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A SATELLITE ESTIMATION MODEL FOR SOLAR ENERGY RESOURCE ASSESSMENT IN CHILE

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Abstract

The recent progress in solar energy resource assessment for Chile is reported, including measurements from a ground station network and satellite estimations from the recently developed Chile-SR model. The results indicate that there are high radiation levels in northern Chile, although the resource variability is higher than previously thought. The satellite estimation model was developed as an adaptation from Brazil-SR model, with an improved formulation for altitude-corrected atmospheric parameters, and a novel formulation for calculating effective cloud covers while at the same time detecting and differentiating it from snow covers and salt lakes. The model is validated by comparison with ground station data.

Keywords: satellite estimation, solar radiation measurements, Chile.

1. The Need for Solar Energy Data in Chile

Renewable Energy promotion in Chile has obtained institutional support by means of a law that mandates a renewable energy quota of up to 10% of the electrical energy generated, which must be met by 2024, with public announcements already being made that would modify this goal in order to achieve 20% of power generation by 2020 from renewable energy [1]. This plan has sparked interest in introducing renewable energy systems to the country´s electricity system. Solar energy is currently at the initial stages of market penetration, with several projects being announced including PV, CSP, and industrial heat supply plants. However, strong barriers still exists due to the absence of a valid solar energy database, adequate for energy system simulation and planning activities. In fact, the current state of Solar Energy utilization in Chile is rather unsatisfactory. Even as the country is being endowed with an exceptional solar potential, the contribution of solar energy to the energy mix in Chile is negligible. Only 1 MW of PV has been deployed and is currently operating for the state mining company Codelco [2], and even when there have been several announcements for commercial and demonstration plants, no other project is currently being executed -either PV or CSP- but for the process heat plant being built at Minera El Tesoro in northern Chile [3]. This facility corresponds to a process heat solar thermal plant based on parabolic trough concentrator technology including thermal energy storage in a pressurized water circuit, which will supply 14 MW_{th} peak to the copper production process thus reducing in more than 50% its previous energy consumption which originally was 6700 m^3 of diesel oil. This project was developed by Minera El Tesoro and Abengoa Solar, and is expected to start its commissioning phase during the last months of 2012. As of May 2012, the environmental impact assessment system listed a total of 685 MW of PV plants already approved that have not yet initiated construction and 1903 MW entered for evaluation, of which 360 MW correspond to a single CSP project (4x90 MW) and 1543 MW are PV plants. However, according to the Chilean Government Renewable Energy Center (CER) [4], none of the projects has already secured funding, with at least 106 MW facing serious financial difficulties. Regarding solar heating and cooling systems, statistics from the "Solar Program" at the Energy Ministry indicate that as of 2010 there are 28,000 m^2 of installed solar thermal collectors for both the residential and commercial sectors, with a deployment rate of over 7,000 m^2/year [5].

There are currently no solar desalination projects in Chile. One of the several reasons that explain this difficulty in financing solar projects lies in the lack of adequate resource assessment activities that could allow reducing the risk associated to the real energy yield of the solar plants to be deployed in Chile. The efforts of our research team aim to produce and make available to the public and industry a proper set of solar radiation data able to allow project development with lower resource-related uncertainty.

Previous reports by the authors identified several databases of solar radiation which are available for Chile and discussed their merits and shortcomings. It has been found that significant deviation exists between sources, and that all ground station measurements display unknown uncertainty levels, thus highlighting the need for a proper, country-wide long-term resource assessment initiative. However, the solar energy levels throughout the country can be considered as high, and it is thought that they are adequate for energy planning activities –although not yet for proper power plant design and dimensioning. As a general conclusion, the previous work by the authors demonstrated that although for Chile there are several databases of ground measurements, a weather simulation model, and satellite-derived data, none of these data sources are completely valid and therefore a nationwide effort of resource assessment was needed [6-8].

As context, it is possible to mention that solar radiation data for large spatial regions can be obtained from ground station networks that provide discrete data points from which a continuous map can be obtained by means of a proper interpolation scheme. In addition, surface radiation can be estimated by satellite data processing. The latest Brazilian Solar Atlas [9], for example, combines both measurement techniques in order to obtain data with low uncertainty levels. Pyranometer-based measurements from ground stations typically have lower uncertainty levels that satellite-derived data obtained by radiative transfer models, although this cannot be guaranteed for locations in between stations for data that has been computed by means of interpolation schemes. However, it has been shown that uncertainty levels for ground stations data are higher than satellite-derived measurements whenever the distance between stations is larger than 35 km [10, 11], and thus, a sensible resource assessment campaign will try to use satellite-derived irradiance for ample terrain coverage, at the same time as the use of ground stations for monitoring and validation purposes. As reference regarding proper time periods for measurement campaigns, the temporal variability of solar irradiance indicates that 5-year data sets can help determine the long-term average solar radiation with a fair degree of accuracy (estimated to be slightly larger than 5%), but do not contain enough information to accurately represent year-to-year variability. A 15-year data set can show inter annual patterns and trends, although statistically these variations are complex and do not follow a simple bell shaped curve of a random distribution. However, as mentioned by [12] a long term accurate average can be obtained by this data. The characteristics of solar irradiance can be described with a high degree of statistical confidence by analyzing 30-year data sets [13]. The current efforts in assessing the solar resource in Chile aim to produce databases that satisfy the previously stated conditions.

This report updates the previous article by presenting the advances made during the last two years regarding solar energy resource assessment in Chile. A new network of ground stations aiming to achieve BSRN standard of operation is being deployed in the country by the authors that provides developers, researchers and policymakers with good quality data. This network includes rotating shadowband radiometer devices (RSBR) is also being deployed by the authors in isolated locations of scientific interest such as high altitude places, salt lakes, snow covered terrain, and others. Finally, a new satellite estimation model is being developed by the authors. The Chile-SR model builds upon the Brazil-SR model partially developed by researchers at the *Instituto Nacional de Pesquisas Espaciais* (INPE) of Brazil, and introduces different treatments for the meteorological variables and the effective cloud cover computations. The report presents results and comparisons for the described data sources. Partial validation of the Chile-SR model is also presented, in which becomes apparent that the model is properly estimating solar radiation for temperate climates, although further refinement of the methodology is needed for desert areas with clear skies, where improved effective cloud cover estimates and better atmospheric aerosol modeling are needed. In what follows, we will first describe each database of ground station measurements that are available to the public. The satellite-based Chile-SR model is then described. Finally, a comparison between the data produced by different sources is attempted when possible.

2. The UC-FONDEF ground station network

Starting in January 2010, a research project directed by the authors and financed through FONDEF grant D08i1097 is deploying a network of 12 ground stations, of which 5 are designed and operated under BSRN standards, and the remaining 7 are of three different configurations of RSBR. The stations designed following BSRN standards are composed of Kipp&Zonnen Solys 2 trackers, sun sensors, CMP 11 and 21 pyranometers, heating and ventilation units, CGR6 pyrgeometers, CHP1 pyrheliometers, CUV4 UV meters, and also temperature, atmospheric pressure, relative humidity, wind speed and direction sensors, all connected to Campbell CR1000 dataloggers, with power supplied from the grid. Both scan and save rates follow BSRN guidelines, as well as the maintenance activities. Table 1 indicates the name, type, and start date of operation for the stations, whose approximate locations is displayed in the map.

Table 1: Ground station network.

Station name	Tipe	Start date of operation
Arica	RSBR	01-08-2011
Pozo Almonte	RSBR	04-04-2012
Sur Viejo	RSBR	07-07-2011
Crucero	RSBR	05-12-2011
Coya Sur	RSBR	05-07-2011
El Tesoro	RSBR	2009
San Pedro	Sun tracker	03-12-2010*
Diego de Almagro	RSBR	16-06-2011
PUC	Sun tracker	22-12-2010
Curicó	Sun tracker	09-08-2012
Talca	Sun tracker	09-08-2012
Marimaura	RSBR	09-08-2012

Figure 1 (right): Northern and Central Chile, and the approximate locations of the ground stations of the UC-Fondef network. As Chile is a long and narrow country, displaying things on a map is always difficult.

The RSBR devices can have any of three different configurations. The basic configuration includes an Irradiance Inc. RSBR2 or RSBR2x device, composed by a Licor radiometer, the motor controller and rotating shadow band, temperature, atmospheric pressure, relative humidity, wind speed and direction sensors, all connected to Campbell CR1000 dataloggers, with power supply from a small-scale PV system. A second configuration lacks all meteorological sensors, and is used in locations that have a meteorological station in order to avoid repeated sensors. A third configuration is similar to the first one, with the addition of a CMP11 pyranometer for a redundant measurement of global horizontal radiation. This is used in sites where radiation conditions are particularly interesting and which have personnel readily available for maintenance and cleaning of the CMP11 device. Figure 4 shows three different configurations of the RSBR, one BSRN-designed station deployed in the field, and the Solar Evaluation Lab at UC in Santiago where all stations are received previous to field deployment. One BSRN-designed and one RSBR are permanently measuring at this location. These stations have the objective of supplying data that satisfies international standards and criteria for design, operation and maintenance, thus providing high quality data for project developers and policymakers, and for the Chile-SR satellite estimation model described in a following section. Calibration certificates for these stations are still valid, and it is planned to trace them to the world reference as suggested by international standards during the first half of 2013. Data qualification algorithms have been transferred from INPE to UC and will allow analyzing the quality of data being generates in the stations.

Figure 2: Four different configurations for RSBR stations (From top left to bottom right: Coya Sur, Sur Viejo, Pozo Almonte and Marimaura); one station with tracker, pyrheliometer and ventilation units for pyranometers (bottom left, at Talca); and author Alberto Ortega enjoying himself at the UC Solar Evaluation Lab in Santiago (bottom right) where both BSRN-standard and RSBR radiometers are tested prior to field deployment. Nice vertical development clouds over the Andes Mountains at the back.

Figure 3 shows daily totals of solar radiation for 2011-2012 at two different sites: Sur Viejo, located at 20° S, and Santiago, located at 33°S. Sur Viejo is located in the Atacama Desert, in extremely arid conditions. We have chosen to present the data from july 2011 to july 2012 as this is the period in which our measurements overlap with the processed satellite estimations. It is commonly said that the Atacama

Desert exhibits a large number of clear days throughout the year, with people referring to the place as where the sun always shine. However, the measurements show otherwise: the radiation levels are effectively high, but display a marked variability with cloudy days occurring every month. Both GHI and DNI are high and can be considered as excellent resources for both PV and CSP plants. The next graph in Figure 3 corresponds to Santiago, located further south in what is referred to as the central zone of Chile. With a Mediterranean climate, the solar resource variability in this city is high, with occurrences of cloudy and clear days throughout the year. Due to the higher latitude, Santiago displays a stronger yearly cycle for GHI and DNI with radiation in summer clearly higher than in winter.

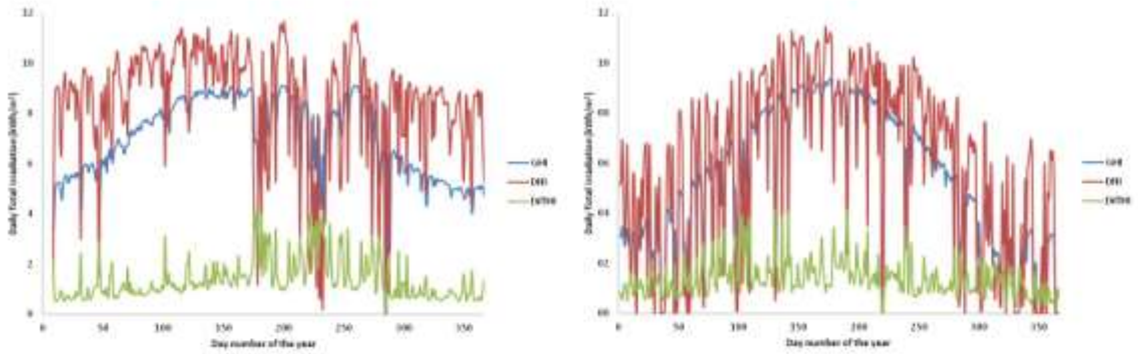

Figure 3: Daily totals of solar radiation for 2011-2012: Sur Viejo (20° S) and Santiago (33° S). Data shown from july 2011 to july 2012.

With a total of 358 days of measurements for Sur Viejo and 364 for Santiago, the daily averages in a year for GHI are 6,998 kWh/m^2 and 5,365 kWh/m^2, giving yearly totals of over 2505 kWh/m^2 and 1952 kWh/m^2, respectively. This clearly shows that even in central Chile the available solar resource is comparable to that of Andalucía, a beautiful place where a large scale development of solar plants has been produced. Once again we can say that Chile has excellent solar radiation potential in northern and also the central parts of the country.

3. Chile-SR Satellite-based Estimation Model

It has been noted before that ground measurement campaigns, although accurate, are expensive and prone to equipment failure. In addition, poor maintenance leads to data of higher uncertainty, while the cost and length of a campaign prevents deploying the large number of ground stations needed to properly cover an extended geographical region such as a country. Satellite estimation of solar radiation at the earth surface combines several advantages over ground measurements that make it a preferred method for identifying sites with high potential before deciding to commit to a ground measurement campaign. Satellite estimation is cheaper yet sufficiently accurate, and it covers a large geographical area with adequate spatial and temporal resolution; however, its basic methodology remains a combination of remote sensing and numerical algorithm, and thus needs validation by ground station data in order to be considered as quality data useful for project development and policy making. Moreover, a methodology that relies on modeling the atmospheric transmittance has to adapt to the different climate conditions that can be present in a geographic region such as a country or continent, and therefore it is desirable to develop region-specific methodologies that are properly validated. Considering this, the authors aimed at developing a satellite estimation model that could produce accurate and low uncertainty data for Chile by taking into account the different climatic characteristics that the country displays, with enough spatial and temporal resolution to be used for project development. The Chile-SR model is being developed by the authors as a modification of the existing Brasil-SR model developed by INPE within the SWERA project (swera.unep.net). The model takes the basic Brasil-SR algorithm and modifies it in order to create an adaptation especially suited for the largely different conditions that Chile presents with respect to Brazil. In particular, the northern region of Chile is the Atacama Desert, characterized by the absence of clouds throughout the year which result in high radiation levels reaching the surface. Moving further south, first a Mediterranean climate is found in the country´s center region, which gives way to a cold forest region in southern Chile. The country itself is a narrow strip of land located between the Pacific Ocean and the Andes Mountains. Therefore, it is possible to roughly divide the country into nine different regions, as defined by a matrix composed of north/center/south and coast/interior/mountains regions. The Chile-SR model had to accommodate for all these combinations, each of which has a different atmospheric profile, cloud cover, and topography. Figure 3 shows a summarized description of the Chile-SR model, its inputs, the atmospheric parametrization, and related outputs.

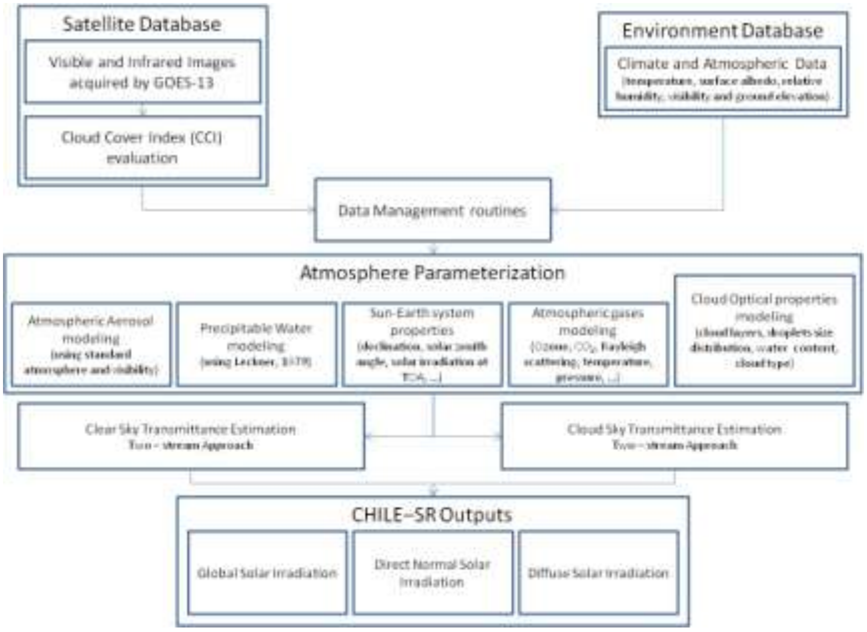

Figure 3: General description of the Chile-SR model.

According to this, the Chile-SR model is made specific for the conditions of Chile by including updated altitude-corrected weather data (temperature, relative humidity, and atmospheric pressure), topography, and surface albedo. GOES images for visible and IR channels are used as input to first classify cloud types, and then determine an effective cloud cover. The atmospheric radiative transfer algorithm that Brasil-SR utilizes is left untouched but for the input data and the effective cloud cover computation. The output data from the Chile-SR model is composed of global horizontal radiation diffuse horizontal radiation and DNI in hourly basis. Figure 4 illustrates the sequence of main steps that Chile-SR takes in order to estimate radiation for April 12, 2012, at 16:40 UTC, for a region of the Atacama Desert in northern Chile. Input data takes of temperature and relative humidity are corrected by altitude, and from this a type of atmosphere is selected. Surface albedo is obtained from Modis data. Channel 1 (visible) and channel 4 (IR) from GOES images are utilized in order to determine the type of cloud, which in turn helps determine the effective cloud cover which, when coupled to the atmospheric transmittance algorithm allows estimating the global horizontal irradiance and the direct normal component.

It can be seen from the visible channel picture that cloud formations were present in the Pacific Ocean, and also covering part of the territory in northern Chile. This first picture also illustrates an additional difficulty that the research team has faced, in the form of salt lakes and snow covers that in a visible channel picture might appear as cloud covers. The next image, IR channel, complements the visible channel image by giving information about the temperatures of each region. By properly combining the information from both channels, a cloud classification can be made, thus determining if a particular region is clear of clouds (type 1 in the figure), or if it has cloud covers (types 2 to 4 in the figure). The next step is processing the cloud type and comparing the instantaneous information from each image to a monthly-established reference, which allows determining an effective cloud cover CCI_{eff}. The next two pictures in Fig. 4 show the results from the

Chile-SR model for both global horizontal irradiance and DNI. It can be observed that northern Chile exhibits a high GHI up to 1200 W/m^2, and that cloud covers decrease the GHI down to about 400 W/m^2, the same as along the Andes Mountains. DNI values are also high, well in excess of 1000 W/m^2, and are severely diminished by the presence of cloud covers. It is interesting to note that contrary to common belief –and as already indicated in the discussion about figure 3- northern Chile does exhibit many days with cloud covers that can take DNI to values close to zero. Thus, we contest the view that in the Atacama Desert all days are identical and sunny, and propose that more research is needed and also that statistical representativity of any database for this region must include long-term estimations and measurements.

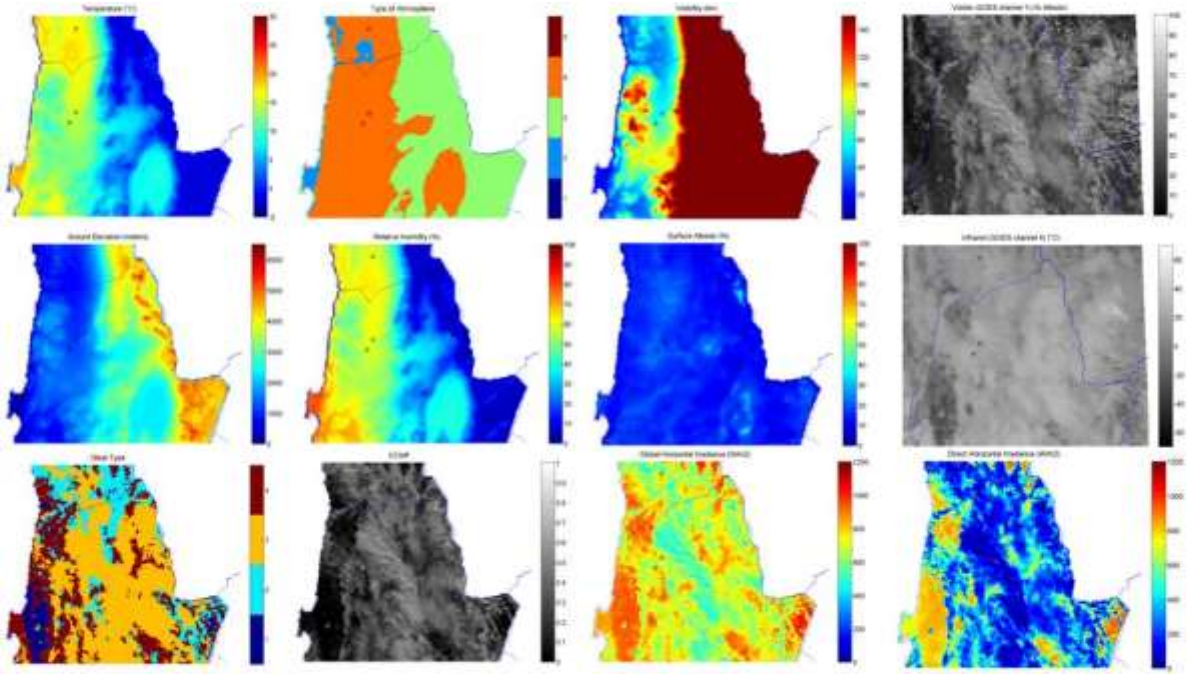

Figure 4: Input data for the Chile-SR model (temp and humidity); atmosphere type, GOES images, effective cloud covers and estimated solar radiation for part of the Atacama Desert in Northern Chile. Interesting to note the presence of cloud covers that severely diminish DNI values. Data for April 12 2012 at 16:40 UTC.

From what can be seen in these results, the Chile-SR model is able to capture the main characteristics of the weather systems influencing solar radiation. This is a significant advance in the solar energy resource assessment for Chile, as it is able to capture the different climate conditions present in the country. In particular, the model aims to capture the cloud-clear conditions present in northern Chile and the cloud variability observed in southern Chile; both conditions have not been fully observed in the time period where both satellite-estimated and ground station data are available. In particular -as a twisted way in which nature enjoys playing with our project schedule- the weather conditions during 2011 and part of 2012 have seen many cloudy days and even rain in northern Chile, something that seldom occurs and is considered as a very rare phenomenon. In fact, during 2011 there was even snow falling in the Atacama Desert! Only further research and time will allow us to elucidate the long-term characteristics of solar radiation in this region.

4. Comparison: Chile-SR satellite-derived data and UC-FONDEF ground stations

Figure 5 shows the comparison for satellite-derived data and ground measurements including both partially-clouded and clear days for Crucero and Santiago. It can first be observed that maximum levels for GHI at Crucero (23°S) reach 1200 W/m^2, while at Santiago (33°S) reach about 1165 W/m^2. This demonstrates that in clear days the available radiation in central Chile is fully comparable to that of northern Chile, which gives us additional ammunition to contest the common paradigm that only northern Chile is fertile ground for solar energy. It can also be seen that excellent agreement between satellite estimations and ground measurements are found for clear days at the two locations (desert and Mediterranean climates), although the agreement is less than fully satisfactory for partially cloudy days when variability of solar radiation is higher. This seems to indicate that further refinement of the cloud cover formulation on the Chile-SR model is needed, although, as can be seen in Figure 6, good agreement is again found when considering longer periods such as monthly averages. However, it is apparent that at least for the central zone of Chile, which as said is characterized by a Mediterranean climate, our satellite data displays a notorious bias towards overestimating solar radiation. One possible reason for this could be that the atmospheric parametrization is not totally effective for Santiago, as this is a highly polluted city in which aerosol content due to smog can decrease solar radiation. This hypothesis is currently being tested but, more importantly, the situation highlights the local nature of solar radiation attenuation due to aerosols and thus merits a better treatment of the particularities exhibited by the different climates in Chile.

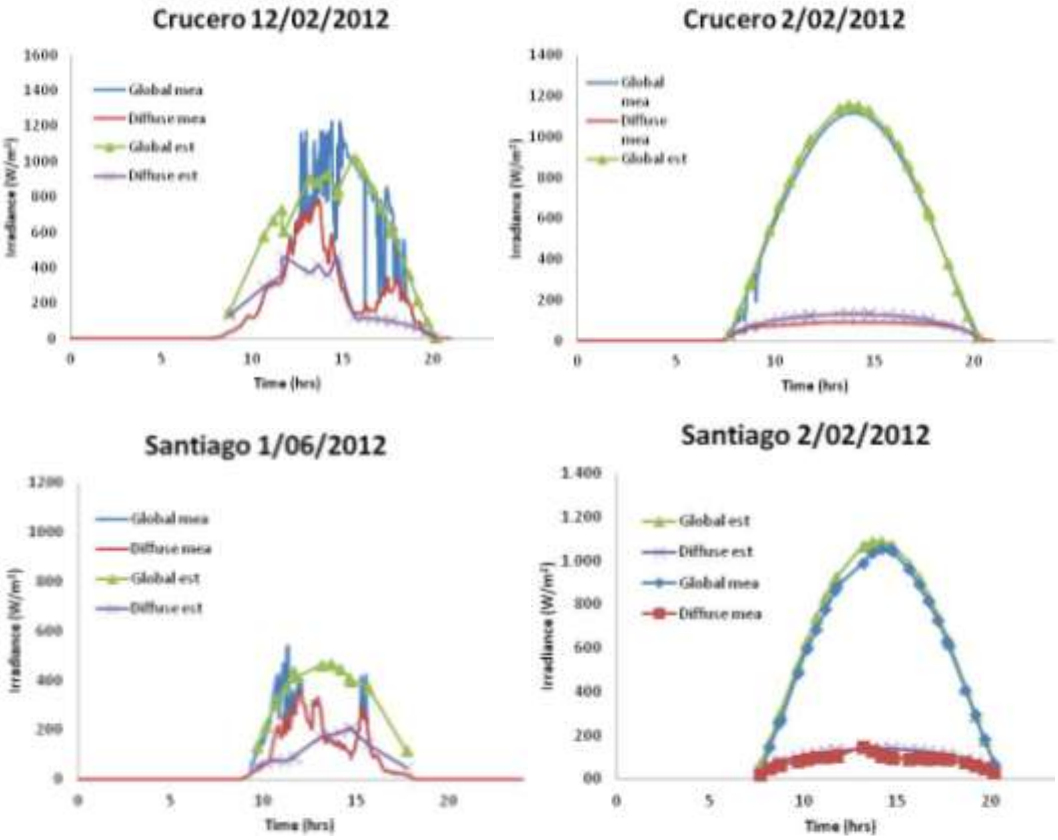

Figure 5: Comparisons between satellite estimations and ground measurements for cloudy and clear days at Crucero (23° S) and Santiago.

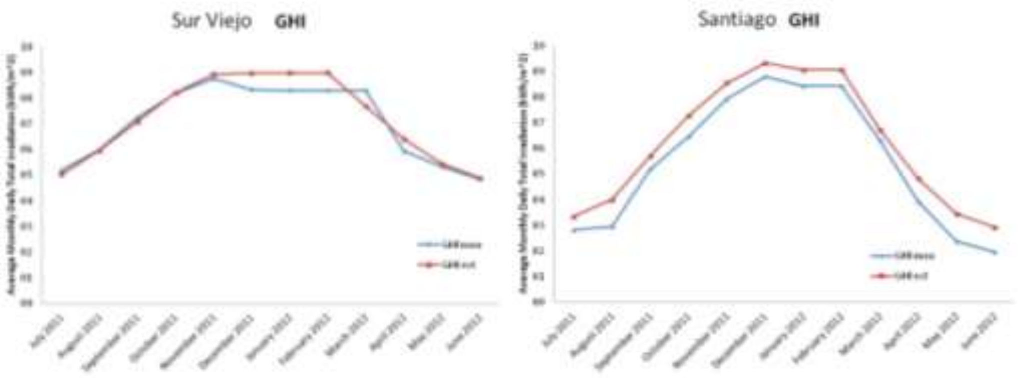

Figure 6: Comparisons between satellite estimations and ground measurements for the monthly averages of daily total radiation at Sur Viejo (left) and Santiago (right).

Figure 7 shows another comparison of satellite estimations and ground station data, combining the data available for Santiago. As in Fig. 6, it can be seen that there is a tendency of Chile-SR to overestimate the radiation. The bias error that is so evident in the hourly data (Fig. 7, left), however, is reduced when comparing in a daily basis. The research team is still trying to improve the visibility and aerosol content formulations, and is expected that fine adjustments to the model and the use of physical data for aerosol content could greatly enhance the quality of estimated data. As usual with scientific activities, we keep improving and work is constantly being done. The Chile-SR is a young model that can benefit from the work and experience of collaboration efforts.

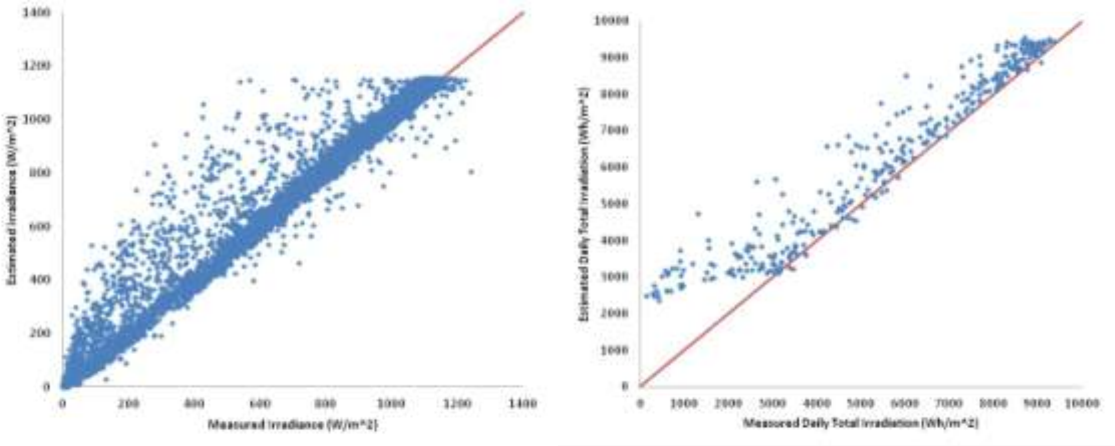

Figure 7: Comparisons between satellite estimations and ground measurements considering averages for the complete 2011 year for Santiago. Left: hourly data. Right: daily data.

5. Conclusions

Renewable Energy promotion efforts in Chile aim to achieve a power production quota of 10% to be met by 2024. This plan has sparked interest in solar energy among other renewable sources, with PV, CSP, and industrial heat supply plants being announced, although only two small scale projects have materialized. Previous reports by the authors have identified several databases of solar radiation finding that significant deviation exists between sources, with most data from ground station measurements displaying unknown uncertainty levels, which highlighted the need for a proper, country-wide long-term resource assessment initiative. This report updates the situation in Chile by considering the efforts performed in the last three years by a resource assessment program based on the development of a satellite estimation model, complemented by a modern measurement ground station network. The UC-FONDEF program has deployed a network of twelve ground stations which are producing data according to international standard and good practices, with the oldest station producing data since December 2008. A satellite estimation model has been developed to account for the particular conditions found in Chile, which is already producing data and it is currently being validated. Preliminary data from the Chile-SR model indicates good agreement with ground measurements, although this preliminary validation is by no means exhaustive and requires further work. As seen, Chile still has no database of solar radiation data that could be considered as valuable for project design and financing activities. However, the current efforts are starting to yield interesting results by producing high quality data that is expected to be released to the public shortly. It is then expected by the authors that the lack of solid data for Chile is about to be solved.

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References

[1] Ministerio de Economía. Ley general de servicios eléctricos, Decreto con fuerza de ley n 4, Art. único N° 2, D.O. 01.04.2008. Febrero de 2007.

[2]http://www.codelco.cl/planta-industrial-solar-estara-operativa-en-2011/prontus_codelco/2011-08-04/173653.html. Last accessed on Aug. 30, 2012.

[3] http://www.revistaei.cl/revistas/imprimir_noticia_neo.php?id=996. Last accessed on Aug. 30, 2012.

[4] www.cer.gov. Last accessed on Aug. 30, 2012.

[5] http://www.programasolar.cl/index.php?start=21. Last accessed on Aug. 30, 2012.

[6] Ortega, Escobar, Vidal, Colle, and Abreu. The *state of Solar Energy Resource Assessment in Chile*. ISES World Solar Energy Congress, Johannesburg, South Africa, October 11-15 2009.

[7] Ortega, A., Escobar, R., Colle, S., Abreu, S. (2010). *The State of Solar Energy Resource Assessment in Chile*. Renewable Energy, 35, 11, 2514-2524.

[8] Ortega, Escobar, Pereira, Ramos. Advances in Solar Energy Resource Assessment for Chile. ISES World Solar Energy CongressKassel, Germany, 2011.

[9] Pereira, E.; Martins, F.; de Abreu, S.; Ruther, R. Atlas Brasilero de Energía Solar. INPE, 2006.

[10] Perez, R.; Seals, R.; Zelenka, A. Comparing Satellite Remote Sensing and Ground Network Measurements for the Production of Site/Time Specific Irradiance Data. Solar Energy 1997; 60 (2): 89-96.

[11] Zelenka, Pérez, Seals and Renne, Effective accuracy of satellite-derived hourly irradiance. Theoretical and Applied Climatology 62: 199-207, 1999.

[12] R. Pitz-Paal, Norbert Geuder, Carsten Hoyer-Klick, Christoph Schillings. How to get bankable meteo data? NREL 2007 Parabolic Trough Technology Workshop, March 8-9, 2007. Golden, Colorado. Last accessed at http://www.nrel.gov/csp/troughnet/wkshp_2007.html on Dec. 29, 2009.

[13] Pacific Northwest Solar Radiation Data book. University of Oregon Solar Monitoring Laboratory, 1999. Last accessed at http://solardat.uoregon.edu on on Dec. 29, 2009.