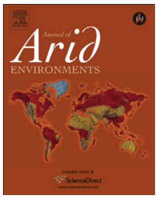
Journal of Arid Environments xxx (2015) 1–5

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv



Climatic characteristics of the semi-arid Coquimbo Region in Chile

S. Montecinos [a], [b], [*], J.R. Gutiérrez [c], [d], [e], F. López-Cortés [c], D. López [d]

[a] Departamento de Física y Astronomía, Universidad de La Serena, Avenida Juan Cisternas 1200, La Serena, Chile
[b] Centro Estudio Recursos de Energía, Universidad Arturo Prat (CERE-UNAP), Avda. Arturo Prat 2120, Iquique, Chile
[c] Departamento de Biología, Universidad de La Serena, Raúl Bitrán 1305, La Serena, Chile
[d] Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Raúl Bitrán 1305, La Serena, Chile
[e] Instituto de Ecología y Biodiversidad (IEB), Casilla 653, Santiago, Chile

ARTICLE INFO

Article history:
Received 17 December 2014
Received in revised form
5 May 2015
Accepted 30 September 2015
Available online xxx

Keywords::
Atmospheric modeling
Semi-arid zones
Desert

ABSTRACT

The climate of the Coquimbo Region, north-central Chile is driven by atmospheric, oceanic and orographic factors. The southeast Pacific anticyclone, the cold Humboldt Current and the rugged topography that characterize the zone, determine thermally induced wind regimes and the formation of low stratocumulus along the coastline. Low precipitation and high solar radiation cause important climatic altitudinal gradients, especially on temperature and humidity, thus different climatic areas can be identified in the region. We summarized the general climatic characteristics of the study area and analyzed meteorological data to understand the behavior of the environmental variables. We used mesoscale modeling to evaluate the spatial characteristics of the mean air temperature, humidity and wind. These atmospheric variables present a strong elevation gradient. The particular topographic characteristics of the region favor the development of a thermally induced wind regime, where land and sea breezes and valley winds are observed.

1. Introduction

The combined effects of atmospheric, oceanic and orographic factors determine the spatial distribution of the main climate elements in north-central Chile (between 29°00′S and 32°10′S). This region is a transition zone between the northern hyperarid Atacama Desert and the southern more mesic Mediterranean region of central Chile. The coastal zone is permanently affected by the Humboldt Current, which is a complex of surface and subsurface ocean water flows which arise in the southern pole and moves toward the north affecting the values of sea and air temperatures, lowering the expected temperature inland (Cereceda and Errázuriz, 1991).

The South-Tropical Pacific Anticyclone effect, a semi-permanent system of high pressure that shifts from 35°S, 90°W in January to 25°S, 90°W in July (Kalthoff et al., 2002) influences the intrusion of unstable polar fronts, stabilizing the atmosphere due to atmospheric upwelling and inhibiting the clouds formation in the mid and upper atmosphere. In particular, when air descends, compressional warming occurs at a mid-elevations but cooler air is retained near the ocean surface. This results in inverse thermal layering in which a warmer layer is "sandwiched" between colder layers above and below. Along the northern Chilean coast, the resulting thermal inversion allows the formation of a permanent cloud stratum throughout the year, albeit with variable altitude (Rutllant et al., 2003; Rundel et al., 1991). Theses stratus can move eastwards by sea breeze, so it is in those hills of the Coastal Range higher than 600 m where typical intense fogs events can be observed, such as in the Bosque Fray Jorge National Park (thereafter BFJNP).

The special topography of the region, with the coast to the west and the high Andes to the east, represents an orographic control that blocks winds coming from the west and east, respectively (Rundel et al., 1991), causing important climatic elevation gradients. Rainfall also varies along this steep altitudinal gradient. Favier et al. (2009) found that the mean annual precipitation in north-central Chile (e.g., 26–32°S) varies from approximately 100 mm at the coast to 300 mm at the top of the Andes, with a predominantly Mediterranean regime with precipitation occurring mainly in winter and resulting from the passage of frontal systems from the

---

[*] Corresponding author. Departamento de Física y Astronomía, Universidad de La Serena, Avenida Juan Cisternas 1200, La Serena, Chile.

E-mail addresses: smontecinos@userena.cl (S. Montecinos), jgutierr@userena.cl (J.R. Gutiérrez), flopez@userena.cl (F. López-Cortés), david.lopez@ceaza.cl (D. López).

http://dx.doi.org/10.1016/j.jaridenv.2015.09.018
0140-1963/

southern Pacific (Falvey and Garreaud, 2007).

The climate of the Coquimbo Region, is strongly influenced by the El Niño/Southern Oscillation (ENSO) phenomenon, which is the primary driver underlying the high interannual variability in precipitation, and which promotes higher than average rainfall during the warm phase (Rutllant and Fuenzalida, 1991).

Mesoscale modeling is a very useful tool to evaluate the spatial distribution of atmospheric variables (Kalthoff et al., 2002; Montecinos et al., 2012). In this paper we used mesoscale models to evaluate the spatial distribution of the mean, maximum and minimum air temperatures, mean relative air humidity and mean wind velocity. The results confirmed the strong variability of the atmospheric variables.

2. Materials and methods

2.1. Study site

The Coquimbo Region (32°S–29°S), located in the semi-arid Norte Chico of Chile, is a transitional zone between the hyper-arid Atacama Desert and the more mesic Mediterranean climate of central Chile. The region is bordered on the west by the Pacific Ocean, and the topography rises to the east in the Andes with heights over 5000 masl.

Three large watersheds, from north to south Elqui, Limarí and Choapa, cross the region from east to west, and provide water for irrigated agricultural activities.

2.2. Climatic characteristics of the Coquimbo Region

The description of the main climatic characteristics of the Coquimbo Region and the climatic zones within is based on results published in the literature.

2.3. Mesoscale modeling

The spatial distribution of the atmospheric models was performed using the non-hydrostatic Karlsruhe Atmospheric Mesoscale Model KAMM which consists of two components or modules, one atmospheric and one soil-vegetation. The model simultaneously solves momentum, heat and humidity equations, transformed onto a coordinate system which follows the terrain. It needs as input data large-scale synoptic weather data (profiles of temperature, humidity and wind) as well as topography, soil types and land use. Complete information about the KAMM model can be found in Bischoff-Gauss et al. (2006), Montecinos et al. (2012, 2013) and references therein.

2.3.1. Simulation region and setups

The simulation region (SR) is located in the Norte Chico region of Chile located between 72.0°W and 70.5°W longitude and 31.8°S and 28.8°S latitude. It covers an area of 265 × 445 km^{2}and includes the entire Coquimbo Region. The upper limit of our atmospheric model was set at 10 km altitude. The numerical simulations were performed for a horizontal grid of 1 km^2 cells. The SR was divided vertically into 40 layers. The land use classification was taken from CONAF and CONAMA (1999), which were adapted to the KAMM land use classification.

The environmental input data needed to initialize the simulations were taken from the following sources: initial vertical profiles from the National Center for Environmental Prediction/NCAR Reanalysis (Kalnay et al., 1996); earth surface temperature was set 1 °C cooler than the lowest air temperature. The temperature of the Pacific Ocean was taken from satellite data (reference in Reynolds et al., 2002).

2.3.2. Spatial distribution of atmospheric variables

We used the KAMM model to evaluate the mean fields of atmospheric variables, over a 16-year period (1990–2006). We performed this procedure for each season separately. The averages were evaluated using a method based on cluster analysis (Anderberg, 1973) which consists in grouping together days with common patterns. For each cluster, we conducted a representative simulation, which were averaged taking into account its statistical weight. More details about the methodology can be found in Montecinos et al. (2012, 2013).

The mean air temperature, air relative humidity and wind velocity were calculated as average over the seasonal model simulations.

2.3.3. Model validation

To test the validity of the numerical results, simulated seasonal diurnal cycles of temperature, humidity, and wind speed and direction were compared with observations taken from 20 meteorological stations distributed in the Coquimbo Region. The meteorological data were obtained from weather stations of different owners, including the Center for Advanced Studies in Arid Zones (CEAZA), public institutions and private companies, so that the amount and type of sensors, as well as its height above ground were different. For the purpose of validation, the model simulations were evaluated at the same height above ground level (agl) as the location of the sensors.

2.4. Climatic characteristics of the Bosque Fray Jorge National Park (BFJNP)

To analyze the climatic characteristic of BFJNP we used the data registered by a weather station in Quebrada de LasVacas (30.66° S; 71.66° W); this station is located on the east side of the coastal hills, in a north–south oriented watershed, where the Long-Term Ecological Research (LTER) is located. The meteorological station was installed at the site in 1999 and has registered several climatic variables. Among these variables are precipitation and temperature data at 1.5 m agl. The accumulated precipitation is registered hourly and temperature every 15 min.

We used these data to evaluate the monthly mean temperature and annual accumulated precipitations of the BFJNP in the period 1999 to 2012.

3. Results

3.1. Climate of the Coquimbo Region

The climate of the Coquimbo Region is the result of the interaction of the synoptic parameters with local factors, such as topography, altitude, soil use and distance to the ocean. The rugged topography of the Coquimbo Region allows for important variation in meteorological variables over short distances.

The first climatic classification was based in the different types of vegetation that grow in the region. Starting from the coast, Koeppen (1948) identified eight classes of climates: very cloudy steppe (BSn), marginal template steppe (BSlW), temperate steppe with precipitations during the winter (BSks), cold mountain desert (BWk'G), transition desert (BWl), coastal desert with abundant cloudiness (BWn), mountain cold steppe (BSk'G), high mountain tundra (EB). All can be considered semi-arid. The BSn, located at the coastal shoreline from La Serena, including BFJNP, is characterized by a strong ocean influence and frequent occurrence of coastal fogs (Antonioletti et al., 1972), and a low temperature amplitude of about 5 °C to 6 °C, high air humidity and winds from S–W. Due to the Coast Range, it is possible to find sites with frequent fog and low

Please cite this article in press as: Montecinos, S., et al., Climatic characteristics of the semi-arid Coquimbo Region in Chile, Journal of Arid Environments (2015), http://dx.doi.org/10.1016/j.jaridenv.2015.09.018

clouds, which provide enough humidity for the establishment of very contrasting plant communities in a relatively small area as is the case of the BFJNP.

Large time series registered in meteorological stations indicate that rainfall has been declining in the northern Chilean semarid zone continuing a gradual aridity trend over the past 100 years (Bahre, 1979). Data registered by meteorological stations in BFJNP document that the average precipitation (10-years window) has been steadily declining from 209 mm yr^{-1} to 113 mm in the period 1940–49 to 1990–99 respectively (Kummerow, 1966; Fulk, 1975). The three largest El Niño events of the 100 years have all occurred since 1987.

3.2. *Mesoscale modeling*

3.2.1. *Model validation*

We found that the simulated results fit very well with the observations, especially in those stations located in coastal and central zone of the region.

For temperature, in the Limarí Basin the Root Mean Square Error (RMSE) between the simulated and observed temperatures in winter and summer varies between 0.2 °C and 0.5 °C (Montecinos et al., 2013). In the meteorological station in BFJNP the model overestimate the temperature and the RMSE is 2.5 °C. For other stations located in the high Andes the RMSE are higher with values of up to 5 °C.

For wind speed and direction, the adjustment between model results and observations depended on the location of the station. In general the adjustment between model results and observation for wind direction was very good for all stations, included the station in BFJNP, with RMSE between 0° and 10°. In the case of wind speed, the adjustment between model results and data was very sensitive to the topography. Specifically, model fit was better for those station located in relative flat zones compared to those located in sites with complex topography. In the station in BFJNP, the RMSE was 0.8 ms^{-1}. The differences were especially large in the high Andes where the model over-estimates the observations, with RMSE up to 10 ms^{-1}. These differences between model simulations and observations can be due to different factors such as: i) snow is not considered in the model and ii) the complex topography of the sites where the meteorological stations are located, which are not compatible with the spatial resolution of the model.

3.2.2. *Temperature*

Fig. 1a and b shows the air temperature at 2 m above agl at 06:00 and 14:00 local time (LT), respectively, which usually corresponds to the daily minimum and maximum temperature, respectively. The isolines represent the topography. At 06:00 LT the temperature near the coast is about 12 °C, and decreases eastwards reaching values below zero in the high mountains. At 14:00 LT the mean temperature reaches about 18 °C near the coast; it increases in the low areas near the valleys and decreases eastwards. In the high mountains the average maximum temperature ranges between 1 °C and 10 °C.

3.2.3. *Relative air humidity*

The relative air humidity pattern depends on topography. Near the coast, humidity can approach saturation, especially in those regions where the altitude increases rapidly eastward, as in BFJNP. Air humidity decreases significantly to the east with values under 40% in the high elevations of the Andes. Fig. 1c displays the average relative air humidity at 2 m agl at 04:00 LT.

3.2.4. *Wind speed*

Winds in the Coquimbo Region also are strongly influenced by the topography. During the day a sea breeze develops at the Pacific coastline. This wind regime combines with the up-valley winds in the three transversal valleys located in the region (Bischoff-Gauss et al., 2006; Kalthoff et al., 2002). The effect on the mean flow at 14:00 LT is shown in Fig. 1d.

3.3. *Climatic characteristics of the Bosque Fray Jorge National Park (BFJNP)*

The BFJNP (30°38′S–71°40′W) is located in the Limarí Basin, 110 km south of La Serena, in the coastal zone of the Coquimbo Region. There is a steep increase in elevation from the coast to the Coastal Range that forces the moist sea wind to climb up through these hills cooling the air masses. At about 2.5 km from the coastline, these hills reach 400 to 650 masl, promoting the formation of fog (López-Cortés and López, 2004) and enabling the survival of a narrow strip of Valdivian Temperate Rainforest typical that otherwise is more characteristic of southern continental Chile, with mean rainfall above 800 mm yr^{-1} (González-Reyes and Muñoz, 2013).

3.4. *Precipitation*

Precipitation in BFJNP between 1999 and 2013 is characterized by a high inter-annual variability (Fig. 2) and is influenced by the El Niño Southern Oscillation. Some years (1987, 1991, 1997, 2002) have high precipitation (to 400 mm yr^{-1}) followed by 3 until 5 years with scarce rainfall. Typical of Mediterranean climates, precipitation is concentrated during winter months (from May to September) where 93% of all rainfall events occur.

3.5. *Temperature*

Mean monthly temperature is characterized by a distinct seasonal cycle (Fig. 2 left panel) and ranges between 10 °C and 17 °C. On average, the minimum and maximum temperatures are achieved in August and February, respectively.

Because of the complex topography of this national park, the results shown in this section are valid in neighboring sites where the station is located. This is especially important for temperature, since this is highly dependent on altitude, proximity to the ocean and, in the case of hills, the orientation.

4. Conclusions

i) Due to the complex topography the climate of the Coquimbo Region shows high variability in space and time of atmospheric variables. Eight climatic zones can be recognized, which differ mainly by their distances to the coast. At the coast the climate is moist with frequent occurrence of clouds and fog, whereas in the Andes the air is dry with a nearly complete absence of vegetation.

ii) Mesoscale modeling shows that the mean minimum temperature decreases from about 12 °C near the coast to below 0 °C in the high mountains. Maximum temperatures reach 18 °C at the coast and near 0 °C in the Andes.

iii) Because of the proximity to the ocean the mean air relative humidity can reach high values especially in the Coastal Range, where values reach saturation, decreasing rapidly eastwards. In the high Andes humidity may drop below 40%.

iv) The wind is strongly affected by both topography (valley winds) and distance to the ocean (sea breeze), such that some regions may experience strong and frequent winds.

Please cite this article in press as: Montecinos, S., et al., Climatic characteristics of the semi-arid Coquimbo Region in Chile, Journal of Arid Environments (2015), http://dx.doi.org/10.1016/j.jaridenv.2015.09.018

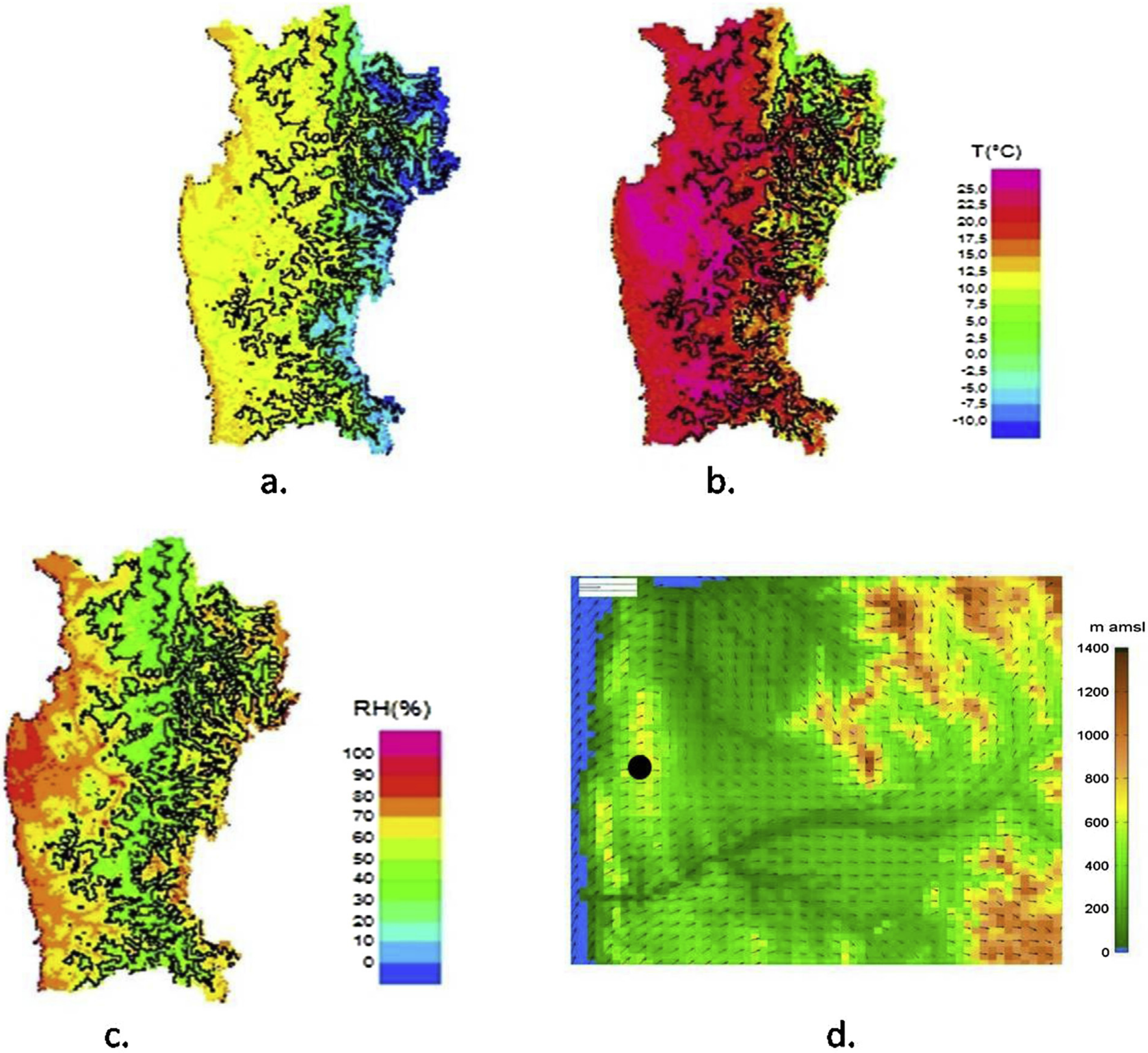


Fig. 1. Spatial distribution of atmospheric variables. (a) and (b): Mean temperature at 2 m above ground level (agl) at 06:00 (a) and 14:00 (b) local time (LT), respectively. (c): mean relative air humidity at 04:00 LT; isolines represent the topography. (d): mean wind velocity at 14:00 LT in the surrounding of BFJNP (black point); here the topography is represented by a color code in meters above mean sea level (amsl) shown at the right side of the panel.

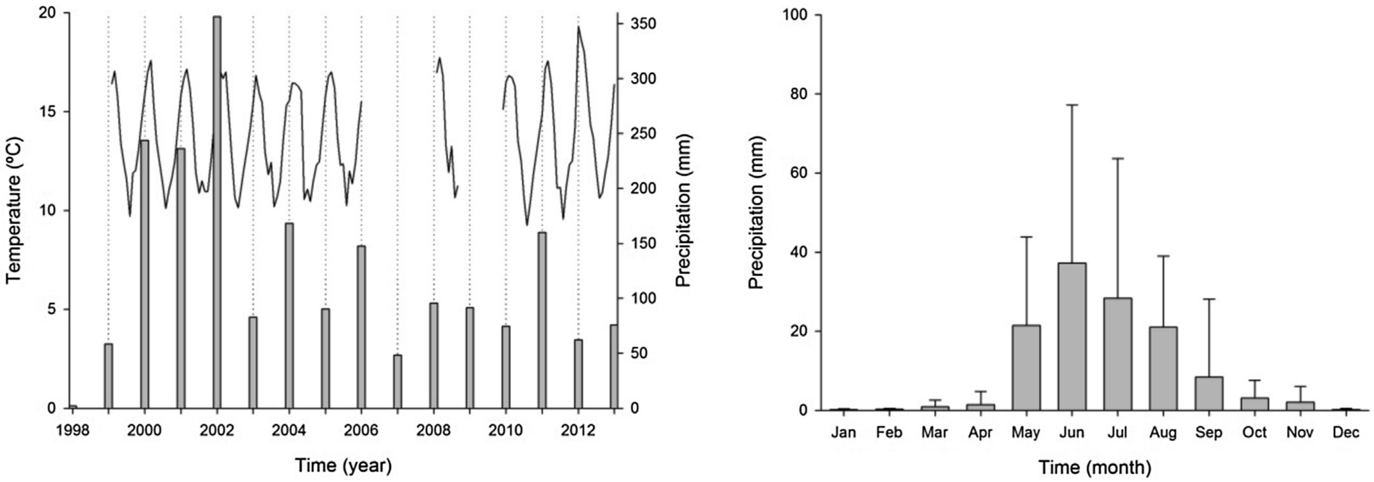


Fig. 2. Climatic characteristics in BFJNP during the period of 1998–2013. Left: mean annual precipitation (bars) and monthly mean temperature (solid line) at 1.5 m agl. Right: Monthly precipitation (means + SD).

Please cite this article in press as: Montecinos, S., et al., Climatic characteristics of the semi-arid Coquimbo Region in Chile, Journal of Arid Environments (2015), http://dx.doi.org/10.1016/j.jaridenv.2015.09.018

Acknowledgments

This work was partially supported by CONICYT, Project FONDEF D05I10038 and the International Exchange Project BMBF – CONICYT 066-2007. The authors thank SCC (Steinbuch Centre for Computing, Karlsruhe Institut für Technologie (KIT), Germany) for the supply of computing time on NEC SX8 in the context of Campus Grid Project.

References

Anderberg, M.R., 1973. Cluster Analysis for Applications. Academic Press, New York, p. 359.

Antonioletti, R., Schneider, H., Borcosque, J.L., Zarate, E., 1972. Características climáticas del Norte Chico (26° a 33° latitud sur). Instituto de Investigación de Recursos Naturales, Santiago, p. 102.

Bahre, C.J., 1979. Destruction of the Natural Vegetation of North-central Chile, 23. University of California Publications in Geography, pp. 1–116.

Bischoff-Gauss, I., Kalthoff, N., Fiebig-Wittmaack, M., 2006. The influence of a storage lake in the Arid Elqui Valley in Chile on local climate. Theor. Appl. Climatol. 85, 227–241.

Cereceda, P., Errázuriz, A., 1991. Ecogeografía: Nueva Geografía de Chile. Editorial Zig-Zag SA, Santiago, p. 225.

CONAF and CONAMA, 1999. Catastro y evaluación de los recursos vegetacionales nativos de Chile, Informe nacional con variables ambientales. BIRF, Universidad Austral de Chile, Pontificia Universidad Católica de Chile, Universidad Católica de Temuco, Santiago, Chile.

Falvey, M., Garreaud, R., 2007. Wintertime precipitation episodes in Central Chile: associated meteorological conditions and orographic influences. J. Hydrometeorol. 8, 171–193.

Favier, V., Falvey, M., Rabatel, A., Pradeiro, E., Lopez, D., 2009. Interpreting discrepancies between discharge and precipitation in high-altitude area of Chile's Norte Chico region (26–32°S). Water Resour. Res. 45, 1–20. http://dx.doi.org/10.1029/2008WR006802.

Fulk, G.W., 1975. Population Ecology of Rodents in the Semi-arid Shrublands of Chile, Occasional Papers the Museum, 33. Texas Tech University, p. 140.

González-Reyes, A., Muñoz, A.S., 2013. Precipitation changes of Valdivia city (Chile) during the past 150 years. Bosque 4, 191–200. http://dx.doi.org/10.4067/S0717-92002013000200008.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Reynolds, R., 1996. The NCEP/NCAR 40-Year reanalysis project. Bull. Am. Meteorol. Soc. 77, 437–471.

Kalthoff, N., Bischoff–Gauß, I., Fiebig–Wittmaack, M., Fiedler, F., Thuerauf, J., Novoa, E., Pizarro, C., Castillo, R., Gallardo, L., Rondanelli, R., Kohler, M., 2002. Mesoscale wind regimes in Chile at 30°S. J. Appl. Meteorol. 41, 953–970.

Koeppen, W., 1948. Climatología. Fondo de Cultura Económica, México, p. 478.

Kummerow, J., 1966. Aporte al conocimiento de las condiciones climáticas del Bosque de Fray Jorge, Boletín Técnico Universidad de Chile. Fac. Agron. 24, 21–24.

López-Cortés, F., López, D.A., 2004. Antecedentes bioclimáticos del Parque Nacional Bosque Fray Jorge. In: Squeo, F.A., Gutiérrez, J.R., Hernández, I.R. (Eds.), Historia Natural del Parque Nacional Bosque Fray Jorge. Ediciones Universidad de La Serena, La Serena, Chile, pp. 45–60.

Montecinos, S., Bacuñan-Godoy, L., Salinas, P., Astudillo, O., Lopez, D., 2013. Estimating spatial distribution of air temperature from meteorological stations using atmospheric model. J. Atmos. Sci. 5, 1682–1687.

Montecinos, S., Salinas, P., Osses, R., González-Silvestre, L., Molina-Montenegro, M., 2012. Linking climatic variability with spatial performance in two varieties of quinoa distributed in a semi-arid zone. Am. J. Plant Sci. 2012 (3), 1682–1687. http://dx.doi.org/10.4236/ajps.2012.312205.

Reynolds, R.W., Rayner, N.A., Smith, T.M., Stokes, D.C., Wang, W., 2002. An improved in situ satellite SST analysis for climate. J. Clim. 15, 1609–1625. http://dx.doi.org/10.1175/1520-0442(2002)015%0c1609:AIISAS%0e2.0.CO;2.

Rundel, P.W., Dillon, M.O., Palma, B., Mooney, H.A., Gulmon, S.L., Ehleringer, J.R., 1991. The phytogeography and ecology of the coastal Atacama and Peruvian Deserts. Aliso 13, 1–49.

Rutllant, J., Fuenzalida, H., 1991. Synoptic aspects of central rainfall variability associated with the Southern Oscillation. Int. J. Climatol. 11, 63–76. http://dx.doi.org/10.1002/joc.3370110105.

Rutllant, J., Fuenzalida, H., Aceituno, P., 2003. Climate dynamics along the arid northern coast of Chile: the 1997–1998 Dinamica del Clima de la Region de Antofagasta (DICLIMA) experiment. J. Geophys. 108, 4538. http://dx.doi.org/10.1029/2002JD003357.

Please cite this article in press as: Montecinos, S., et al., Climatic characteristics of the semi-arid Coquimbo Region in Chile, Journal of Arid Environments (2015), http://dx.doi.org/10.1016/j.jaridenv.2015.09.018