WEATHER OBSERVATIONS ACROSS THE SOUTHERN ANDES AT 53°S

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Abstract: Regional variations of weather pattern were analyzed along a west-to-east profile across the Southern Andes (53°S), one of the most pronounced climate-divides in the world. For the first time we present a meteorological record from an array of three automatic weather stations (AWS), operated by the authors, for the central part of the climate divide which, together with previously existing Chilean weather stations, complete the transect. These data cover a time period of 3 yr. from October 1999 until September 2002. Air temperatures along the profile are highly correlated. Annual precipitation drops from between 6000 mm and 7000 mm at sea level along the main divide of the mountains to only about 1000 mm at the eastern slopes of the Andes and to as little as 430 mm at Punta Arenas. The variations of rainfall with wind direction and synoptic weather types are markedly different between the central part of the Andes and Punta Arenas. At the center of the climate divide precipitation correlates positively with wind speed from the west, whereas at Punta Arenas, east of the Andes, higher rainfall rates occur with easterly air flow. It is assumed that this reflects the barrier effect of the mountain range of the Andes. The results indicate that in order to make references about present or past climatic variations in Patagonia, it is essential to consider the effect of changes in circulation patterns. [Key words: regional climate, Patagonia, Chile.]

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INTRODUCTION

Climate in southwest Patagonia can be described as cool and windy with a fairly small daily and seasonal temperature cycle (e.g., Zamora and Santana, 1979a; Casassa, 1985; Weischet, 1985; Endlicher, 1991a; Tuhkanen, 1992; Weischet, 1996; Coronato and Bisigato, 1998). Strong westerly surface winds are dominant due to limited friction within the west wind zone of the Southern Hemisphere, essentially because there is little land mass between 40°S and 60°S when compared to the Northern Hemisphere (Cerveny, 1998). The west wind zone in the Southern hemisphere forms a straight zonal band. There are no large continents with high mountain barriers that could generate perturbations of the mean air flow besides the southernmost Andes of South America and the mountain ranges of the Antarctic Peninsula (Hobbs et al., 1998). For that reason, the southernmost Andes provide a unique location to study climate and climate variations of the west wind drift between 40°S and 60°S. Proximity to the Antarctic continent and the Circum-Antarctic-Oceanic-Current cause the overall cool temperatures of Patagonia. Mean annual air temperature at Punta Arenas on the Strait of Magellan is only 6.5°C (Zamora and Santana, 1979b; Endlicher and Santana, 1988). Moreover, the presence of the cold Antarctic continent leads to a 15 hPA to 25 hPa stronger pressure gradient between the high latitudes and the subtropics of the Southern Hemisphere when compared to the Northern Hemisphere (Aceituno et al., 1993). In consequence, much higher wind speeds are encountered within the west wind zone of the Southern Hemisphere (Capel, 1983). Westerly winds are dominant throughout the region. The mountain range of the Andes, running north to south, form an orographic obstacle approximately perpendicular to the main air flow (Miller, 1976; Prohaska, 1976). Therefore, the mountains comprise one of the most extreme climate divides worldwide. The locations of weather stations used in this study are indicated in Figures 1 and 2. Figure 2 shows the orography across the western part of South America at 53°S. A profile of altitudes across the mountains at 53°S running from WNW to ESE is given in Figure 3.

The climate on the west side of the mountain range, within the mountains, and in the fjord zone differs markedly from the climate encountered on the lee side to the east. Rainfall shows a dramatic variation between the Pacific west coast and the leeward-side of the mountains (Endlicher, 1991b). At Faro Evangelistas, an island at 52°24'S, 75°06'W off the west coast, an annual precipitation of approximately 2600 mm is observed. Farther east but still on the west coast at Bahia Felix, this rises to 4025 mm. Punta Arenas—located at 53°S and to the east of the mountain range—only receives 430 mm of annual precipitation (Zamora and Santana, 1979a; Endlicher, 1991a).

Despite this strong spatial gradient of precipitation no measurements of climate parameters from permanently operated automatic weather stations (AWS) have been published earlier from the mountain range itself. Climatic conditions on the Southern Patagonia Icefield (SPI) obtained from short-term measurements and from models (Carrasco et al., 1998; Carrasco et al., 2000; Casassa et al., 2000) indicate comparatively moderate temperatures and precipitation exceeding 10,000 mm

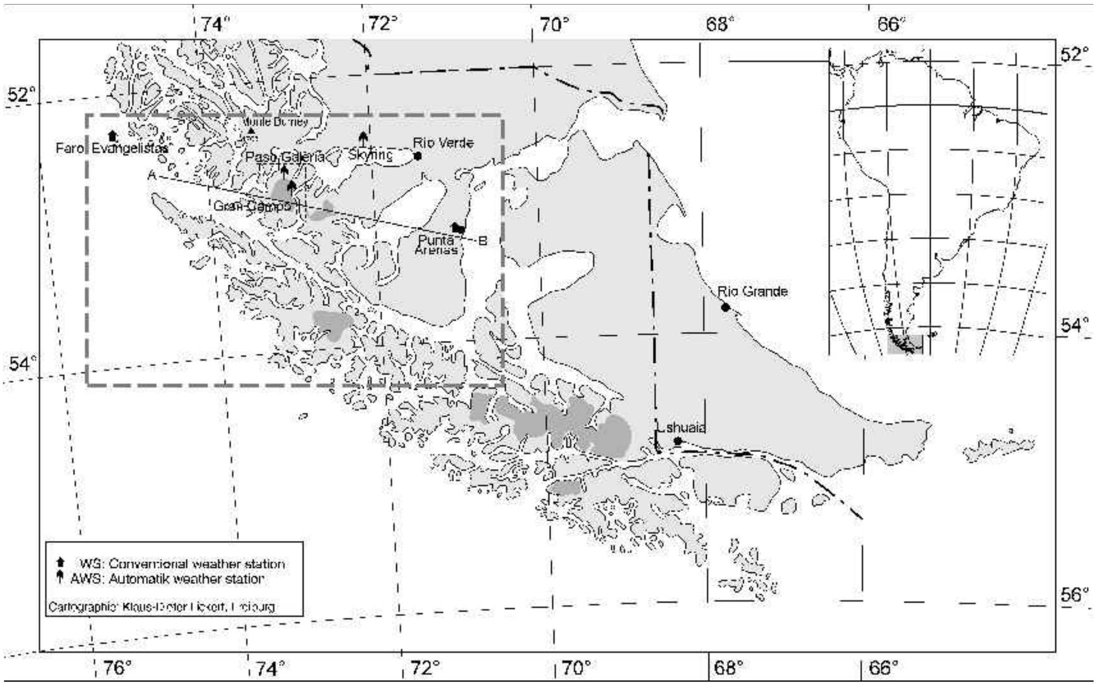

Fig. 1. Location map of AWS and meteorological stations used in this study: (1) Faro Evangelistas, (2) Paso Galería, (3) Gran Campo Nevado PB, (4) Seno Skyring, and (5) Punta Arenas JS. The large rectangle with the broken line denotes the region covered in Figure 2. The small rectangle corresponds to the area shown in Figure 12. The profile line in Figure 3 is given as a straight line from A to B (Cartography: D. Lickert).

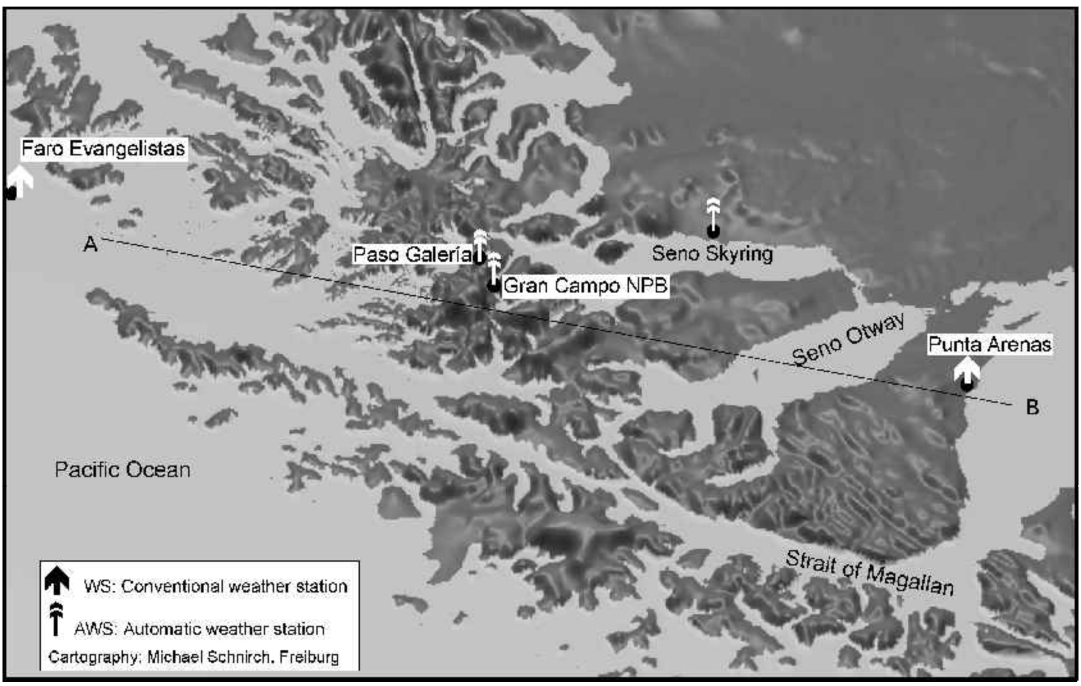

Fig. 2. Orography of southwest Patagonia. Data was obtained from the Global Land One-kilometer Base Elevation (GLOBE) Web site at http://www.ngdc.noaa.gov/seg/topo/report/report_.html (Cartography: M. Schnirch, Freiburg). The region shown in Figure 2 is denoted as a rectangle with a broken line in Figure 1. The profile line in Figure 3 is given as a straight line from A to B.

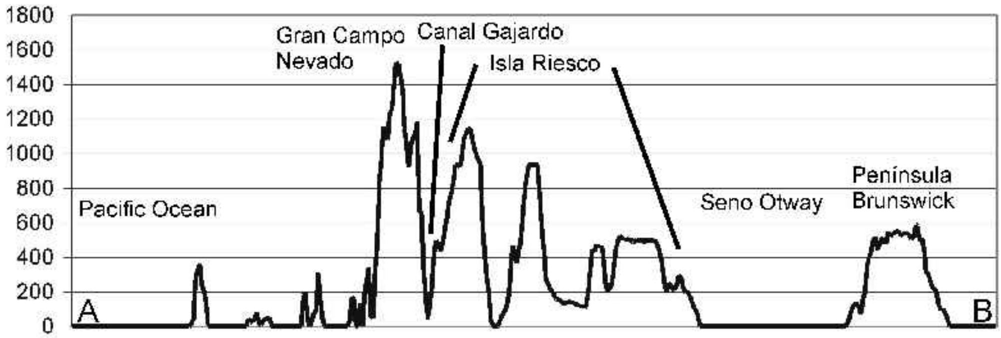

Fig. 3. Profile in meters across the Andes at 53°S; digital elevation data was obtained from the Global Land One-kilometer Base Elevation (GLOBE) Web site at http://www.ngdc.noaa.gov/seg/topo/report/report_.html. The profile line is indicated in Figures 1 and 2 as a straight line from A to B.

water-equivalent of annual snowfall. Long-term trends in temperature and precipitation data have been analyzed both for stations on the west and on the east side of the Andes (Rosenblüth et al., 1995, 1997; Ibarzabal y Donángelo et al., 1996; Carrasco et al., 2002) indicating that a warming trend to both sides of the Andes, and partly a decrease in precipitation on the west coast, have occurred over the last several decades. The temperature record of Punta Arenas compiled at the Instituto de la Patagonia at Punta Arenas from 1888 to 1998 does not indicate any significant warming trend. Most glaciers of the Gran Campo Nevado (53°S) show signs of a general retreat during the last century. The glaciers of SPI have also generally retreated during recent decades (Casassa et al., 2002). A better understanding of climate and especially temperature and precipitation fields are of great significance for the understanding of glacier mass balance in Patagonia. Furthermore, climate variability associated with variations of the position and the strength of the west wind zone are important to understanding past climate changes in the Holocene (McCulloch et al., 2000). However, modelling and interpreting climate variations of the west wind zone of the Southern Hemisphere are greatly hindered by the lack of data, especially from the mountain range of the Andes (Moreno, 2002).

This study presents the first measurements from AWS within the Andes at Gran Campo Nevado (GCN) (53°S, 72°W) and from the northern shore of Seno Skyring (Figs. 1 and 2). The data are compared and analyzed in conjunction with weather-station (WS) data from Punta Arenas and Faro Evangelistas.

MEASUREMENTS

Since October 1999 an automatic weather station (AWS) has operated at 26 m asl at 52°48'S and 72°56'W in Puerto Bahamondes, a widening of Canal Gajardo close to the main divide of the Andes and located just west of the Gran Campo Nevado Icefield (GCNI) (Fig. 4). We call this station Gran Campo NPB. It is fixed on rock surface close to a steep cliff that leads down to the shore of the Puerto de Bahamondes. The surrounding mountainous area is covered partly by magallanic moorland and by rock and debris. Adjacent slopes and the valley floor at about 0.4 km

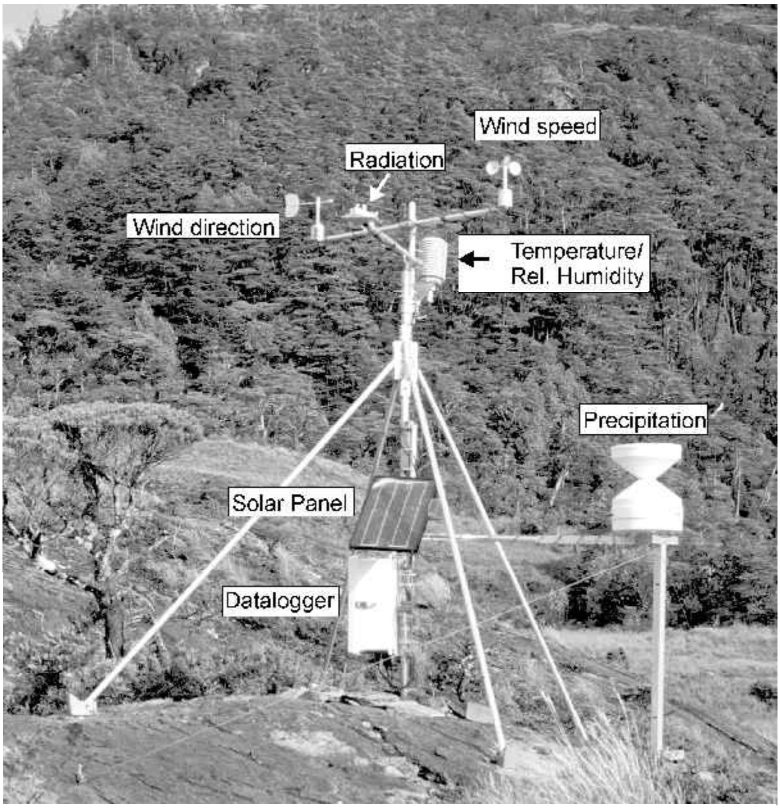

Fig. 4. Photograph of AWS Gran Campo NPB in Puerto Bahamondes, Canal Gajardo, at 52°48'S, 72°56'W. The instrumentation presented is the same for AWS Gran Campo NPB Nevado, AWS Galería and AWS Skyring. All instruments, the solar panel and the data logger were provided by Campbell Sci. Ltd. (UK).

from the station are covered with dense deciduous forest mainly composed by *Nothofagus betuloides* and *Drimys winteri.*

A second AWS (AWS Galería) with similar instrumentation is located farther north on a mountain pass between two outlet glaciers of the GCNI to the east and to the west of the pass at 383 m asl. To the south of the location the slopes rise to the Gran Campo Nevado Ice Cap to 1000 m asl, whereas to the north the broad ridge rises only little to a minor summit. The rugged surface is composed of rock and debris. Vegetation cover is less than 10%, composed by small bushes of *Nothofagus antarctica* and some grass species, lichens and mosses.

In addition, an AWS has been operating since March 2001 at Estancia Skyring on the north shore of Seno Skyring to complete an east-to-west profile at 53°S from the mountain range of the Andes to the Patagonian plains around Punta Arenas. It is located on flat pasture with grass height of between 10 and 20 cm. The location is approximately 300 m to the north of the shore of Seno Skyring.

All of these three AWS at Gran Campo Nevado and at Seno Skyring are similarly designed and carry the same type of instruments. The AWS are manufactured by Campbell Scientific Ltd. (United Kingdom). They are equipped with sensors for air temperature, air humidity, wind speed, wind direction, and precipitation (Fig. 4).

Table 1. Instrumentation and Sensors at AWS Gran Campo NPB Nevado, AWS Galleria, and AWS Skyring, as Used in This Study

Variable	Instrument[a]	Precision
Air temperature	Thermistor within a combined air temperature and air humidity sensor, "HMP-35-AC" (Vaisala)	< 0.1 K
Relative humidity	Capacitor within a combined air temperature and air humidity sensor, "HMP-35-AC" (Vaisala)	±3%
Precipitation	Tipping-gauge rain bucket, "AGR100"	up to -20%
Wind direction	Wind vane, "W200P"	±2°
Wind speed	Anemometer, "A100R"	1% ± 0.1 m/s
Shortwave radiation	Silicon Photocel Type, "SP1110"	±5%

[a]All but precipitation are measured at 2 m above the surface. Precipitation is measured at 1 m above the surface.

Table 2. Pertinent Data to Weather Stations and Automatic Weather Stations Used in This Study

Station	Type[a]	Longitude/latitude	Altitude	Operating since
Faro Evangelistas	WS	52°24'S/75°06W	Sea level	Early 20th century
Punta Arenas JS	WS	53°08'S/70°53W	6 m	Approximately 1970
Gran Campo NPB	AWS	52°48'S/72°56W	26 m	October 1999
Paso Galeria	AWS	52°45'S/73°01W	383 m	March 2000
Skyring	AWS	52°33'S/71°58W	8 m	March 2001

[a]WS: weather station, AWS: automated weather station.

All but precipitation are measured at 2 m above the surface. Precipitation is measured using unshielded tipping-bucket rain gauges fixed at 1 m of height above the surface. Instrumentation details are summarized in Table 1. Measurements are taken every 60 sec. and stored as 3 hourly means from the data logger to a 192 KB storage module. The capacity of the storage module is good for a 9-mo. time period. The system is powered by a 10 W solar panel which is backed up by an additional battery pack to cover time periods with low solar radiation during winter.

The data from AWS Gran Campo NPB and AWS Skyring can be compared to the long-time record obtained at the WS of the Instituto de la Patagonia, Universidad de Magallanes, at Punta Arenas near the shore of the Strait of Magellan (WS Jorge C. Schythe, which we call WS Punta Arenas JS) (Santana, 1999). Measurements at WS Punta Arenas JS include among other parameters air temperature, air humidity, wind speed, wind direction, and precipitation. This WS is operated according to World Meteorological Organization (WMO) standards including wind measurements at a height of 10 m above the surface. Monthly mean values of temperature and precipitation from WS Faro Evangelistas (52°24'S, 75°06'W), operated by the Chilean Navy, are also included into the analysis (Fig. 1).

Pertinent data for all stations are presented in Table 2. Measurement periods at the WS Punta Arenas JS, AWS Gran Campo NPB, AWS Galería and AWS Skyring

Table 3. Mean Annual Air Temperature at the Different Stations

Station	Averaging period[a]	Mean annual temperature (°C)
Faro Evangelistas	January 1988–December 2001	6.9
Punta Arenas JS	January 1988–November 2002	6.5
Faro Evangelistas	October 1999–December 2001	6.8
Punta Arenas JS	October 1999–September 2002	6.1
Gran Campo NPB	October 1999–September 2002	5.7
Skyring	March 2000–September 2002	6.4

[a]Average values for each mo. were calculated before computing the annual mean from the 12 mean values of the individual mo.

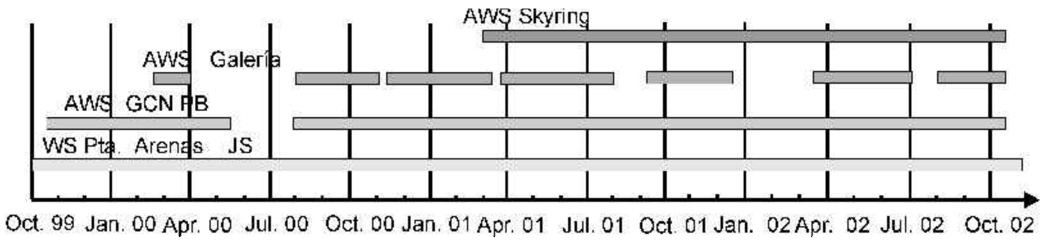

Fig. 5. Measurement periods at the AWS Gran Campo NPB, AWS Galería, AWS Skyring and the WS Punta Arenas JS.

are shown in Figure 5. Data loss from the end of May 2000 until August 2000 at AWS Gran Campo NPB was due to a failure of the power supply of the AWS. During this time period the additional battery pack was not yet installed. AWS Galería stopped operating at several time intervals due to harsh climatic conditions. Nevertheless, the limited data obtained so far from this location add important information in terms of vertical gradients of climate parameters and local climate variations at Gran Campo Nevado.

DATA AND RESULTS

Temperature

Mean annual air temperatures at different stations are listed in Table 3. The differences in mean annual air temperature between the west and the east side of the mountains generally decrease toward the south (Prohaska, 1976). Mean annual air temperature at WS Punta Arenas JS for the period from 1988 until 2002 was +6.5°C. During the same period annual mean temperature at Faro Evangelistas was +6.9°C. Annual mean air temperature during the 3-yr. period from October 1999 until September 2002 was +6.1°C at WS Punta Arenas JS, 0.4°C less than the long-term mean. At AWS Gran Campo NPB during the same 3-yr. period a mean annual air temperature of +5.7°C was measured. The small difference might be attributed to the cooling effect of the nearby icefield at the AWS Gran Campo NPB. At AWS

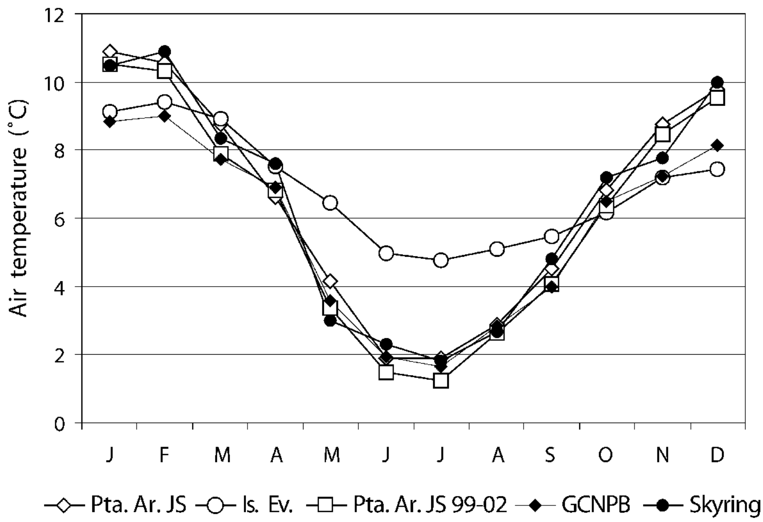

Fig. 6. Mean monthly air temperature at WS Punta Arenas JS (Pta. Ar. JS), WS Faro Evangelistas (Is. Ev.), AWS Gran Campo NPB (GCNPB) and AWS Skyring.

Skyring, mean annual air temperature between March 2001 and September 2002 was +6.4°C.

Mean values of air temperature for individual mo. for a time period of 4 yr. from January 1997 until February 2002 are presented in Figure 6. This shows the more maritime character of air temperature at Faro Evangelistas, consistent with Miller (1976). Winter temperatures are slightly more moderate at AWS Gran Campo NBP and AWS Skyring than at WS Punta Arenas JS. During the summer season mean monthly values at AWS Skyring are about the same as at WS Punta Arenas JS. At AWS Gran Campo NBP summer temperatures are at the same level as at WS Faro Evangelistas. It is deduced that AWS Gran Campo NPB in summer represents a temperature regime similar to Faro Evangelistas. However, during the winter season temperature at AWS Gran Campo NPB follows the temperature regime as measured in Punta Arenas. It is suggested that during winter—with generally lower wind speeds—cold air tends to settle along the deep valley floors of the mountains around AWS Gran Campo NPB. The combination of more maritime conditions at AWS Gran Campo NPB compared to WS Punta Arenas and the vicinity of the ice cap of the Gran Campo Nevado are responsible for the course of the air temperatures at AWS Gran Campo NPB. Even from the limited data available so far, it can be stated that AWS Skyring just east of the mountains clearly shows a temperature regime similar to the one found at Punta Arenas.

Mean daily air temperature data for a period of 16 mo. at AWS Gran Campo NPB, AWS Skyring and WS Punta Arenas JS from January 2001 until April 2002 are presented in Figure 7. The data were filtered with a running mean filter of 5 data points width. There is an excellent correlation between the three temperature records, with $r = .94$ between WS Punta Arenas JS and AWS Gran Campo NPB and $r = .93$ between WS Punta Arenas JS and AWS Skyring for the original data. Therefore, data gaps at AWS Gran Campo NPB can be filled using the linear regression

Table 4. Mean and Absolute Air Temperatures at the Different Stations

Air temperature (°C)	Gran Campo NPB	Skyring	Punta Arenas JS
Averaging period	October 1999–September 2002	April 2000–September 2002	October 1999–September 2002
Absolute maximum	-7.5	-11.3	-14.4
Absolute minimum	+21.8	+21.6	+23.6
Absolute range	29.3	32.9	38.0
Mean daily minimum	2.8	1.5	2.3
Mean daily maximum	8.3	8.6	10.0
Mean daily range	5.5	7.1	7.7

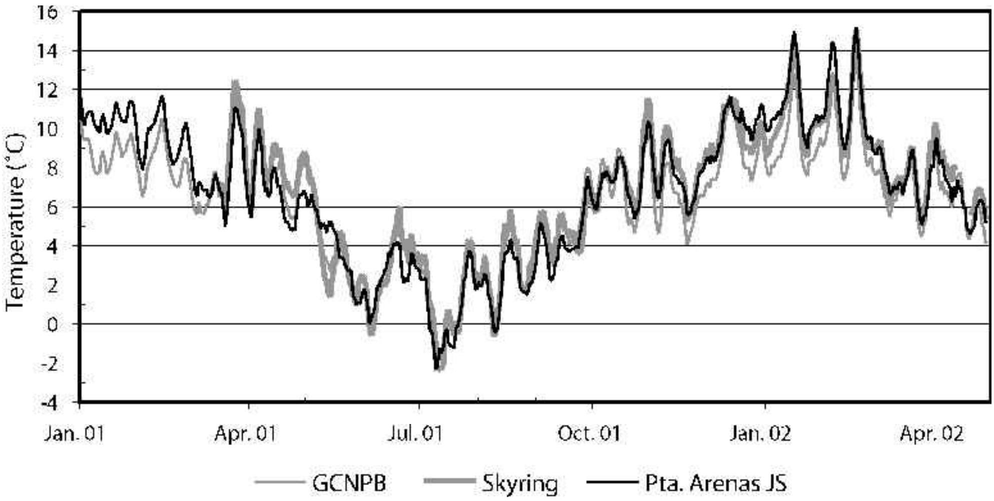

Fig. 7. Temperature records of mean daily air temperature of AWS Gran Campo NPB, AWS Skyring and WS Punta Arenas JS from January 2001 until April 2002. A running mean filter with a width of 5 data points was applied to the records.

coefficients and data from WS Punta Arenas JS. It can be seen in Figure 7 that during summer warm days with mean air temperature above 12°C occur very seldom. This indicates that due to high mean wind speed strong turbulence prevents the development of a warm surface layer as has been described e.g. by Weischet (1996).

The mean daily temperature range can be calculated by subtracting mean daily minimum air temperature from mean daily maximum air temperature (Table 4). At AWS Gran Campo NPB this ranges from +2.8°C to +8.3°C with a temperature difference between mean minimum and mean maximum daily observations of 5.5°C. This temperature range at WS Punta Arenas JS is 7.7°C, ranging from +2.3°C to +10.0°C during the same period. At AWS Skyring, 18 mo. of data from April 2001 to September 2002 yield a mean temperature range of 7.1°C ranging from +1.5°C to +8.6°C. AWS Skyring and WS Punta Arenas JS show a much wider temperature range than AWS Gran Campo NPB. The higher mean daily temperature ranges at AWS Skyring and WS Punta Arenas JS reflect the slightly smaller influence of the Pacific Ocean on the temperature regime. Furthermore, their location to the east of the mountain range results in reduced cloud cover because of foehn winds. This can also be seen from the radiation data which will be discussed later.

Absolute temperatures at AWS Gran Campo NPB range from -7.5°C to +21.8°C with a total temperature range during the measurement period of 29.3°C (Table 4). Temperature range at WS Punta Arenas JS is 38.0°C, ranging from -14.4°C to +23.6°C during the same period from October 1999 until September 2002. At AWS Skyring during the 18 mo. of available measurements from April 2001 to September 2002, the data yield an absolute temperature range of 32.9°C, from -11.3°C to 21.6°C. The larger differences between absolute minimum and absolute maximum temperatures at WS Punta Arenas JS and AWS Skyring when compared to AWS Gran Campo NPB support the interpretation given above with respect to mean daily temperature range.

The comparably small daily, monthly and annual temperature ranges confirm the interpretation by Lauer and Rafiqpoor (2002) describing southern Patagonia as one of the most even climates of the world.

For the time intervals when temperature data were available from both AWS at Gran Campo Nevado (AWS Galería, 383 m asl and AWS Gran Campo NPB, 26 m asl) the mean temperature difference between both locations was 2.25°C. This implies a vertical temperature gradient of 0.62°C/100 m. This gradient perfectly matches the expectations of a saturated adiabatic lapse rate of temperature under cold and humid conditions.

Solar Radiation

Solar radiation measurements were only available at AWS Gran Campo NPB and AWS Skyring. For the time period from April 2001 to March 2002, mean daily solar radiation amounts to 80 W/m^2 at AWS Gran Campo NPB and 116 W/m^2 at AWS Skyring. At Seno Skyring, located only 60 km west of GCNI, the solar radiation was 45% higher than at AWS Gran Campo Nevado NPB. This effect can be attributed to a strong overall decrease of the cloud cover related to downward air flow (foehn winds) on the east side of the mountain range with predominant westerly wind direction (e.g., Miller, 1976). A secondary explanation is that the horizon is significantly limited at AWS Gran Campo NPB because of the mountains surrounding Puerto Bahamondes, thus leading to shorter time intervals with direct insolation.

Wind Direction and Wind Speed

Frequencies of wind directions during the investigation period from October 1999 until March 2002 are given in Figure 8. Not surprisingly, the wind directions from the western quadrant comprise more than 80% of all situations. At AWS Paso Galería and at WS Punta Arenas JS, northwest winds are most frequent. However, AWS Gran Campo NPB reveals west wind direction to be dominant. This is attributed to the topographic situation in Puerto Bahamondes which is channelling the air flow along the valley. Wind directions from northeast to southeast are encountered only occasionally. These rare situations occur 3% of the time at AWS Gran Campo NPB and 8% of the time at WS Punta Arenas JS. At AWS Skyring, easterly

Table 5. Mean Wind Speed and Mean Maximum Wind Speed at the Weather Stations[a]

m/s	Paso Galeria	Gran Campo NPB	Skyring	Punta Arenas JS
Mean wind speed	4.6	3.7	3.7	4.6
Mean daily maximum wind speed	15.6	13.4	8.8	11.9

[a]Data from WS Punta Arenas JS was standardized for a measurement height of 2 m above the ground, assuming a logarithmic wind profile and a surface roughness length for grass of 0.03 m. All other data were measured at 2 m above the ground. Mean daily maximum wind speed was averaged from the highest values of wind speed of each day of all measurement intervals of 60 sec.

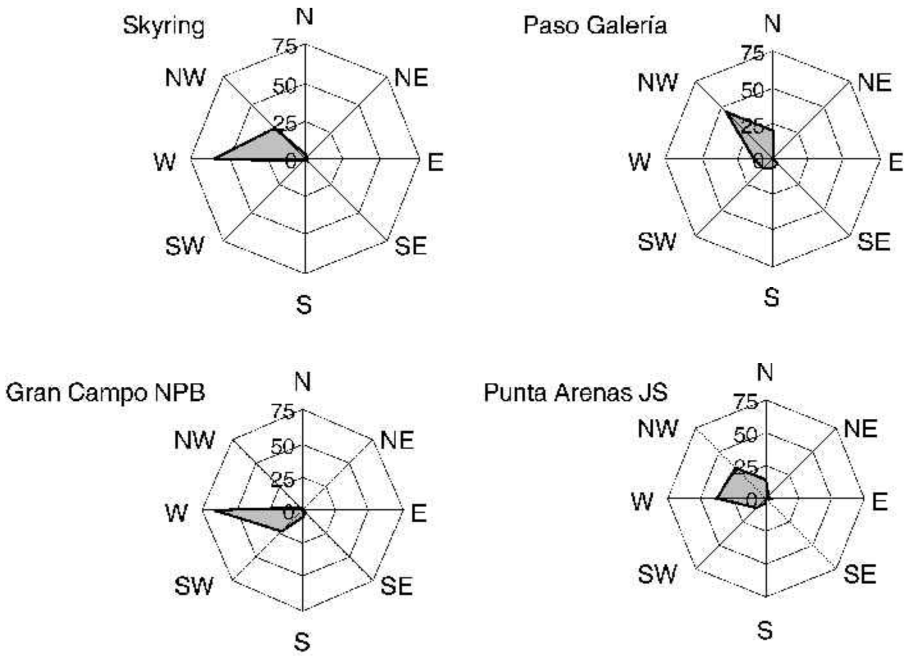

Fig. 8. Frequency of wind directions at AWS Skyring, AWS Galería, AWS Gran Campo NPB and WS Punta Arenas JS. Measurements at the three AWS were taken every 60 sec. Values for WS Punta Arenas JS were calculated from three observations per day.

winds occurred on 5% of all days from April 2001 until March 2002. It is inferred that air flow from the east which can be observed at Punta Arenas and to a lesser extent at AWS Skyring, does not always penetrate the mountain range farther west.

Table 5 summarizes mean wind speed and mean maximum wind speed at the four WS along the profile. Wind speed was measured at 2 m above ground at AWS Gran Campo NPB, Galería and Skyring. However, instrument height at WS Punta Arenas JS was 10 m. Therefore, measurements from WS Punta Arenas JS were recalculated assuming a logarithmic wind profile and a surface roughness length for grass of 0.03 m. The cited values of WS Punta Arenas JS in Table 5 and in the text refer to the reduced values after recalculation. As anticipated, highest wind speeds are encountered during west wind storms. AWS Paso Galería shows higher mean wind

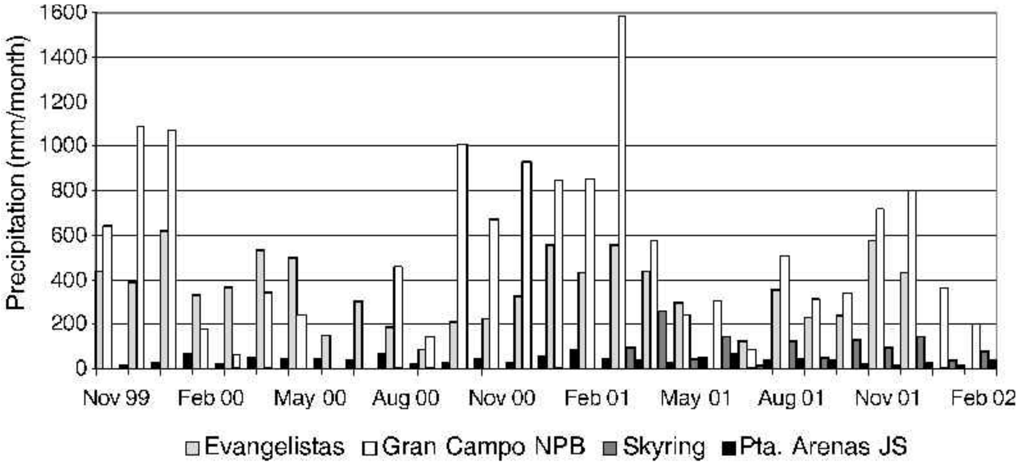

Fig. 9. Monthly precipitation at WS Faro Evangelistas, WS Punta Arenas JS, AWS Gran Campo NPB and AWS Skyring from November 1999 to February 2002.

speed (4.6 m/s) than AWS Gran Campo NPB (3.7 m/s) because it is directly exposed to winds from the northwest on the mountain pass and because of its higher altitude of 383 m asl. At AWS Skyring a mean wind speed of 3.7 m/s is obtained, which is the same as at AWS Gran Campo NPB. However, WS Punta Arenas JS—also near sea level—shows a much higher mean wind speed of 4.6 m/s which agrees with the value of 4.5 m/s given by Endlicher (1991a). Enhanced aerodynamic roughness in the morphologically structured and partly forested mountains is believed to be the reason for the lower values at AWS Gran Campo NPB. Mean maximum wind speed is higher at AWS Gran Campo NPB (13.4 m/s) than at AWS Skyring (8.8 m/s) and WS Punta Arenas JS (11.9 m/s). This shows that strong gusty winds are an important feature of the mountains again as a consequence of the morphologically structured landscape. Mean maximum wind speed at AWS Galería (15.6 m/s) is even higher. This finding also supports the interpretation given above.

All mean values of wind speed measured at the four stations are smaller than the high wind speeds measured directly at the Pacific coast (Faro Evangelistas, 12 m/s) and on the Argentine plains in the east (9 m/s) (Weischet, 1996). This indicates that all four stations are located in or near the mountains, where wind speed at sea level is reduced because of enhanced surface roughness.

Precipitation

Precipitation shows the strongest gradient of all climate elements along the profile defined by the five weather stations (Fig. 9; Endlicher, 1991b). However, absolute values of precipitation must be carefully examined, since this parameter is subject to various measuring problems. During situations with high wind speed, unshielded rain gauges typically underestimate rainfall because of the deformation of the wind field around the collecting bucket (Yang et al., 1999). However, vibrations of the tipping gauge may produce extra counts during storms, thus overestimating rainfall. In both cases correction factors were not applied because no

Table 6. Precipitation at WS Faro Evangelistas, AWS Skyring, and WS Punta Arenas JS in Relation to AWS Gran Campo NPB

	Faro Evangelistas	Paso Galeria	Skyring	Punta Arenas JS
Time period	11/99–12/01[b]	02/29/00–04/12/00; 08/11/00–11/16/00; 11/22/00–03/13/01; 03/25/01–08/11/01; 09/06/01–12/18/01; 10/11/02–03/15/02 (527 days[d])	03/14/01–10/15/02 (588 days)	11/99–11/02[c]
Total precipitation during time period	8,431	15,724	1,520	1,427
Calculated annual precipitation	4,399	10,902	988	505
Total precipitation during time period at AWS Gran Campo NPB	14,277[b]	9,555	6,346	18,823[a]
Percentage relative to AWS Gran Campo NPB	59%	165%	25%	8%

[a]70 days of instrument failure from May 31 to August 8, 2000.

[b]Without June and July 2000, and without June 2001.

[c]Without data from June 1 until August 7, 2000.

[d]Only days with positive mean daily air temperature at AWS Paso Galeria were considered.

calibration procedure was available for the type of rain gauge used. It is assumed that the calibration factors provided by the manufacturer account for systematic errors during most standard weather situations. Snowfall cannot be measured with the sensors because the power supply is not sufficient for heating the instrument. Further investigations using an especially designed long-term rain collector will help to minimize these uncertainties in the future. Despite the restricted accuracy of the data, important conclusions can be drawn from the precipitation data (Table 6): Annual precipitation at AWS Gran Campo NPB is expected to be approximately 6600 mm, much higher than at Faro Evangelistas (2300 mm) and Bahia Felix (4000 mm) on the west coast (Endlicher, 1991b). During the 3-yr. measuring period from October 15, 1999, until October 14, 2002 (exactly 1096 days), AWS Gran Campo NPB was out of service during 70 days from May 31, 2000, until August 8, 2000. A total of 18,356 mm of precipitation were collected. On 48 days mean daily air temperature was below 0°C. Hence, potential snow precipitation on these days was not measured. A mean daily rainfall rate of 6.9 mm/day on days with mean daily air temperature between +1°C and +2.5°C was calculated (108 days) and afterwards used to extrapolate precipitation on the so-called cold days with air temperature below 0°C. Since the number of cold days was only 48 out of 1026 days (5%), it is assumed that the bias introduced by this procedure is small. The mean annual precipitation during the 3-yr. period then amounts to 6642 mm. This extrapolation should only be taken as a rough estimate, and for the multiple systematic errors of the precipitation measurement we consider this estimate to be good only within ±20%. Nevertheless, the enormous differences between Pacific west coast, the Gran Campo Nevado, and Punta Arenas in the east strongly exceed the range of uncertainty. Therefore, the following interpretation holds despite the technical problems when measuring precipitation.

Between October 1999 and October 2002 individual events with more than 50 mm of precipitation within a 3-hr. period were measured on 34 days at AWS Gran Campo Nevado NPB. These rain storms are generally associated with strong westerly air flow with a mean wind speed of 12.4 m/s and a mean daily maximum wind speed (maximum value of all averages of wind speed during the standard measurement intervals of 1 min.) of 27.1 m/s. These events make up 20% of all precipitation measured at AWS Gran Campo NPB. The westerly rain storms are an important feature of the mountain climate of this part of the Andes. More than 100 mm of precipitation were recorded at AWS Gran Campo NPB on 10 occasions and mean wind speed during these times was 14.8 m/s with a mean daily maximum wind speed of 31.0 m/s. Such heavy rain storms were only twice encountered at AWS Skyring from March 2001. No such rainfall events are reported from WS Punta Arenas JS during the investigation period even though heavy wind storms are just as frequent as at the Gran Campo Nevado. For WS Faro Evangelistas no analysis of heavy rainfall events could be accomplished because only mean monthly data of temperature and precipitation until December 2001 were available from this station. The occurrence of heavy rainfall caused by advection of warm and moist air from the Pacific to the mountains agrees with the interpretation given by Weischet (1996) for other locations farther north in the southern Andes.

At AWS Paso Galería measurements of rainfall were available for 527 days from February 2000. During these days rainfall at AWS Paso Galería exceeded rainfall measured at AWS Gran Campo NPB by 65% (Table 6). The calculated annual precipitation amounts to just over 10,000 mm. Since AWS Paso Galería is located northwest of the GCNI at only 383 m asl, it is concluded that accumulation on the GCNI at altitudes well above 1000 m asl is even higher than 10,000 mm per yr. This agrees with hydrological estimates for the Northern and Southern Patagonia Icefield (Dirección General de Aguas, 1987; Escobar et al., 1992) and measurements from firn cores at Glaciar Tyndall in Southern Patagonia Icefield (Godoi et al., 2001). The recent estimates of precipitation for the summit areas presented here are much higher than previous estimates of 3000 mm to 5000 mm (Lliboutry, 1956) or 7000 mm to 8000 mm (Schwerdtfeger, 1976).

Measurements at AWS Skyring are available only from April 2001 to October 2002. During this period 1570 mm of precipitation were collected. During the same period 6346 mm of precipitation were collected using the same type of instrument at AWS Gran Campo NPB. Despite the systematic errors inherent with both measurements, it can be stated that during this period the precipitation at AWS Skyring was 25% of the precipitation measured at the AWS Gran Campo NPB. Farther to the east, precipitation decreases to even smaller values. At Punta Arenas mean annual precipitation is as little as 430 mm (Santana, 1984). During the 3-yr. period considered in this study, annual rainfall was 505 mm. This means that only

Table 7. Synoptic Weather Types of Southernmost South America (after Frank 2002)

Type	Frequency (%) (1980–2000)
Advection from the west	34
Advection from the southwest	11
Advection from the northwest	7
Low pressure trough	8
High pressure ridge over southernmost South America	4
High pressure bridge over southernmost South America	10
Advection from the south	3
High pressure to the east of southernmost South America	2
Advection from the north	4
Overall weak pressure gradient	6
Unclassified	10

8% of the precipitation sum at AWS Gran Campo NPB are measured at WS Punta Arenas JS. This number reflects one of the most outstanding precipitation gradients of the world from a humid location in the Andes to almost semi-aridity in eastern Patagonia along a distance of only 160 km. The data confirm similar precipitation gradients measured farther north at around 48°S (Endlicher, 1991a; Weischet, 1996).

Overall, a mean annual total of 8431 mm of precipitation was measured at Faro Evangelistas from November 1999 to December 2001. This number corresponds to 59% of the precipitation obtained at AWS Gran Campo NPB during the same period. Figure 9 illustrates monthly rainfall from 1999 to 2001 along the profile from Faro Evangelistas to Punta Arenas. Although precipitation is much higher at AWS Gran Campo NPB compared to Faro Evangelistas, this is not strictly true for individual mo. Variations from mo. to mo. are considerable. Figure 9 also reveals that precipitation is highest during the summer season in accordance with Prohaska (1976). During the summer 2001/2002 the precipitation was much smaller than in the earlier years of 1999 and 2000.

Table 6 summarizes precipitation measurements during the 2-yr. period. The numbers illustrate (1) the enormous gradient along the profile in accordance with Miller (1976) and (2) that the highest rainfall rates are not to be expected along the west coast of the Pacific Ocean but along the main divide of the Andes.

Temperature, Humidity, Radiation, and Precipitation in Relation to Wind Directions

Wind speed, precipitation, temperature, and radiation data were separated according to the three major types of synoptic-scale weather patterns: westerlies (winds from the southwest to the northwest), northeasterlies (winds from the north to the east) and southerlies (winds from the southeast and the south). The separation was accomplished according to a weather-type classification based on 10 different

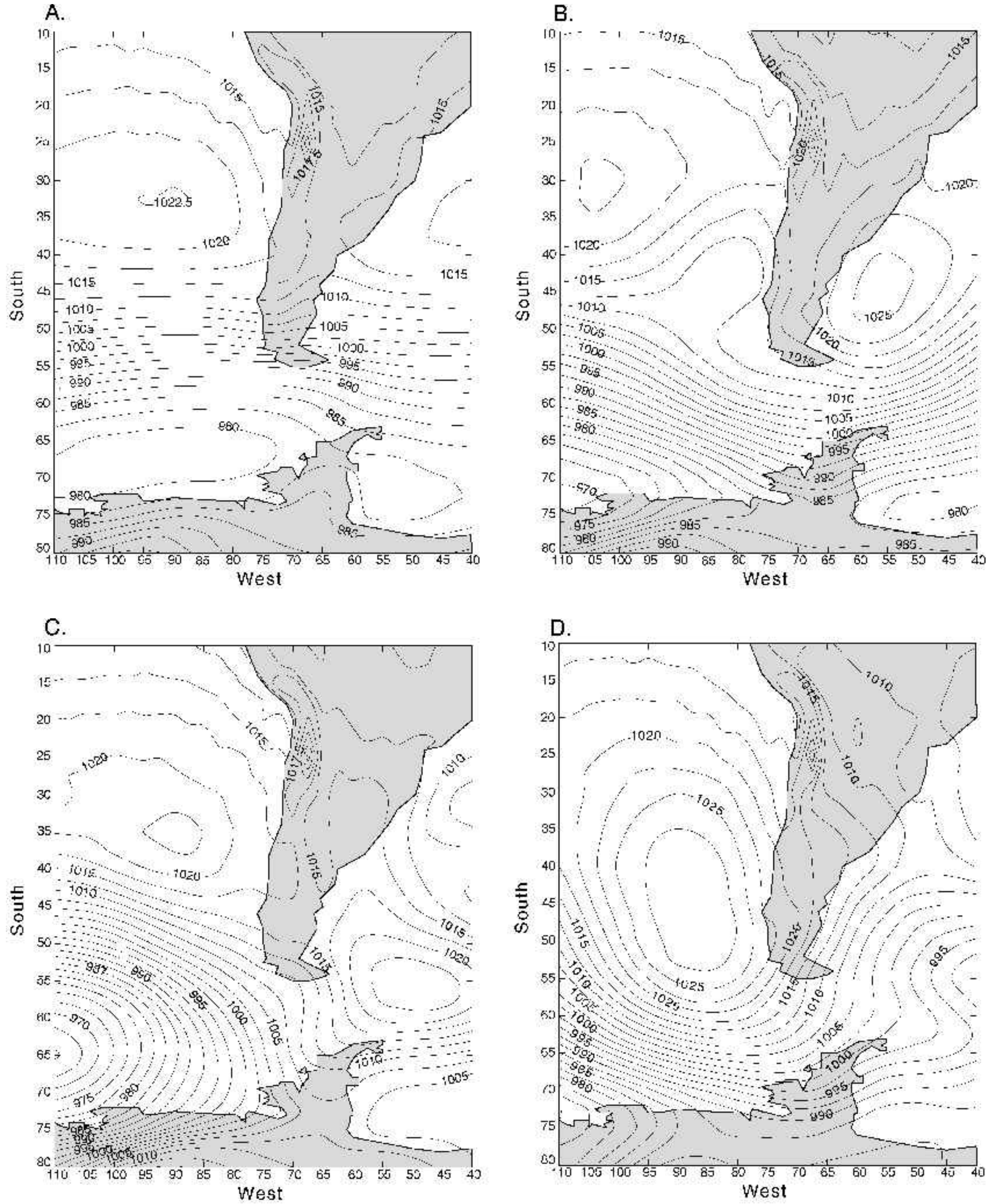

Fig. 10. Major synoptic type weather patterns over southernmost South America with advection from the (A) west, (B) the north, (C) the east, and (D) the south.

types of weather pattern as delineated by Frank (2002) (Table 7) using 20 yr. of NCEP/NCAR reanalysis data (Kalney et al., 1996). Mean sea level pressure fields of the key weather types are presented in Figure 10. The westerly winds (west, southwest, northwest, and low pressure trough) account for 60.5% of all situations during the investigation period of the weather stations used in this study (Fig. 10A). The high percentage of westerly weather patterns reflects the generally zonal alignment

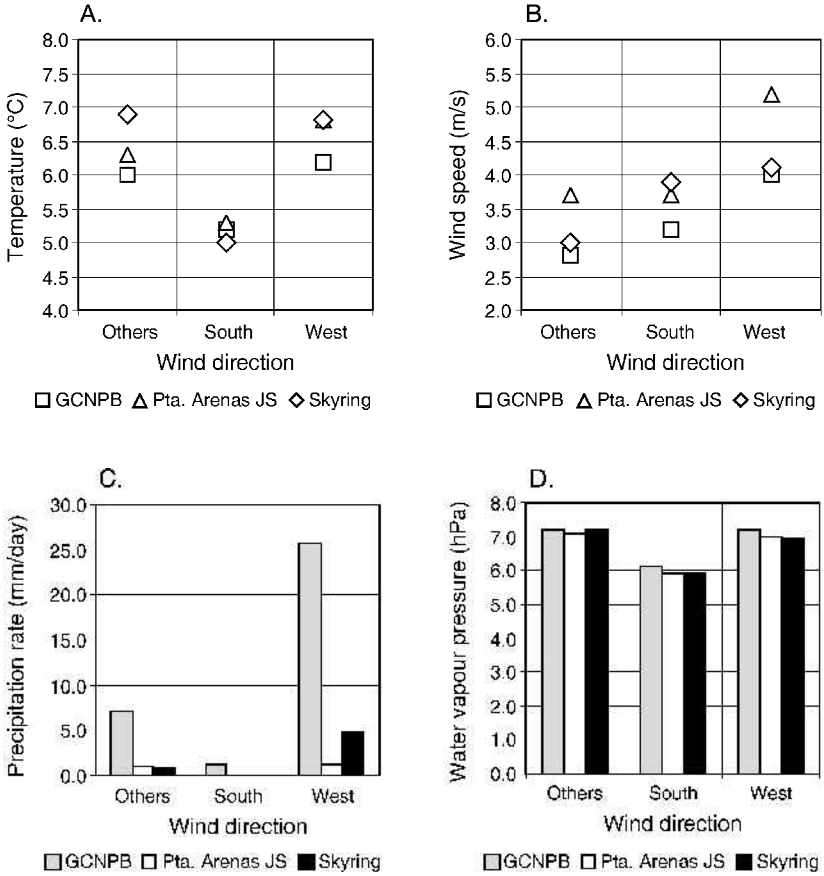

Fig. 11. Variation of climate parameters at WS Punta Arenas JS, AWS Gran Campo NPB and AWS Skyring classified according to the three major wind directions: (1) north to east, (2) south, and (3) west. The climate parameters considered are (A) air temperature, (B) wind speed, (C) precipitation, and (D) water-vapor pressure.

of Southern Hemisphere circulation (Rumney, 1968). Northerly (Fig. 10B) to easterly (Fig. 10C) winds (north, high pressure ridge, high pressure bridge over southern South America, east and weak pressure gradient in Table 7) are found during 26.3% of the measurement period. Southerly air flow was encountered on 2.9% of all days (Fig. 10D). Unclassified days make up 10.4% of all days. Figure 11 gives mean annual values for temperature, wind speed, precipitation, and water-vapor pressure for the three stations AWS Gran Campo NPB, AWS Skyring, and AWS Punta Arenas JS, separated into the three main wind directions as outlined above. A proportion of 1% of all days for a specific wind direction implies that only 7 days within a time period of 2 yr. show this weather pattern. Therefore, mean values calculated for southerlies should only be interpreted with care, since the data are not always statistically significant due to the small number of data points. Nevertheless, important conclusions can be drawn from the data.

Mean air temperatures show important variations with the three main wind directions. During westerly air flow local influences are smallest because similar mean air temperatures are obtained at all three weather stations. This can be

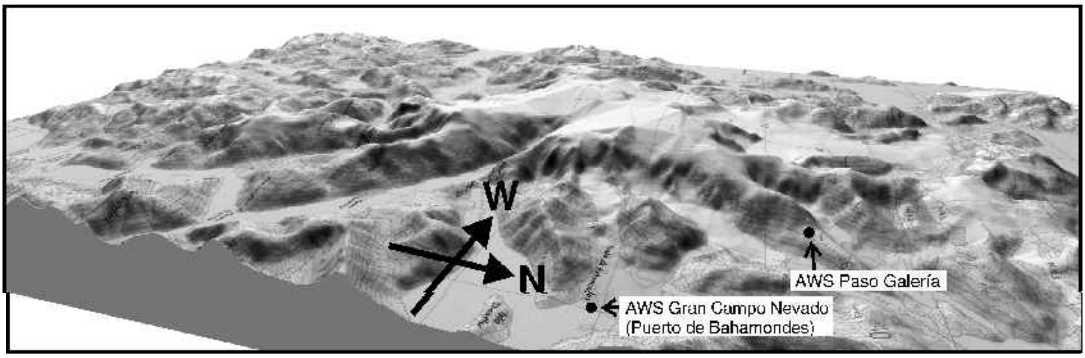

Fig. 12. 3-D view of Gran Campo Nevado from the northeast. The image was produced from a digital elevation model with the topographic map (scale 1:100.000) draped upon. The region corresponds to the small dotted rectangle in Figure 1 (Cartography: M. Schnirch).

attributed to the high mean wind speed that is associated with westerly conditions that efficiently removes locally influenced surface air. The generally lower air temperature at AWS Gran Campo NPB during the westerly and the other weather patterns may be related to the nearby Gran Campo Nevado Ice Cap and the proximity to the Pacific ocean as outlined earlier. A sharp drop in mean air temperature is associated with southerly air flow. This rare situation drives sub-antarctic air toward Patagonia. Although these situations do not frequently occur, they are of major importance, especially in winter, for ecosystems and sheep farming because they can bring heavy snowfall and very low air temperatures down to -10°C to the southwest parts of Patagonia (Endlicher and Santana, 1997).

Wind speed at all stations is highest during periods with westerly winds as compared to all other wind directions. This effect is very pronounced at AWS Gran Campo NPB where high mountains to the south shelter the location from wind from this direction (Fig. 12). Wind from the southeast and the east is weak at all locations, indicating weather situations with a rather small pressure gradient in the whole region.

Precipitation classified according to the three main wind directions shows an important pattern. Whereas WS Punta Arenas JS obtains high rainfall during synoptic weather patterns other than from the west, the opposite is true for AWS Gran Campo NPB, where mean daily rainfall on days with weather patterns other than westerly is less than 20% of the daily precipitation on days with westerlies. At WS Punta Arenas JS precipitation on days with westerly air flow is about the same amount of precipitation rate as measured on days with other wind directions. AWS Skyring experiences a situation similar to AWS Gran Campo NPB. Highest rainfall rates at AWS Skyring are measured during days with westerly air flow but the difference in precipitation rate when compared with all other wind directions is not as extreme as at AWS Gran Campo NPB. The precipitation rate at AWS Skyring during westerlies is about one-fourth of the precipitation rate at AWS Gran Campo NPB which is a consequence of its location to the east of the mountains (Table 6). The sheltering effect of the high mountain chain south of Puerto Bahamondes again can be observed at AWS Gran Campo NPB (Fig. 12). Precipitation associated with south and southeast winds is smallest at AWS Gran Campo NPB. In addition, air flow from the south implies a rather cold air mass which can transport only limited moisture. Hence, water-vapor pressure drops slightly by approximately 1 hPa during these time periods at all stations (Fig. 11D).

It is concluded, with respect to precipitation, that AWS Skyring to the east of the mountains still depends mainly on air flow from the west, although most of the precipitation falls farther west. On many days with westerly winds, AWS Skyring experiences foehn weather conditions instead of heavy rainfall as observed farther to the west. The effect of foehn conditions can best be seen at WS Punta Arenas JS where water-vapor pressure is similar for situations with westerly air flow and for other situations. However, since mean air temperature is higher during the westerly weather patterns this indicates a smaller mean value of relative humidity.

The data show that more humid conditions in one part of southernmost Patagonia are not necessarily associated with generally moister conditions, but could also be explained through slightly changed circulation patterns. This implies that wetter conditions on the west coast and along the main divide of the mountains due to enhanced west winds, supposedly lead to drier conditions in the east at Punta Arenas, and vice versa. Consequently, it is not necessarily correct to speak of generally drier or generally wetter past climates in southern Patagonia inasmuch as possible changes of circulation patterns are considered. The local effects of such changes must be considered and ought to be interpreted with respect to the spatial relation to the mountain range.

At AWS Gran Campo NPB solar radiation is highest during days with southerly air flow (112 W/m^2). This is in accordance with the sheltering effect of the mountain range to the south of Puerto Bahamondes as outlined earlier (Fig. 12). With respect to solar radiation lee effects imply a decrease in cloud cover because of foehn effects. At AWS Skyring mean solar radiation on days with westerly winds (122 W/m^2) was more than twice the mean value measured on days with southerly or easterly wind directions. It is concluded that AWS Skyring just to the east of the mountains is strongly influenced by foehn wind which are most frequently found during westerlies, when the local cloud cover decreases just behind the mountain range. Again, this is in good agreement with what was outlined earlier with respect to precipitation and relative humidity.

CONCLUSION

Climate data from a transect along 53°S in southwestern Patagonia were analyzed with respect to regional climate. All data sets show the importance of the climate divide of the Andes in conjunction with dominant wind directions. Westerly and northwesterly wind directions make up more than 60% of all cases at all weather stations. This is most evident when considering precipitation data: Precipitation at sea level on the Pacific coast is only 59% of the precipitation measured at sea level within the mountains where an annual mean of 6642 mm was calculated for a 3-yr. measuring period from October 15, 1999, until October 14, 2002. To the east, precipitation drastically drops to 25% at Seno Skyring and to only 8% at Punta Arenas. At higher altitudes in the mountains precipitation is even higher, probably exceeding 10,000 mm of annual precipitation at the summits. Rainfall in the mountains at Gran Campo Nevado mostly originates from the west, whereas precipitation at Punta Arenas is just as much associated with northeasterly and southerly wind directions. Therefore, any change in the strength or frequency of the circulation pattern will affect the west coast, the mountains and the east side of the mountains in different ways. Wetter conditions caused by a change in circulation on one side will probably cause drier conditions on the other side of the mountain chain and vice versa. Variations of the strength of the west wind zone will directly affect precipitation regimes and must have consequences on the mass balance of local glaciers. Therefore, the general retreat of glaciers in Patagonia could originate not only from a temperature increase but could also be triggered by a weakening of the westerlies.

Temperatures are generally very similar across the profile, reflecting the moderately cold and well-balanced climate of southern Patagonia. However, small differences are found related to local cloud cover, to the specific distance of the weather stations from the open sea and to the surrounding surface conditions. As expected, overall wind speeds are rather high, with more gusty winds developing in the mountains, but overall higher mean wind speeds on the plains in the east. The three AWS (Gran Campo NPB, Galería, and Skyring) will be permanently operated during the coming years. It is expected that statistically more reliable results can be presented in the future. The data records from these stations can be obtained from the first author of this study via www.grancampo.de

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REFERENCES

Aceituno, P., Fuenzalida, H., and Rosenblüth, B. (1993) Climate along the extratropical west coast of South America. In H. A. Mooney, E. R. Fuentes, and B. I. Kronberg, eds., *Earth System Responses to Global Change: Contrasts between North and South America.* San Diego, CA: Academic Press, 61–69.

Capel, J. J. (1983) Reflexiones geográficas acerca del clima frío oceánico del hemisferio sur, Punta Arenas (Chile) [Geographical thoughts about the cold oceanic climate in the southern hemisphere, Punta Arenas (Chile)]. *Revista de Geografía Norte Grande,* Vol. 10, 3–16.

Carrasco, J., Casassa, G., and Rivera, A. (1998) Climatologia actual del campo de hielo sur y posibles cambios por el incremento del efecto invernadero [Current climatology of the Southern Icefield and possible changes by an increase of the greenhouse effect]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 26, 119–128.

Carrasco, J., Casassa, G., and Rivera, A. (2000) Meteorological in situ observation in the southern ice cap, Patagonia. *Proceedings of the 6th International Conference* *on Southern Hemisphere Meteorology and Oceanography*. Santiago, Chile: American Meteorological Society, 300–301.

Carrasco, J., Casassa, G., and Rivera, A. (2002) Meteorological and climatological aspects of the Southern Patagonia Icefield, Patagonia. In G. Casassa, F. Sepúlveda, and R. Sinclair, eds., *The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos*. New York, NY: Kluwer Academic/Plenum, 29–41.

Casassa, G. (1985) Clasificación del clima en la Región Austral de Chile [Climate classification of the Austral region of Chile]. *Trapananda,* Vol. 5, 174–175.

Casassa, G., Rivera, A., and Carrasco, J. (2000) Glacier variations in the Southern Patagonia Icefield and their relation with climate. *Proceedings of the 6th International Conference on Southern Hemisphere Meteorology and Oceanography*. Santiago, Chile: American Meteorological Society, 312–313.

Casassa, G., Rivera, A., Aniya, M., and Naruse, R. (2002) Current knowledge of the Southern Patagonian Icefield. In G. Casassa, F. Sepúlveda, and R. Sinclair, eds., *The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos.* New York, NY: Kluwer Academic/Plenum, 85–87.

Cerveny, R. S. (1998) Present Climates of South America. In J. E. Hobbs, J. A. Lindesay, and H. A. Bridgman, eds., *Climates of the Southern Continents: Present, Past and Future.* New York, NY: John Wiley, 107–135.

Coronato, F. and Bisigato, A. (1998) A temperature pattern classification in Patagonia. *International Journal of Climatology,* Vol. 18, 765–773.

Dirección General de Aguas (1987) *Balance Hídrico de Chile* [Hydrolographical Balance of Chile]. Santiago, Chile: Ministerio de Obras Públicas.

Endlicher, W. (1991a) *Zur Klimageographie und Klimaökologie von Südpatagonien. 100 Jahre klimatologische Messungen in Punta Arenas* [On the Climatology and Eco-Climatology of South Patagonia. 100 Years of Climatological Measurements at Punta Arenas]. Freiburger Geographische Hefte, University of Freiburg, Germany, Vol. 32, 181–211.

Endlicher, W. (1991b) Südpatagonien—Klima- und agrarökologische Probleme an der Magallanstraße [South Patagonia—Eco-climatological problems and ecological problems of agriculture at the Strait of Magellan]. *Geographische Rundschau,* Vol. 43, 143–151.

Endlicher, W. and Santana, A. (1988) El clima del sur de la Patagonia y sus aspectos ecológicos. Un siglo de mediciones climatológicas en Punta Arenas [The climate of South Patagonia and its ecological aspects. A century of climatological measurements at Punta Arenas]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 18, 57–86.

Endlicher, W. and Santana, A. (1997) El invierno de 1995: Un fenomeno climatico muy severo en la Patagonia Austral [The winter of 1995: A severe climatological phenomena in southern Patagonia]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 25, 77–88.

Escobar, F., Vidal, F., Garín, C., and Naruse, R. (1992) Water balance in the Patagonia Icefield. In R. Naruse and M. Aniya, eds., *Glaciological Researches in Patagonia.*

Nagoya, Japan: Japanese Society of Snow and Ice, Data Center for Glacier Research, 109–119.

Frank, A. (2002) Semi-objektive Klassifikation und statistische Auswertung von Wetterlagen Südpatagoniens [Semi-objective classification and statistical analysis of weather types of South Patagonia]. Unpublished master's thesis, Department of Physical Geography, University of Freiburg, Freiburg, Germany.

Godoi, M. A., Casassa, G., and Shiraiwa, Y. T. (2001) Rese a de estudios paleoclimáticos mediante testigos de hielo: Potencialidades y evidencia obtenida en el cono sur de Sudamérica [Summary of paleoclimatic studies based on ice: Potential and evidence obtained from southern South America]. *Anales del Instituto de la Patagonia. Serie Ciencias Naturales,* Vol. 29, 45–54.

Hobbs, J. E., Lindesay, J. A., and Bridgeman, H. A. (1998) Introduction: A southern hemisphere overview. In J. E. Hobbs, J. A. Lindesay, and H. A. Bridgeman, eds., *Climates of the Southern Continents: Present, Past and Future*. New York, NY: Wiley.

Ibarzabal y Donángelo, T., Hoffmann, J., and Naruse, R. (1996) Recent climate changes in southern Patagonia. *Bulletin of Glacier Research,* Vol. 14, 29–36.

Kalney, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredall, M., Saha, S., White, G., Wollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebiuszaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D. (1996) The NCEP-NCAR 40-year reanalysis project. *Bulletin of American Meteorology Society,* Vol. 7, 437–471.

Lauer, W. and Rafiqpoor, M. D. (2002) *Die Klimate der Erde. Eine Klassifikation auf der Grundlage der ökophysiologischen Merkmale der Vegetation* [The Climates of the Earth. A Classification on the Basis of the Eco-Physiological Criterias of the Vegetation]. Stuttgart, Germany: Steiner Verlag.

Lliboutry, L. (1956) *Nieves y glaciares de Chile: Fundamentos de Glaciologia* [Snow and Glaciers in Chile: Principles of Glaciology]. Santiago de Chile, Chile: Universidad der Chile.

McCulloch, R. D., Bentley, M. J., Purves, R. S., Hulton, N. R. J., Sugden, D. E., and Clapperton, C. M. (2000) Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America. *Journal of Quaternary Science,* Vol. 15, 409–417.

Miller, A. (1976) The climate of Chile. In W. Schwerdtfeger, ed., *Climates of Central and South America. World Survey of Climatology.* Amsterdam, The Netherlands: Elsevier, 113–146.

Moreno, P. I. (2002) Western Patagonia: A key area for understanding quaternary paleoclimate at southern mid-latitudes. In G. Casassa, F. Sepúlveda, and R. Sinclair, eds., *The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies. Series of the Centro de Estudios Científicos.* New York, NY: Kluwer Academic/Plenum, 55–65.

Prohaska, F. (1976) The Climate of Argentina, Paraguay and Uruguay. In W. Schwerdtfeger, ed., *Climates of Central and South America. World Survey of Climatology.* Amsterdam, The Netherlands: Elsevier, 13–112.

Rumney, G. R. (1968) *Climatology and the World's Climates.* London, UK: Collier-Macmillan.

Rosenblüth, B., Casassa, G., and Fuenzalida, H. A. (1995) Recent climatic changes in western Patagonia. *Bulletin of Glacier Research,* Vol. 13, 127–132.

Rosenblüth, B., Fuenzalida, H. A., and Aceituno, P. (1997) Recent temperature variations in southern South America. *International Journal of Climatology,* Vol. 17, 67–85.

Santana, A. (1984) Variación de las precipitaciones de 97 a os en Punta Arenas como índice de posibles cambios climáticos [Precipitation variations in Punta Arenas during 97 years as an index of possible climatic changes]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 15, 51–60.

Santana, A. (1999) Resumen meteorológico a o 1998 estación "Jorge C. Schythe" [Meteorological summary 1998, "Jorge C. Schythe" station]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 27, 117–124.

Schwerdtfeger, W. (1976) Introduction. In W. Schwerdtfeger, ed., *Climates of Central and South America, World Survey of Climatology, Vol. 12*. Amsterdam, The Netherlands: Elsevier.

Tuhkanen, S. (1992) The climate of Tierra del Fuego from a vegetation geographical point of view and its ecoclimatic counterparts elsewhere. *Acta Botanica Fennica,* Vol. 145, 5–107.

Weischet, W. (1985) Climatic constraints for the development of the far south of Latin America. *Geo Journal,* Vol. 11, 79–87.

Weischet, W. (1996) *Regionale Klimatologie Teil 1, Die Neue Welt. Amerika Neuseeland Australien* [Regional Climatology Part I, The New World. America New Zealand Australia]. Stuttgart, Germany: B. G. Teubner.

Yang, D., Goodison, B. E., Metcalfe, J. R., Louie, P., Leavesley, G., Emerson, D., Hanson, C. L., Golubev, V. S., Elomaa, E., Gunther, T., Pangburn, T., and Kilkovic, J. (1999) Quantification of precipitation measurement discontinuity induced by wind shields on national gauges. *Water Resources Research,* Vol. 35, 491–508.

Zamora, E. and Santana, A. (1979a) Características climáticas de la costa occidental de la Patagonia entre las latitudes 46°40' y 56°30' [Characteristics of the climate of the west coast of Patagonia between the latitudes 46°40' and 56°30']. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 10, 109–143.

Zamora, E. and Santana, A. (1979b) Oscilaciones y tendencias térmicas en Punta Arenas entre 1888 y 1979 [Oscillations and trends of the temperature at Punta Arenas between 1888 and 1979]. *Anales del Instituto de la Patagonia, Serie Ciencias Naturales,* Vol. 10, 147–154.