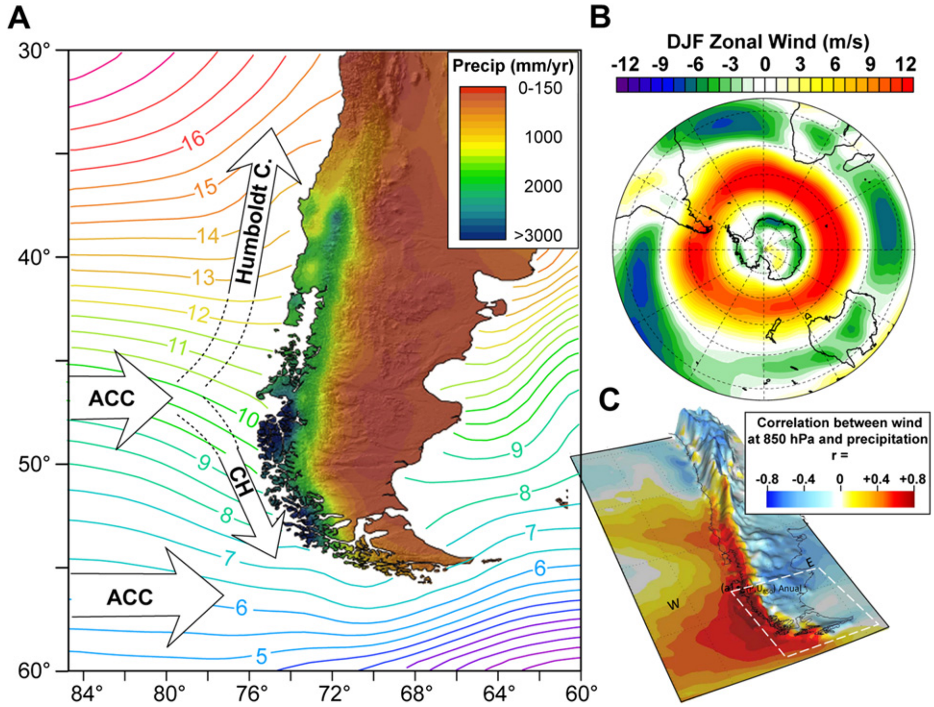

Fig. 1. A) Southernmost South America with average annual precipitation New et al., 2002) and the modern annual mean sea surface temperature distribution of the surrounding oceans (data from the NOAA-CIRES Climate Diagnostics Center http://www.cdc.noaa.gov/index.html). The Antarctic Circumpolar Current (ACC) and Cape Horn Current (CH) are indicated. B) December to February zonal wind distribution over the Southern Hemisphere based on NCEP/NCAR reanalysis data (Kalnay et al., 1996) and C) correlation between 850 hPa zonal wind and precipitation (Garreaud et al., in press).

scales, e.g. during the globally known Little Ice Age (LIA; e.g. Moy et al., 2008; Schimpf et al., 2011).

Besides SWW reconstructions which are primarily based on precipitation proxies and their correlation to wind changes, paleotemperature reconstructions in southernmost Patagonia may help to understand atmospheric and ocean temperature behaviour in the Southern Hemisphere. These are for example essential for evaluating coupled atmospheric-ocean circulation changes as well as timing and dynamics of interhemispheric climate changes including the bipolar seesaw (e.g. Stocker and Johnsen, 2003; Lamy et al., 2007; Barker et al., 2009). Furthermore, the southern Patagonian Ice field (PIF) is of special interest, because it constitutes the

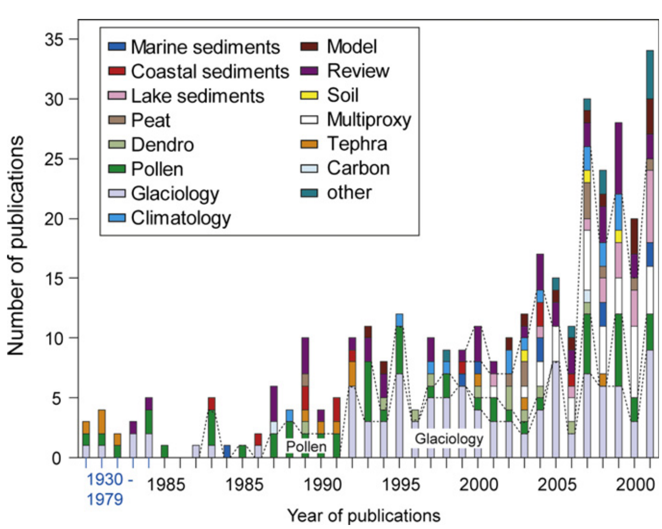

Fig. 2. Number of published paleoclimate studies in southernmost Patagonia over the past decades.

largest continental ice-sheet outside the polar regions (Casassa et al., 2000) which is highly sensitive to temperature as well as precipitation changes (Warren and Sudgen, 1993) and contributes significantly to global sea level changes (Rignot et al., 2003; Glasser et al., 2011).

As with the paleoclimate data, also modelling studies on the position and strength of the SWW that have been performed in particular for the Last Glacial Maximum (LGM) are not yet conclusive (Rojas et al., 2009). Holocene changes of the SWW have also been addressed by for example mid-Holocene and preindustrial simulations (Wagner et al., 2007; Rojas and Moreno, 2011) and modelling studies that focus on the impact of solar variability during the past 3000 years (Varma et al., 2011).

Instrumental climate and weather data collected over the past ca 50 years show that SSW extends more than 3000 km north–south with significant latitudinal variations on seasonal to decadal times-scales (Fig. 1A and B). Due to the few weather station data in the Southern Hemisphere, it is likely that the SWW variability is spatially more complex than presently known (Garreaud, 2007; Garreaud et al., in press). Regarding paleo-SWW reconstructions, it is therefore important to note that past changes of the SWW cannot be estimated from a record of a single site. Further complicating is the west-east distribution of sites across the Patagonian Andes, where the SSW forces in one of the most pronounced climate divide on earth (Fig. 1C). This strong precipitation gradient produces different, highly sensitive ecosystems at the hyperhumid western and evaporation controlled arid eastern side of the Andes. Paleoclimate archives from such contrasting environments often require different and not directly comparable proxies. Therefore, local climate characteristics are very important in southern Patagonia as well as proxy calibration and proxy monitoring which has only started within the past few years (e.g. Schimpf et al., 2011). A further complication of paleoclimate reconstructions from Patagonia is the fact that some proxy records may have been affected by