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Solar energy resource assessment in Chile: Satellite estimation and ground station measurements

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ABSTRACT

The progress from the last four years in solar energy resource assessment for Chile is reported, including measurements from a ground station network spanning from two to three years of data, and satellite estimations from the recently developed Chile-SR model including two full years of data. The model introduces different procedures for the meteorological variables and the effective cloud cover computations that allow estimation of the global horizontal and diffuse irradiation on an hourly basis. Direct normal irradiation is computed by applying proper solar geometry corrections to the direct horizontal irradiation. 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. The results indicate that there are high radiation levels throughout the country. In particular, northern Chile is endowed with one of the highest solar resources in the world.

1. The need for solar energy data in Chile

Recently, Chile has renovated his law of Renewable Energy promotion. The new regulation sets a quota for energy coming from renewable sources of 20% of the total electricity production to be achieved in 2025 [1]. This plan increases the quota previously established by the former governments (10% of electrical energy generated by 2024 [2]) and encourages power generating companies to incorporate 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 photovoltaics (PV), concentrated solar power (CSP), and industrial process 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 6.7 MW of PV are currently in operation and 126 MW are being built [3]. Although there have been several announcements for commercial and demonstration plants, no additional projects are currently in execution – either PV or CSP. Worth mentioning that there are two projects to deliver process heat: a parabolic trough collector's plan was built at Minera El Tesoro in Northern Chile [4]; and a flat-plate collector plant for Codelco, located in Division Gabriela Mistral, is at construction stage [5]. As of November 2013, the Environmental Impact Assessment System (SEIA) listed a total of 5167 MW of solar plants approved that have not yet initiated construction. Also several projects have applied for environmental evaluation, totalizing 2695 MW; of which 360 MW correspond to a single CSP project (4×90 MW), 400 MW belong to a solar power tower project and the rest are PV plants. However, according to the Chilean Government Renewable Energy Center (CER) [6], none of the projects has already secured funding and are facing serious financial difficulties. Regarding solar heating and cooling systems, statistics from the "Solar Program" at the Energy Ministry indicate that as of 2011 there are 58,000 m^2 of installed solar thermal collectors for both the residential and commercial sectors, projected to reach 190,000 m^2 by 2015 [7]. There are

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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 [8–10].

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 [11], 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 [12,13], 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 [14] a long term accurate average can be obtained by this data. The characteristics of solar irradiance can be described with a high degree of

Table 1
Ground station network.

Station name	Type	Start date of operation
1. Arica	RSBR	01/08/2011
2. Pozo Almonte	RSBR	04/04/2012
3. Patache	RSBR	16/01/2013
4. Sur Viejo	RSBR	07/07/2011
5. Crucero	RSBR	16/01/2012
6. Coya Sur	RSBR	05/07/2011
7. San Pedro	Sun Tracker	03/12/2010[a]
8. El Tesoro	RSBR	01/01/2009
9. Diego de Almagro	RSBR	02/08/2011
10. Santiago	Sun Tracker	22/12/2010
11. Curicó	Sun Tracker	01/06/2012
12. Talca	Sun Tracker	09/08/2012
13. Marimaura	RSBR	12/07/2012

[a] Operation finished 04/07/2011.

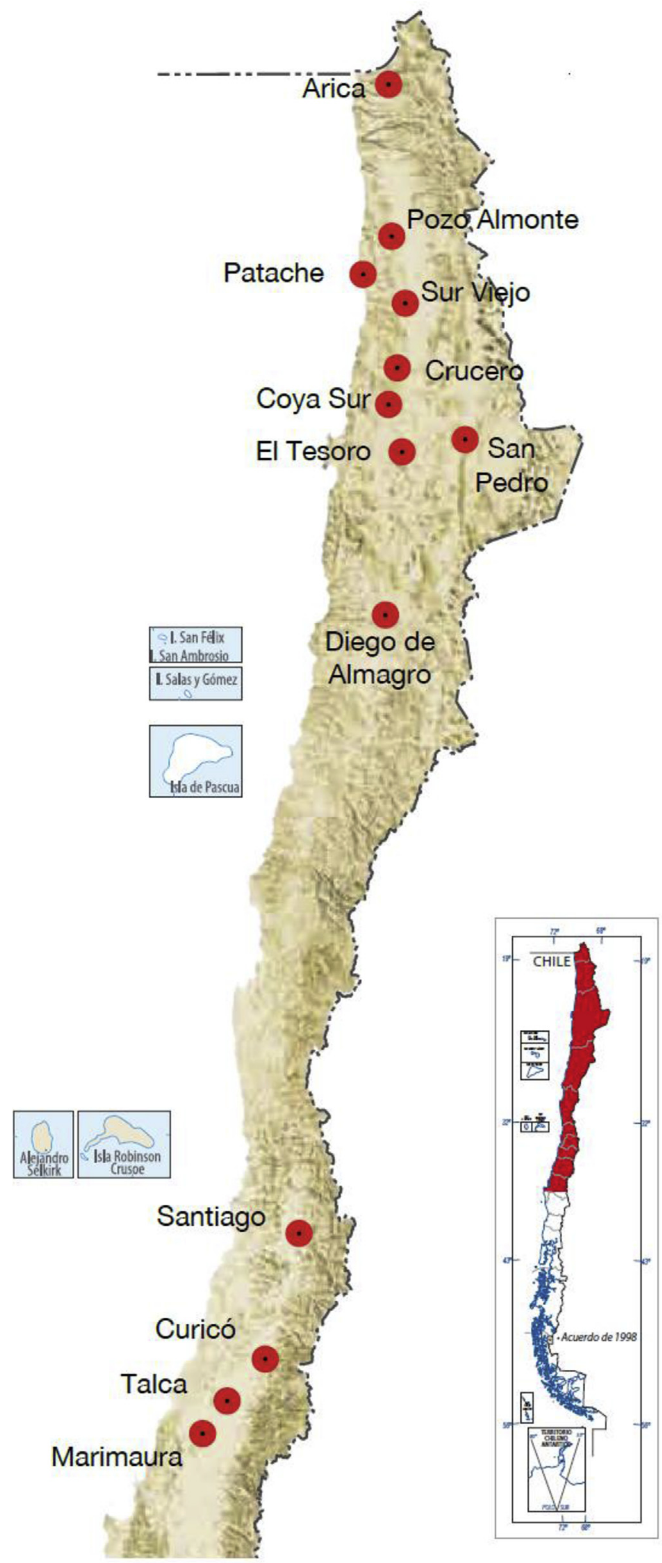

Fig. 1. Northern and Central Chile, and the approximate locations of the ground stations of the UC-FONDEF network.

statistical confidence by analyzing 30-year data sets [15]. 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 four years regarding solar energy resource assessment in Chile. A network of ground stations aiming to achieve BSRN standard of operation has been deployed in the country and can provides developers, researchers and policymakers with good quality data. This network includes rotating shadow band radiometer devices (RSBR), also deployed in isolated locations of scientific interest such as high altitude places, salt lakes, snow covered terrain, and others. Finally, a new satellite estimation model has been developed, building upon the Brasil-SR model partially developed by researchers at the Instituto Nacional de Pesquisas Espaciais (INPE) of Brazil, and introducing different treatments for the meteorological variables and the effective cloud cover computations. The report presents results and comparisons for the described data sources. Validation of the Chile-SR model is also presented, in which becomes apparent that the model is properly estimating solar radiation for the range of climates present in Chile. In what follows, we will first describe the ground station network and the characteristics of its data. The satellite-based Chile-SR model is then described. Finally, a comparison between the data produced by the two allows us to validate the data produced by Chile-SR.

2. The UC-FONDEF ground station network

Starting in January 2010, a research project directed by the authors and financed through FONDEF grant D08i1097 has deployed a network of 13 ground stations, of which 4 are designed and operated under BSRN standards, and the remaining 9 are of three different configurations of RSBR. The stations designed following BSRN standards are composed of Kipp&Zonnen Solys 2 trackers, sun sensors, CMP11 and 21 pyranometers, heating and ventilation units, CGR4 pyrgeometers, CHP1 pyrheliometers 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.

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.

In the northern regions of Chile is the Atacama Desert, characterized, 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. Table 1 indicates the name, type, and start date of operation for the stations, whose approximate locations is displayed in the map as in Fig. 1.

Fig. 2 shows two different configurations of the ground stations: one RSBR, and one BSRN-designed station deployed in the field. 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. Also the data is important to validate the Chile-SR satellite estimation model described in a following section. Data qualification algorithms have been transferred from INPE to UC and will allow analyzing the quality of data being generated in the stations.

Fig. 3 shows daily totals of solar radiation for 2012 at two different sites: Crucero, located at 22°S in the Atacama Desert, in extremely arid conditions, and Santiago, located at 33°S. We have chosen to present the data from January to December 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 Fig. 3 corresponds to Santiago, located further south in what is referred to as the central zone of Chile. With a

Fig. 2. RSBR station in Crucero (left) and one station with tracker, pyrheliometer and pyranometers in Talca (right).

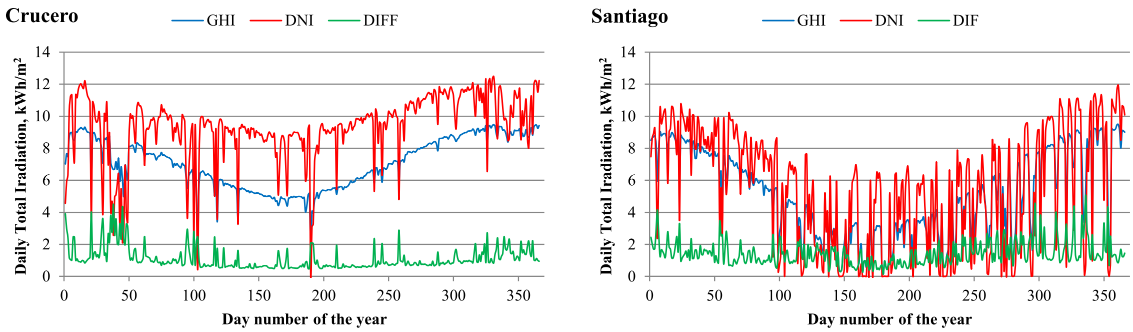

Fig. 3. Daily totals of solar radiation from January to December 2012: Crucero (22°S) and Santiago (33°S).

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.

With a total of 366 days of measurements for Crucero and Santiago (leap year), the daily averages in a year for GHI are 7.044 kWh/m^2 and 5.121 kWh/m^2, giving yearly totals of over 2578 kWh/m^2 and 1874 kWh/m^2, respectively. This clearly shows that even in central Chile the available solar resource is comparable to places where a large scale development of solar plants has been produced.

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. Besides, poor maintenance leads to data of higher uncertainty. Satellite estimation is cheaper yet sufficiently accurate, and it covers a large geographical area with adequate spatial and temporal resolution. 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 has been developed as a modification of the existing Brasil-SR model developed by INPE within the SWERA project, taking its basic algorithm and modifying it in order to create an adaptation especially suited for the largely different conditions that Chile presents. The model is able to capture all these climates and provide accurate estimations. Fig. 4 shows a summarized description of the Chile-SR model, its inputs, the atmospheric parameterization, and related outputs.

The Chile-SR model is made specific for the conditions of Chile by including updated altitude-corrected weather data (temperature and relative humidity), topography, and surface albedo. The

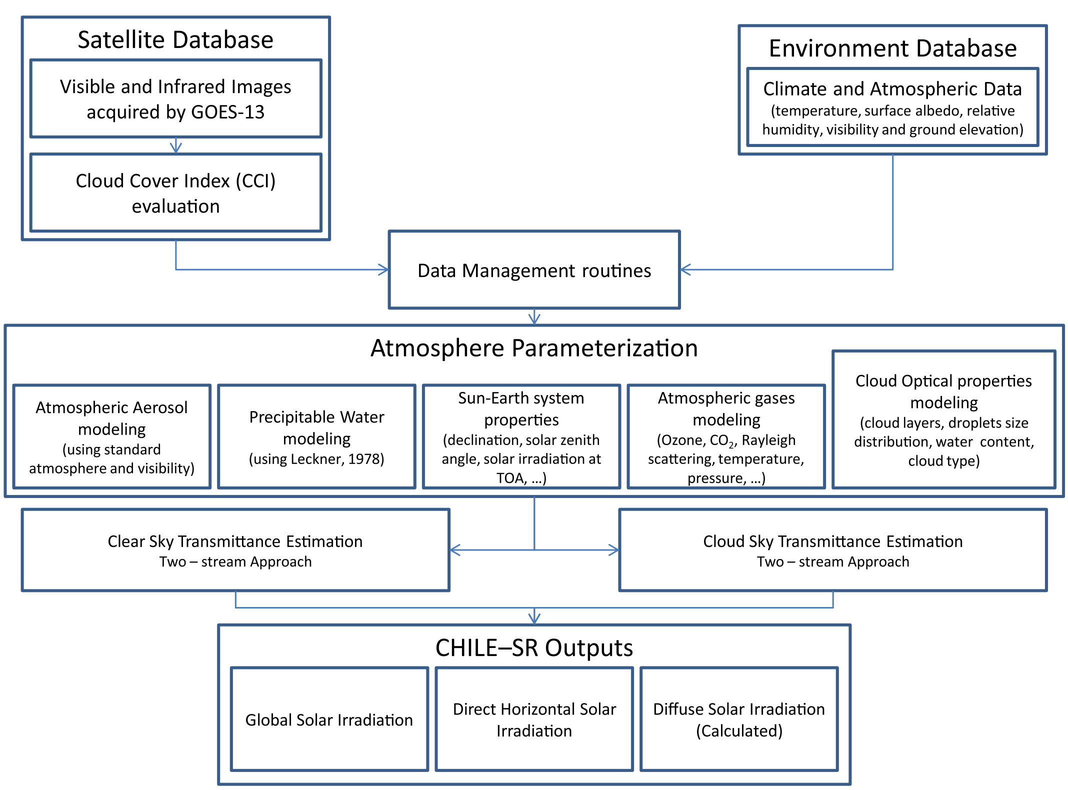

Fig. 4. General description of the Chile-SR model.

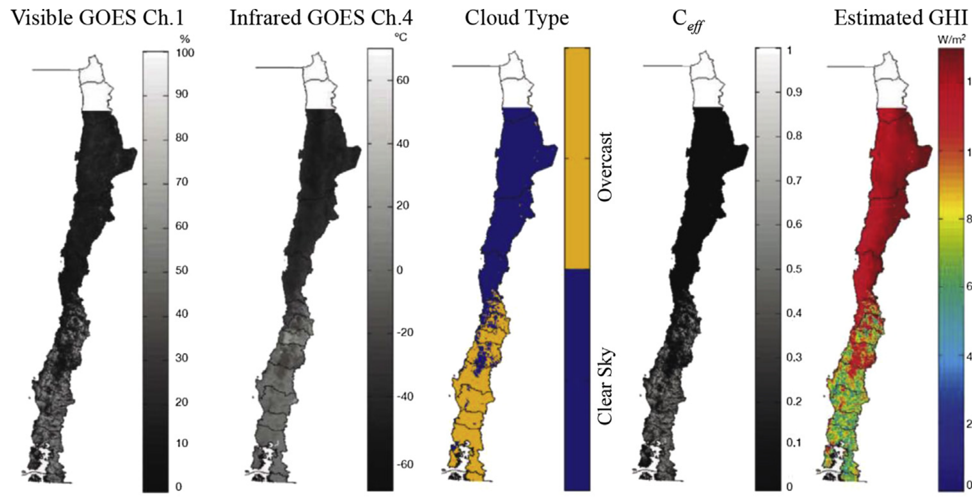

Fig. 5. Input data and results of the Chile-SR model for January 4th 2011 at 16:40 UTC. It can be observed that the Chile-SR estimate does not provide data for locations farther north than −20.7° nor to places farther south than −45.1°. This is due to source satellite image that contains only part of the territory. Satellite images covering the entire Chilean territory are available but were not used in this study because their frequency of acquisition is lower than the satellite image actually used (GOES). Images acquired with lower frequency increase the estimation uncertainty of the model.

visibility data are obtained from empirical expressions as there are no available ground measurements for Chile [10]. GOES images for visible and IR channels are used as an input to first identify clouds, and then determine an effective cloud cover. The output data from the Chile-SR model is composed of global horizontal radiation and direct horizontal radiation in hourly basis. Fig. 5 illustrates the sequence of main steps that Chile-SR takes in order to estimate radiation for January 4, 2011, at 16:40 UTC, for a large portion of the Chilean territory. Channel 1 (visible) and channel 4 (IR) from GOES images are utilized in order to identify clouds, which in turn helps determine the effective cloud cover that 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 clouds covering part of the territory in southern Chile. This picture also illustrates an additional difficulty that the research team has faced, in the form of salt lakes and snow covers that might appear as cloud covers in a visible channel image. These phenomena are present mainly in the north region of Chile at high altitude. The IR channel complements visible image channel to provide information on the upper surface temperature observed by the satellite. This may be the top of the highest cloud, if there is cloud cover, or the temperature of the surface of the Earth if the sky is clear. By properly combining the information from both channels, a cloud classification can be made, thus determining if a particular region is clear of clouds or if it has cloud covers. The next step is comparing the instantaneous information from each image to a monthly-established reference, which allows determining an effective cloud cover C_{eff}. It can be observed that there is high GHI up to 1200 W/m^2, and that cloud covers decrease the GHI down to about 700 W/m^2.

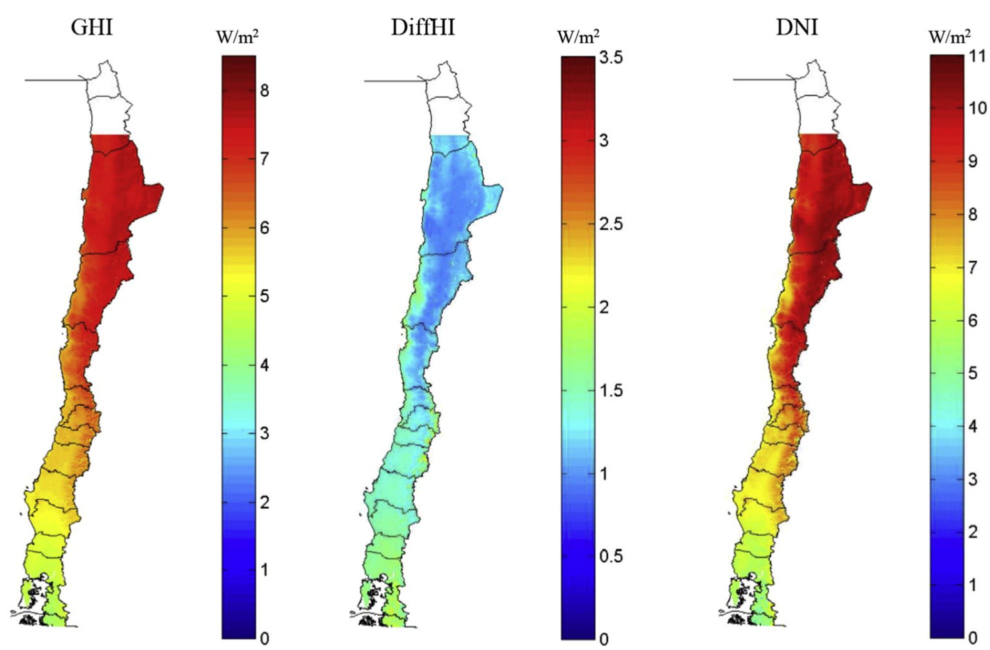

Fig. 6. Annual averages of daily totals for GHI, DNI and DIffHI.

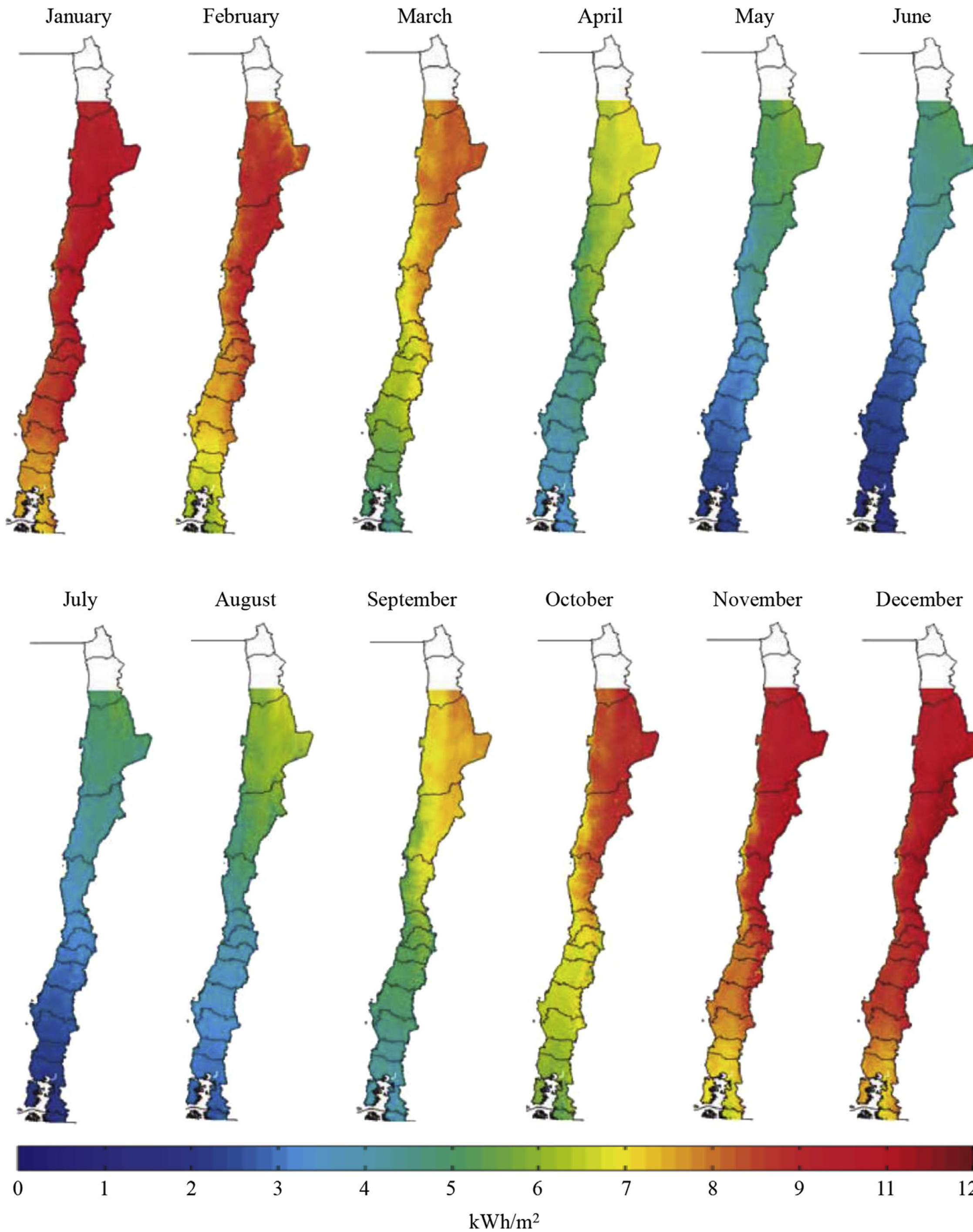

Fig. 7. Monthly average of daily totals for GHI with satellite data from period 2011 to 2012.

The temporal frequency that satellite images are received is not even throughout the day and between different days. This results in time intervals greater than 1 h during the day with no estimates available. Thus, once the results of the model are obtained for each satellite image, an interpolation for the clearness index of each image is performed. The interpolation is weighted by the inverse of the distance to the point sought. This algorithm builds an hourly database in order to obtain the magnitude of the incident solar radiation on the ground surface for the entire day. In addition, the interpolation algorithm uses the inverse of the time interval between aim result and the preceding and subsequent values to increase the weight of the nearest. Results for the beginning and the end of day were interpolated using the sunrise and sunset time for each pixel.

Fig. 6 shows the average of years 2011 and 2012 of Chile-SR annual average of daily totals for GHI, DNI and DIffHI. It can be observed that highest GHI and DNI values are reached in the Atacama Desert, predominantly in the Región de Antofagasta and Región de Atacama. The annual average for daily irradiation exceeds 7.5 kWh/m^2 for GHI and 9 kWh/m^2 for DNI in some areas where large and flat terrain is available. Thus, the available solar resource and flat terrain in the Northern part of the country exhibit

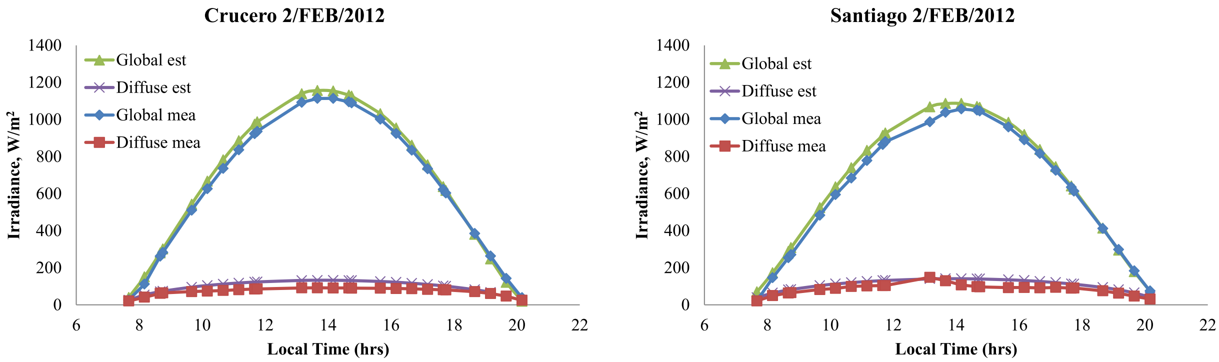

Fig. 8. Comparisons between satellite and ground data at Crucero (22°S) and Santiago (33°S).

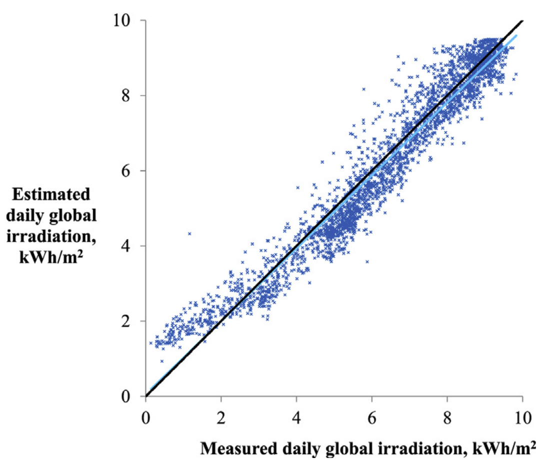

Fig. 9. Comparisons between satellite and ground data considering daily totals of irradiation.

favorable conditions for the implementation of solar projects. It can also be noted in the central and southern regions that the increasing latitude causes a continuous decrease in solar radiation. Nonetheless, at the higher latitudes covered by Chile-SR model (43°S) the year average of daily totals achieve values over 4.5 kWh/m^2.

With the purpose of illustrate the seasonal variation of the solar resource, Fig. 7 shows the monthly averages of daily totals for Chile-SR GHI estimates. In Northern Chile the daily totals range from 9.5 kWh/m^2 during summer to 4.5 kWh/m^2 in winter. In the southern regions during June the average for the daily total of GHI can be as low as 1.5 kWh/m^2. Although, during December and January the daily GHI surpass 7 kWh/m^2 at the highest latitudes covered by Chile-SR (43°S).

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

In order to validate the model results, the satellite-derived estimations have been compared with ground measurements. Fig. 8 shows the comparison for clear days in Crucero and Santiago. It can be observed that maximum levels for GHI at Crucero (22°S) reach 1200 W/m^2, while at Santiago (33°S) reach about 1165 W/m^2. This indicates that in clear days the available radiation in central Chile is comparable to that of Northern Chile. It can also be seen that excellent agreement between satellite estimations and ground measurements is found for clear days at the two locations (desert and Mediterranean climates, respectively).

Fig. 9 shows a comparison of satellite estimations and ground station data for daily totals combining the data available for all ground stations for the period 2011–2012. It can be seen that there is good agreement between satellite and ground station data, resulting in a rRMSE of 8.9% (Table 2). It can be noted that for values of irradiation lower than 3 kWh/m^2/day the satellite-derived data overestimates systematically the actual solar resource.

For hourly average of irradiance comparison of satellite estimates and ground measurements (Fig. 10) the data have been splitted into two geographical zones: a) Northern Chile and b) Central Chile. There is also a good agreement in an hourly basis, with a mean bias error (MBE) of 0.4% and a resulting rRMSE of 12.8%. The effect of overcast sky conditions (lower irradiance values) can be seen in both graph with a slightly overestimation of the model results. This phenomenon is greater in Central and Southern Chile, thus the rRMSE is higher than in Northern Chile, as it can be seen in Table 2.

It is worth mentioning that ground station data with which the Chile-SR model is validated have its own uncertainty associated to the operation of sensor used. In the case of equipment RSBR, Li-200

Table 2
Deviations observed for Chile-SR daily total irradiation and hourly averages irradiance estimates for each location of the ground stations.

	Daily total irradiation						Hourly average irradiance			
	MBE, kWh/m^2	rMBE, %	RMSE, kWh/m^2	rRMSE, %	KSI, %	OVER, %	MBE, W/m^2	rMBE, %	RMSE, W/m^2	rRMSE, %
Pozo Almonte	0.15	2.3	0.60	9.4	19.3	0.6	14.3	2.6	69.0	12.4
Sur Viejo	−0.20	−2.9	0.57	8.1	17.6	0.2	−16.1	−2.7	69.7	11.6
Crucero	−0.19	−2.7	0.55	7.9	11.4	0.9	6.1	1.0	62.9	10.4
Coya Sur	−0.09	−1.2	0.54	7.5	14.7	4.0	14.0	2.3	63.4	10.3
Diego de Almagro	−0.36	−4.5	0.56	7.1	15.3	0.4	−6.5	−1.0	53.8	8.3
Santiago	−0.01	−0.2	0.51	10.2	25.6	8.7	−0.3	−0.1	73.0	16.5
Curicó	−0.12	−2.7	0.65	14.6	31.3	14.0	22.1	5.7	92.8	24.0
Talca	−0.27	−4.8	0.64	11.2	28.5	16.0	6.1	1.3	87.4	18.9
Marimaura	−0.23	−0.1	0.79	19.8	27.5	24.9	4.8	1.4	86.0	24.0
Total	**−0.13**	**−2.1**	**0.57**	**8.9**	**21.2**	**18.7**	**2.4**	**0.4**	**70.0**	**12.8**

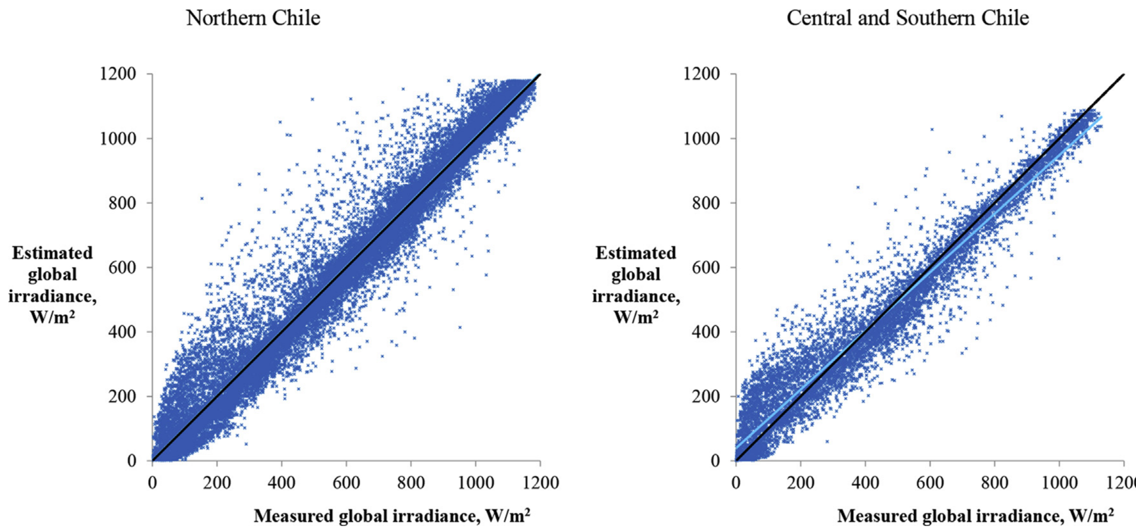

Fig. 10. Comparisons between satellite and ground data considering hourly averages of irradiance.

photodiode used has an error of 5%, declared by the manufacturer [16]. The CMP11 pyranometer composing the Sun Tracker stations have an uncertainty associated with the measurement of 2% [17]. Finally, the KSI indicator (Kolmogorov–Smirnov test integral) and the OVER parameter are also evaluated as suggested in Ref. [18]. There, the KSI parameter (Kolmogorov–Smirnov test integral) is defined as the integrated differences between the cumulative distribution functions (CDFs) of the two data sets (ground station and satellite estimation). The minimum value of the KSI index or percentage is zero, meaning that the CDFs of the two sets compared are equal. The OVER parameter indicates the area over the critical parameter of the Kolmogorov–Smirnov test and thus also indicates how similar two data sets are regarding their respective CDFs.

5. Conclusions

Renewable Energy promotion efforts in Chile aim to achieve a power production quota of 20% to be met by 2025. This plan has sparked interest in solar energy among other renewable sources, with PV, CSP, and industrial heat supply plants being announced. 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 stations network. A satellite estimation model has been developed to account for the particular conditions found in Chile, which has produced and validated data for the period 2011–2013. The satellite model takes GOES images to estimate the cloud cover index for the surface covered by implementing an algorithm of cloud recognition using both the visible and infrared channels. Additionally, it estimates the atmospheric transmittance from monthly averages of climatic variables. The UC-FONDEF program has deployed a network of thirteen ground stations which are producing data according to international standard and good practices. The data from the Chile-SR model have been compared to ground station data and good agreement is found with rRMSE of 8.9% for daily total irradiation and an rRMSE of 12.8% for hourly average irradiance, thus validating the satellite data. The results of Chile-SR model show the annual and monthly averages of the daily total solar irradiation in spatial distribution maps.

From the maps it can be observed that the annual average for daily irradiation exceeds 7.5 kWh/m^2 for GHI and 9 kWh/m^2 for DNI in some areas where large and flat terrain is available in the Atacama Desert. It can also be noted that at the higher latitudes covered by Chile-SR model (43°S) the year average of daily totals achieve values over 4.5 kWh/m^2. In the seasonal maps obtained, it can be see that in Northern Chile the daily totals range from 9.5 kWh/m^2 during summer to 4.5 kWh/m^2 in winter. In the southern regions during June the average for the daily total of GHI can be as low as 1.5 kWh/m^2. Regarding the similarity of the CDFs of both data sets, ground stations and satellite estimations, it can be observed that the model performs very well for the clear-sky conditions of northern Chile, with larger deviations for southern Chile.

The information generated by the Chile-SR model displays acceptable accuracy for the difficult and varying conditions present in Chile, and can thus help close the information breach that exists regarding public access to solar radiation data for project development and public policy formulation.

Acknowledgments

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