The Southern Westerlies During the Holocene: Paleoenvironmental Reconstructions from Chilean Lake, Fjord, and Ocean Margin Sediments Combined with Climate Modeling

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Abstract This project aimed at investigating centennial to millennial-scale changes of the strength and position of the southern westerly wind belt (SWW) using multi-proxy paleoprecipitation and paleoceanographic records combined with transient model runs. The proxy data records reveal a distinct latitudinal anti-phasing of wind changes between the core and northern margin of the SWW over the Holocene. During the early Holocene, the SWW core was enhanced and the northern margin was reduced, whereas the opposite pattern is observed in the late Holocene. These Holocene changes resemble modern seasonal wind belt variations and can be best explained by varying sea-surface temperature fields in the eastern South Pacific. Transient modeling experiments from the mid- to late Holocene are not yet consistent with these proxy results. However, a good data-model agreement exists when investigating the potential impact of solar variability on the SWW at centennial time-scales during the latest Holocene with periods of lower (higher) solar activity causing equatorward (southward) shifts of the SWW.

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M. Schulz and A. Paul (eds.), *Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC)*, SpringerBriefs in Earth System Sciences,
DOI 10.1007/978-3-319-00693-2_13

Keywords Paleoclimatology · Paleoceanography · Climate modeling · Holocene · Solar variability · Westerly winds

1 Introduction

The westerlies are major zonal atmospheric circulation systems in both northern and southern hemispheres. Particularly, the southern westerly wind belt (SWW) exerts a strong control on global climate and oceanography. On a hemispheric scale, SWW changes contribute substantially to the forcing of the deep and vigorous Antarctic Circumpolar Current, while wind-induced upwelling in the Southern Ocean raises large amounts of deep water to the surface affecting the global thermohaline circulation and atmospheric CO_2 contents. Observational data suggest that the southern margin of the SWW has intensified over the past 40 years, a trend that is expected to proceed over the next centuries. This may provide a positive feedback on global warming through reducing the uptake of anthropogenic CO_2 or even promoting outgassing of old naturally stored CO_2 through upwelling.

Southern South America is the only landmass intersecting both the present core (southernmost Patagonia) and the northern margin (central Chile) of the wind-belt. Since the SWW nearly entirely control precipitation on the western side of the southern Andes, proxy records of past precipitation changes from this region are ideal to reconstruct past variability of the SWW. Furthermore, the ocean margin, lake, and fjord sediments provide high resolution paleoclimate archives along the southern Chilean continental margin suitable to reconstruct precipitation changes and related ocean variations during the Holocene (e.g., Kilian and Lamy 2012). These sediment records combined with climate modeling can be used to place the short instrumental data-sets into a longer-term perspective covering centennial-millennial-scale SWW changes during the complete Holocene.

2 Materials and Methods

Our primary goal is to integrate southern Chilean lake, fjord, and ocean margin proxy archives with climate modeling in order to reconstruct Holocene changes in vegetation, rainfall, and lake/sea-surface temperatures and relate those to changes in the strength and latitudinal position of the SWW. Therefore, we applied a number of different methods including non-destructive core-logging methods to obtain ultra-high-resolution records, sedimentological, and palynological approaches (Lamy et al. 2010). Large efforts were devoted to generate detailed and reliable age models by radiocarbon dating and tephrostratigraphy. Furthermore, we investigated the regional calibration and applicability of novel organic biomarkers including glyceryl dialkyl glycerol tetraether (GDGT)—based proxies (such as TEX86 to reconstruct water temperature and the MBT/CBT index to reconstruct mean air temperature) as well as compound-specific hydrogen isotopic composition of lipids derived from land-plant leafwaxes (e.g., long-chain, odd-numbered n-alkanes) to reconstruct the hydrological cycle. Application of these molecular proxies on a Holocene fjord sediment record from the center of the SWW and covering the Holocene shows promising results.

Numerical transient experiments using the comprehensive global climate model CCSM3 (Community Climate System Model version 3) were carried out in order to simulate the evolution of the SWW under orbital forcing from the mid-Holocene [7,000 years (ka) before present (BP)] to pre-industrial modern times (250 years BP). These simulations were accompanied by a model inter-comparison with orbitally forced Holocene transient simulations from four other coupled global climate models (Varma et al. 2012a). In order to study the response of SWW to solar variability, model runs with idealized solar forcing were performed (Varma et al. 2011). Finally, we investigated the influence of the stratosphere and its ozone content on SWW variability, using two transient simulations (one with fixed and one with solar-induced varying stratospheric ozone) with the coupled atmosphere-ocean general circulation model EGMAM (ECHO-G with Middle Atmosphere Model) focusing on the periods of the Late Maunder Minimum (LMM: 1675–1715 AD) and Pre-Industrial (PI: 1716–1790 AD) (Varma et al. 2012b).

3 Key Findings

Our multi-proxy compilation based on fjord and lake sediment records from the hyperhumid zone of southernmost Chile provides a consistent picture of Holocene SWW variability (Fig. 1; Lamy et al. 2010). Precipitation and thus SWW strength changes deduced from humidity sensitive pollen, precipitation-dependent terrestrial organic carbon accumulation in lake and fjord sediments (Fig. 1e), and salinity dependent decrease in biogenic carbonate accumulation indicate wetter/windier conditions between ~12.5 and ~8.5 ka BP, intermediate conditions thereafter until ~5.5 ka BP, and finally reduced precipitation and less intense westerlies during the late Holocene (Fig. 1). At the northern margin of the SWW in central Chile reconstructed rainfall changes are generally anti-phased to those from the core zone. A rainfall reconstruction based on Lake Aculeo level changes (34°S; Fig. 1a; Jenny et al. 2003) reveals substantially reduced precipitation during the early and mid-Holocene in agreement with reduced terrigenous sediment input in Lake LleuLleu (37°S; Fig. 1b) and increased input of Andean-derived versus coastal-derived terrestrial material at the continental margin (41°S; Fig. 1c; Lamy et al. 2001). All three records show a pronounced shift to more humid conditions starting at ca. 5.5 ka BP and extending throughout the late Holocene. Though these records only reach back to ~8–10 ka BP, substantially lower rainfall during the early Holocene and thus reduced westerly influence has been reconstructed at many sites in the region (Latorre et al. 2007).

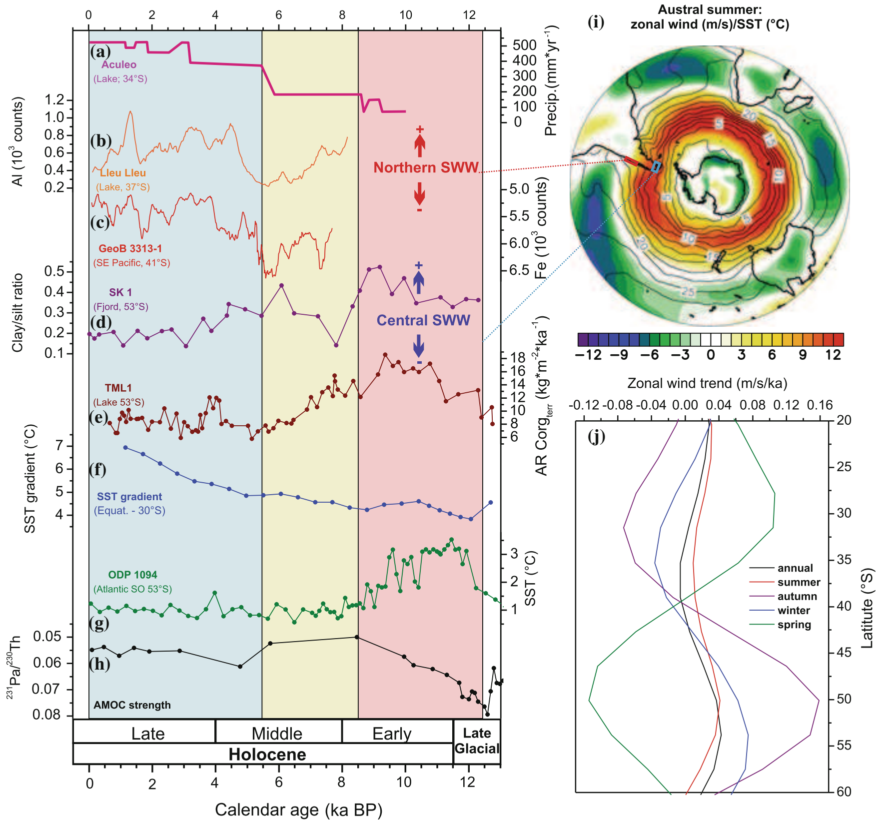

Fig. 1 Proxy records for Holocene changes of the SWW compared to transient model results. **a** Precipitation reconstruction from Lake Aculeo, central Chile (Jenny et al. 2003). **b** Al content record from core LL-KL009, Lake LleuLleu, central Chile as a paleoprecipitation proxy. **c** Fe content changes recorded in core GeoB 3313-1 retrieved from the Chilean continental margin at 41°S. **d** Silt/clay ratio record from core SK1 (fjord Seno Skyring) recording the long-distance eastward transport of illite-rich Andean clay from the Patagonian Batholith, which can be taken as a "direct" wind strength proxy (Lamy et al. 2010). **e** Terrestrial organic carbon accumulation rate record from lake core TML1 in the Strait of Magellan fjord region (Lamy et al. 2010). **f** SST gradients between the eastern tropical Pacific (core V19-28; Koutavas and Sachs 2008) and a mid-latitude SE Pacific record (core GeoB 7139; Kaiser et al. 2008). **g** Diatom assemblage-based summer SST record from the Atlantic sector of the Southern Ocean at ~53°S (Bianchi and Gersonde 2004). **h** $^{231}Pa/^{230}Th$ record from a subtropical North Atlantic sediment core taken as a proxy for the strength of the Atlantic meridional overturning circulation (McManus et al. 2004). *Vertical bars* mark the multi-millennial Holocene periods (*red* = early Holocene intensification of the core SWW and weakening of the northern margin; *blue* = late Holocene weakening of the core SWW and intensification of the northern margin; *yellow* = intermediate conditions during the middle Holocene). **i** Southern hemisphere zonal wind (m/s) climatology at 850 hPa and SSTs for austral summer. Study areas in central and southern Chile are marked. **j** Zonally averaged seasonal and annual trends in low-level zonal wind for the period 7 ka BP to pre-industrial. Results are from CCSM3 (Varma et al. 2012a)

The early Holocene SWW core maximum coincides with a widespread warming at southern hemisphere mid-latitudes as evidenced by sea-surface temperature (SST) records from the Atlantic Southern Ocean (53°S; Fig. 1g) (Bianchi and Gersonde 2004) as well as offshore southern (Caniupan et al. 2011), central (Lamy et al. 2002) and northern Chile (Kaiser et al. 2008). At the same time, SSTs in the eastern tropical Pacific were relatively cold (Koutavas and Sachs 2008) reducing the low to mid-latitude SST gradient in the South Pacific (Fig. 1f) and consequently the SWW at their northern margin as during present-day summer. Warming in the eastern tropical Pacific and cooling further south during the late Holocene possibly enhanced the latitudinal SST gradients resulting in stronger winds at the northern margin of the SWW (Lamy et al. 2010) and reduced winds across the southern tip of South America as presently occurring during winter.

Some of our proxy data are inconsistent with our numerical model results which suggest that the annual and seasonal mean SWW is subjected to an overall strengthening and poleward shifting trend during the course of the mid-to-late Holocene under the influence of orbital forcing, except for the austral spring season, where the SWW exhibit an opposite trend of shifting towards the equator (Fig. 1j) (Varma et al. 2012a). The major change in the proxy data occurs during the early Holocene (not yet covered by the transient model runs) rather than the mid- and late Holocene. However, the modeled poleward shifting and strengthening of the westerlies during most of the year from the mid to the late Holocene is inconsistent with the trend to more humid conditions and stronger northern margin westerlies in central Chile shown by the data (Fig. 1a–c). An exception is the modeled austral spring enhancement of the northern westerlies, which is however not the major rainfall season in central Chile assumed to be recorded by the proxies (Fig. 1j). Further work is therefore needed to reconcile these model-data inconsistencies including an extension of the transient experiments into the early Holocene where processes such as the ocean-driven bipolar see-saw become important (Fig. 1h).

More consistent data-model results have been obtained for centennial-scale SWW changes in central Chile over the past 3 ka (Fig. 2) (Varma et al. 2011, Varma et al. 2012b). The proxy and model results suggest that centennial-scale periods of lower (higher) solar activity caused equatorward (southward) shifts of the annual mean SWW. Under a "bottom-up" mechanism, where applied changes in total solar irradiance mostly affect the climate system through shortwave absorption by the surface, the strength and position of the SWW are strongly related to meridional surface temperature gradients. By contrast, a "top-down" mechanism influences the troposphere via stratospheric ozone responses to variations in ultraviolet radiation and dynamical coupling between the atmospheric layers. The SWW response in simulations with varying stratospheric ozone (EGMAM2) is more pronounced and robust compared to the one with fixed ozone (EGMAM1) (Fig. 2) suggesting an important contribution from the middle atmosphere through a "top-down" mechanism.

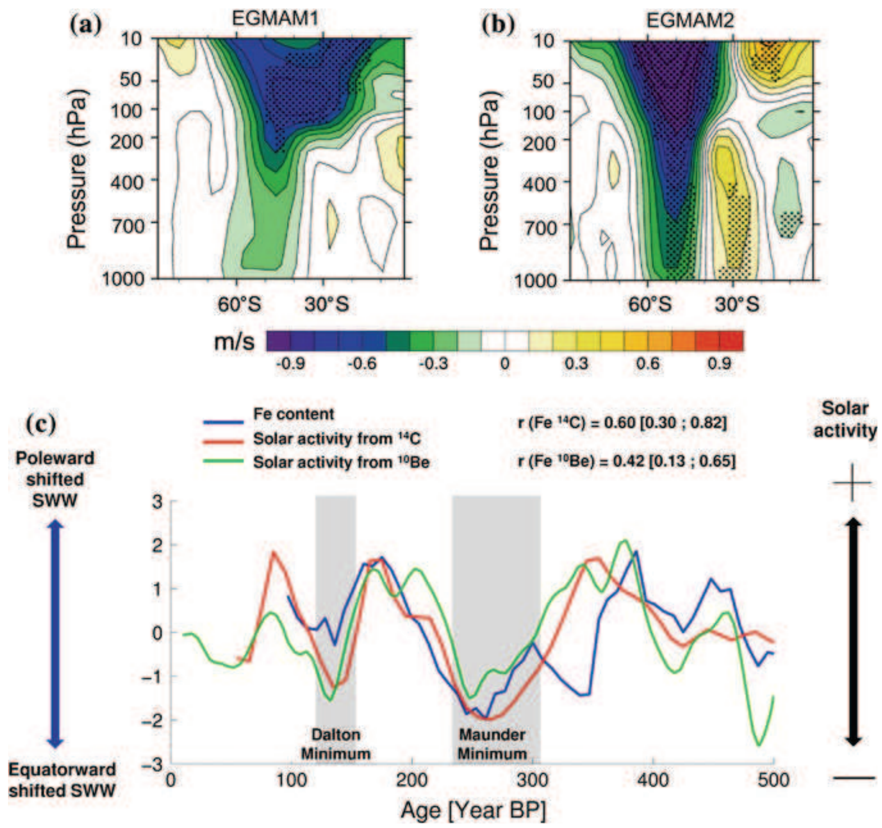

Fig. 2 Annual-mean zonal wind anomalies (LMM-mean minus PI-mean) in the EGMAM simulations along with the reconstructions for SWW position and solar activity. **a** and **b** Zonally averaged zonal wind anomalies in the Southern Hemisphere in EGMAM1 (fixed ozone) and EGMAM2 (varying ozone) simulations respectively. Stippling indicates significance of the anomaly at the 0.05 level according to a Student's t-test. **c** Reconstruction of the SWW position [*blue line*, based on the GeoB3313-1 iron record (Lamy et al. 2001)] versus solar activity based on ^{10}Be (*green line* Steinhilber et al. 2009) and ^{14}C (*red line* Solanki et al. 2004), for the last 500 years. *Grey bars* mark the low solar activity periods of the Dalton minimum and the Maunder minimum. Time series are unsmoothed, detrended and standardized. The negative (positive) iron anomalies suggest northward (southward) shifted SWW (Lamy et al. 2001; Varma et al. 2011). 95 % confidence intervals (in brackets) for Pearson correlation coefficients (r) were calculated using a bootstrap method, where autocorrelation has been taken into account

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