DEVELOPMENT OF A TEST REFERENCE YEAR ON A LIMITED DATA BASE FOR SIMULATIONS ON PASSIVE HEATING AND COOLING IN CHILE

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ABSTRACT

The application of building simulation for the thermal improvement of buildings in developing countries is limited by the scarcity of hourly climate data and test reference years. Therefore a generally applicable method was developed to select and combine monthly periods of hourly data, that correspond best to long-time mean values and assure representative mean temperatures and global radiation in the TRY for Central Chile. Realistic sequences of climate situations and true correlation of climate parameters result from the use of real time series of hourly data instead of a general statistical model. Standard models for missing climate variables are discussed and adapted with special emphasis on infrared sky radiation. The analysis of simulations on passive heating and cooling confirms the usefulness of this TRY for sustainable building.

INTRODUCTION

Building simulation is a promising tool for the thermal improvement of buildings in developing countries like Chile. It facilitates the evaluation of a wide range of constructive alternatives at a low cost, whereas experimental buildings would be too expensive and limited to a small number of alternatives. That way building simulation constitutes an adequate tool for sustainable building. An important obstacle for its wider use in developing countries is the lack of the necessary hourly climate data, called test reference year (TRY). Official TRYs, which are common in Europe and North America, normally are not available and even the raw hourly climate data are difficult to obtain and present relatively short measuring periods and a limited set of climate parameters.

No TRY existed for Chile, so that the only available information was hourly air temperature and global radiation for about 5 years at one station in Santiago de Chile (with some hourly data missing), together with long-time monthly mean values for the same parameters from a nearby station. The objective was to generate a TRY that fulfills the following criteria:

1. representative for the climate zone: mean values of main climate parameters as close as possible to longtime mean values;
2. realistic dynamics: hourly sequences and variation during single days and series of days that are typical for the climate zone;
3. true correlation between different parameters, especially temperature and solar radiation.

In literature, different types of standard procedures for the preparation of TRYs can be found:

- The generation of a synthetic year based on mean values with some statistical model (e.g. commercial Meteonorm – software [http://www.meteotest.ch/products/meteonorm/]. The problem here lies in the cost (in case of a commercial software, at least for third world countries) and the necessary confidence in the statistical model, that it can reproduce the real climate dynamics with the typical local sequence of climate situations and the local correlation of climate parameters. If no hourly measured data are available, this is the best solution, but the use of real climate data offers realistic dynamics and correlation in a more direct way.
- The generation of the TRY from a complex statistical analysis and selection process based on long and statistically representative periods of measured data, as described in [Lund 1981] and [Jahn 1977]. In Chile and in many other developing countries, complete hourly data are not available for sufficiently long periods of well over 10 years.

Considering this analysis and the limited, but typical data availability, an own method was created to comply as well as possible with the criteria established before. It was based on data analysis and the evaluation and adaptation of models for the different parameters.

GENERAL TRY METHODOLOGY

The basic philosophy for this TRY was to use real data as far as possible, reducing the use of theoretical values and interpolations. The data were selected for complete months: The difficulty to have complete data series grows with the length of the selection period and long-time mean values are available only on a monthly level. On the other hand, one month is sufficiently long for a sequence of different weather situations and superior to the typical time that a building needs to enter into a steady state when exposed to a periodic climatic influence [Jahn 1977]. The comparison of climate data with long-time mean values made it possible to work with time series of measured data that are close to long-time mean values and represent the real variation of the local climate.

The Swedish simulation program DEROB-LTH used here (developed at Lund University from the original DEROB of Prof. F. Arumi-Noé, Univ. of Austin), needs an hourly input of data for air temperature, sky temperature, (direct) normal and diffuse solar radiation. The missing parameters had to be calculated as a function of the hourly temperatures and global radiation with a minimum of additional assumptions. Humidity and the speed and direction of wind are not considered in DEROB-LTH and the TRY here.

Therefore the method for the preparation of the TRY can be resumed as follows:

1. Preparation and selection of the hourly climate data (temperature, global radiation): the 12 months with complete hourly data that corresponded best to the mean values from a reference station were selected and combined to create the basic data set of the TRY;
2. Calculation of missing parameters: diffuse and normal solar radiation, sky temperature;
3. Final export and formatting of the TRY.

DATA SET

Hourly climate data were available from August 1994 to September 1999 for the station of La Platina in the out-skirts of Santiago de Chile, the capital. First, the data were controlled for completeness: For each month 100% availability was demanded for global radiation when sun is above the horizon (missing 0 radiation during the night was completed when necessary), only single hours with missing temperature data were permitted and completed with the mean value of the two neighboring hours (less than 10 cases in the TRY). Then daily and monthly mean values were calculated. The official definition used by the Chilean National Meteorological Office for the reference values [Dirección Meteorológica de Chile 3] was applied to calculate daily mean temperatures T_{m_off} from the hourly data for the following comparisons (T_8 / T_{20} = hourly mean temperature at 8 / 20 o'clock):

$$T_{m\_off} = (T_8 + T_{20} + T_{max} + T_{min}) / 4$$

As the station did not exist before, long-time mean values from La Platina do not exist. Instead, the nearby station Pudahuel at the airport of Santiago had to be used, where longtime mean values and individual monthly mean values for temperature and global radiation were available: Mean global radiation I_{gm} from 1988 to 1998 from [Dirección Meteorológica de Chile 4], normal values of monthly mean global radiation I_{gn} for Pudahuel from [Sarmiento 1995], normal mean temperatures T_{mn} from 1968 to 1990 and from 1961 to 1990 for Quinta Normal and Los Cerrillos in Santiago from [Dirección Meteorológica de Chile 1991]. For the period of the hourly data, mean global radiation was available for almost all months for Pudahuel from [Dirección Meteorológica de Chile 1, 2] and mean temperatures from [Dirección Meteorológica de Chile 3] for the stations Pudahuel, Quinta Normal and Los Cerrillos. The comparison of monthly temperatures from the 3 stations in Santiago showed that they shared the same variation with respect to longtime mean values, so that the use of Pudahuel, the only station with radiation data, was justified as a reference. This is confirmed by the minimal difference of monthly temperature values between the stations in Pudahuel and La Platina in Figure 1.

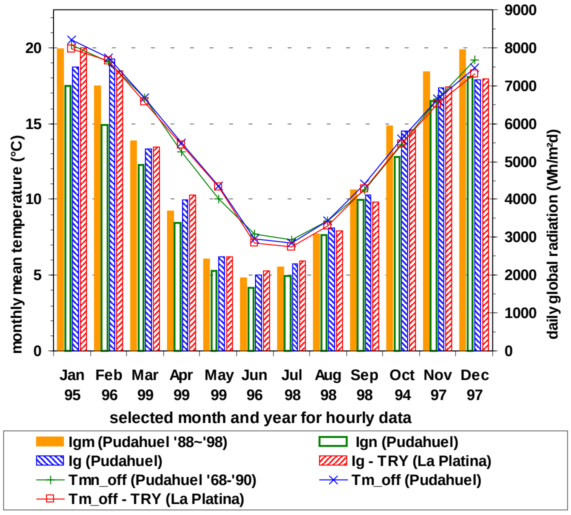

Figure 1. Test Reference Year for Santiago: monthly mean values and data selection

For each month of the TRY, the month of that year that showed the best coincidence with the longtime mean values was selected as the best according to the following criteria:

1. The difference of monthly mean temperature and longtime mean temperature in Pudahuel;
2. The quotients of monthly mean global radiation and longtime mean global radiation in Pudahuel for the two references I_{gn} and I_{gm}; this leads to a different choice in May to avoid the selection of an extremely sunny May.

The resulting selection of months for the TRY together with the reference values is shown in Figure 1. It can be observed that the differences of monthly mean temperatures are very small and that the TRY shows the same typical curves during the year as the normal values, although the period of hourly data available for the selection had been relatively short.

($T_{m\_off} – T_n$) for Pudahuel is in the range [-0,5°C; 0,9°C] or 0,15°C ± 0,4°C for the 12 months. The differences for global radiation are not so small, but the deviations between the TRY and the reference values are comparable to those between the two reference sources themselves and the monthly values in Pudahuel. For the reference I_{gm}, I_g / I_{gm} is in the range [90%; 110%] or 100% ± 6% for the 12 months; for the reference I_{gn}, I_g / I_{gn} is in the range [99%; 129%] or 112% ± 8% for the 12 months.

A modification of the hourly data in order to enforce exact mean values was avoided, because this could affect the correlation between temperatures and radiation, that is not linear: e.g. a clear and sunny day in winter may have higher diurnal and lower nocturnal temperatures than a cloudy day. Moreover the previously resumed analysis had shown differences between years are greater than the deviations observed here. The great importance of real climatic variations to understand the thermal dynamics of a building will be shown later in Figures 9 and 10.

The 12 selected blocks of monthly data were attached to form the basic data set of temperatures and global radiation. Differences between months from different years were verified: in case of a high "temperature jump" at midnight, the two limiting temperatures could be increased / decreased by the same value, leaving the annual mean unchanged, but in the final version no change was necessary. Solar radiation is zero at midnight (outside the polar circles) and therefore did not cause problems.

SOLAR RADIATION MODELS

For diffuse solar radiation and normal solar radiation standard formulae are available, but some additional considerations and corrections were essential.

Diffuse solar radiation I_d was calculated according to [Duffie 1991; sec. 2.10] and [Erbs 1982] as a function of the hourly clearness index $k_T = I_g / I_o$, that is defined as the quotient of global radiation I_g and extraterrestrial radiation I_o. I_o was calculated according to [Duffie 1991; sec. 1.10] considering exact solar time with corrections for longitude and the equation of time corresponding to the measurements. Then direct ("beam") radiation I_b on a horizontal surface was calculated from $I_b = I_g – I_d$.

The model used for the division of solar radiation into its direct and diffuse component is not exact, as the author himself describes and shows in [Duffie 1991; p.81f]; e.g. during sunny hours with white clouds, that do not shade sun, solar radiation values can be higher than on a clear day because of the additional diffuse radiation. Therefore the calculated direct radiation was compared to the theoretical direct radiation I_{b_th} from a clear sky according to the model of [Hottel 1976] described in [Duffie 1991; sec. 2.8]. If $I_b > 1{,}25 * I_{b\_th}$, then I_b was set to $1{,}25 * I_{b\_th}$ and the diffuse radiation was increased and re-calculated from $I_d = I_g – I_b$, so that global radiation remained unchanged. The tolerance factor 1,25 was applied as a conservative measure, because I_{b_th} is the approximate result of a theoretical model, that depends on climate and atmospheric transparency.

Finally the (direct) normal radiation I_n was calculated according to $I_n = I_b / \sin(\alpha_s)$, with the solar altitude α_s calculated hourly according to [Duffie 1991; sec. 1.6]. Like other simulation programs, DEROB-LTH assumes exact solar time for the climate data of the TRY to calculate solar position and solar radiation on different surfaces. The original data had been measured at 70,6° west for standard time with the standard meridian at 60° west. In order to avoid the interpolation of climate data according to the 42,4 minutes difference (plus equation of time), that would have smoothed out rapid changes of radiation, time in the TRY was corrected by 1 hour instead as the best approximation to calculate solar altitude.

The factor $1 / \sin(\alpha_s)$ can assume extremely high values when sun is close to the horizon, but solar altitude is approximated for the center of the 1 hour – interval of the climate data and for the center of the time interval with sun above the horizon when sun crosses the horizon during the hour of sunrise and sunset. Other small differences in effective solar position can result from: the solar time approximation used; the fact that DEROB-LTH calculates solar declination only four times a month; the formulae for solar altitude, that consider only the day and month, not the year; deviations of the clock of the original datalogger. Moreover atmospheric scattering and refraction can increase solar radiation at sunrise and sunset. These small effects can result critical for $1 / \sin(\alpha_s)$ when sun is very low, so that direct radiation was set to 0 and diffuse radiation equal to global radiation, when $\sin(\alpha_s) < 0{,}1$. This limit corresponds to a minimum solar altitude of 5,74° or approximately half an hour for the consideration of direct solar radiation. It's important to stress that all these corrections only improved the separation of global radiation into its components and the preparation for the simulation program, but measured global radiation values remained unchanged in the TRY.

SKY TEMPERATURE

As measured information was not available, hourly sky temperature T_{sky} had to be calculated from air temperature and solar radiation data. Sky temperature is important for the infrared radiation balance of a building, especially in the hot and dry mediterranean climate zone here. Depending on the simulation program used, the TRY can include the equivalent information of sky temperature T_{sky}, global thermal sky radiance S or apparent sky emissivity ε_a, because they are linked by the following basic relations [Berdahl 1982] with the absolute air temperature T_a and Boltzmann constant σ:

$$S = \sigma * T_{sky}^4;\ S = \varepsilon_a * \sigma * T_a^4;\ \varepsilon_a = (T_{sky} / T_a)^4$$

Therefore the following discussion for sky temperature is easily applicable for any of the three equivalent characteristic magnitudes and a model of infrared sky radiation for S or ε_a can be transformed to T_{sky}.

Many models for infrared sky radiation depend on information on the humidity of the air, that is correlated with sky radiation; e.g. see the resume in [Rosenlund 1995] and [Feist 1994] or the discussion in [Berdahl 1982] and [Martin 1984]. No hourly information on humidity is available for Santiago, so that these models could not be used for the TRY, although they may be interesting elsewhere.

Earlier work with DEROB-LTH from [Adamson 1992] and [Rosenlund 1995] had been realized with models for sky temperature based on [Unsworth 1975], whose original model uses air temperature and cloudiness c as independent variables to calculate global thermal sky radiance and apparent sky emissivity. His model can be summarized as:

$$T_{sky} = [(1\text{-}0{,}84c)*(1{,}06\text{-}119Wm^{-2}/(\sigma T_a^4))+0{,}84c]^{1/4}*T_a$$

As the two authors before do not offer details on the background of their simple models for cloudiness as a function of solar radiation data, a standard model for cloudiness as a function of the clearness index K_T from [Iqbal 1983; p.238] was used here for the comparison in Figure 2. Using the monthly average of daily values, the relation can be transformed (for $0 \le c \le 0{,}8$) into:

$$c = \{ -0{,}34 + [1{,}832*(0{,}803\text{-}K_T)+0{,}34^2]^{1/2} \} / 0{,}916$$

But various authors, including Iqbal himself, [Bennett 1968] and [Duffie 1991] have argued that the correlation between cloudiness and solar radiation data is not very good due to the uncertainties of visual determination of c, especially for periods shorter than a month [Norris 1968]. A small cloud can shade all direct solar radiation or a small hole in the cloud cover can show the sun. Therefore a model based on [Unsworth 1975] and a cloudiness model did not seem to be the best solution for the TRY here, but can be interesting where information on c is available.

[Ineichen 1984] describes two models for daily values of the earth-sky radiative deficit ΔS:

$$\Delta S = \sigma * T_a^4 - \sigma * T_{sky}^4$$

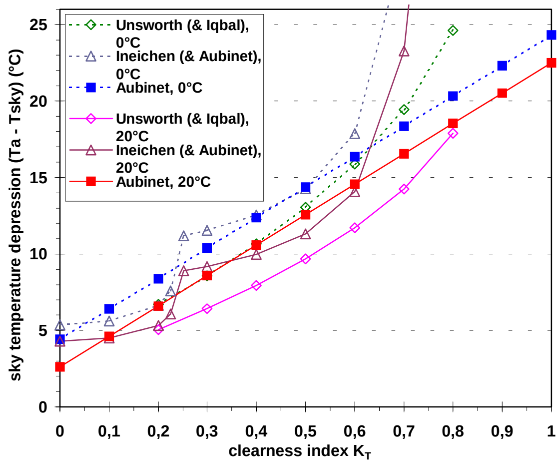

Figure 2. Comparison of different models for T_{sky} and air temperatures 0°C and 20°C

One model relates the earth-sky radiative deficit to the ratio of the beam solar radiation incident on an horizontal plane to its theoretical maximum value for clear days, the other model relates it to the ratio between the diffuse solar radiation and the global radiation in the horizontal plane. [Aubinet 1994] shows that these two models can be combined to express the earth-sky radiative deficit ΔS in terms of the clearness index. Using the formula for ΔS above, T_{sky} can be calculated from this Ineichen (& Aubinet) - model as a function of air temperature and clearness index, as is shown in Figure 2. Moreover, Aubinet shows that Ineichen's model, that is based on data from Geneva, correlates will with his own data from Belgium. Finally, Aubinet presents a set of own models for daily mean values of infrared sky radiation (T_{sky} and ε_a) as a function of different combinations of 1, 2 or 3 parameters out of air temperature, clearness index and water vapor pressure. His following model corresponds best to the information available and needed here:

$$T_{sky} = -\ 29K + 1{,}09 * T_a - 19{,}9K * K_T$$

The only difference with the TRY is, that this model is formulated for daily, not hourly values. No suitable model of hourly sky radiation could be found in literature and it appears difficult with the information available here, because of the importance of clouds for sky radiation (cf. [Unsworth 1975], [Martin 1984], [Blümel 1968]) and the bad correlation of cloudiness with solar radiation for short periods.

Aubinet's model is shown in Figure 2 together with others described before. It can be observed that all models present similar values for the sky temperature depression ($T_a - T_{sky}$), the difference between air temperature and sky temperature, especially for medium and low values of K_T. This confirms the validity of the models, because they are the result of independent studies with climate data from the English

Midlands and Sudan [Unsworth 1975], Geneva and Belgium. The worst "model" would be not to consider sky temperature in the TRY and in simulations, as it would be equivalent to the x-axis with $(T_a - T_{sky}) = 0$. The model from Aubinet presents the important advantages, that it does not depend on other models, like the Unsworth (& Iqbal) combination, and is applicable for the whole range of K_T - values, that can vary from 0,06 to 0,78 in the TRY here.

Only a small adaptation is sufficient in order to apply the model of Aubinet for hourly sky temperatures in the TRY:

- the use of hourly air temperatures;
- a mobile daily mean K_T was calculated for the 24 h-interval around each hour, because the definition of an hourly k_T is not possible without solar radiation during the night. Moreover, the mobile mean avoids a discontinuity at midnight and uses the values closest to each hour.

The German TRYs contain only calculated values for infrared sky radiation [Blümel 1968] and no Chilean measurements are available. Therefore the T_{sky} - model was tested with measured T_{sky} - data for Lund in 1988 from a Swedish test-year: In Figure 3, $(1{,}09 * T_a – T_{sky})$ was calculated to separate the influence of the daily clearness index K_T in Aubinet's model and show that it is well correlated with sky radiation, although there is some scatter. Figures 3 and 4 show the direct correlation between calculated and measured values of sky temperature for hourly and mean daily sky temperature, calculated from the 24 hourly values. The scatter is much smaller for daily mean values than for hourly values, what is not surprising due to the use of the 24h mean value for K_T. The correlation is especially good for medium and high temperatures, that are much more frequent.

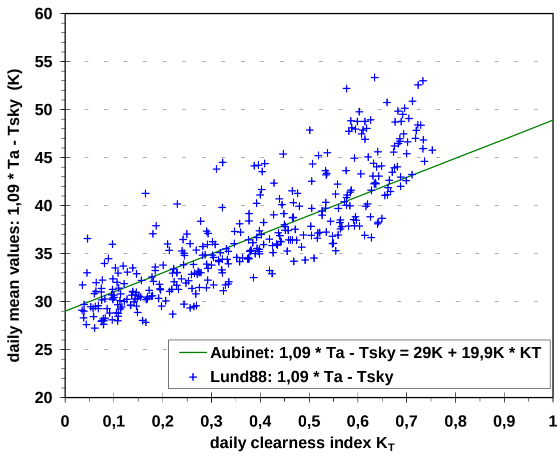

Figure 3. Comparison of calculated daily sky temperature with measured values

Additionally, the correlation of calculated and measured hourly values was verified with the same criteria used by [Aubinet 1994] - the modeled–to-measured correlation coefficient r, calculated from the mean square error (MSE) between calculated and measured values of sky infrared radiation and the variance (VAR) of the distribution of the measured values:

$$r = (1 – (MSE / VAR))^{½}$$

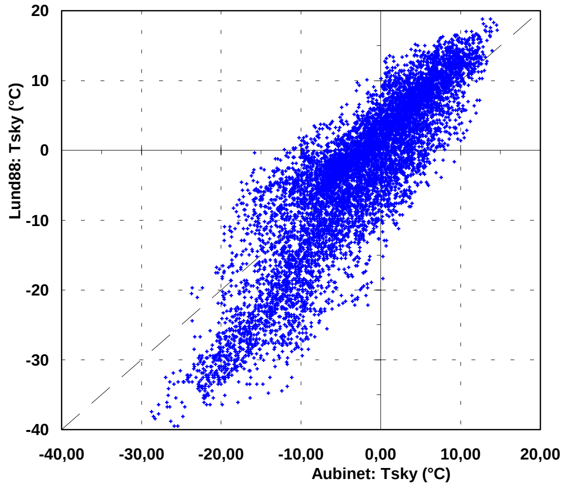

Figure 4. Comparison of calculated hourly mean sky temperature with measured values

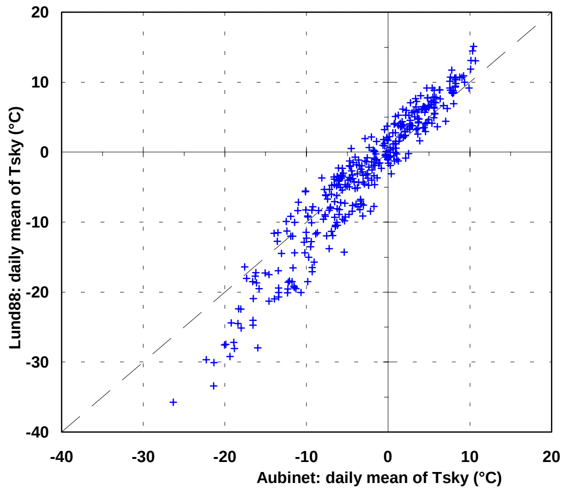

Figure 5. Comparison of calculated daily mean sky temperature with measured values

The correlation coefficient for the hourly data from Lund and sky infrared radiation S calculated from sky temperature is 0,864 compared to 0,934 for the daily values of the original publication with the data set used for its preparation. Other models for daily infrared sky radiation from Aubinet had obtained correlation coefficients from 0,771 to 0,958. The correlation coefficient for hourly sky temperature with Lund data here is 0,857, equally quite a good level. These values confirm the validity of the model for sky temperature and its adaptation made here.

A further improvement of the model for T_{sky} with the data from Lund was not possible, because the climate zone is different from central Chile, so that an improvement with respect to the models from literature compared before could not be expected nor could have been verified.

TEST REFERENCE YEAR

The main characteristics of the Chilean TRY are shown in Figure 6 on a monthly level with mean and mean extreme temperatures, mean global radiation, the percentage of diffuse radiation and the monthly mean and mean extreme sky temperature depression. Sky temperature depression can be better understood when it is expressed with Aubinet's formula:

$$T_a - T_{sky} = 19{,}9K * K_T - 0{,}09 * T_a + 29K$$

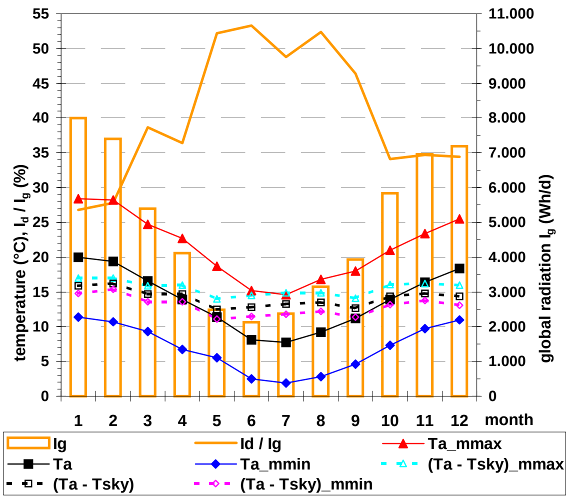

Figure 6. Test Reference Year - Santiago de Chile monthly mean and mean extreme values

It is highest in summer, when the dominant factor K_T is highest (visible form low I_d / I_g in Figure 6) and lowest in May and September, when K_T is already low but T_a still above the winter minimum.

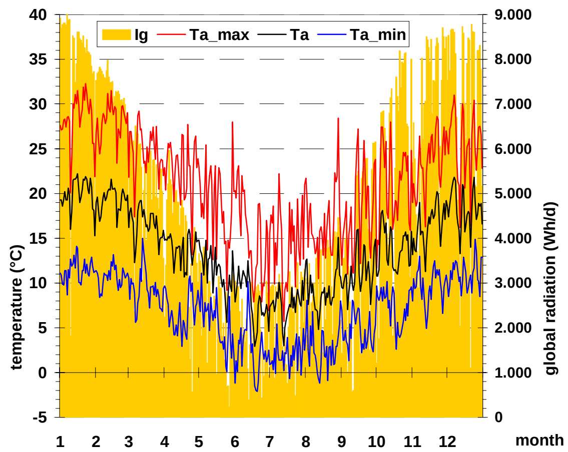

Figure 7. Test Reference Year - Santiago de Chile daily values of temperature and global radiation

The next Figure 7 confirms the importance of using a TRY with real climate variations and not just "typical" or design – days with hourly values of temperature and global radiation calculated from monthly mean values: Whereas only the main summer months, January and February, present relatively constant climatic conditions with high solar radiation, during the rest of the year and especially in winter, climatic conditions vary strongly between cloudy days with mild temperatures, small temperature differences, low solar radiation and clear days with high solar radiation, colder nights and larger temperature differences. The dynamical reaction of a building to such a combination of days can be very different from the behavior on a middle day, depending on thermal mass and the relation between gains and losses.

SIMULATIONS

The final objective of this investigation was the realization of thermal simulations for the development of design recommendations and simple tools for passive heating and cooling in the Central Region of Chile. Only a few examples of simulations of normal and improved housing designs with different passive elements can be shown here. The designs share the same ground plan with standard orientation of the main façade to the north.

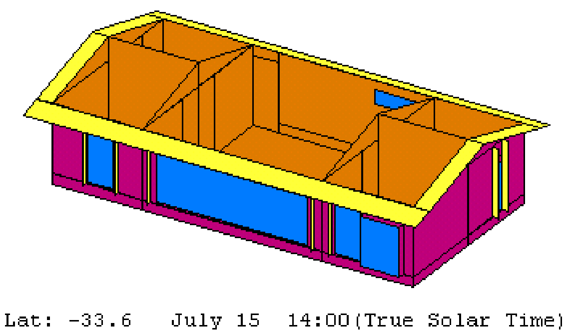

Figure 7. Proposal of Prototype House Trombe wall (at volume 4 on the right side)

The normal brick and light houses (not insulated panels) are typical for Chile with no fixed shading, simple curtains, simple glazing, no roof insulation, constant ventilation of 3ach in summer and high infiltration of 1,5ach in winter. The other proposals have an optimized roof overhang, better curtains, 8cm of roof insulation and 40cm rammed earth walls. The standard house has still simple glazing, but only 1ach of infiltration and night ventilation in summer. An economic solution with improved thermal comfort is the proposed prototype, shown in Figure 7: double glazing, walls of low-conductivity, light rammed earth, only 0,5ach in winter and a Trombe wall, that combines solar gains with good earthquake resistance. The solar house is further improved at a higher cost with bigger north windows for direct solar gain and additional insulation in the roof and walls. It shows that in Central Chile a simple solar design can offer thermal comfort in summer and winter. This is proven by the daily degree-hours of heat in summer (> 0, base 26°C) and daily degree-hours of cold in winter (< 0, base 19°C) in Figure 8 (operative temperatures).

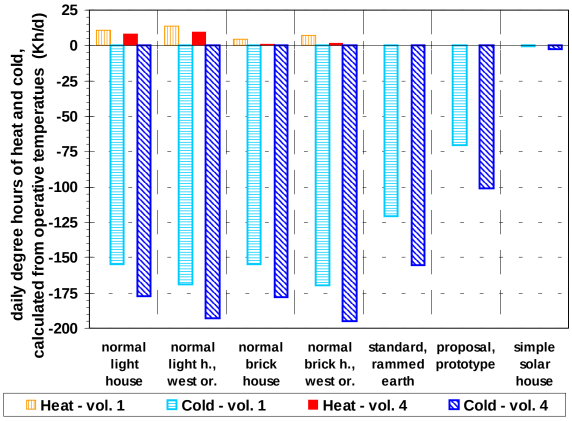

Figure 8. Daily degree-hours of heat and cold

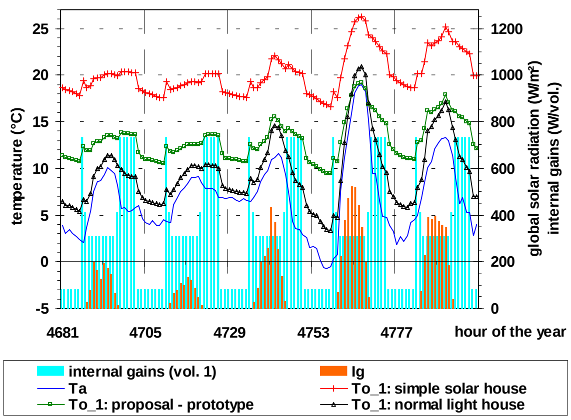

Figure 9. Operative temperatures in volume 1

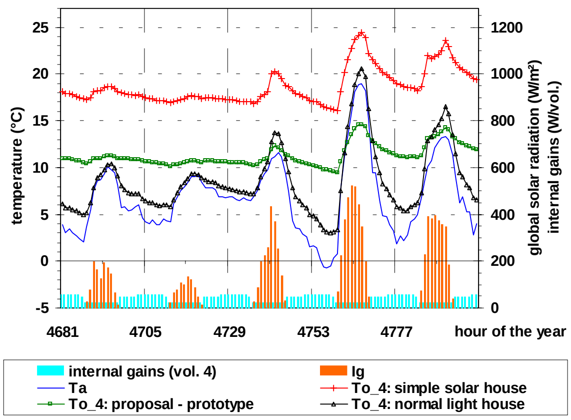

Figure 10. Operative temperatures in volume 4

Furthermore, these simulations demonstrate the importance of real climate variation in the TRY: In Figure 9 for 5 days in July, it can be observed, that in the central living room 1, internal gains dominate the daily curve on cloudy winter days, especially in a well insulated house, whereas on sunny winter days solar radiation is dominant. In Figure 10 with lower internal gains for a sleeping room, solar gains are always dominant. Moreover, the increase of daily temperature variation on clear days and the variable building response depending on the design characteristics can be easily observed .

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CONCLUSIONS

The TRY developed here formed the base for extensive parametric studies, that permitted the development of design recommendations for passive climatisation for the Central Region of Chile [Müller 2000], [Müller 2001]. Moreover, thermal simulations of standard and improved housing designs with different passive elements led to the thermal improvement of a prototype house of rammed earth, that is now under construction for future measurements. The TRY and simulations are applicable to the houses of approximately 40% of the Chilean population living in the Metropolitan Region and some neighboring regions on up to 1000m of altitude, considering the new thermal zoning (zone 3) defined in [MINVU 2000].

This paper offers a complete description and references for the preparation process of the TRY, applicable to other simulation programs as well. This permits the reader to prepare his/her own TRY under comparable circumstances where the availability of climate data is limited.

The method presented here for the preparation of the TRY can be useful for many other regions, especially in developing countries, and thus can facilitate a wider use of thermal simulations for the design of sustainable buildings with passive heating and cooling.

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NOMENCLATURE

c	cloudiness
I	irradiation (Wh/m²)
I_g	global irradiation (Wh/m²)
I_{gn}	daily global irradiation (Wh/m²d),"normal" monthly mean value
I_{gm}	daily global irradiation (Wh/m²d), monthly mean value
I_d	diffuse irradiation (Wh/m²)
I_b	direct (beam) irradiation (Wh/m²)
I_{b_th}	theoretical direct (beam) irradiation (Wh/m²)
I_n	normal irradiation (Wh/m²) = beam radiation normal to receiving surface, 0° incidence angle (term according to DEROB-LTH manual)
I_o	extraterrestrial irradiation (Wh/m²)
k_T	hourly clearness index
K_T	daily clearness index
S	global thermal sky radiance (W/m²)
T_a	air temperature (K); (°C) when indicated
T_o	operative indoor temperature (°C)
T_{max}	daily maximum temperature (°C)
T_{min}	daily minimum temperature (°C)
T_{mn_off}	monthly “normal” temperature, calculated according to the official definition of the National Meteorological Office (°C)
T_{m_off}	monthly mean temperature, calculated according to the official definition for the specific month and year (°C)
T_{sky}	sky temperature (K)
$X_{\_mmax}$	monthly mean of daily maximum value of X
$X_{\_mmin}$	monthly mean of daily minimum value of X
α_s	solar altitude angle
ε_a	apparent sky emissivity
σ	Boltzmann constant = 5,6697 10^{-8} W/m²K^4