AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2013JD021167

Key Points:

- Assesses the performance of ERA-Interim in the south of South America
- Focuses in the high complex terrain region of the southern central Andes
- ERA-Interim well represents winter climate of southern central Andes region

Correspondence to:
N. Zazulie,
nzazulie@at.fcen.uba.ar

Citation:
Rusticucci, M., N. Zazulie, and G. B. Raga (2014), Regional winter climate of the southern central Andes: Assessing the performance of ERA-Interim for climate studies, *J. Geophys. Res. Atmos.*, *119*, 8568–8582, doi:10.1002/2013JD021167.

Received 8 NOV 2013
Accepted 26 JUN 2014
Accepted article online 30 JUN 2014
Published online 18 JUL 2014

Regional winter climate of the southern central Andes: Assessing the performance of ERA-Interim for climate studies

Matilde Rusticucci[1], Natalia Zazulie[1], and Graciela B. Raga[2]

[1]Departamento de Ciencias de la Atmósfera y los Océanos, FCEN, Universidad de Buenos Aires, Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina and UMI-IFAECI/CNRS-CONICET-UBA, Buenos Aires, Argentina, [2]Centro de Ciencias de la Atmosfera, Universidad Nacional Autónoma de Mexico, Mexico City, Mexico

Abstract In order to determine the feasibility of using reanalysis (ERA-Interim) for climate studies over the southern central Andes in South America, we have compared the most recent version of different data sets available to the community. The data sets include gridded in situ observations: Climate Research Unit (CRU), Global Precipitation Climatology Centre (GPCC), and University of Delaware; merged satellite and in situ data: Global Precipitation Climatology Project; and satellite estimates: Tropical Rainfall Measuring Mission. We pay particular attention to the region between 30° and 37°S and also the period 1970–1976 to evaluate the data sets. This is the period of maximum availability of meteorological stations in the region. Whereas all data sets provide an adequate representation of mean winter, GPCC provides the best for winter precipitation due to the large number of stations included in gridding. The CRU data set has fewer observations throughout the period. Although it cannot reproduce the localized maxima in the Andes, it provides a better representation of the regional precipitation and is best suited to evaluate trends. The temperature in the region is best estimated by CRU. We evaluate the ERA-Interim reanalysis to determine potential shortcomings. The trends in the region were analyzed during the period 1979–2010, and while CRU indicates a significant decrease in winter precipitation, ERA-Interim shows virtually no significant trends. Interannual variability is well represented by ERA-Interim, and the El Niño–Southern Oscillation, which has been proven to be the principal source of year to year precipitation variability in the region, is highly correlated there.

1. Introduction

The presence of the Andes mountain range, which extends from 10°N to the southern tip of the American continent (≈53°S), plays a fundamental role in determining the climate of South America. Due to its latitudinal extension and its altitude (with peaks of more than 6000 m), the Andes significantly disrupt atmospheric circulations, resulting in a variety of mesoscale and regional-scale phenomena, as well as sharply contrasting climate conditions along the eastern and western slopes and adjacent lowlands [*Garreaud*, 2009]. The maximum precipitation during austral winter is observed over the southern Andes and is mainly produced by the passage of extratropical systems and cutoff lows [*Garreaud*, 2009]. Interannual variability of winter precipitation over the southern Andes has been linked to the El Niño–Southern Oscillation (ENSO), with also some influence of the Southern Annular Mode and the sea surface temperature over the Indian Ocean [*Gonzalez and Vera*, 2010].

In the region known as the southern central Andes (between 30° and 37°S), some of the highest peaks are found. Glaciers are present in the high Andes from which originate several of the main rivers that flow through Chile to the Pacific and through Argentina to the Atlantic. Because of the temperate climate in the foothills on both sides of the Andes, this region is inhabited by the majority of the Chilean population as well as the largest fraction of the population in western Argentina. It is located in the transition between the region where the maximum precipitation over the Andes is observed and the desert regions of northern Chile. In this transition region, winter precipitation (mainly snow) associated with extratropical systems is sporadic in space and time and the melting of the yearly snowpack is the main source of summer river flow. The timing and amount of snowmelt affect water availability for human consumption, irrigation, hydropower generation, and other industries, such as mining, during the dry months. While monitoring precipitation and its changes in this region has a clear economic importance, and recognizing that long-term observations are key in

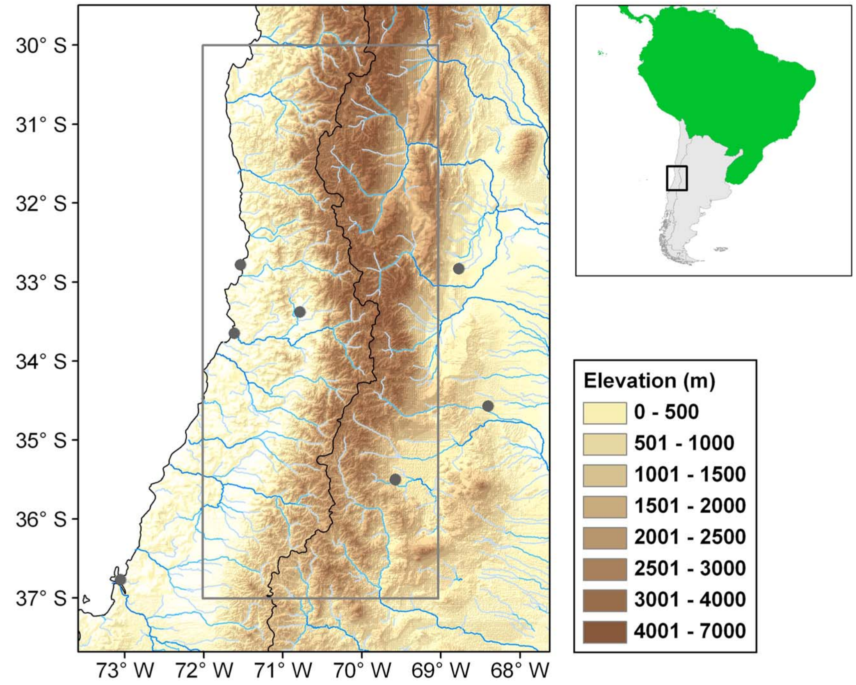

Figure 1. (left) Topography of the studied area. Dark grey dots indicate the location of in situ station mentioned in Table 2. Southern central Andes (SCA) box is presented with a rectangle. (right) Schematic location of the studied region. Argentina and Chile are highlighted in grey and the rest of the countries of America in green.

climate studies, the reality is that few in situ stations exist in this region. Moreover, some of the stations that had long records, particularly in the high mountains, have been discontinued both in Chile and Argentina.

The glacier mass balance and the extension of the snowpack obviously depend on the winter precipitation. Both precipitation and river stream flow in this region have been linked to ENSO [*Montecinos and Aceituno*, 2003; *Rutlland and Fuenzalida*, 1991; *Compagnucci and Vargas*, 1998]. Studies of the extent of snowpack and glaciers have indicated somewhat conflicting results, given that both directly depend on precipitation and temperature. On the one hand, *Masiokas et al*. [2006] found a positive, though nonsignificant, linear trend of snowpack for the period 1951–2005, whereas *Masiokas et al*. [2009] reported an overall retreat during the twentieth century in the central Andes of Argentina and Chile. In a follow-up study *Masiokas et al*. [2010] showed the influence of the Pacific Decadal Oscillation on the low-frequency modes of hydroclimatic variability from stream flow and precipitation data.

The reanalyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) have been used in climate and synoptic studies over South America as well as acting as inputs for regional models [e.g., *Solman et al*., 2013; *Carril et al*., 2012]; however, an evaluation of the performance of the latest version of the reanalysis, also known as ERA-Interim [*Dee et al*., 2011], has not been carried out over South America.

Given the scarcity of station data in the region of the southern central Andes, there is a need to evaluate how well-gridded data sets and reanalysis represent the climate of the region. The purpose of the present work is to assess the performance of the ERA-Interim reanalysis and to determine its strengths and drawbacks in a region where few surface meteorological observations currently exist. ERA-Interim with its moderately high spatial resolution is the only reanalysis available that could be applicable to this narrow region of about 400 km in the E-W direction over the Andes. In particular, we focus on the latitude band 30°S–37°S (Figure 1), where winter snowfall is crucial for water availability for human consumption and agriculture.

2. Data Availability and Analysis Methodology

The lack of meteorological information over the Andes has always been an issue when carrying out climate studies in the region. In the last three decades the National Weather Services from Argentina and Chile

Table 1. Data Sets Analyzed in This Study

Data Set	Resolution	Temporal Domain
GPCC v6	0.5° × 0.5°	1901–2010
CRU TS3.21	0.5° × 0.5°	1901–2012
University of Delaware	0.5° × 0.5°	1900–2010
GPCP v2.2	2.5° × 2.5°	1979–2010
TRMM v7 3B42	0.25° × 0.25°	1998–2012
ERA-Interim reanalyses	0.75° × 0.75°	1979–2012

have closed a considerable number of meteorological stations there. A national effort was started in Argentina in 1990 to monitor hydrological resources in the country, and a number of meteorological and hydrological stations have been installed on several rivers. At elevated sites, only a few stations were installed that measure snow water equivalent from snow pillows, replacing the previous direct snow measurements. Although these improvements are helpful, the spatial coverage is still poor in regions of complex terrain and there is a need for meteorological stations at high elevations. Figure 1 shows the location of the region selected for this study and clearly highlights the steepness of the Andes at this latitude and the proximity to the Pacific Ocean. In the figure, the box between 30°–37°S and 72°–69°W is highlighted and named SCA from now on.

We have selected monthly gridded variables of some of the observational and satellite data sets for southern South America to determine which one can be considered most representative of the climate of the region. Some of their characteristics are summarized in Table 1, and more details are provided here:

1. *Climate Research Unit (CRU), University of East Anglia: CRU TS3.21* [*Harris et al*., 2014]. This monthly gridded data set spans the period 1901–2012 and has a resolution of 0.5 × 0.5°. The variables near-surface temperature and precipitation were analyzed.
2. *Global Precipitation Climatology Center (GPCC), WMO/DWD*. This data set includes monthly, land surface precipitation from rain gauges built on GTS-based and historic data [*Becker et al*., 2013; *Schneider et al*., 2011]. The GPCC version 6.0 is available at spatial resolutions of 0.5, 1, and 2.5° for the period 1901–2010. The 0.5° version was used in this study.
3. *University of Delaware's data set (UDEL)*. Version 3.01 of this data set is from monthly global gridded high-resolution station (land) data. It is available at a 0.5 × 0.5° resolution for the period 1900–2010. Both air temperature and precipitation were used in this study.
4. *Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis, NASA*. Product 3B42 V7 provides an estimate of daily combined microwave-IR-gauge precipitation on a 0.25 × 0.25° grid around the globe between 50°N and 50°S from 1998 to the present [*Huffman et al*., 2007].
5. *Global Precipitation Climatology Project data set (GPCP)*. A monthly precipitation data set [*Adler et al*., 2003] that combines ground-based observations and satellite precipitation data into 2.5 × 2.5° global grids. It covers the period from 1979 to 2010.

The period 1979–2010 was selected since it is the maximum period that ERA-Interim and the observational databases have in common, except for TRMM since it only extends back to 1998. Sometimes TRMM or GPCP are left out from the comparison with other data sets.

As part of the methodology, we have defined the period June to September (JJAS) as winter (rather than only 3 months), since September values are similar to June values as shown by the annual cycle of the altitude of the 0° isotherm between two stations on each side of the Andes (not shown). *Masiokas et al*. [2006] also used the same 4 month period in their study of snowpack in the region. Daily radiosonde data were downloaded for this analysis from the webpage of the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html) for two stations in Chile and Argentina. The radiosonde station Quintero (32.78°S, 71.53°W, 3 m) in Chile was relocated approximately 100 km south along the coast of Chile in August 1999 and renamed Santo Domingo (33.65°S, 71.61°W, 75 m). Unfortunately, the stations did not coexist, so there is no overlapping period available to evaluate possible differences due to location. A Student's *t* test was applied to the altitude of the 0° isotherm, seasonal means, to determine homogeneity in the series. There is no statistical difference between the variances; however, the means do not belong to the same population, at an annual basis and for every 4 month period except from March-April-May-June. For this reason a single time series cannot be constructed without a correction. The time series of the height of the 0° isotherm in Santo Domingo showed systematically lower values than in Quintero, so we corrected the latter series with the monthly differences of the mean between the two series. We used the station Mendoza (32.83°S, 68.77°W, 704 m) in Argentina east of the Andes, with data available since 1976 but with more than 10 years of missing data especially in winter months. The 0°C temperature was identified in every daily profile, and the highest altitude was selected where this value was

Table 2. Meteorological Stations Used[a]

Name	Latitude	Longitude	Elevation (m)	Available Period	Source
Mendoza	−32.83	−68.77	704	1961–2012	SMN
San Rafael	−34.57	−68.40	748	1961–2012	SMN
Malargüe	−35.50	−69.57	1425	1961–2012	SMN
Santiago	−33.38	−70.78	475	1961–2012	DMC
Concepción	−36.77	−73.05	75	1961–2012	DMC
Quintero	−32.78	−71.53	3	1975–1999	UW
Santo Domingo	−33.65	−71.61	75	1999–2013	UW

[a] SMN: Servicio Meteorológico Nacional, Argentina; DMC: Dirección Meteorológica de Chile, Chile; UW: University of Wyoming, USA.

found. In most of the cases 0°C was not reported at one of the standard levels, so a linear interpolation between the nearest levels was performed.

We selected the latest high-resolution reanalysis from the ECMWF, known as ERA-Interim [*Dee et al.*, 2011], to assess its performance against gridded observational data sets. Because of the moderately high horizontal resolution of ERA-Interim (0.75° × 0.75° horizontal resolution and 37 vertical levels), it is the best reanalysis that can be used in the region of interest that rises from sea level to over 6000 m in less than 300 km. Several aspects have now been improved in ERA-Interim from the previous ERA-40 reanalysis [*Uppala et al.*, 2005]: 6-hourly, four-dimensional variational analysis (4D-var); better formulation of background error constraint; new humidity analysis; improved model physics; quality control of data drawing on experience from ERA-40; variational bias correction of satellite radiance data; and other improvements in bias handling and more extensive use of radiances [*Simmons et al.*, 2007; *Uppala et al.*, 2008; *Dee and Uppala*, 2009]. Data from this reanalysis were originally created starting from 1989, but these were recently extended back to 1979 and these are continuously updated forward in time. Monthly 2 m temperature, temperature from 1000 to 200 hPa, and surface precipitation are analyzed for the period 1979–2010. Temperature is derived from assimilated observations (satellite data and surface reports from land stations, ships, buoys, aircrafts, dropsondes, and radiosondes) while precipitation estimates are produced by the forecast model.

Finally, we have calculated the areal mean of precipitation in the SCA box and studied the temporal series from the gridded data sets and the reanalysis. When averaging data from ERA-Interim and TRMM over SCA box, grid points over the ocean were excluded using their land-sea mask available for each data set. The data from five meteorological stations from Chile and Argentina are also used to evaluate the temporal variability of all data sets. The station characteristics are shown in Table 2, and their location relative to the high Andes can be seen in Figure 1. Monthly precipitation and temperature data were obtained from the National Weather Services of Argentina (Servicio Meteorológico Nacional) and Chile (Dirección Meteorológica de Chile) for records longer than 30 years.

3. Results

3.1. Precipitation

3.1.1. Southern South America

The spatial distribution for the mean precipitation in winter (JJAS) for all databases in the period 1979–2010 (except for TRMM: 1998–2010) and the differences, calculated as ERA-Interim minus each of the observational data sets, are shown in Figure 2. When calculating the differences, all databases were interpolated into the ERA-Interim grid. All data sets show the winter maximum over the Patagonian Andes and the southern central Andes. A secondary winter maximum is located over southeastern Brazil, and the data sets all agree on its position, also consistent with previous studies using different periods and databases [e.g., *Garreaud*, 2009; *Boulanger et al.*, 2005; *Grimm et al.*, 2000].

Note that while GPCP captures the position of the maxima, it is not useful for regional studies due to its coarse resolution. However, the added value of this data set is that it combines in situ data over land with satellite precipitation estimates so it provides information from over the ocean. The TRMM data set is crucial in supplying much needed spatial coverage, which is in turn very valuable to assess the performance of the ERA-Interim reanalysis; however, the drawback is its limited length of time for climatological studies. A broad

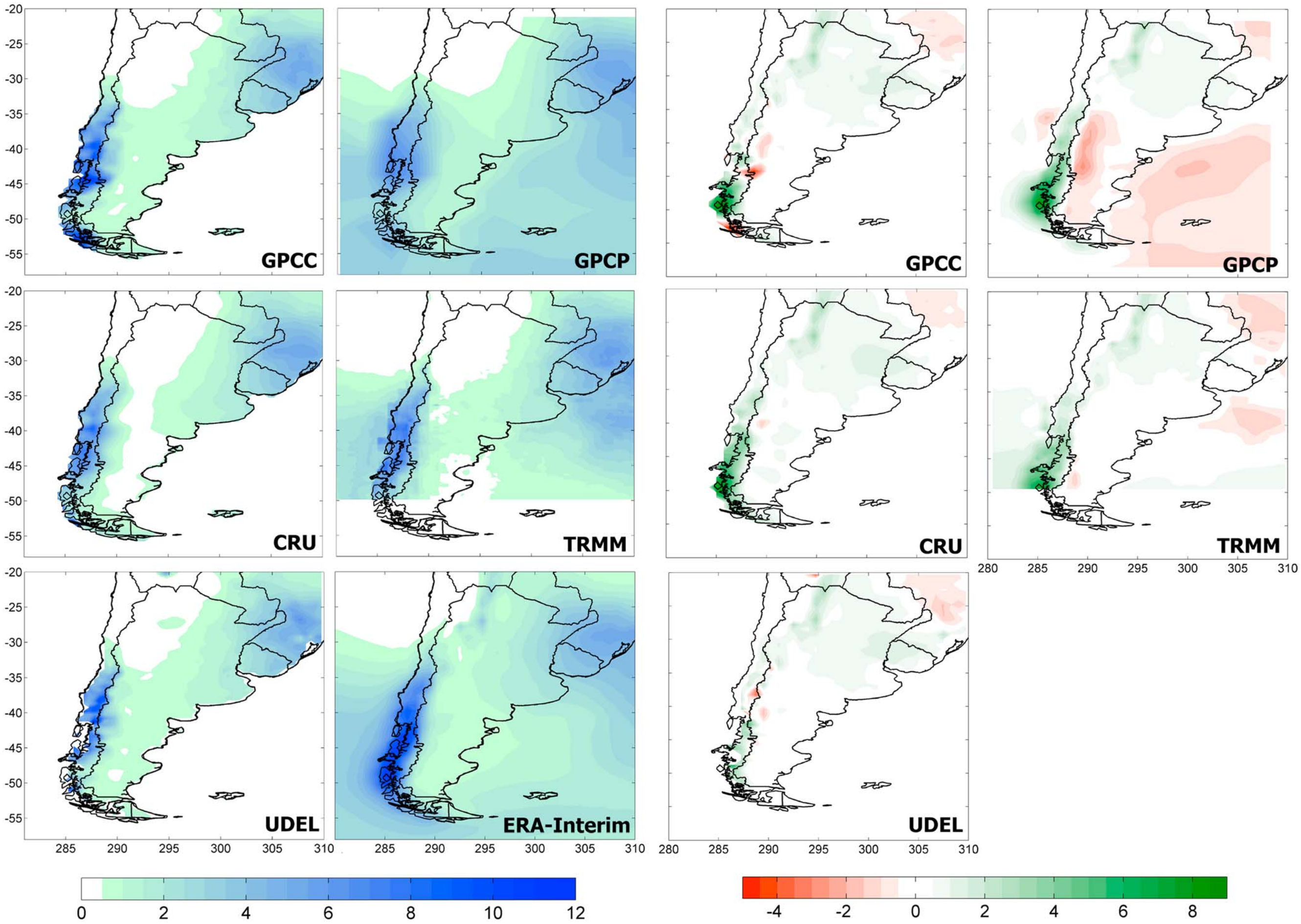

Figure 2. (left) Mean precipitation (mm/d) between June and September for the period 1979–2010 for the different databases. (right) Difference between ERA-Interim and the different data sets. TRMM database in the period 1998–2010.

comparison of ERA-Interim with all the other databases indicates that the reanalysis satisfactorily represents the spatial distribution of winter precipitation. Note, however, that ERA-Interim shows precipitation where none of the others data sets do in central and northwest Argentina (approximately between −20°S and −30°S and around 67°W) and this is shown as an overestimation of precipitation in the differences figures. In the summer season (figure not shown), the overestimation over this region is more evident. The biggest differences in magnitude between ERA-Interim and the rest of the databases are found in the south of Chile where ERA-Interim overestimates winter precipitation. In the southwest of Argentina, some data sets present higher values of precipitation than the reanalysis.

Figure 3 shows the temporal correlations between ERA-Interim and every data set for the period 1979–2010. A Student's *t* test was performed, and significant correlations at 95% level of confidence are marked with crosses. All data sets were regridded into ERA-Interim resolution, and the correlation coefficient between every grid point was calculated. A generalized pattern of significant positive correlations is found in every data set, except with the TRMM database. There is a lack of correlation in northwest Argentina consistent with the overestimation seen in the spatial distribution of precipitation of Figure 2.

3.1.2. Southern Central Andes Region

We now focus on the region of the southern central Andes that was studied by *Viale and Nuñez* [2011]. In their study, they analyzed precipitation during the period 1970–1976, from April to September, corresponding to the period of the most dense rain gauge network available over the mountains. Their Figure 3a shows the spatial distribution of accumulated precipitation for the season April–September over the Andean region between 30° and 37°S interpolated from 78 stations in Argentina and Chile, including the high-elevation

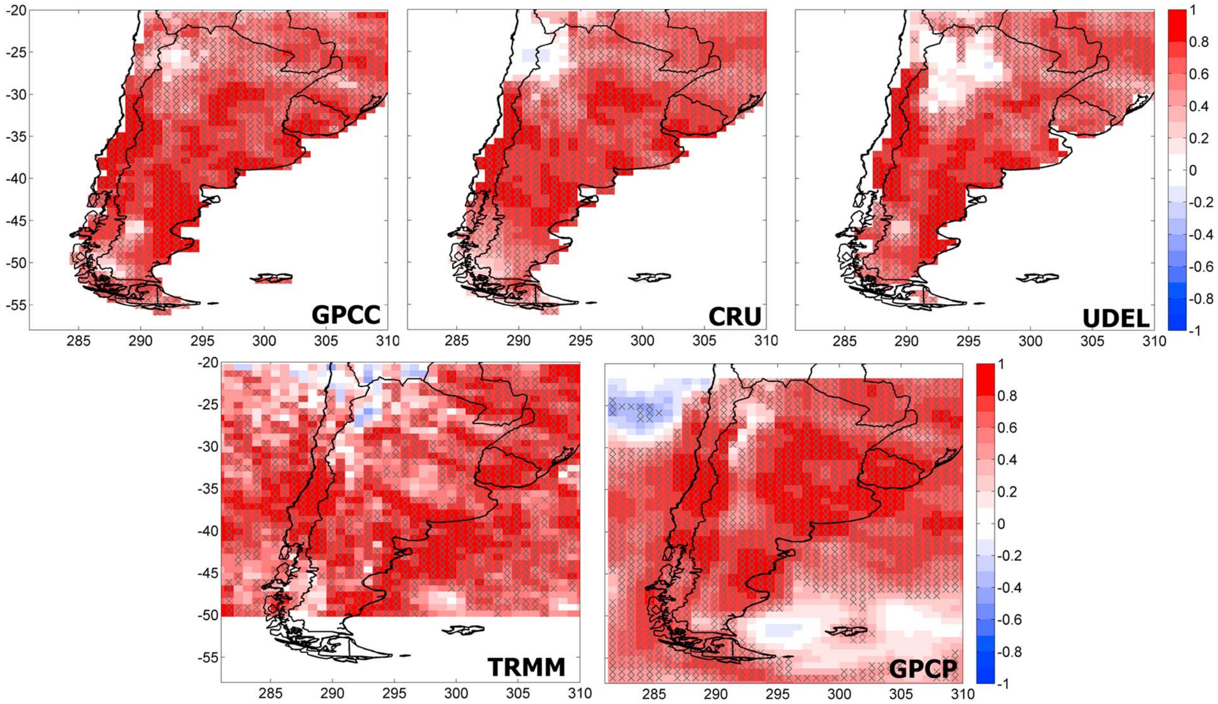

Figure 3. Correlations between winter (JJAS) precipitation for every data set and ERA-Interim for the period 1979–2010. Correlations with TRMM data set were calculated over the period 1998–2010. Significant correlations (95% level) are shown with crosses.

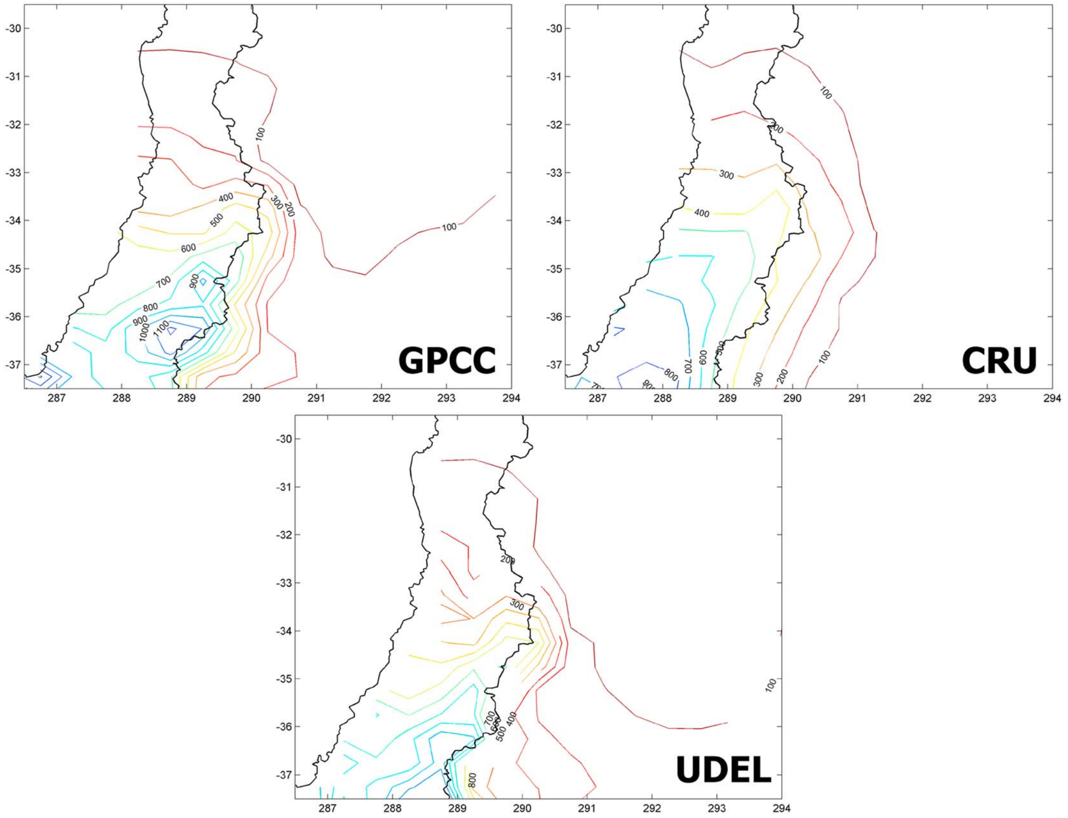

Figure 4. April–September accumulated precipitation (mm) for the period 1970–1976 for GPCC, CRU, and UDEL databases. Intervals between consecutive contours: 100 mm.

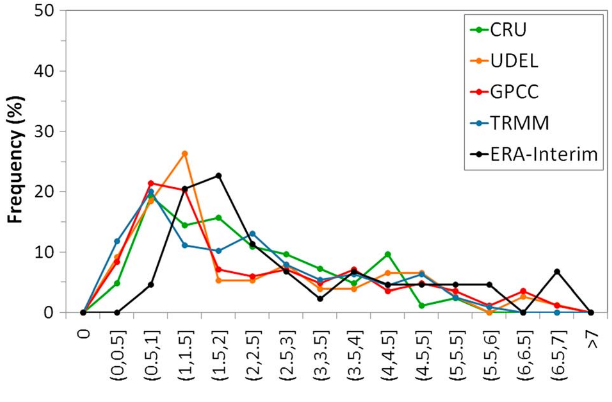

Figure 5. Frequency distribution of JJAS mean precipitation (mm/d) for 1979–2010 in the SCA box.

stations that were discontinued in the 1980 decade. We have produced here (Figure 4) a comparable spatial distribution for the three gridded data sets that have data in the same period: CRU, GPCC, and UDEL. The figure shows that GPCC locates the maximum as in *Viale and Nuñez* [2011], whereas CRU and UDEL show the maximum precipitation shifted to the south. The magnitudes are also well represented by GPCC. Note that CRU does not capture the east-west gradient in precipitation at the border between Argentina and Chile. An important factor that should be considered when analyzing gridded data sets is the number of stations used in gridding. The number of stations per grid point was available online for GPCC (in the website http://kunden.dwd.de/GPCC/Visualizer) and for CRU. We have compared them in the southern central Andes region. For example, in the year 1974, the number of stations used by GPCC was 102 and only 41 for CRU, whereas *Viale and Nuñez* [2011] used 78 stations. This difference in the number of stations is reflected in the detailed spatial distribution shown by GPCC. Consequently, we conclude that the GPCC data set reproduces more accurately the spatial distribution determined from the best station observations available in the region for 1970–1976.

Both data sets, GPCC and CRU, have experienced a dramatic decrease in the number of stations considered so that by 2010, only 18 stations were included in the GPCC data set and only 12 in the CRU data set. It should be noted that these decreases in the number stations used by the different data sets may introduce an unwanted bias in the estimates of trends over several decades. We noted above that the CRU spatial distribution does not locate the magnitude over the Andes correctly but the regional amount of precipitation is similar to *Viale and Nuñez* [2011]. Hence, even though GPCC showed best agreement with the detailed study by *Viale and Nuñez* [2011], we recommend the CRU data set for estimating precipitation trends when considering the whole region.

Figure 5 shows the frequency distribution of mean 1979–2010 winter precipitation for every data set over the SCA region. GPCP was left out of this analysis since it has very few grid points over this box. Data over the ocean were excluded from ERA-Interim and TRMM using their land-sea mask. All the data sets agree on the shape of the left tail of the histogram. Values smaller than 1 mm/d are found in the northeastern side of the box in every data set, where ERA-Interim shows precipitation greater than 1 mm/d. The maximum precipitation is situated in the southwest corner of the SCA box, where ERA-Interim shows larger values than the other data sets and it is reflected in the right tail of the distribution. UDEL and GPCC present almost the same distribution, while CRU shows more similarities with TRMM. GPCC, CRU, and TRMM present their mode in 1 mm/d, and UDEL in 1.5 mm/d. The distribution of ERA-Interim is shifted to the right, with the most probable value in 2 mm/d and an overestimation of high values. It also shows a greater standard deviation compared to CRU data set.

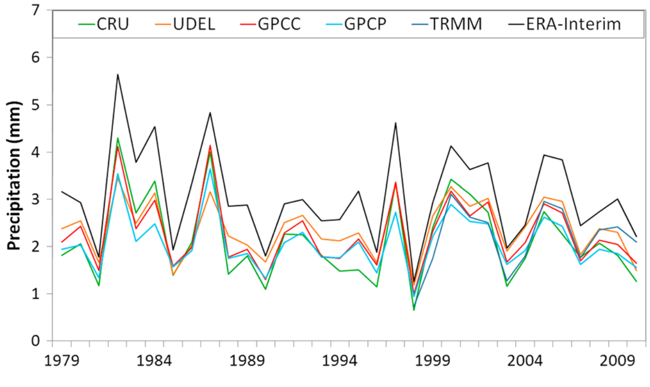

Figure 6. JJAS mean precipitation (mm/d) averaged over the SCA region.

In order to study the interannual variability the spatial average of precipitation for the SCA box was calculated, and the time series of the winter areal mean for the six data sets in the period 1979–2010 is shown in Figure 6. ERA-Interim captures the interannual variability, but it tends to show larger values than the observational data sets over the entire period. In the last decade, the time

Table 3. Correlation Coefficients Between JJAS Precipitation and the Different Data Sets in SCA Region for the Period 1979–2010[a]

	ERA-Interim	CRU	GPCC	UDEL	GPCP	TRMM
ERA-Interim	1	-	-	-	-	-
CRU	0.95	1	-	-	-	-
GPCC	0.95	0.96	1	-	-	-
Udel	0.92	0.91	0.93	1	-	-
GPCP	0.94	0.95	0.99	0.92	1	-
TRMM	0.94	0.84	0.89	0.83	0.88	1

[a] Correlations with TRMM were calculated for the period 1998–2010. A Student's *t* test was applied with 95% significance. All correlations resulted significant.

series from TRMM shows a coherent interannual variability although in some years, it shows indicates lower values of winter precipitation than the rest of the in situ data sets. In the Peruvian and Bolivian Andes, TRMM has been shown to underestimate monthly and annual precipitation [*Scheel et al*., 2011]. Errors in the spaceborne precipitation estimates are likely due to the complexity of the terrain and the presence of ice or snow in the surface.

The correlations between mean winter precipitations in every data set are presented in Table 3. Note that all the correlations were calculated over the period 1979–2010 except the correlations with the TRMM database that were calculated for the period 1998–2010. Almost all correlations are higher than 0.9, implying broad agreement in the representation of interannual variability. In particular, ERA-Interim is well

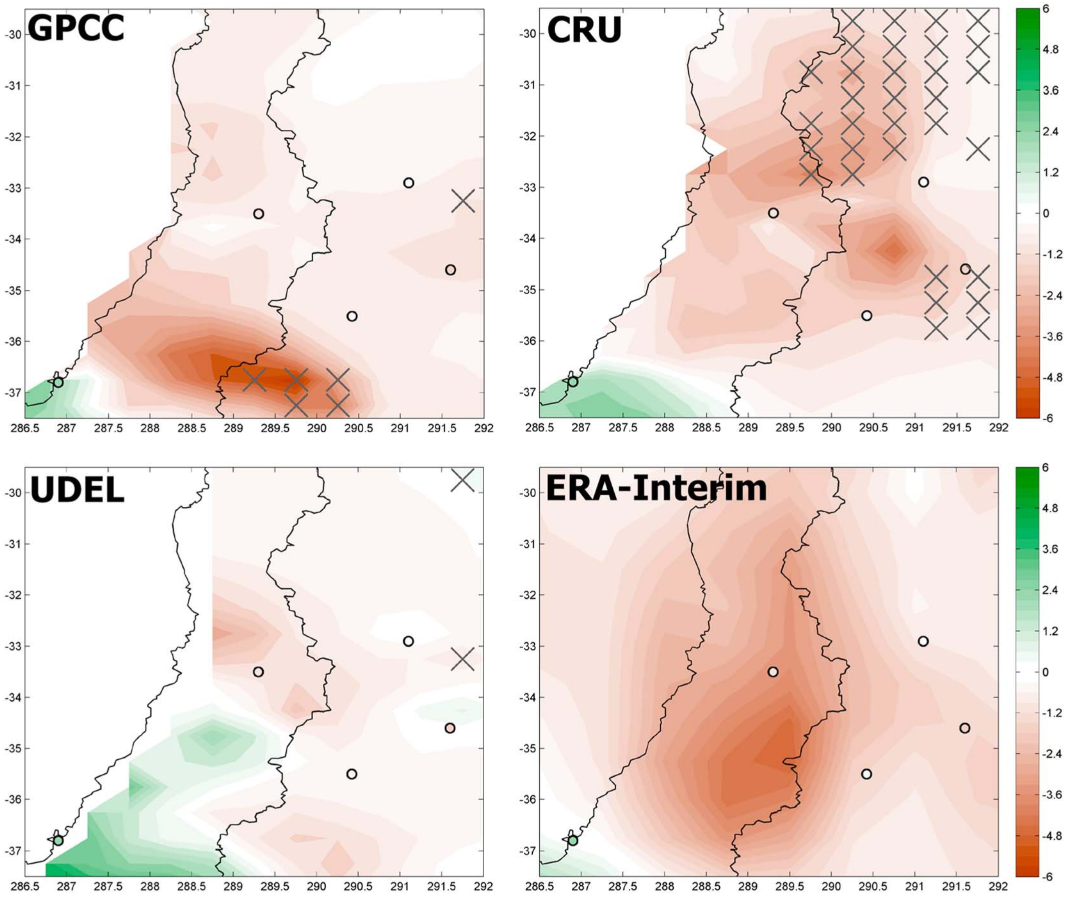

Figure 7. Winter precipitation linear trend (mm/yr) for the period 1979–2010. Crosses indicate significant trend at 95% confidence with a Student's *t* test.

Table 4. Correlation Coefficients Between Every Database's JJAS Precipitation in SCA and El Niño 3.4 Index in JJAS for the Period 1979–2010[a]

Database	*r*
CRU	**0.48**
UDEL	**0.52**
GPCC	**0.56**
GPCP	**0.53**
TRMM	0.30
ERA-Interim	**0.48**

[a] Correlation with TRMM was calculated for the period 1998–2010. A Student's *t* test was applied with 95% significance. Significant correlations are highlighted in bold.

correlated with observational data sets, especially with GPCC and CRU in this box covering the southern central Andes region.

Linear trends were calculated for every grid point of the GPCC, CRU, UDEL, and ERA-Interim data sets and the five meteorological stations in Chile and Argentina in the SCA region for the period 1979–2010 (Figure 7). GPCC, CRU, and ERA-Interim agree, showing a generalized pattern of decreased precipitation over almost the entire region with positive values in the southwest corner of the region. Note that on the Chilean side, except for UDEL, precipitation has decreased according to every data set as has been shown in previous studies [*Quintana and Aceituno*, 2012; *Haylock et al*., 2006; *Minetti et al*., 2003]. The linear trends of individual meteorological stations were not statistically significant. We have compared them with their nearest grid point of ERA-Interim, and they show agreement in the sign of the trends though the reanalysis presents somewhat larger magnitudes. The same occurs with CRU and GPCC, but opposite trends are found when comparing stations Mendoza and San Rafael with UDEL. When calculating trends with these interpolated data sets, it should be kept in mind that the number of meteorological stations has decreased during the period considered in this study. For example, in 1979, 98 stations in this region were used by GPCC to interpolate precipitation while at the end of the period only 18 stations were used. CRU also decreased the number of stations over this area from 32 in 1979 to 12 in 2010. Information on the number of stations used was not found for the UDEL data set.

The influence of the El Niño–Southern Oscillation in different hydroclimatic variables in the region has been widely studied by various authors [*Montecinos and Aceituno*, 2003; *Rutlland and Fuenzalida*, 1991; *Compagnucci and Vargas*, 1998]. A further analysis to assess the validity of the interannual variability of precipitation in ERA-Interim is to determine whether the reanalysis captures the ENSO signal. Correlations between winter precipitation in the SCA box for the different databases and the Niño 3.4

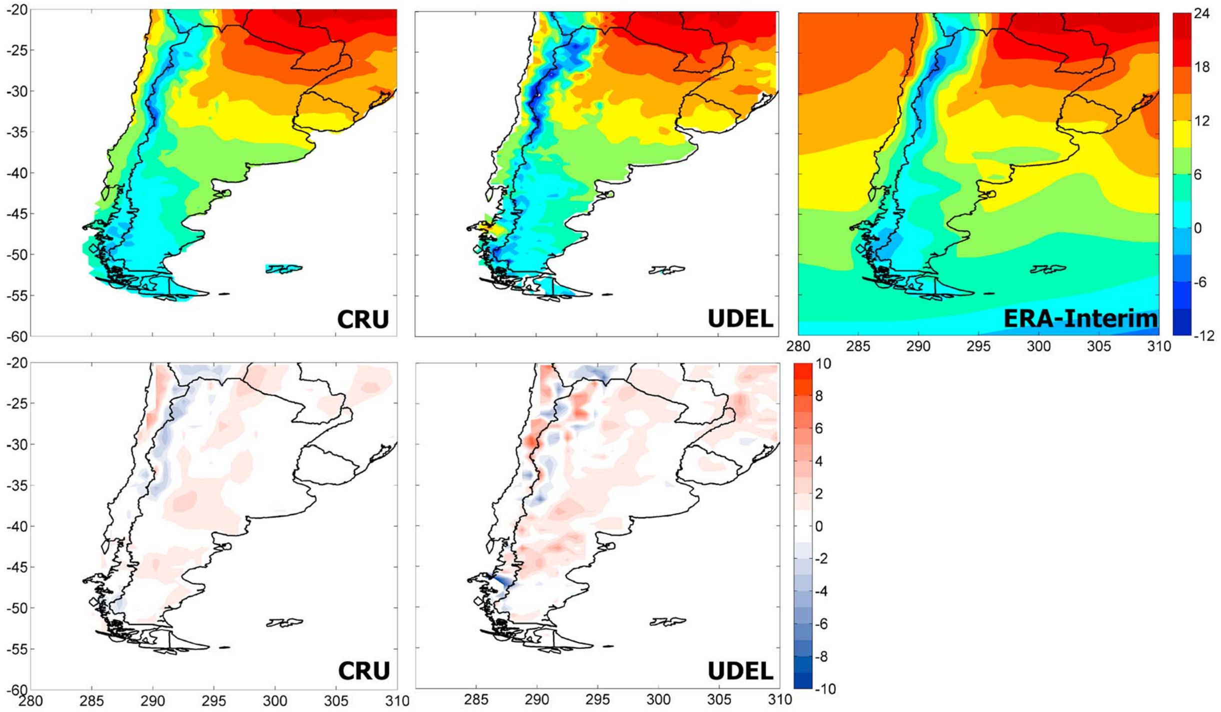

Figure 8. (top) Mean temperature (°C) between June and September for the period 1979–2010 for the different databases. (bottom) Difference between ERA-Interim and the different data sets.

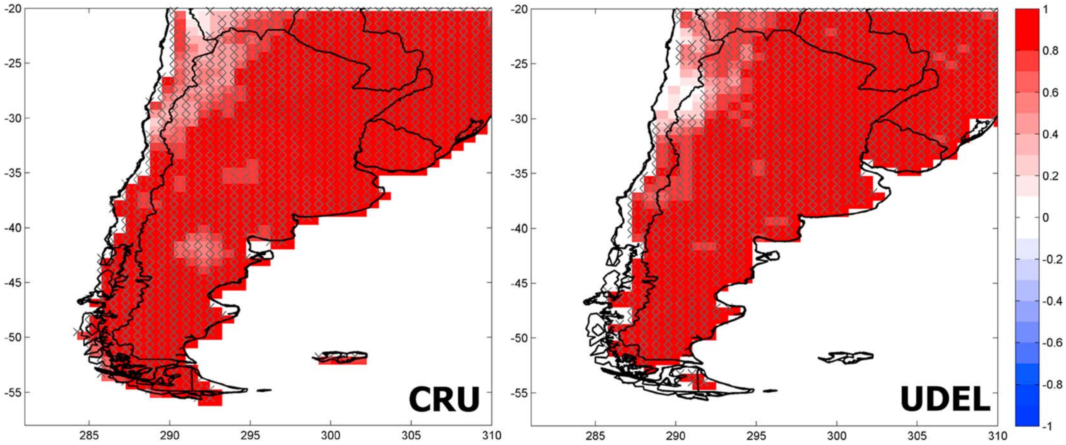

Figure 9. Spatial correlations between winter (JJAS) temperature for every data set and ERA-Interim for the period 1979–2010. Significant correlations (95% level) are shown with crosses.

index were calculated for the period 1979–2010 (Table 4). A Student's *t* test was applied with a 95% level of significance. All correlations were significant at this level except for the TRMM database. The results from these databases indicate an excess of precipitation in the region during the El Niño phase of the Southern Oscillation, in agreement with previous studies. Therefore, it shows that ERA-Interim captures the most important interannual variability mode in this region. Although a relationship between hydroclimatic variables on the southern central Andes region and the Pacific Decadal Oscillation was suggested by previous studies [*Masiokas et al*., 2010, 2006], in this study connections with the Pacific Decadal Oscillation index are not evident from the correlation coefficients (results not shown).

3.2. Temperature

Figure 8 shows the spatial distribution of 1979–2010 mean winter temperatures from ERA-Interim, CRU, and UDEL data sets and the differences between them. ERA-Interim shows the minimum of temperature over the highest sector of the Andes in agreement with the observational data sets. UDEL indicates lower values than the others in this high elevated region. The south-north gradient in the east sector of the region is also present both in reanalysis and gridded observational data. The differences between ERA-Interim and CRU show that the reanalysis underestimates temperature over the Andes between 20° and 35°S and overestimates on the north of Chile and the center of Argentina. Differences with UDEL show a less clear pattern over the Andes, but the same overestimation in central Argentina is evident.

Temporal correlations of winter temperature between ERA-Interim, CRU, and UDEL for the period 1979–2010 are presented in Figure 9. Note the general pattern of positive, significant correlations with only smaller values found in northwest Argentina, the same region where precipitation correlations are almost zero.

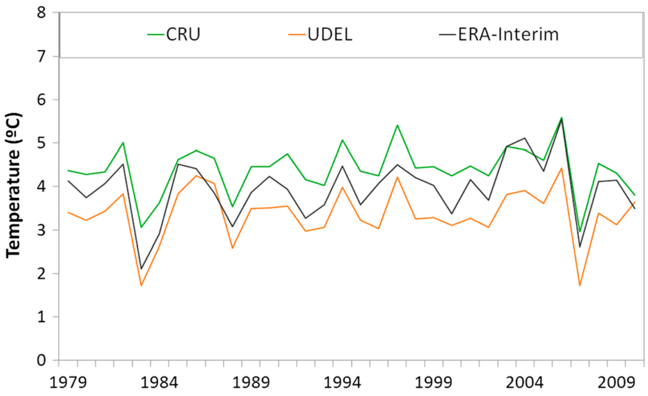

Figure 10. Mean winter JJAS temperature averaged over the SCA region.

The mean winter temperature averaged over the SCA region is shown in Figure 10 for the three gridded databases. During almost the entire period UDEL shows systematically lower values than CRU and ERA-Interim in most of the years. Reanalysis data have more coincidences with CRU, especially in the last decade, and, overall, ERA-Interim satisfactorily captures the interannual variability of temperature. Correlations between ERA-Interim winter temperature in the SCA region and the observational data sets for the period 1979–2010 (not shown) are

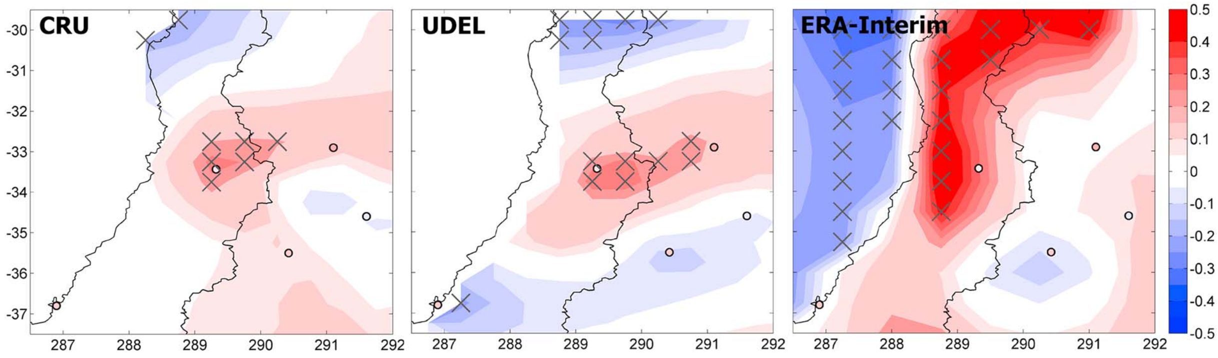

Figure 11. Winter temperature linear trend (mm/yr) for the period 1979–2010. Crosses indicate significant trend at 95% confidence.

also high (around 0.9) and significant at the 95% level, although slightly lower than those for precipitation. Correlation between ERA-Interim and CRU is higher than correlation with UDEL.

Linear trends were calculated for every grid point from UDEL, CRU, and ERA-Interim for the winter temperature and meteorological stations and are presented in Figure 11. Both CRU and UDEL show similar patterns, with significant trends in almost the same region. Negative trends appear in the northern and southern parts of the region in the UDEL data set. ERA-Interim shows strong positive trends over Chile, opposite to the other data sets, and a cooling in the southern part on the Argentinean side. The comparison between individual stations and their nearest grid point in the data sets shows that CRU adequately represents the lee side trends (both in sign and magnitude) and UDEL shows values opposite of those from San Rafael. All data sets overestimate the trend in Santiago. Over the ocean near the Chilean coast, ERA-Interim indicates a significant cooling in the last three decades consistent with the results of *Falvey and Garreaud* [2009] who found a cooling in the sea surface temperatures along the coast of Chile from two data sets: ERSST, NOAA (2° spacing), and HadISST, Hadley Center (1° spacing).

3.3. Vertical Structure: Comparison ERA-Interim With Radiosondes

We have calculated the height of the 0° isotherm from the ERA-Interim reanalysis to evaluate the performance of the reanalysis against radiosonde data at stations on both sides of the Andes. The nearest grid point to each radiosonde station was selected from the reanalysis, and the monthly height of the 0° isotherm was obtained by linear interpolation between the smallest positive and negative observed values (on average an interpolation over 600 m).

Figure 12 shows the winter time series of the corrected station Santo Domingo, station Mendoza, and the ERA-Interim grid points closest to each station. ERA-Interim slightly overestimates the radiosonde values, but the interannual variability is adequately represented. East of the Andes (station Mendoza) the comparison again indicates that the overall interannual variability by the ERA-Interim is well represented, but some particular years indicate large differences (some hundreds of meters), which could be a result of several years of missing data at station Mendoza early in the 21st Century. In summary, although some differences are observed (particularly in Mendoza), the time series from ERA-Interim can be reliably used as an indicator of interannual variability of the 0° isotherm in the region of study.

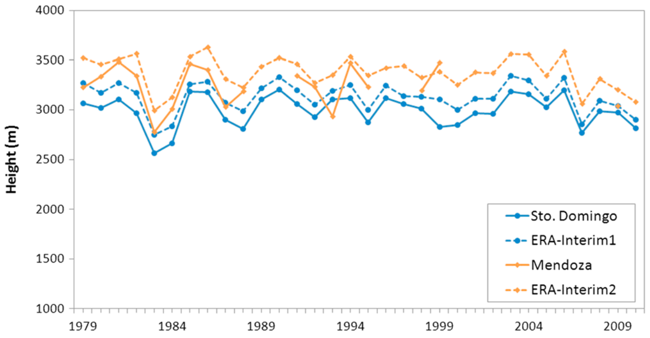

Figure 12. JJAS height of the 0° isotherm from the radiosonde stations Santo Domingo and Mendoza and their nearest grid point from ERA-Interim.

Linear trends were calculated for stations Santo Domingo and Mendoza and the respective nearest grid points from ERA-Interim for the period 1979–2010. None of the linear trends were statistically significant at the 95% level. The linear trend for station Santo Domingo was positive while the trend for ERA-Interim nearest grid point was negative. The linear trend of the nearest ERA-Interim grid point to Mendoza was negative, but it cannot be compared to radiosonde data due to the number of missing data. Given these results, caution should be exercised when estimating trends from single grid points in ERA-Interim.

Carrasco et al. [2005] analyzed the trends in the height of the 0°C isotherm from the radiosondes of Quintero and Santo Domingo for the period 1975–2001 and found an increase of 152 ± 4 m for the annual mean and 122 ± 8 m for the winter mean. The authors have suggested that this midtroposphere warming might be the main cause for glacier retreat in central Chile. In a later study, *Carrasco et al.* [2008] extended the period to 1958–2006 and found for the annual mean a positive trend of 2.3 m/yr for the complete period and 1.9 m/yr in 1978–2006. The results from these studies are not in agreement with our results that indicate no significant trends; however, note that the periods are not exactly the same and also that we have applied a correction to the series due to the change in location of one of the radiosonde stations that showed a systematic increase in the height of the 0°C isotherm at the new location. *Falvey and Garreaud* [2009] also studied temperature trends from radiosonde data along Chile for the period 1979–1998 and found a negative near-surface trend and a warming trend aloft, from approximately 1300 to 3500 m. In the midtroposphere (where the 0°C isotherm is normally found) the trend was found to be smaller and negative, which is more in agreement with our results.

4. Discussion

In the region considered in this study, labeled southern central Andes (SCA, see Figure 1), the bulk of the precipitation is associated with winter frontal systems and falls in the form of snow. This winter snow contributes to the mass balance of glaciers in the region and gives rise to the snowpack that upon melting, serves as the primary fresh water source for the populated adjacent areas in central-western Argentina and central Chile, motivating the study of the seasonal timescale, rather than shorter ones (e.g., daily). As mentioned before, the Andes steeply rise from only a few hundred meters above sea level (Mendoza in the eastern side is located about 747 m above mean sea level (amsl), Santiago in the western side is located 520 m amsl, both shown in Figure 1). While the highest mountain (Aconcagua at 6962 m amsl) is located within the SCA, the average altitude in the region is close to 4000 m amsl and about 150 km in the E-W direction at the latitude of the SCA box. This narrow and high topographic feature could almost be considered as a “delta function,” and such steep topography is very difficult to handle in most global models including reanalysis; therefore, the mean height of the Andes is decreased to avoid numerical instabilities. Both surface temperature and precipitation derived from models will be affected by this reduction in height. Moreover, since the E-W extent of the Andes is less than 200 km, the horizontal resolution of many gridded data sets makes them unsuitable to study the regional climate characteristics and evaluate its temporal evolution. We attempt in this study to evaluate these climate variables at the winter average scale in the SCA box, from global gridded data sets and ERA-Interim reanalysis. However, we need to answer the question: what is “ground truth” in this region?

The results of the study of *Viale and Nuñez* [2011] have been presented in the previous section to highlight the complexity of precipitation clearly influenced by the rugged topography. The study constitutes the most complete evaluation from surface observations to date. However, the study only covers 7 years (1970–1976), a period prior to the available high-resolution reanalysis. The strength of the study is having analyzed the period of highest station density in history for the SCA region. Unfortunately, many of the stations whose data were analyzed were discontinued soon after 1976. While we believe that the results of *Viale and Nuñez* [2011] could be considered as ground truth, there are a couple of problems with doing so. First, the short period analyzed does not allow a climatological study. Second, while we compare the gridded data sets GPCC, CRU, and UDEL for the same period and at the relatively high 0.5° × 0.5° resolution, we observe that the small-scale features shown in *Viale and Nuñez* [2011] appeared smoothed out. Both GPCC and UDEL show qualitative spatial better agreement with their results than CRU, which presents less spatial variability. One is tempted to select GPCC or even UDEL as gridded ground truth against which to compare the results from ERA-Interim. As mentioned in the previous section, we know that GPCC included 102 stations in 1970, more even that the total number of stations used in the observational study (78). But most of those stations were discontinued, so that the density of stations incorporated into the gridded databases decreased dramatically, down to only 18 stations by 2010. Unfortunately, we were unable to find the detailed numbers of stations as a function of time for UDEL, but given the more detailed spatial distribution, it must have also included many more stations than CRU in the 1970s. As an example, if GPCC or UDEL databases were used for a study of decadal variability of precipitation, the changes in the spatial variability due to the decrease in station density would affect the significance of the derived trends. Therefore, selecting as ground truth a gridded database that has fewer stations incorporated (such a CRU), but a more consistent overall number throughout the decades, while counterintuitive, may be considered a better approach and it is the one that we recommend.

After selecting CRU ground truth, we proceeded with the evaluation of ERA-Interim, focusing on the spatial pattern of the winter average and interannual variability in the SCA box. The analysis of the frequency distributions of the average winter precipitation from the gridded data sets and ERA-Interim (Figure 5) suggests several differences between them that should be taken into account. The first difference is a clear overestimation of ERA-Interim of the mode of the distribution of precipitation, as well as its standard deviation. In particular, if CRU is considered ground truth as we suggest, then the populations are different: CRU displays the mode at 1 mm/d while ERA-Interim shows it at 2 mm/d for the spatial average in the SCA box. Moreover, ERA-Interim shows a large underestimation of the cases with less than 1 mm/d, in clear contrast will all the gridded data set, not only CRU. The observational data sets all show broader distributions than ERA-Interim, and while some of the station data have been assimilated into ERA-Interim, clearly, there are other factors that are more important in the determination of the frequency distribution in this region. Another important difference is observed in the large-value tail of the distribution where ERA-Interim overestimates all gridded data sets for values larger than 5.5 mm/d. This overestimation can introduce a bias in climate studies in the region, and such analysis using ERA-Interim should be performed with care and conclusions have to reflect this potential bias. This overestimate in the large categories is most likely responsible for the overestimate of the winter average in the interannual variability shown in Figure 6. Note that the year-to-year variability is captured in the SCA box, but the magnitude from ERA-Interim is always larger than all gridded data sets, resulting in good correlations and significant at the 95% level (as shown in Table 3). The evaluation of trends from the gridded data sets in the box indicates than only CRU shows a large number of grid points in which the trend is significant (at 95%), further supporting the use of CRU as ground truth as was recommended earlier. In contrast, note that ERA-Interim shows virtually no significant trends in the SCA box from 1979 to 2010. This is a very important result and again supports our comment that the determination of trends from ERA-Interim for climate studies in the region should be accompanied with these caveats. Furthermore, studies of trends in the future from climate model simulations and the conclusions derived from those studies should be put into this context.

The analysis of the surface temperature from the gridded data sets CRU and UDEL and ERA-Interim shows different results from the discussion presented above. Temperature is a continuous variable and more likely that reanalysis would capture the observed spatial and temporal variability. There is no significant bias in ERA-Interim, as shown in Figure 10, where the reanalysis values are bounded by the gridded data sets and also display similar interannual variability. However, again the spatial analysis of trends brings out systematic differences in the SCA box. While both CRU and UDEL show significant positive trends only in the central region of the SCA box (between 32° and 35°S), ERA-Interim shows significant positive trends over land all along the Chilean coastline. In the northern regions of the box, the large positive trends in ERA-Interim are opposite to the significant cooling trends shown in both CRU and UDEL. Again, caution should be taken when analyzing these regions for trends in surface temperature. While there was no systematic bias in surface temperature, evaluation of the vertical structure of ERA-Interim does indicate a bias. The analysis of the 0°C isotherm from soundings at either side of the Andes (see Figure 12) indicates a systematic overestimate of the height in ERA-Interim. The height of the 0°C isotherm is related directly to the melting of snowfall in the high Andes. A systematic overestimate of a few hundred meters (200–300 m) as shown is important in the partition between solid and liquid in the reanalysis and in estimating the extent of the winter snowpack. Neither the observations nor reanalysis shows any significant trends in the height of the 0°C isotherm in the region.

5. Conclusions

The lack of long-term meteorological information has hampered efforts to study climate variability over the southern central Andes region. In this study we have compared different precipitation and temperature gridded data sets in order to evaluate the performance of the ERA-Interim data set and to establish which one might be more suitable in terms of spatial and temporal representations of the climate in winter, with focus on the Andes between 30° and 37°S. The observational data sets analyzed were CRU, UDEL, GPCC, TRMM, and GPCP. ERA-Interim satisfactorily represents the spatial distribution of winter precipitation but overestimates winter precipitation in central and northwest Argentina. The overestimation over northwest Argentina is more evident in the summer.

The gridded data sets of surface land precipitation (GPCC, UDEL, and CRU) were compared in the southern central Andes region with the results of the most detailed observational study to date, to determine which one could be considered ground truth. The study of *Viale and Nuñez* [2011] analyzed the in situ observations from a large number of stations in that region from the period 1970–1976, many of which have since been discontinued. The evaluation of the spatial distribution indicates that both GPCC and CRU are able to reproduce the results of *Viale and Nuñez* [2011]. However, both these data sets (GPCC and CRU) have experienced a dramatic decrease in the number of stations used, more significant in GPCC. Our results indicate that the decrease in the number of stations used by the different data sets may introduce an unwanted bias in the estimates of trends over several decades. Therefore, our evaluation not only included the spatial distribution but also this bias into account, to conclude that the CRU data set should be taken as ground truth against which ERA-Interim should be assessed.

The interannual variability in the SCA box was captured well by ERA-Interim; this variability is dominated by El Niño–Southern Oscillation, as has been reported by different authors. Significant positive correlations were found in all data sets (except TRMM, possibly affected by its shorter period of data) between the El Niño 3.4 index and JJAS precipitation in the SCA region, and ERA-Interim captures this mode of variability. However, the trends determined by ERA-Interim resulted not significant at the 95% confidence level, and studies focusing on trends should clearly include this caveat.

Winter temperature was also analyzed from the available data sets. The spatial pattern shows agreement between the CRU and UDEL databases and ERA-Interim, and the interannual variability from reanalysis is bounded by the gridded data. Note that UDEL shows systematic colder temperatures than CRU over the entire period. The analysis of the spatial distribution of trends indicates that ERA-Interim shows significant warming in a much larger region than indicated by CRU and UDEL. In particular, in the northern regions of the box, the large positive trends in ERA-Interim are opposite to the significant cooling trends shown in both CRU and UDEL.

The vertical structure of ERA-Interim in the region was evaluated using radiosonde data available on either side of the Andes (only one station on each side), compared with the nearest grid point of ERA-Interim. On the west side of the Andes, the reanalysis overestimates the altitude but captures the interannual variability. In Mendoza the radiosonde data indicate larger variability due to the amount of missing data, but it is illustrative of the representation of year-to-year variability exhibited by the ERA-Interim reanalysis.

In summary, we note that ERA-Interim can be used for climate studies in the selected region, as long as the following caveats are taken into account:

1. *Spatial distribution large scale*. ERA-Interim satisfactorily represents the spatial distribution of winter precipitation but overestimates winter precipitation in central and northwest of Argentina. The temperature field compares better with gridded data sets, with somewhat lower correlations in the subtropical-tropical Andes, most likely due to an underestimate of the mean height of the orography.
2. *Spatial distribution in the southern central Andes*. ERA-Interim exhibits a different frequency distribution than gridded data sets, overestimating the modal frequency, underestimating the frequency of low-intensity events (1 mm/d) and overestimating the frequency of large intensity events (>5.5 mm/d). The trends in precipitation determined using ERA-Interim were not significant. The interannual variability of the mean winter temperature in the region is represented well by ERA-Interim and the magnitude bounded by CRU and UDEL (which is systematically colder in the box). The positive trends estimated in surface temperature from ERA-Interim show significance in the northern regions of the SCA box, where gridded data sets indicate significant cooling.
3. *Height of the 0°C isotherm*. ERA-Interim overestimates the height by 200–300 m compared with radiosonde data, which could be important in the partition of liquid and solid precipitation and the estimation of the extent of the snowpack in the Andes. The interannual variability is adequately represented by ERA-Interim. Neither observations nor reanalysis shows any significant trends in the height of the 0°C isotherm in the region.

Acknowledgments
This work was funded by the Universidad de Buenos Aires through the UBA- 20020100100789 project, the Consejo Nacional de Investigaciones Científicas y Técnicas of Argentina through CONICET PIP 227 project, the Consejo Nacional de Ciencias y Tecnología through grant Sep-Conacyt 154729, and the Universidad Nacional Autonoma de Mexico. We acknowledge the institutions that made available the data sets used in this study. The GPCC precipitation, University of Delaware air temperature and precipitation, and GPCP precipitation data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. TRMM data were obtained from the IRI/LDEO Climate Data Library from the website http://iridl.ldeo.columbia.edu/. CRU data were obtained from http://badc.nerc.ac.uk. ERA-Interim data were obtained from the ECMWF Data Server. We thank the reviewers for the useful comments and suggestions on the manuscript.

References

Adler, R. F., et al. (2003), The version-2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, *4*, 1147–1167.

Becker, A., P. Finger, A. Meyer-Christoffer, B. Rudolf, K. Schamm, U. Schneider, and M. Ziese (2013), A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present, *Earth Syst. Sci. Data*, *5*, 71–99, doi:10.5194/essd-5-71-2013.

Boulanger, J.-P., J. Leloup, O. Penalba, M. Rusticucci, F. Lafon, and W. Vargas (2005), Observed precipitation in the Paraná-Plata hydrological basin: Long-term trends, extreme conditions and ENSO teleconnections, *Clim. Dyn.*, *24*, 393–413, doi:10.1007/s00382-004-0514-x.

Carrasco, J. F., G. Casassa, and J. Quintana (2005), Changes of the 0°C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century, *J.. Hydrol. Sci.*, *50*, 933–948, doi:10.1623/hysj.2005.50.6.933.

Carrasco, J. F., R. Osori, and G. Casassa (2008), Secular trend of the equilibrium-line altitude on the western side of the southern Andes, derived from radiosonde and surface observations, *J. Glaciol.*, *54*, 538–550, doi:10.3189/002214308785837002.

Carril, A. F., et al. (2012), Performance of a multi-RCM ensemble for South Eastern South America, *Clim. Dyn.*, *39*, 2747–2768, doi:10.1007/s00382-012-1573-z.

Compagnucci, R. H., and W. M. Vargas (1998), Inter-annual variability of the Cuyo rivers' streamflow in the Argentinean Andean mountains and ENSO events, *Int. J. Climatol.*, *18*, 1593–1609.

Dee, D. P., and S. M. Uppala (2009), Variational bias correction of satellite radiance data in the ERA-Interim reanalysis, *Q. J. R. Meteorol. Soc.*, *135*, 1830–1841, doi:10.1002/qj.493.

Dee, D. P., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*, 553–597, doi:10.1002/qj.828.

Falvey, M., and R. D. Garreaud (2009), Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006), *J. Geophys. Res.*, *114*, D04102, doi:10.1029/2008JD010519.

Garreaud, R. D. (2009), The Andes climate and weather, *Adv. Geosci.*, *22*, 3–11.

Gonzalez, M. H., and C. S. Vera (2010), On the interannual wintertime rainfall variability in the Southern Andes, *Int. J. Climatol.*, *30*, 643–657, doi:10.1002/joc.1910.

Grimm, A., V. Barros, and M. Doyle (2000), Climate variability in southern South America associated with El Niño and La Niña events, *J. Clim.*, *13*, 35–58.

Harris, I., P. D. Jones, T. J. Osborn, and D. H. Lister (2014), Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset, *Int. J. Climatol.*, *34*, 623–642, doi:10.1002/joc.3711.

Haylock, M. R., et al. (2006), Trends in total and extreme South American rainfall in 1960–2000 and links with sea surface temperature, *J. Clim.*, *19*, 1490–1512, doi:10.1175/JCLI3695.1.

Huffman, G. J., R. F. Adler, D. T. Bolvin, G. Gu, E. J. Nelkin, K. P. Bowman, Y. Hong, E. F. Stocker, and D. B. Wolff (2007), The TRMM multi-satellite precipitation analysis: Quasi-global, multi-year, combined-sensor precipitation estimates at fine scale, *J. Hydrometeorol.*, *8*, 38–55, doi:10.1175/JHM560.1.

Masiokas, M. H., R. Villalba, B. Luckman, C. Le Quesne, and J. C. Aravena (2006), Snowpack variations in the central Andes of Argentina and Chile, 1951–2005: Large-scale atmospheric influences and implications for water resources in the region, *J. Clim.*, *19*, 6334–6352, doi:10.1175/JCLI3969.1.

Masiokas, M. H., A. Rivera, L. E. Espizua, R. Villalba, S. Delgado, and J. C. Aravena (2009), Glacier fluctuations in extratropical South America during the past 1000 years, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *281*, 242–268, doi:10.1016/j.palaeo.2009.08.006.

Masiokas, M. H., R. Villalba, B. Luckman, and S. Mauget (2010), Intra- to multidecadal variations of snowpack and streamflow records in the Andes of Chile and Argentina between 30° and 37°S, *J. Hydrometeorol.*, *11*, 822–831, doi:10.1175/2010JHM1191.1.

Minetti, J. L., W. M. Vargas, A. G. Poblete, L. R. Acuña, and G. Casagrande (2003), Non-linear trends and low frequency oscillations in annual precipitation over Argentina and Chile, 1931–1999, *Atmósfera*, *16*, 119–135.

Montecinos, A., and P. Aceituno (2003), Seasonality of the ENSO-related rainfall variability in central Chile and associated circulation anomalies, *J. Clim.*, *16*, 281–296.

Quintana, J. M., and P. Aceituno (2012), Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30–43° S, *Atmósfera*, *25*, 1–22.

Rutlland, J., and H. Fuenzalida (1991), Synoptic aspects of the central Chile rainfall variability associated with the southern oscillation, *Int. J. Climatol.*, *11*, 63–76.

Scheel, M. L. M., M. Rohrer, C. Huggel, D. Santos Villar, E. Silvestre, and G. J. Huffman (2011), Evaluation of TRMM Multi-satellite Precipitation Analysis (TMPA) performance in the Central Andes region and its dependency on spatial and temporal resolution, *Hydrol. Earth Syst. Sci.*, *15*, 2649–2663, doi:10.5194/hess-15-2649-2011.

Schneider, U., A. Becker, P. Finger, A. Meyer-Christoffer, B. Rudolf, and M. Ziese (2011), GPCC full data reanalysis version 6.0 at 0.5°: Monthly land-surface precipitation from rain-gauges built on GTS-based and historic data, doi:10.5676/DWD_GPCC/FD_M_V6_050.

Simmons, A. J., S. Uppala, and D. P. Dee (2007), Update on ERA-Interim, *ECMWF Newslett.*, *111*, 5.

Solman, S. A., et al. (2013), Evaluation of an ensemble of regional climate model simulations over South America driven by the ERA-Interim reanalysis: Model performance and uncertainties, *Clim. Dyn.*, *41*, 1139–1157, doi:10.1007/s00382-013-1667-2.

Uppala, S. M., et al. (2005), The ERA-40 reanalysis, *Q. J. R. Meteorol. Soc.*, *131*, 2961–301, doi:10.1256/qj.04.176.

Uppala, S. M., D. P. Dee, S. Kobayashi, P. Berrisford, and A. J. Simmons (2008), Towards a climate data assimilation system: Status update of ERA-Interim, *ECMWF Newslett.*, *115*, 12–18.

Viale, M., and M. N. Nuñez (2011), Climatology of winter orographic precipitation over the subtropical central Andes and associated synoptic and regional characteristics, *J. Hydrometeorol.*, *12*, 481–507, doi:10.1175/2010JHM1284.1.