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# The Southern Westerlies in Central Chile: Holocene precipitation estimates based on a water balance model for Laguna Aculeo (33°50′S)

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**Abstract** Central Chile (32–35°S) lies at the northern border of strong influence of the Westerly circulation belt (Westerlies) and is therefore characterized by a steep precipitation gradient. In this region, quantitative reconstructions of Holocene precipitation are scarce. Hence, the present study estimates precipitation changes, based on lake level fluctuations of Laguna Aculeo (33°50′S, 70°54′W). The lake level curve has been reconstructed using a multi-proxy study of lake sediments. Lake level changes have been simulated using a simple water balance model. As a result, palaeo-precipitation could be estimated: uncertainties concerning the input parameters and past conditions have limited the precision of precipitation estimates. The results suggest that during the beginning of the Holocene, when the lake level (< 1.5 m) was low, precipitation was < 200 mm/year. Before 8000 cal yr BP, the lake frequently dried out. Between 8000 and 6000 cal yr BP, precipitation appeared to be higher (150–300 mm/year) and after about 6000 cal yr BP, precipitation increased dramatically (350–450 mm/year). Around 3000 cal yr BP, modern lake level and precipitation (450–550 mm/year) were generally established. The dry conditions during the early and mid-Holocene are in good agreement with other records from Central Chile and northern Patagonia. The Westerlies were probably deflected southward by the southeast Pacific subtropical high-pressure cell during the mid- and early Holocene. Subsequently, the increase in moisture in Central Chile during the late Holocene appears to be strongly related to intensified Westerly activity and probably also to increased El Niño activity.

## 1 Introduction

The northern border of strong Westerly influence lies in the Mediterranean part of Central Chile (32–35°S). Hence, the gradient of precipitation is especially steep in this region with high rainfall towards the south (lake district) and increasingly dry conditions towards the north (Norte Chico). Therefore, palaeo-archives in Mediterranean Central Chile are expected to have reacted very sensitively to former moisture fluctuations of the Westerlies. There has been much discussion on humidity changes due to fluctuations of the Westerly circulation belt (Westerlies) in southern South America (e.g. Heusser 1983, 1990; Markgraf 1989, 1998; Ruttlant and Fuenzalida 1991; Ariztegui et al. 1997; Lamy et al. 1998, 1999). For the late-glacial and last glacial maximum period, there is a dispute about the interpretation of pollen profiles in Central Chile. While Markgraf (1989) proposes mainly a temperature depression and hence reduced evaporation, Heusser (1983, 1990) suggests a strong precipitation increase due to a northward shift of the Westerlies. Nevertheless, the authors agree that the early to mid-Holocene in the region was dry.

The mid-Holocene in general represents a period of profound change, a topic addressed e.g. by Stager and Mayewski (1997), Steig (1999) and Sandweiss et al. (1999). During this period, arid conditions persisted in Mediterranean Chile, as indicated by lakes and peat bogs (Heusser 1983, 1990; Villagrán and Varela 1990; Jenny et al. 2002b), marine sediments (Lamy et al. 1999, 2001) and palaeosols (Veit 1996). More humid conditions were established in the late Holocene as shown e.g. by studies of tree-rings (Villalba 1990, 1994).

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In general, estimates of Holocene precipitation in Mediterranean Chile are very scarce, as only Heusser (1990) indicates an annual precipitation below 200 mm at the Laguna de Tagua Tagua site (34°30′S) during the mid-Holocene, derived from pollen data. The present study was therefore designed to evaluate precipitation changes derived from lake level fluctuations during the Holocene. Water balance models have proven to provide reliable estimates of former precipitation (e.g. Hastenrath and Kutzbach 1983; Street-Perrott and Harrison 1985; Hostetler 1995). They have been widely applied in Europe (e.g. Harrison et al. 1993; Cheddadi et al. 1997; Vassiljev 1998), in Africa (Hastenrath and Kutzbach 1983; Hoelzmann et al. 2000) and on the South American Altiplano (Hastenrath and Kutzbach 1985; Kessler 1985; Grosjean 1994). In Mediterranean Chile, Laguna Aculeo (33°50′S, 70°54′W) provides detailed information about Holocene lake level changes from a multi-proxy study (Jenny et al. 2002a, 2002b). The lake lies in a tectonic depression and is one of few natural lakes in the lowlands of Central Chile. In the present study, these data are used in a water balance model to estimate the amount of precipitation needed to sustain the lake in equilibrium at different lake levels. Strong seasonal fluctuations, which exist today, are also assumed for the entire Holocene.

## 2 Research area

Laguna Aculeo (33°50′S, 70°54′W, 350 m asl) is situated 50 km southeast of Santiago de Chile. With a surface area of 12 km$^2$, it is one of the largest natural lakes in the Mediterranean region of Chile. There is no river from the Andes draining into the lake. The lake lies in a tectonic basin in the Coastal Cordillera of Central Chile (Fig. 1). Apart from the southeast the catchment area is clearly defined by these mountains. The southeastern part, which is not included in the model catchment area, drains mainly to the east directly into the river Maipo, so only a very small proportion could possibly drain into the lake. This uncertainty is taken into account in the sensitivity study in Sect. 5.3. The catchment area that is used for this model is indicated in grey. This area drains directly into the lake. The lake has a very small outflow on the eastern side, which runs dry in summer and is rarely filled with water even in winter, functioning partly as a very small inflow during extremely rainy winters (Cabrera and Montecino 1982). Since the outflow is only active during very rainy winters, when lake level is higher, it can be neglected for simulations of the Holocene, which are based on low lake level and low rainfall. Hence, evaporation is the main process for water loss. There is no groundwater flow data available, but we consider the groundwater inflow negligible compared to river input. The summer is dry with high radiation and evaporation rates because the frontal system of the Westerlies is blocked by the stable subtropical high-pressure cell. The winter is cooler and humid, with a positive moisture balance as the Westerlies reach Central Chile (Weischet 1996). Consequently, precipitation and evaporation show highly seasonal fluctuations. Annual precipitation is 544 mm (72-year average, DGA unpublished data 1998), but over 1000 mm are common in El Niño years in the twentieth century. Today, extremely rainy winters in Central Chile (32–35°S) are generally strongly correlated with El Niño (Rutllant and Fuenzalida 1991; Montecinos et al. 2000). The mean temperature in Central Chile is around 8–10 °C in winter and 18–20 °C in summer (Weischet 1996).

## 3 Methodology

The lake level changes have been simulated using a simple water balance model. The mathematical approach is based mainly on Hostetler (1995) and Hastenrath and Kutzbach (1983). In view of the highly seasonal amplitude of the annual precipitation and evaporation cycle, the interannual variability is included in the model. The surface outflow is negligible, since it only functions when the lake level is very high (see Sect. 2). The groundwater outflow is considered minimal, but this uncertainty will be discussed in the sensitivity study. Hence, the lake is assumed to behave as a closed system. According mainly to Hostetler (1995), the time rate of changes to the lake level $z$ (m) is given by

$$\frac{\mathrm{d}z}{\mathrm{d}t} = (P_L - E_L) + \frac{A_B(z)}{A_L(z)}(rP_B) \ . \qquad (1)$$

Here, $P_L$ is the precipitation over the lake surface in (mm/month), $E_L$ is the evaporation from the lake surface in (mm/month), $A_L(z)$, in (m$^2$), is the surface area of the lake at the elevation $z$, $A_B(z)$, in (m$^2$), is the surface area of the catchment excluding the lake, $P_B$ is the precipitation over the lake catchment in (mm/month) and $r$ is the runoff coefficient. The runoff coefficient defines the ratio of the catchment precipitation draining into the lake. The ordinary differential equation is integrated in time using a (first order) forward Euler scheme (see e.g. Hirsch 1989). For stability reasons, we used a time step of $\Delta t = 0.1$ month. It should be noted that we also employed a fourth order Runge-Kutta scheme (e.g. Hirsch 1989) and generally obtained the same results as with the forward Euler method.

## 4 Lake level input data

The lake level history of Laguna Aculeo during the Holocene has been estimated based on a multi-proxy study of several sediment cores dated with 16 $^{14}$C dates and a $^{210}$Pb chronology of the upper 50 cm of sediments (Jenny et al. 2002b). Quantitative lake level data are often difficult to infer from palaeoproxies. However, the range of estimated lake level can be assessed based on the sedimentary facies, pollen and diatom analyses. Sedimentary facies analyses provide useful data to estimate water depth, chemical water concentration and past depositional conditions (Fig. 2).

The eight sedimentary facies can be grouped in four lake level categories: (a) high lake level (facies 1, 2 and 3); (b) intermediate lake level (facies 5 and 6); (c) low lake level (facies 7 and 8) and (d) desiccation and subaerial exposure (facies 4). In facies 1, the high organic matter content, absence of carbonates and dominance of freshwater diatom assemblages indicate a freshwater lake without significant detrital input and an average lake level similar to today's (about 6 m deep) or even higher. Facies 2 shows evidence of intense fluvial input and higher depositional energy during flooding episodes reaching the deepest area of the lake. Facies 3 reflects fluvial input during high lake levels. Facies 5 and 6 are light-grey silts with a low organic content and variable amounts of carbonate charac-

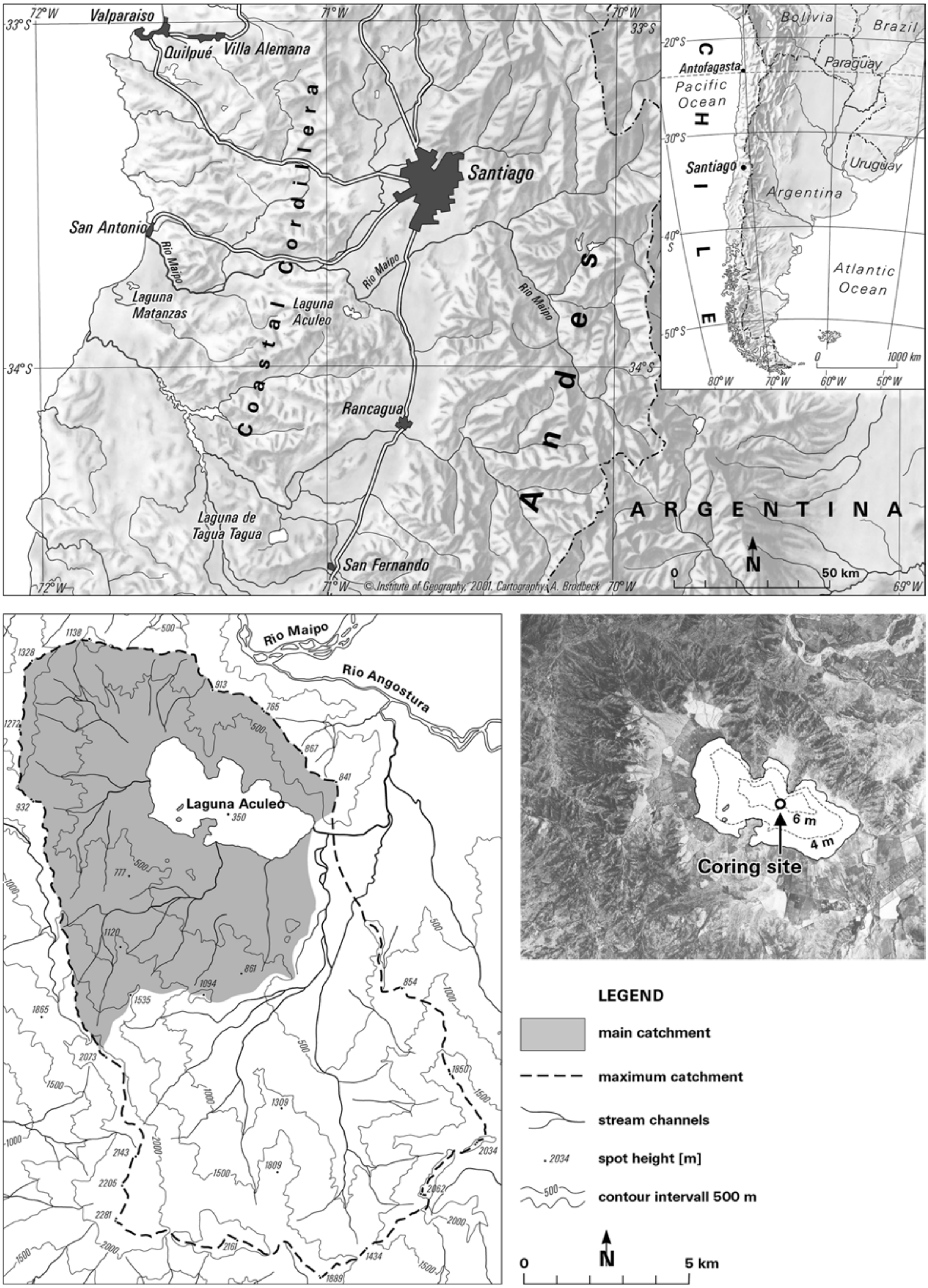

**Fig. 1** Geographical overview of Laguna Aculeo

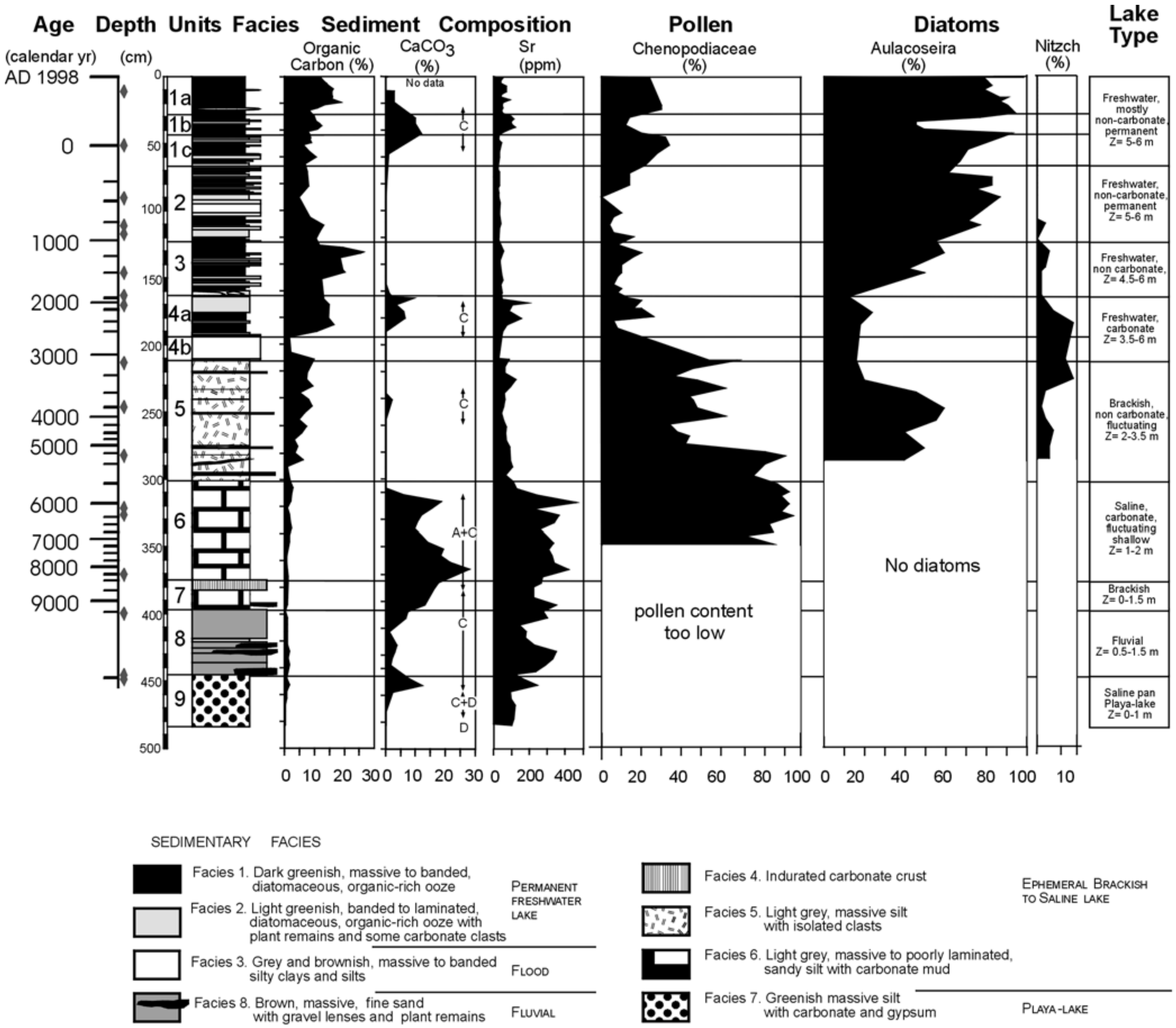

**Fig. 2** Holocene multi-proxy record of Laguna Aculeo. Carbonates: *A* (aragonite), *C* (calcite), *D* (dolomite). Data are adapted from Jenny et al. (2002b)

teristic of aragonite and calcite-producing saline lakes (facies 6) and non-carbonate shallow lakes (facies 5). Facies 7 consists of calcite and dolomite-bearing ( ≤ 10%) silts with gypsum ( ≤ 10%), indicating deposition in a playa-lake system with frequent desiccation stages. Facies 8 is coarse-grained and composed of brown, massive gravel and sands arranged in fining-upward sequences. The coarse-grained and oxidized nature of the sediments indicates fluvial deposition in the lake basin during low lake level. Facies 4 is a unique layer composed of carbonate clasts in a siliciclastic matrix, topped by a massive calcite-cemented horizon giving evidence of lake desiccation.

Based on the sedimentological facies, the lake history can be drawn and a range of estimated lake levels, which accounts for the semi-quantitative approach, can be given (Fig. 3a). Early in the Holocene (around 10,000 and 9500 cal yr BP), Laguna Aculeo was an ephemeral playa with large seasonal water level oscillation between desiccation and up to 1 m water depth. Deposition of clastic facies 8 around 9000 cal yr BP indicates stronger river activity, likely caused by an increase in precipitation, which would produce a temporary increase in the lake level. However, the presence of brackish diatoms suggests that the lake level increase was relatively small. The development of the carbonate hardground (facies 4) at the top of this unit indicates a period when the lake experienced frequent desiccation phases around 9000 cal yr BP. At some point before 8000 cal yr BP, desiccation phases became less pronounced, and shallow saline lake environments dominated afterwards with deposition of aragonitic and calcitic sediments (facies 5 and 6), suggesting that the lake level was around 1 to 2 m. Pollen analysis shows the dominance of Chenopodiaceae during the early and mid-Holocene, indicating large littoral areas around the lake colonized by grasses and generally dry conditions. Around 6000 to 5500 cal yr BP, the lake level rose. Absence of carbonate precipitates after 5700 cal yr BP indicates that lake waters were progressively more diluted and non-saturated in carbonate and limnological conditions characterized by fresher waters, a more positive water balance, and an increasing lake level. Between 5700 and 3000 cal yr BP, the lake level fluctuated at higher levels. It is difficult to verify a precise water depth. Therefore a wide range is shown, since the lake did not dry out or produce any carbonate as before at a lower lake level, but had not reached the modern level yet. The presence of inter-

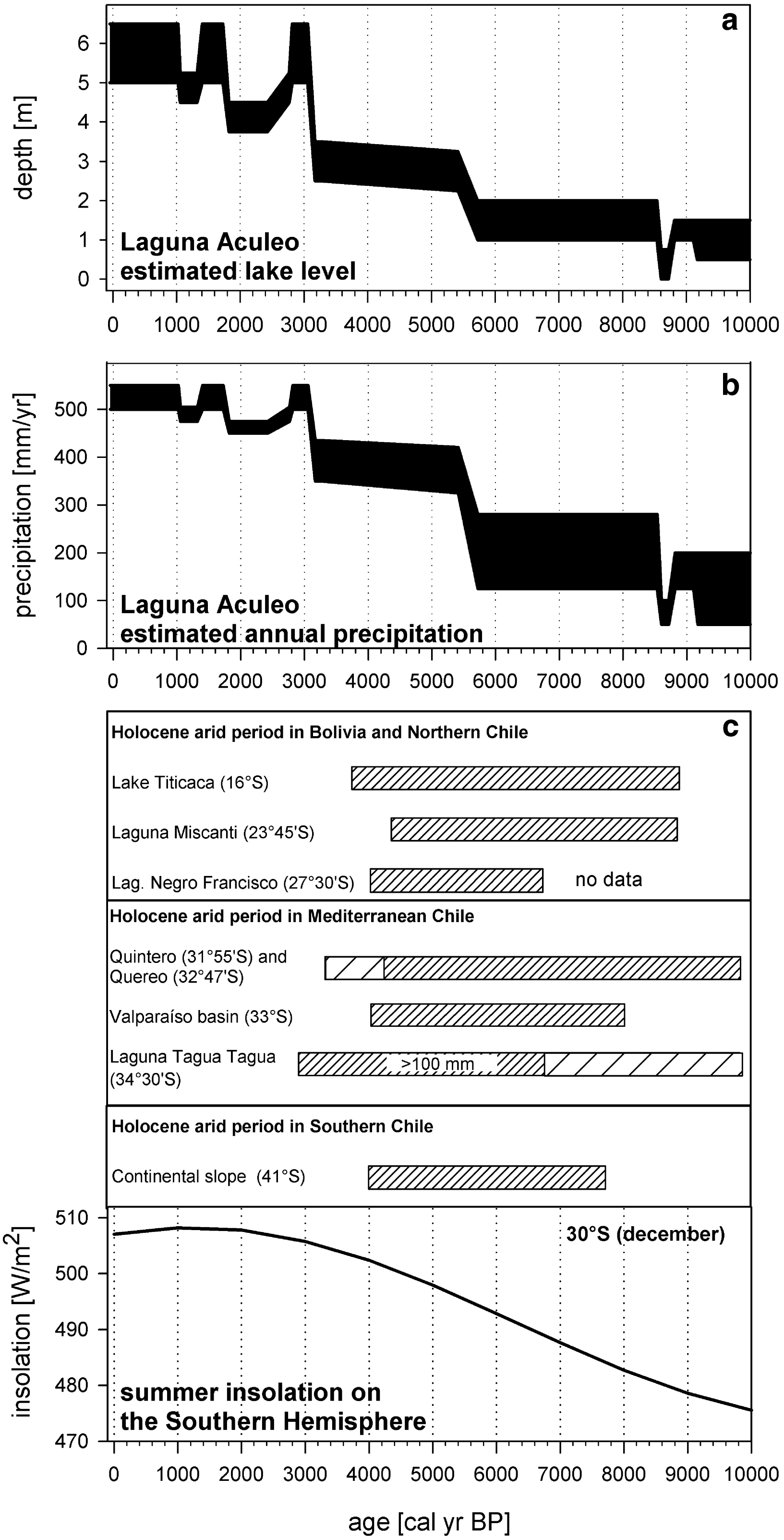

**Fig. 3a–c** Overview of the Holocene in southern South America. **a** Estimated lake level of Laguna Aculeo; **b** estimated annual precipitation at Laguna Aculeo; **c** palaeoclimatic data of southern South America. Only the very dry phases (*dense grid*) and the less pronounced, but still drier phases (*coarse grid*) are indicated. Data are based on Wirrmann and Mourguiart (1995) and Cross et al. (2000) for Lake Titicaca, Valero-Garcés et al. (1996) for Laguna Miscanti, Grosjean et al. (1997) for Laguna Negro Francisco, Villagrán and Varela (1990) and Villa-Martínez and Villagrán (1997) for Quereo and Quintero, Lamy et al. (1999) for the Valparaíso basin, Heusser (1990) for Tagua Tagua, and Lamy et al. (2001) for the continental slope (41°S). Insolation data were obtained from Berger and Loutre (1991)

calated clay and silt layers reflects flooding episodes in the basin. At around 3000 cal yr BP, the lake level rose after deposition of a 15 cm thick, silty layer interpreted as an intense flooding period. An abrupt decrease in Chenopodiaceae at about 3000 cal yr BP was synchronous with an increase in Gramineae, aquatic plants and arboreal pollen, indicating more humid conditions. Diatom assemblages are dominated by planktonic taxa. Since then, lake levels have fluctuated around the modern lake level, except for a period of lower lake level around 2000 cal yr BP, when carbonates were precipitated and diatoms indicate brackish conditions.

# 5 Results

## 5.1 Calibration

The water balance model has been calibrated according to climate data of the period 1986 to 1998. Modern climate and catchment parameters for the Laguna Aculeo basin are shown in Table 1. The average elevation of the catchment of about 610 m asl is 260 m higher than the lake (350 m asl). Based on the data of several climate stations (DGA 1998) between 33° and 34°S, a precipitation lapse rate of about 25 mm/100 m elevation was calculated. The change of 260 m in elevation corresponds to an increase in precipitation of about 65 mm, and an average annual precipitation of 609 mm results for the catchment. If the climate regime is drier, then the gradient decreases. In Central Chile, between 32° and 33°S, where climate is significantly drier, the precipitation gradient, as calculated from climate data (DGA 1998), is only about 13 mm/100 m elevation change. This value is comparable to the dry Altiplano at 23°S (Kull 1999), where precipitation only changes by about 10 mm/100 m elevation change. Since climate conditions around 34°S were much drier in the early and mid-Holocene, this fact has to be taken into account and the annual precipitation $P_L$ at lake level is multiplied by a factor in order to achieve $P_B$. For the catchment of Laguna Aculeo, this factor is 1.12 (=1 + 65 mm/544 mm). Hence, the absolute amount of precipitation increase per 100 m higher elevation decreases with a lower $P_L$.

Monthly precipitation closely follows a Gauss function with a peak in winter (Fig. 4a). The integration of the Gauss function results in the modern annual precipitation of 544 mm (average of 72 years). For the simulation of past lake levels, the amplitude of the Gauss function was damped, assuming still mainly winter precipitation from the Westerly frontal system (Fig. 4a). Uncertainties concerning precipitation measurements are taken into account in the sensitivity study. Monthly evaporation data from DGA (1998) are available for 1989–1990 and 1995–1997 (Fig. 5). The average annual evaporation over the lake, $E_L$, is 1230 mm and shows a strong seasonality (Fig. 4b). Many water balance studies estimate the evaporation from an energy budget model (e.g. Hastenrath and Kutzbach 1983, 1985; Grosjean 1994; Vassiljev 1998). At the Laguna Aculeo, pan evaporation measurements are available (Fig. 5, DGA 1998). During the early and mid-Holocene, precipitation appeared to have been lower than today and cloud cover was probably reduced and hence evaporation enhanced. Since winter is assumed to have

**Table 1** Climate and catchment parameters for Laguna Aculeo

| Parameter | Symbol (unit) | Modern conditions | Reference |
|---|---|---|---|
| Precipitation over lake surface | $P_L$ (mm/month) | Seasonal distribution see Fig. 4; Annual precipitation 544 mm | Climate stations: Aculeo (33°51′S, 70°54′W, 360 m asl), 1913–1963, 1995–1998;<br>Pirque (33°40′S, 70°35′W, 670 m asl), 1967–1989;<br>Paine (33°49′S, 70°54′W, 350 m asl), 1990–1994 |
| Precipitation over catchment surface | $P_B$ (mm/month) | Seasonal distribution see Fig. 4; Annual precipitation 609 mm | |
| Evaporation over lake surface | $E_L$ (mm/month) | Seasonal distribution see Fig. 4; Annual evaporation 1230 mm | Climate station Aculeo (33°51′S, 70°54′W, 360 m asl) |
| Lake surface area | $A_L(z)$ (km$^2$) | Variable (see Fig. 6) | Cabrera and Montecino (1982) |
| Catchment surface area | $A_B(z)$ (km$^2$) | 85 km$^2$ – $A_L(z)$ (see Fig. 1) | Topographic map 1:25,000 |
| Runoff coefficient | $r$ | 0.18 | Modern calibration |

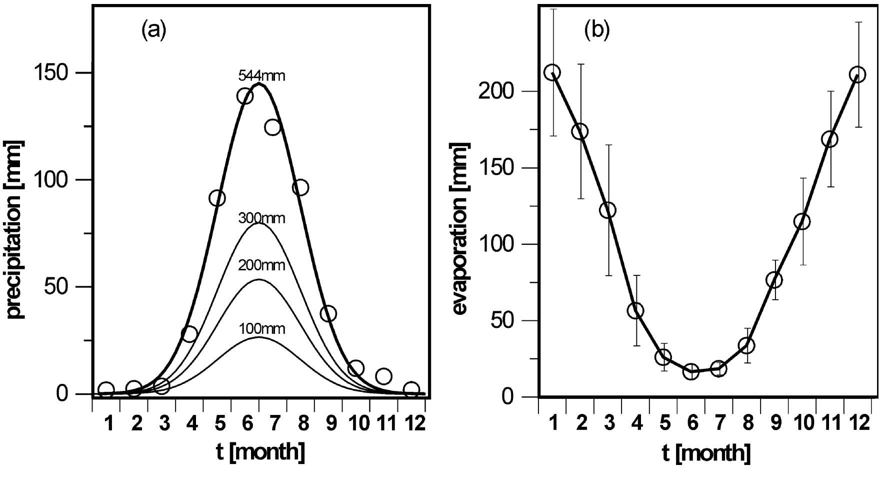

**Fig. 4a, b** Precipitation and evaporation distribution at Laguna Aculeo. **a** Measured monthly precipitation (*circles*, 72 year average, DGA 1998), approximated by a Gaussian function; **b** measured monthly evaporation and its standard deviation (average of the years 1989–1990 and 1995–1997, DGA 1998). Months: (*1*) is January and (*12*) December

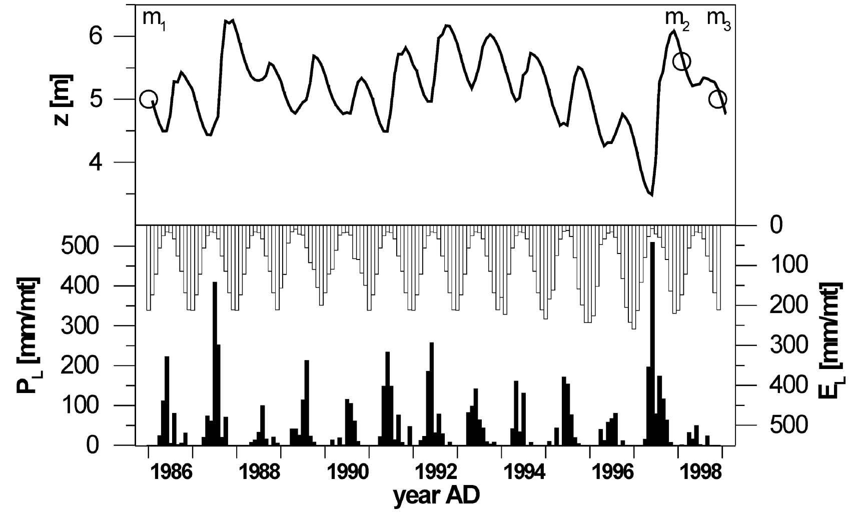

**Fig. 5** Modern climate conditions and calibration. *Upper part*: simulated lake level $z$ and measured lake levels (*circles*), $m_1$ is derived from the Dirección General de Aguas in Chile and $m_2$, $m_3$ from field measurements. *Lower part*: measured monthly precipitation over the lake surface ($P_L$) obtained from DGA (1998). Evaporation from the lake surface ($E_L$) was measured from 1989–1990 and 1995–1997, while average monthly values are indicated for the years where no data exist

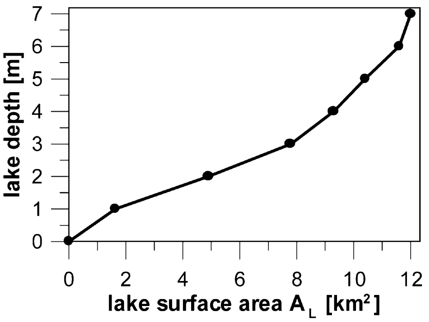

**Fig. 6** Relation between lake depth and lake surface area of Laguna Aculeo. The bathymetry is based on Cabrera and Montecinos (1982)

been the rainy season during the entire Holocene, the change in evaporation was probably very small. This assumption is based on the fact that the reduction of precipitation took place during winter, when evaporation is generally low. Therefore, evaporation and its seasonality were assumed to be constant for Holocene climate conditions with high values in summer and low values in winter, as is shown for modern conditions in Fig. 4b. Possible changes in evaporation during the Holocene, however, are taken into account in the sensitivity study.

The lake surface area $A_L(z)$ could be derived from the bathymetry of Laguna Aculeo (see Fig. 6), which has been measured for different lake levels $z$ by Cabrera and Montecino (1982). For our simulations, the much more realistic smaller catchment surface area $A_B(z) = [85\ \text{km}^2 - A_L(z)]$ is used. Based on all known parameters, the runoff coefficient $r$ was estimated and assumed to be constant over time. Changing vegetation cover during the Holocene, however, could have changed the runoff coefficient, which is taken into account in the sensitivity study in Sect. 5.3.

The simulation started in 1986, with a measured lake depth of 5 m. Monthly precipitation and evaporation data (DGA 1998), as indicated in Fig. 5, allow for a simulation of highly seasonal lake level fluctuations. As expected, and also mentioned by the local population, lake level appears to rise during winter, when precipitation is high and evaporation low, and to decrease during summer, when precipitation is low and evaporation high. Furthermore, simulations suggest a notable rise in lake level during El Niño years, e.g. in 1987 and 1997. In contrast, during a period of several drier years from 1993 to 1996, the simulated lake level fell significantly. Average seasonal fluctuations of the simulated lake level are about 1 m.

## 5.2 Simulation of Holocene precipitation

Under modern conditions, an initial lake level $z_0$ of 6 m has been chosen (Fig. 7). Figure 7 presents four climatic scenarios of simulated lake levels for Laguna Aculeo with an annual precipitation of (a) 400 mm, (b) 300 mm, (c) 200 mm, and (d) 100 mm. The initial lake level $z_0$ is 6 m and all scenarios are compared with a simulation under modern climate conditions with an average annual precipitation of 544 mm. In simulations with an annual precipitation of 400 mm, the average lake level drops by about 3 m. Considering precipitation of 300 and 200 mm, the average lake level lies between 0.5 m and 2 m. Based on an annual precipitation of 100 mm, the lake does not totally dry out, but the average lake level is lower than 1 m and the lake probably dries out occasionally. The time needed to reach the new equilibrium lake level depends on the amount of precipitation change. The stronger the decline in precipitation is, the faster new equilibrium conditions appear to be achieved. As shown in Fig. 7, the fastest equilibrium is reached in less than 10 years with an annual precipitation of 100 mm (Fig. 7d), while it takes between 20 and 30 years with an annual precipitation of 400 mm (Fig. 7a).

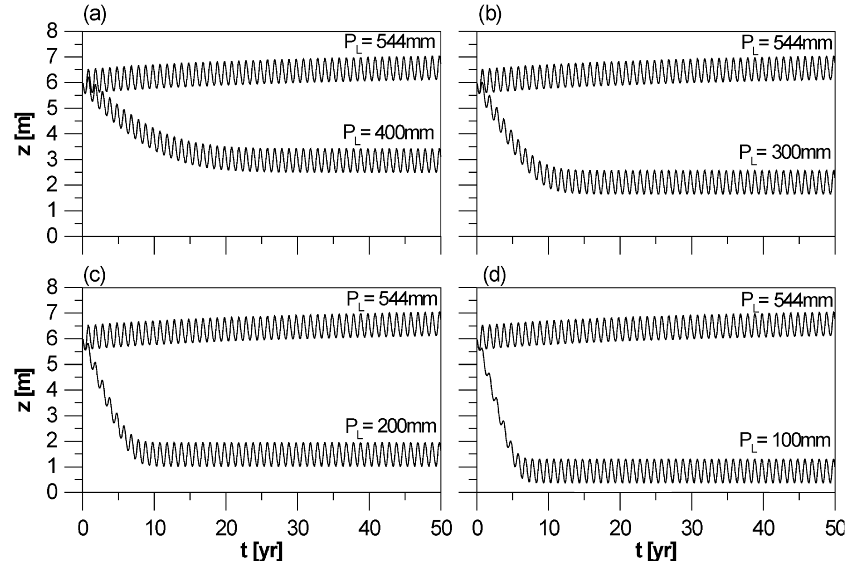

**Fig. 7a–d** Simulated lake level $z$ for different precipitation levels at lake elevation over 50 years. The simulations are based on a seasonal distribution of precipitation and evaporation (Fig. 4)

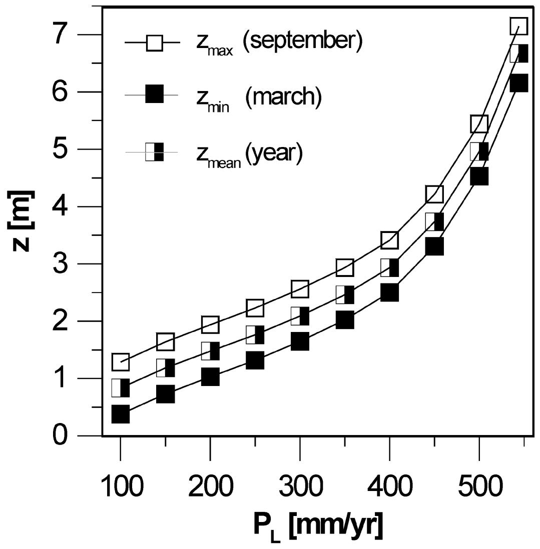

**Fig. 8** Relationship of precipitation $P_L$ and simulated lake level $z$. During austral spring, water level $z$ is low ($z_{min}$), while during austral autumn, water level is high ($z_{max}$)

Figure 8 provides an overview of lake level $z$ in relation to precipitation $P_L$. The water depth of Laguna Aculeo reacts more sensitively to precipitation changes at lake level $z$ between 3 m and 6 m compared to $z$ between 0 m and 3 m. This difference is due to the lake basin morphology, which is indicated in Fig. 6. In Fig. 3a, the estimated lake level of Laguna Aculeo during the Holocene is shown.

### 5.3 Sensitivity study and uncertainties

The sensitivity study evaluates how sensitive the lake level reacts to (a) uncertainties of the input parameters, which will be discussed first, and to (b) possible changes of different parameters during the Holocene. In the following, data are compared with the reference model conditions given in Sect. 5.2, and the scenarios are presented in Table 2.

For the calibration of $r$, several parameters were used. In the following the effects of the uncertainty of these input parameters are shown. The measurement of precipitation and evaporation bears an uncertainty, which has been assumed to be around $\pm 10\%$ (scenario 1). A higher or lower runoff coefficient $r$ results, when adopting the calibration for the changes in $P_L$ or $E_L$. Therefore, for palaeoclimatic conditions of 100 mm and 200 mm annual precipitation, respectively, a deviation from $z$ of 1 to 4% results. Scenario 2 is based on a maximum catchment surface area $A_B(z)$. The assumption that the maximum catchment area (Fig. 1) drains into Laguna Aculeo is highly unlikely. Most probably, only a negligible part of the southeastern region drains into the lake. A larger catchment area would influence the calibration of the model. With an increased catchment surface, $r$ is adapted so that the product of $A(z)$ and $r$ remains constant. Therefore, the newly determined runoff coefficient $r$ would be 0.095. Simulations for past annual precipitation of 100 and 200 mm result in a deviation of $z$ of less than 10%. Not taken into account is an outflow, which only functions when the lake level is very high. But during the Holocene, conditions were mostly drier than today. No measurements of groundwater flow are available and its influence is assumed to be negligible.

It is possible that the input parameters during the Holocene were not constant. Therefore, scenario 3 deals with a decline of $r$ due to decreasing precipitation. For palaeoclimatic conditions with annual precipitation of 100 and 200 mm, a reduction of $r$ of 25% results in a lake level decrease of about 21%. Scenario 4 shows the possible effect of an increased evaporation, when precipitation was lower and therefore cloud cover reduced. Since it rains mainly during the winter season, when evaporation is low, evaporation changes might have

**Table 2** Sensitivity tests of the water balance model. $\langle z \rangle$ indicates the average annual lake level, $A_B{}^* = A_B(z) + A_L(z)$, deviation from $\langle z \rangle$ indicates the difference of the lake level compared to the model conditions actually applied. For other parameters, see Sect. 5.3

| Conditions | $A_B{}^*$ (km$^2$) | $r$ | $P_L$ (mm/yr) | $E_L$ (mm/yr) | $\langle z \rangle$ (m) | Deviation from $\langle z \rangle$ |
|---|---|---|---|---|---|---|
| Modern climate conditions | | | | | | |
| 1986–1998 | 85 | 0.18 | 492 | 1230 | 4.75 | |
| 72-year average | 85 | 0.18 | 544 | 1230 | 6.67 | |
| Model conditions | 85 | 0.18 | 200 | 1230 | 1.47 | |
| | 85 | 0.18 | 100 | 1230 | 0.83 | |
| Calibration of $r$ | | | | | | |
| Scenario 1 | | | | | | |
| $P_L$ (+10%) | 85 | 0.150 | 200 | 1230 | 1.42 | 4% |
| $P_L$ (–10%) | 85 | 0.198 | 200 | 1230 | 1.45 | 2% |
| $E_L$ (–10%) | 85 | 0.150 | 200 | 1107 | 1.43 | 3% |
| $E_L$ (+10%) | 85 | 0.198 | 200 | 1353 | 1.46 | 1% |
| Scenario 2 | | | | | | |
| Variable $A_B{}^*$, constant product ($r$ $A_B{}^*$) | 160 | 0.095 | 200 | 1230 | 1.38 | 6% |
| | 160 | 0.095 | 100 | 1230 | 0.76 | 9% |
| Changes during the Holocene | | | | | | |
| Scenario 3 | | | | | | |
| Reduction of $r$ of 25% ($r$ = 0.135) | 85 | 0.135 | 200 | 1230 | 1.22 | 17% |
| | 85 | 0.135 | 100 | 1230 | 0.66 | 21% |
| Scenario 4 | | | | | | |
| Increase of $E_L$ (+10%) | 85 | 0.18 | 200 | 1353 | 1.37 | 7% |
| Increase of $E_L$ (+20%) | 85 | 0.18 | 200 | 1476 | 1.28 | 13% |

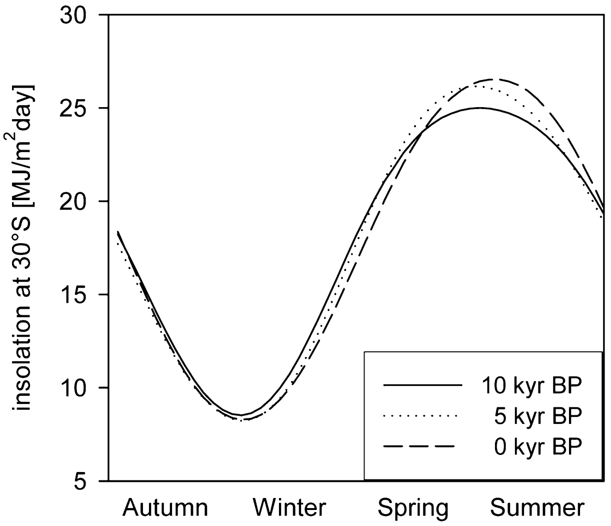

**Fig. 9** Insolation at 30°S for 10, 5 and 0 kyr BP (after Blatter et al. 1984)

been very small. Even the unlikely increase of 20% would only result in a lake level change of about 13%. For the simulations presented here, monthly values of the evaporation $E_L$, which is also strongly influenced by insolation, have been kept constant. It must be taken into account that insolation varied during the Holocene (Fig. 9). In the early Holocene, insolation changes were smaller compared to today, with slightly higher values during winter and lower values during summer. According to Blatter et al. (1984), maximum deviations of insolation comparing 10 with 0 kyr BP were –10% in December (summer) and +6% in June (winter). Insolation was therefore slightly higher during winter and somewhat lower during summer in the early and mid-Holocene compared to modern conditions, but overall, changes in evaporation appear to have been small. Grosjean (1994) also showed that for the Chilean Altiplano at 20°S, variations in the annual evaporation due to changing orbital parameters at 10 and 5 kyr BP were less than 1%. For the entire Holocene in Central Chile, the assumption of a seasonal distribution of precipitation and evaporation with winter rain and summer dryness is reasonable, because the region lies in the westerly zone and was not influenced by the tropical circulation with summer rainfall.

## 6 Discussion

### 6.1 Lake history

The early Holocene appears to have been very dry with precipitation below 200 mm per year, as derived from the Laguna Aculeo record. Around 8500 cal yr BP, the Laguna Aculeo dried out and precipitation, as suggested by the simulations, was possibly below 100 mm/year. The end of this arid phase is not precisely dated, but took place before 8000 cal yr BP. The lake refilled and precipitation appears to have been between 150–300 mm/year until about 6000 cal yr BP. The lake level still remained low, between 1 and 2 m. A transitional zone between 6000 and 5500 cal yr BP indicates a change to more humid conditions with an annual precipitation around 350–450 mm. The onset of generally humid conditions in the lowlands of Mediterranean Central Chile started at around 3200 cal yr BP. The supply of moisture then increased noticeably, modern humid conditions were established and simulations suggest that annual precipitation fluctuated between 450 and 550 mm. A detailed description of the most humid period in Central Chile, the late Holocene, is given by Villalba (1994) and Jenny et al. (2002a).

### 6.2 Uncertainties and limitations of the model

As described in the sensitivity study (see Table 2), there are several uncertainties which implicate limitations of the model. In the following, their influence will be discussed on the base of an annual precipitation of 200 mm, which implies rather dry climate conditions. First, calibration uncertainties and their effect on lake level simulations of the past are discussed. Measurement precision of ± 10% for precipitation and evaporation has been considered (scenario 1), which resulted in a minor effect on $z$ (7%). A possibly larger catchment, though unlikely (see Sect. 2), also has an effect on the calibration under modern conditions and therefore on the palaeolake level, but changes are around 6%. As mentioned earlier, outflow is not considered in the model, because it only works as an overflow during very rainy periods, when lake level is higher, but rainfall during the early and mid-Holocene was generally lower than today. An unknown component is the groundwater flow, where no measurements exist. The rapid and seasonal response of the lake level to rainfall distribution observed during the last decades suggests that there are no deep aquifers connected to the lake and that the total groundwater inflow and outflow are small. Most groundwater flows, in and out of the lake, are likely through surface aquifers, whose dynamics follow probably closely the precipitation pattern.

Second, the effect of parameter changes during the Holocene is discussed. As shown in scenario 3 of the sensitivity study, a decrease of $r$ of 25% results in a noticeable lowering in lake level of about 20%. Therefore, precipitation estimates are probably too low for periods when lake level was extremely low. Also evaporation might have changed during the Holocene, though the effect of lower precipitation was probably minor (see Sect. 5.3). A general increase in former evaporation of 20%, while annual precipitation was 200 mm, resulted in a lake level change of 13% and has therefore a minor influence.

Third, lake level estimates based on proxy data also carry uncertainties. Absolute values can only be assigned to the maximum lake level, determined by the outflow level (above 6 m), and the minimum (0 m), when the lake dried out. Intermediate values have to be assigned to stages defined by deposition of distinctive facies (see Sect. 4). Therefore, not an absolute value, but a lake level range has been indicated (Fig. 3).

In the following, the maximum influence of these uncertainties is estimated (Table 2). Uncertainties in the measurement of $P_L$ and $E_L$ point to a possible decline of $z$ of about 7%. In addition, $E_L$ might have been about 10 to 20% higher during arid periods, which would result in a decline of $z$ of about 10%. The runoff coefficient $r$ possibly changed during the Holocene. A plausible decrease of about 25% forces a decline of $z$ of 17%. Therefore, if all these uncertainties accumulated, the error would result in a lowering of the lake level $z$ by about 34%. Overall, for simulations of extremely low lake levels, the estimates of the palaeo-precipitation are probably too low. Nevertheless, the dry conditions during the early and mid-Holocene would still remain significant. In addition, it should be taken into account that a major proportion of this error exists probably only during dry periods, when lake level was low, because evaporation and the runoff coefficient are thought to decline during drier conditions.

### 6.3 Regional climate comparison

The pronounced early and mid-Holocene aridity shown in Laguna Aculeo is in good agreement with other palaeoclimate records in Central Chile (Fig. 3c). The pollen record of Tagua Tagua (34°30′S) even indicates that annual precipitation may have dropped close to 100 mm from about 6800 to 2600 cal yr BP (6000 to 2500 $^{14}$C yr BP, Heusser 1990). Lamy et al. (1999) point to arid conditions based on marine sediments between 8000 and 4000 cal yr BP. Pollen data from Villagrán and Varela (1990) and Villa-Martínez and Villagrán (1997) at Quintero and Quereo also suggest an arid mid-Holocene, increasingly wet conditions around 4500 cal yr BP (4000 $^{14}$C yr BP) and the onset of modern conditions around 2000 cal yr BP (2000 $^{14}$C yr BP). The main cause for the mid-Holocene aridity appears to be the strong influence of the southeast Pacific high-pressure cell, which blocks the Westerly frontal system (Markgraf 1989, 1998).

The dry mid-Holocene is also indicated in other regions in southern South America. Marine sediments from offshore Patagonia (41°S), which is strongly influenced by the Westerlies, indicate a dry mid-Holocene from 7700 to 4000 cal yr BP (Lamy et al. 2001). Galloway et al. (1988) concluded that lakes at the same latitude in Argentina were dry or shallow during most of the Holocene in contrast to high lake levels during lateglacial times.

Toward the north, on the Altiplano, modern moisture availability is increasingly influenced by summer rainfall and not winter rainfall related to the Westerlies. Nevertheless, Laguna del Negro Francisco (27°30′S) and Laguna Miscanti (23°45′S) also provide further evidence of a mid-Holocene aridity and an onset of humid conditions around 4500 cal yr BP (4000 $^{14}$C BP) (Valero-Garcés et al. 1996; Grosjean et al. 1997; Schwalb et al. 1999). Controversially, only Betancourt et al. (2000) claim more humid mid-Holocene conditions based on spring deposits on the Chilean Altiplano. Further north, at Lake Titicaca, the lake level was at least 50 m lower by 9200–8400 yr BP (8200–7700 $^{14}$C yr BP) (Wirrmann and Mourguiart 1995) and even 85 to 100 m lower by

5900 cal yr BP (5200 $^{14}$C yr BP) compared to present day levels (Cross et al. 2000; Seltzer et al. 1998). This early to mid-Holocene dry period lasted until about 4000 cal yr BP (3600 $^{14}$C yr BP). In conclusion, the mid-Holocene generally appears to have been a pronounced dry period not only in Mediterranean Central Chile, but also in most areas of southern South America. The climatic forcing, however, is different for each area. The main cause for the mid-Holocene aridity in Central Chile appears to be the stronger influence of the southeast Pacific high-pressure cell blocking the Westerly frontal system (Markgraf 1989, 1998). In contrast to the extratropics, the Altiplano is strongly influenced by monsoonal rainfall from the east.

The late Holocene effective moisture increase is probably due to strengthened Westerly influence in Mediterranean Central Chile. Markgraf (1998) even assumes that the modern, clearly seasonal shifts of the storm tracks, poleward in summer and equatorward in winter, were established only around 4000 years ago when seasonality of the insolation began to increase strongly.

Interestingly, clastic layers during periods with heavy rain and possibly during El Niño years, appear to be absent during part of the mid-Holocene in Laguna Aculeo. They reappear around 5700 cal yr BP, and are much more frequent after 3200 cal yr BP. Such a possible reappearance or strengthening of ENSO (El Niño/ Southern Oscillation) in this region would be in good agreement with palaeorecords e.g. in Peru (Sandweiss et al. 1996; Fontugne 1999). Moreover, recent modelling studies (Clement et al. 2000) point to weakened ENSO activity or even to a suppression of El Niño during the mid-Holocene in the tropical Pacific region and, subsequently, a steady increase to the present. The numerical model of Clement et al. (2000), driven mainly by orbital forcing, suggests that an increase in ENSO activity in the tropical Pacific could have been largely the response to an increase in insolation. ENSO may actually cause overall higher levels of precipitation, such as in coastal areas of northern Peru and Ecuador and Central Chile (Rutllant and Fuenzalida 1991; Markgraf 1998; Montecinos et al. 2000). Markgraf (1998) summarizes that, with the exception of the interval between 8000 and 7000 cal yr BP, prior to about 5000 cal yr BP, climatic variability was relatively low and precipitation greatly reduced in Central and Northern Chile and Southern Peru.

For the early and mid-Holocene, Markgraf (1998) suggests that westerly storm tracks focused their full strength instead between latitudes 45° and 50°S. As a result, lower latitudes received substantially less precipitation than today. Overall, moisture availability during the Holocene in Central Chile seemed to increase when summer insolation increased and insolation seasonality strengthened, reaching a maximum in the late Holocene. Therefore, the Southern Westerlies appear to have been intensified in Central Chile during the late Holocene compared to the early and mid-Holocene. The lake level and precipitation increases in Central Chile parallel the general increase in summer insolation, but possibly represent a rapid climate response to a gradual insolation forcing.

## 7 Conclusions

The water balance model of Laguna Aculeo provides a detailed history of Holocene humidity changes in Mediterranean Central Chile. Based on a simple water balance model, lake level changes have been simulated and hence precipitation estimated. During the early and mid-Holocene, generally dry conditions persisted, with a dramatic change to more humid conditions during the late Holocene. Several uncertainties concerning the input parameters put limitations on the precision of precipitation estimates. More detailed measurements of input parameters for the region as well as further climate simulations and proxy data in Central Chile are needed. Nevertheless, the Laguna Aculeo water balance model, despite its limitations, is one of the few attempts to quantitatively estimate precipitation in Central Chile and indicates significant humidity changes during the Holocene.

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