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High-latitude forcing of regional aridification along the subtropical west coast of South America

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[1] Precipitation in north-central (subtropical) Chile has been declining over the last 130 years. This is of concern in a region where precipitation is already low and which hosts considerable economic activity and a large population. Interannual variability of precipitation is primarily controlled by ENSO, but the reasons for the increasing aridity have remained elusive. Here we show that the negative trend in precipitation is not related to tropical Pacific forcing and that recent El Niño activity instead helped to alleviate the worst drought conditions. Based on data from 1979–2004 we further show that sea surface temperatures and sea-ice concentration in the Amundsen Sea and associated blocking activity in the Bellingshausen Sea are related to winter precipitation in subtropical Chile, independently of ENSO. High latitude forcing from the Amundsen Sea region may provide an alternative explanation for the observed secular drying trend. **Citation:** Vuille, M., and J.-P. Milana (2007), High-latitude forcing of regional aridification along the subtropical west coast of South America, *Geophys. Res. Lett.*, *34*, L23703, doi:10.1029/2007GL031899.

1. Introduction

[2] In many subtropical regions, such as the Sahel, drying trends have been noted for much of the 20th century. One of the most severe, yet largely unnoted and unexplained precipitation reductions has taken place in north-central, subtropical Chile (∼28°–35°S). This region has seen a significant decline in precipitation since the beginning of measurements in the second half of the 19th century [e.g., *Luckman and Villalba*, 2001; *Minetti et al.*, 2003; *Milana et al.*, 2006]. *Le Quesne et al.* [2006], using an 800-year long tree-ring chronology, have shown that the current risk for drought conditions in this region is unprecedented in an 800-year context. While the last few decades have seen no significant change in precipitation, the long-term (secular) trend is nonetheless disconcerting given the large population density and the growing industrial, agricultural and municipal demand for water [*Masiokas et al.*, 2006]. Total precipitation amounts in coastal areas near 30°S are only ∼120 mm yr^{-1}, mostly falling during the winter months from May through August, when winter storm tracks reach their northernmost location. Much of the water needed for socioeconomic activities is therefore derived from rivers fed by annual snowmelt in the high Andean catchments. Given the observed and projected future temperature increase in the region [*Carrasco et al.*, 2005; *Bradley et al.*, 2006], and its impact on Andean snow cover and glaciation [*Rivera et al.*, 2000], this water supply may no longer meet the demand in the near future.

[3] A number of studies have identified the key role played by ENSO on interannual timescales. During El Niño an upper tropospheric wave-train, energized through the anomalous tropical Pacific heat source, extends from the Pacific warm pool to the Bellingshausen Sea, where increased blocking activity of equivalent barotropic nature, in conjunction with a weakened SE-Pacific High, leads to a northward deflection of the storm tracks and hence increased precipitation in north-central Chile [*Rutllant and Fuenzalida*, 1991]. The La Niña phase is characterized by rainfall anomalies of the opposite sign [e.g., *Montecinos and Aceituno*, 2003].

[4] There is some speculation that the secular rainfall decline may be related to changes in ENSO variability, but at the same time it has also been recognized that other, hitherto unknown causes must be at play [*Montecinos and Aceituno*, 2003; *Masiokas et al.*, 2006]. *Milana et al.* [2006] were the first to suggest that sea surface temperature (SST) in the South Pacific may influence precipitation in central Chile, independently from ENSO. The aim of this paper is to assess the validity of their hypothesis and to investigate what other mechanisms may be responsible for the rainfall decline in subtropical Chile.

2. Data and Methods

[5] We make use of CRU TS 2.1. gridded precipitation data [*Mitchell and Jones*, 2005], to document that the observed drying trend is a region-wide phenomenon, affecting entire north-central Chile between ∼28° and 35°S. Since the negative trend is most disconcerting along the regions' arid northern border, and tree ring data document that the secular drying trend reaches back into the 19th century [*Le Quesne et al.*, 2006], not covered by CRU TS 2.1., we also make use of individual precipitation records from La Serena (29.9°S, 71.2°W, 142 m, 1869–2004) and Ovalle (30.6°S, 71.2°W, 1250 m, 1897–2003). These two records are among the longest time series available from the southern hemisphere, are well documented and of high quality [*Minetti and Vargas*, 1998]. Both stations are located in the arid zone of north-central Chile, near the southern border of the Atacama Desert. Mean annual precipitation totals, averaged over the entire record are 128.4 mm (Ovalle) and 113.7 mm (La Serena) respectively. As monthly values were not available for the early part of the record, we instead used annual calendar-year precipitation totals to

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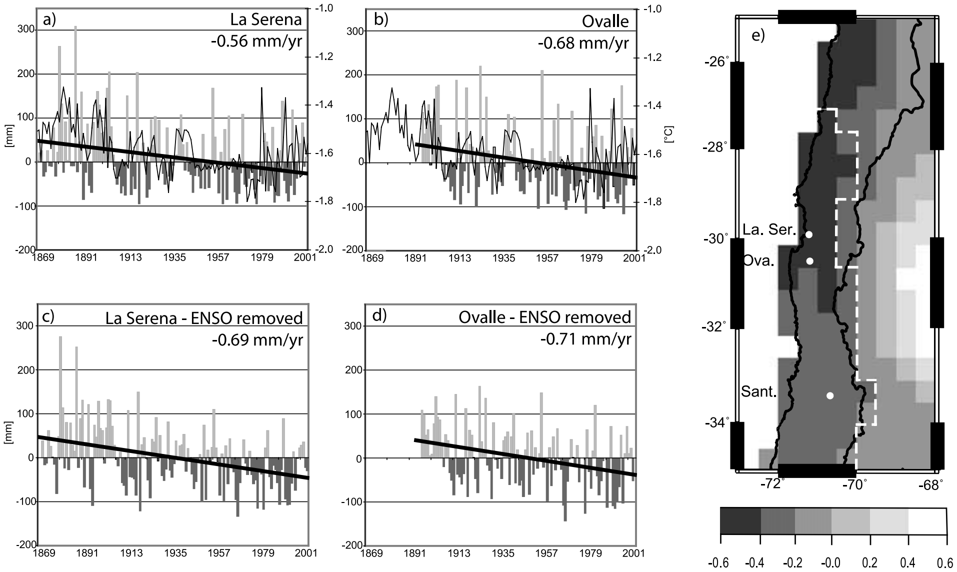

Figure 1. Annual precipitation departures (bars, scale on the left) from 1901–2000 mean in (a) La Serena and (b) Ovalle. Thick lines denote precipitation trend. (c, d) Same as in Figures 1a and 1b but with ENSO-related variance removed. Thin line in Figures 1a and 1b indicates MJJA SST in the Amundsen Sea (127°W–107°W; 67°S–71°S), scale on the right. (e) Trend in MJJA precipitation (in % yr^{-1}) in north-central Chile based on CRU TS 2.1 data (1901–2002). All areas to the west of the white dashed line show significant downward trend.

make use of the full record length. Almost all precipitation in this region falls during the winter months as a result of the general northward displacement of the southern hemisphere westerlies and the embedded cyclonic activity. In Ovalle the four winter months May-August (MJJA) account for 85.9% of the annual rainfall total (average, 1947–2003). In addition seasonal (MJJA) and annual precipitation totals are highly correlated (r = 0.96, significance level p = 0.0001). Hence we consider annual precipitation totals to be representative of austral winter precipitation and compare total precipitation with austral winter conditions (e.g. SST, sea-ice) elsewhere. All reported significant correlations and trends are at the 95% level, unless noted otherwise.

[6] Besides precipitation data additional gridded data sets were employed. The NOAA Extended Reconstructed SST (ERSST V2, *Smith and Reynolds* [2004]) data set is provided as monthly means on a 2° × 2° grid since 1854. To characterize ENSO conditions we use the MJJA Niño-3.4 index, defined as SST averaged over the region 5°S–5°N and 170°–120°W. Monthly Antarctic sea-ice concentration (SIC) retrieved from the Scanning Multichannel Microwave Radiometer (SMMR) on the Nimbus satellite and the Spatial Sensor Microwave/Imager (SSMI) on several defense meteorological satellites provided since 1979 on a 25 km × 25 km grid [*Cavalieri et al.*, 1996] and sea level pressure (SLP) and 1000 hPa NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] were used to characterize high-latitude winter conditions between 1979 and 2005.

3. Results

[7] Figures 1a and 1b show the annual precipitation anomalies for La Serena and Ovalle. While there is no significant decline in precipitation over the past 40–50 years, both stations exhibit a clear negative secular trend superimposed on strong interannual to multidecadal variability. Ordinary least squares regression analysis shows a significant precipitation decrease of -0.68 mm yr^{-1} at Ovalle ($p = 0.006$, 1897–2003) and -0.56 mm yr^{-1} at La Serena ($p = 0.001$, 1869–2004). This translates to a total rainfall reduction of 72.8 mm or 57% at Ovalle since recordings started in 1897. Similarly precipitation at La Serena has decreased by 74.8 mm or 66% since 1869. Even though precipitation has remained more or less constant over the past few decades, these numbers are alarming in a region where precipitation is already very limited. Trend analyses based on CRU TS 2.1 data show that the precipitation decline during the 20th century (1901–2002) is not limited to these two stations, but significant throughout north-central Chile (Figure 1e). The fact that trends are insignificant both in La Serena and Ovalle if only the reanalysis period since 1948 is considered, may explain why there is little discussion of this long-term negative trend in the published literature, as most studies tend to focus on the reanalysis period where links with large-scale atmospheric dynamics can be more reliably assessed [e.g., *Montecinos and Aceituno*, 2003]. Consistent with these studies, the interannual variability of precipitation at both stations is primarily driven by tropical Pacific SSTs (Figures 2a and 2c). Correlation fields show the well known ENSO pattern with significant positive correlations near the equator, from the west coast of South America to the dateline and negative correlations to the south extending from the northwest to the southeast across the South Pacific. Significant positive correlations are also visible in the Amundsen Sea region between 90°W and 150°W, off the coast of Antarctica.

[8] To examine the influence of ENSO on the long-term precipitation trend we regress the MJJA Niño3.4 index against the time series from La Serena and Ovalle and then consider the residual time series from this regression, which

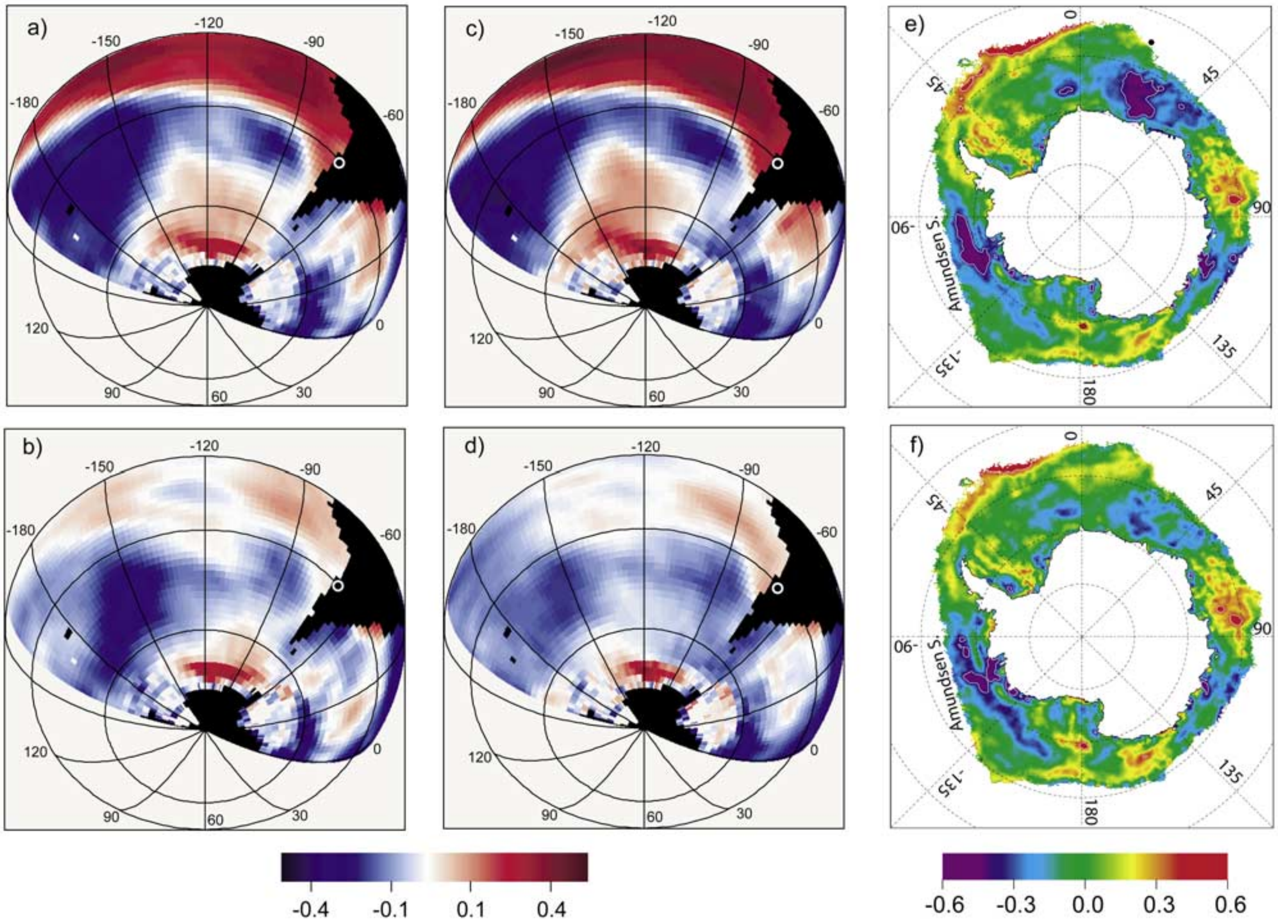

Figure 2. Correlation of (a) La Serena and (c) Ovalle precipitation with MJJA SST. (b, d) Same as in Figures 2a and 2c but with ENSO-related variance removed. Correlations $> |0.17|$ ($|0.19|$) are significant in Figures 2a and 2b (Figures 2c and 2d). White dot in Figures 2a–2d indicates location of La Serena and Ovalle. (e) Correlation of La Serena precipitation (with ENSO variance removed) with MJJA SIC (1979–2004). (f) Same as in Figure 2e but for Ovalle (1979–2003). White lines in Figures 2e and 2f delimit significant correlations.

contain the non-ENSO related precipitation variance. While there may be some nonlinear ENSO- influence, most studies indicate that linear predictors indeed capture most of the ENSO–related precipitation signal in north-central Chile [e.g., *Montecinos et al.*, 2000]. Both residual time series show a significant decline in precipitation (Figures 1c and 1d), which is even more negative than in the original time series (-0.71 mm yr^{-1} at Ovalle and -0.69 mm yr^{-1} at La Serena; both trends significant at $p = 0.001$). An F-test of the null-hypothesis that the slopes before and after removal of the ENSO-variance are not significantly different from one another is rejected at $p = 0.05$ for both records, indicating a significantly more negative trend after ENSO removal. Hence the long-term behavior of ENSO is not responsible for the precipitation decline, but rather acted to alleviate some of the worst droughts. This is confirmed by a two-tailed t-test of precipitation since 1975 with and without ENSO-variance removed, indicating significantly higher precipitation ($p = 0.002$ for Ovalle, $p = 0.02$ for La Serena) in the original time series with ENSO variance included, thus revealing the beneficial impact of intensified (1982/83, 1997/98) and prolonged (1991–95) El Niño activity since the mid 1970's.

[9] The SST correlation field of the residual series (Figures 2b and 2d) shows the effect of the ENSO removal, with correlations that are insignificant throughout the tropical Pacific. There is, however, still a region of conspicuous positive correlations in the Amundsen Sea, which was already present in the original correlation field (Figures 2a and 2c). As this high-latitude signal persists after removal of the ENSO-variance, it is independent of the well-known ENSO-Antarctic teleconnection [e.g., *Liu et al.*, 2004]. To assess what fraction of the negative trend in precipitation is linearly congruent with a contemporaneous change in the Amundsen Sea, we regressed the detrended, ENSO-removed precipitation records from Ovalle and La Serena onto the detrended Amundsen SST data (averaged over 127°W–107°W; 67°S–71°S, where all local correlations in Figures 2b and 2d are significant) and then multiplied the regression coefficients by the trend of the latter. This yields an estimate of the fraction of the trend which can be attributed solely to SST forcing in the Amundsen Sea region. Our results indicate that 45.0% (40.1%) of the overall drying in Ovalle (La Serena) since 1897 (1869) is accounted for by secular changes in Amundsen SST alone. Inspection of the SST trend in the Amundsen Sea (Figure 1) shows that it is highly

non-linear and that therefore the linear trend attribution may not adequately describe the precipitation decrease throughout the entire period. The SST decrease between 1870 and the 1930s, however, is consistent with the major precipitation decline observed in central Chile over the same time period, while no trend in precipitation is evident over the past 40 years, when SST have again started to rise. While these results suggest that precipitation in semi-arid Chile may be linked to SST anomalies (SSTA) in the Amundsen Sea, two cautionary notes are in order. First, early observations from the Amundsen Sea are scarce and SST data may not be very reliable in the early part of the record. Secondly the Amundsen Sea is usually covered by sea ice during the austral winter. ERSST V2 data includes information on SIC but data becomes less reliable before the start of the satellite record in the late 1970's.

[10] In the following we therefore limit our analysis to the time period 1979–2004, for which well-calibrated sea ice data is available. Figures 2e and 2f show the spatial correlation pattern of the residual precipitation series with SIC in circum-Antarctica from SMMR/SSMI. Negative correlations are highly significant in the Amundsen Sea, in the exact same location where significant correlations were found previously based on the much longer SST record (Figures 2b and 2d). We next stratify the MJJA SIC data in the Amundsen Sea (same region as defined above, blue box in Figure 3b) between 1979 and 2003 into years with high (upper tercile), medium and low (lower tercile) SIC and create composites for high and low cases. Figure 3b shows the difference in 1000 hPa geopotential height, wind and specific humidity between high and low SIC years. Figure 3c is a composite of the same variables, but based on the difference between dry and wet years in La Serena/Ovalle (composites again based on upper and lower terciles). As has been documented previously [*Rutllant and Fuenzalida*, 1991] precipitation in north-central Chile is reduced (increased) at times when 1000 hPa pressure in the Bellingshausen Sea is anomalously low (high) due to the southward (northward) deflection of the storm tracks (Figure 3c). A strikingly similar pattern of enhanced meridional circulation, driven by a large-scale pressure anomaly over the Bellingshausen Sea and related southward (northward) deflection of the storm tracks and hence reduced (increased) humidity levels in north-central Chile is also apparent during years with above (below) average SIC in the Amundsen Sea (Figure 3b). The same north-south dipole in specific humidity over central and southern Chile that characterizes the wet-dry composite is also apparent in the composite defined by SIC in the Amundsen Sea. Also noteworthy is that the changes observed in the Amundsen Sea region (reduced low-level humidity and anomalous equatorward flow) during years of high SIC are also apparent in the dry-wet composite based on precipitation anomalies in La Serena and Ovalle. The strong resemblance between the composites is indicative of the significant interannual covariance that exists between MJJA SST and SIC indices, both averaged over the same box as above, MJJA SLP in the Bellingshausen Sea (80°W; 65°S) and the residual time series of Ovalle and La Serena precipitation (Figure 3a). Both precipitation series are significantly positively correlated with SST (Figures 2b and 2d) and SLP ($r = 0.41$ in Ovalle and 0.44 in La Serena, respectively) and negatively with SIC ($r = -0.40$ in Ovalle and -0.41 in La Serena respectively).

[11] While the link between pressure anomalies in the Bellingshausen Sea and precipitation variability in central Chile is quite well documented, the influence of SIC in the Amundsen Sea is less evident. In particular it remains uncertain whether pressure anomalies over the Bellingshausen Sea represent a response to rather than a forcing of Amundsen SIC. It has been observed that such downstream low pressure anomalies tend to develop and persist for several months in the SE Pacific, in response to anomalous heat transport associated with upstream increase in SIC [*Renwick*, 2002]. On the other hand SIC may respond to equatorward flow of cold air implied by the pressure pattern in Figure 3. Lead-lag correlation analyses on monthly timescales (not shown) remain inconclusive as pressure and SIC appear to respond to one another on timescales shorter than months.

4. Summary and Conclusions

[12] Precipitation variability in north-central Chile has long been attributed to pressure variations in the Bellingshausen Sea, mostly in connection with ENSO [*Rutllant and Fuenzalida*, 1991]. However, while pressure variations in the Bellingshausen Sea, documented in Figure 3, are significantly correlated with SIC and with precipitation in Ovalle and La Serena, they are not related to ENSO, as ENSO variance has explicitly been removed from our analysis. Our results therefore suggest that a high-latitude forcing, independent of ENSO, affects precipitation in north-central Chile, by modulating the location of the winter storm tracks. Whether pressure variations in the Bellingshausen Sea are themselves the result of changes in SIC in the Amundsen Sea, or whether they rather represent their cause, remains to be seen and cannot be answered conclusively here. Recent studies, however, suggest that variations in Antarctic SIC indeed have the potential to significantly influence winter precipitation in the southern hemisphere subtropics [e.g., *Blamey and Reason*, 2007]. In any case it is clear that factors other than ENSO influence precipitation variability in subtropical Chile. In particular the secular drying trend is not caused by changes in ENSO behavior; rather the recent increase in El Niño intensity, frequency and

Figure 3. (a) Time series of annual precipitation anomalies in La Serena and Ovalle with ENSO variance removed (in mm), MJJA SIC and SST in the Amundsen Sea and SLP in the Bellingshausen Sea. SIC is plotted on an inverted scale. (b) Composite analysis of difference in MJJA 1000 hPa geopotential height (contours), wind (vectors), and specific humidity (color shading) during high-low MJJA SIC composite in the Amundsen Sea. Contour interval is 3 m, 0-contour omitted, negative contours dashed. Vectors in m s^{-1} are only plotted where zonal or meridional component is significant at $p = 0.05$. Scale for vectors indicated in lower right. Scale for shading is shown below, values <0.2 and >-0.2 omitted. (c) Same as in Figure 3b but for dry-wet composite based on MJJA precipitation in Ovalle/La Serena.

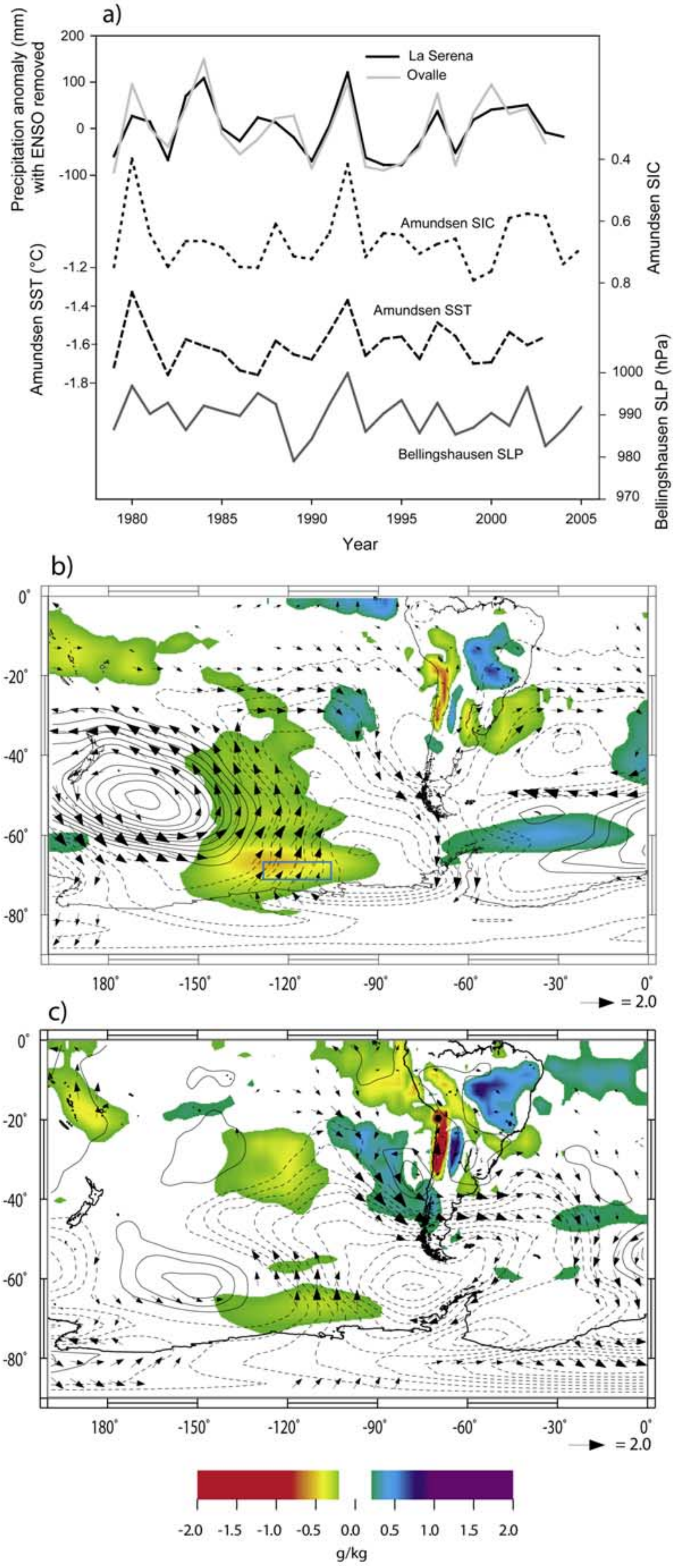
a)
Precipitation anomaly (mm) with ENSO removed
200
100
0
-100
La Serena
Ovalle
Amundsen SIC
0.4
0.6
0.8
Amundsen SST (°C)
-1.2
-1.4
-1.6
-1.8
Amundsen SST
Bellingshausen SLP (hPa)
1000
990
980
970
Bellingshausen SLP
1980
1985
1990
1995
2000
2005
Year
b)
0°
-20°
-40°
-60°
-80°
180°
-150°
-120°
-90°
-60°
-30°
0°
= 2.0
c)
0°
-20°
-40°
-60°
-80°
180°
-150°
-120°
-90°
-60°
-30°
0°
= 2.0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
g/kg

Figure 3

duration has helped to alleviate the drought in recent decades.

[13] If SIC in the Amundsen Sea is indeed linked to precipitation in north-central Chile, it would suggest that projections of future climate change, which indicate further drying in this region at the end of the 21st century [*Vera et al.*, 2006], may depend on how sea ice will respond to increasing global temperatures. Today the Amundsen Sea region is undergoing dramatic changes with accelerated glacier discharge from the West Antarctic ice sheet, and rapid ice thinning through basal melting due to a warmer ocean [*Thomas et al.*, 2002]. While conventional wisdom would hold that sea-ice will decrease in a warmer world, which might enhance precipitation in north-central Chile, it is also conceivable that sea ice will at least temporarily increase due to the stabilizing effect of increased snowfall or regionally due to the continued positive polarity of the SAM [*Liu et al.*, 2004]. In either case a better understanding of high-latitude forcing mechanisms and the potential influence of sea-ice variability is needed, given the sensitivity and dependence of the Chilean economy to an uninterrupted water supply.

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