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Analyzing Regional and Local Changes in Irradiance during the 2019 Total Solar Eclipse in Chile, Using Field Observations and Analytical Modeling

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Abstract: Solar eclipses are astronomic phenomena in which the Earth's moon transits between the planet and the Sun, projecting a shadow onto the planet's surface. As solar power installed capacity increases, detailed studies of this region-wide phenomenon's effect in irradiance is of interest; however, the literature mainly reports its effects on localized scales. A measurement campaign spanning over 1400 km was pursued for the 2 July 2019 total solar eclipse in Chile, to register the event and establish a modeling framework to assess solar eclipse effects in irradiance over wide regional scales. This work describes the event and presents an estimation framework to decompose atmospheric and eclipse effects on irradiance. An analytical model was applied to study irradiance attenuation throughout the Chilean mainland territory, using satellite-derived and astronomical data as inputs compared to ground measurements in eight stations. Results showed good agreement between model and observations, with Mean Bias Errors of -0.008 to 0.98 W/m² for Global Horizontal Irradiance and -0.004 to -4.664 W/m² for Direct Normal Irradiance, with Normalized Root Mean Squared Errors of 0.7–5.8% and 1.4–12.2%, respectively. Energy losses due to obscuration corresponded between 20–40% for Global Horizontal Irradiance and 25–50% for Direct Normal Irradiance over Chilean territory.

Keywords: solar eclipse; atmospheric modeling; irradiance attenuation; Linke turbidity; Chile

1. Introduction

On Tuesday, 2 July 2019 there was a total solar eclipse that was seen along the Pacific Ocean, reaching Chile at the end of the afternoon and being observable in Argentina and Uruguay during the dusk. The entire shadow band traveled 11,252 km from west to east, starting in the morning in the South Pacific Ocean east of New Zealand, from where it travelled across the Pacific Ocean until it touched the mainland in South America, first in Chile and then moving to the southern tip of the Río de la Plata in Argentina. The eclipse could be seen partially in a very wide area of South America through the territories of Ecuador, Peru, Chile, Bolivia, Paraguay, Colombia, Argentina, Venezuela, Uruguay, and Brazil, as observed in Figure 1.

All of the Chilean territory could see the eclipse at least as partial, from the city of Arica, in the north of the country, where the phenomenon was observed with 65% obscuration, to the southernmost city of Punta Arenas, where it was seen with 46% obscuration. The partial eclipse was also seen on Easter Island. The umbra or strip of shadow that reached 100% obscuration during the eclipse passed through the north of the Coquimbo Region in a south-east direction, being approximately 150 km wide, and fully obscuring from the town of Domeyko to the town of Guanaqueros.



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Figure 1. 2019 solar eclipse trajectory, indicating magnitude bands (green lines) and umbra zone (dark blue area). Figure generated using Google Earth (2019) and an eclipse data overlay elaborated by [1].

Within the area of effect of the eclipse, some of the main astronomical observatories of the country are located, such as La Silla and Cerro Tololo, which took advantage of the good visibility conditions of the sky to make observations of the eclipse. Additionally, several large photovoltaic solar power plants are located in the area, such as Acciona's "El Romero Solar", with a capacity of 246 MW.

During a solar eclipse, the Moon partially or totally covers the solar disc, and during this process several phases can be identified, as shown in Figure 2. The eclipse begins at the first contact point between the solar and lunar discs (C1). In the case of an annular or total eclipse, the second contact point (C2) marks the beginning, and the third contact point (C3) marks the end of the annular/total eclipse (in an annular eclipse, the solar disc). Finally, the last contact point (C4) occurs when the lunar disc no longer covers the solar disc. Geographically, the eclipse has different effects in different affected regions, namely the penumbra and the umbra, which correspond to areas where the solar disc is observed as partially or totally covered, respectively. To describe the effect, the magnitude of the eclipse is used, which represents the fraction of the solar disc's diameter that is being covered by the lunar disc, or the obscuration, which is the fraction of the solar disc's area covered by the lunar disc [2].

Although a non-frequent occurrence, according to NASA, "during the 5000-year period from –1999 to +3000 (2000 BCE to 3000 CE), Earth will experience 11,898 eclipses of the Sun. The statistical distribution of eclipse types for this interval is as follows: 4200 partial eclipses, 3956 annular eclipses, 3173 total eclipses, and 569 hybrid eclipses" [3]; additionally, their coverage of the Earth's surface has been significant, as: "during the past 3000 years most of the earth's surface has been affected by one or more eclipses" [4].



Figure 2. Stages of a solar eclipse. C1 and C4 mark the beginning and end of eclipse, respectively. C2 and C3 mark beginning and end of annular or total eclipse during these cases.

Many studies have focused on analyzing atmospheric dynamics during eclipse conditions, mainly centered in aerosol behavior, such as [5–9]; however, fewer studies have been tasked with analyzing the behavior of meteorological variables and also irradiance changes in conditions of a solar eclipse, much less for a total eclipse.

Selvanayagam and Chinnappa [10] is one such study in which the authors measured the relative direct normal irradiance with respect to the value at the start of the eclipse, during a partial solar eclipse in Colombo, Ceylon in 1955, but also, more modern references, such as [11] also report the effects of a total eclipse. In their work, they measured the dynamics of luminance during a total solar eclipse in Turkey in 2006 and proposed a model, based on the geometry of the event, to describe the decrease in luminance during the transit. In Kalafatoglu et al. [12], the effect on the ambient temperature is observed and compared against estimations of no eclipse conditions using measurements during the partial solar eclipse in Turkey in 1999. During the transit, the temperature drops as the uncovered area of the solar disk decreases, achieving temperature decreases in the order from 2.47 °C to 4.46 °C. A conclusion from these studies is that solar eclipses reduce the irradiance received at the Earth surface by an amount that depends on the percentage of solar disk covered by the Moon.

Petkov et al. [13] analyzed the March 2006 partial eclipse in three sites in Italy to study how the surroundings affect incoming global irradiance for a location at different wavelengths, finding that the dynamics of irradiance during occultation may differ from results obtained through radiative transfer models, as well as predicted occultation times, due to the effect of surface albedo and atmospheric scattering across great distances, affecting the diffuse component of irradiance. Finally, Romano et al. [14] analyzed changes in short and long wave fluxes, meteorological parameters, and aerosol properties for three sites in Italy during a partial eclipse in 2015, registering attenuations of 238–307 W/m² for short-wave irradiance, increases up to 10 W/m^2 for long-wave irradiance, temperature drops between 0.5–0.7 K, and increases in relative humidity up to 4.5% for the event.

Nevertheless, more than the astronomical importance of the phenomenon, the effect of the eclipse on irradiance has a direct effect on the production of solar-powered plants. Libra et al. [15] monitored the performance of a photovoltaic system during a partial solar eclipse in Prague, the Czech Republic, in 2015 and compared it with the previous day as a reference. In this event, the solar disc was 68% covered and the maximum registered decrease in electric production was 69% with respect to no eclipse conditions. A similar finding was presented by Kurinec et al. [16] for a partial solar eclipse in Rochester, the United States, in 2017, in which, for a 70% partial eclipse, a maximum drop of 80% in energy production was measured; however, in this instance, a clouded sky also contributed to this decrease.

Naturally, the impact of a solar eclipse on the dynamics of power generation on a regional scale is highly interesting, especially in electric systems with a high penetration of solar technologies. On the occasion of the 2017 eclipse, which achieved total obscuration

in the United States and had effects up to the north of South America, such studies were conducted to assess the impact it had on distribution networks. Sundararajan et al. [17] and Arzani et al. [18] analyzed the effect on medium and utility-scale grid-tied photovoltaic systems, respectively, and Flores et al. [19] analyzed the effect in the Honduran electric network. The results from these works confirm that the impact of a solar eclipse in solar generation systems is significant, especially as more installed capacity is located within the affected area.

In light of this, the present work is tasked with analyzing the effect of the 2019 solar eclipse at local and regional scales in a wide range of conditions regarding coverage of the solar disc by analyzing simultaneous measurements from a network of solar radiation measurement stations, employing some stations described in [20,21] as well as deploying new ones for this study. After the introductory section, Section 2 presents the instrumentation and location of the measurement stations used in this study, as well as the criteria for data quality assessment. Section 3 presents the methodology used for clear sky modeling and solar disk occultation modeling, as well as the methodology used to estimate the overall atmospheric attenuation. Section 5 states the methodology used to compare the estimated effects with the measured data. Section 6 describes the field observations and Section 7 presents the effect of the eclipse on a regional scale throughout the Chilean territory. Finally, Sections 8 and 9 are concerned with the discussion of results and conclusions, respectively.

2. Description of Measurement Stations and Data Quality Assessment Criteria

The experimental measurements and data for this study was obtained from eight solarimetric stations, localized in zones with different solar eclipse obscuration. Two types of solarimetric stations were employed, the first is a Rotating Shadowband Irradiometer (RSI) with a fast response photodiode radiometer, and the second is a complete solarimetric station with solar tracker and thermopile radiometer with spectrally flat Class A pyranometers, classified according to ISO 9060:2018 [22]. The specific characteristics of each station are presented in Table 1, while their locations and eclipse obscurations are shown in Figure 3.

Station	Location	Temporal Resolution	Instrumentation		
TMG	20.8° S, 69.4° W				
TOC	22.1° S, 69.5° W	1 min	Photodiode pyranometer (Li-COR 200) on a Rotating Shadowband Irradiometer, Barometer (Setra), Temperature and Humidity probe (Campbell Scientific), Anemometer (Young)		
LIK	22.7° S, 68.6° W		(empediocidinic), ruchioniciel (roung)		
DDA	26.3° S, 70° W	2.6	Photodiode pyranometer (Li-COR 200) on a Rotating Shadowband Irradiometer, Barometer (Vaisala), Temperature and Humidity probe (Vaisala), Anemometer (Young)		
СРО	27° S, 69.8° W	55	Photodiode pyranometer (Li-COR 200) on a Rotating Shadowband Irradiometer, Barometer (Vaisala), Temperature and Humidity probe (Campbell Scientific), Anemometer (Young)		
SHA	30.1° S, 70.7° W		Solys 2 Two-Axis Tracker, Global and Diffuse thermopile pyranometers (Kipp&Zonen CMP11), Thermopile pyrheliometer (Kipp&Zonen CHP1),		
PUC	33.5° S, 70.6° W	1 s	Barometer (Vaisala), Temperature and Humidity probe (Campbell Scientific) Anemometer (Young).		
UCL	33.5° S, 70.7° W		Solys 2 Two-Axis Tracker, Global and Diffuse thermopile pyranometers (Kipp&Zonen CMP11), Thermopile pyrheliometer (Kipp&Zonen CHP1), Barometer (Vaisala).		

Table 1. Measurement station locations and characteristics.



Figure 3. Station locations and maximum obscurations throughout Chilean territory, along with distances across measurement stations.

Due to the considerable amount of touristic and scientific observers gathered to observe the phenomenon, a remote location was chosen to ensure reporting the phenomenon in the most accurate manner possible, without obstructions or alterations caused by their presence. After a prospection process, a suitable observation site was located in the field approximately 8 km south of the town of Vicuña, with its coordinates stated in Table 1. Access to this measurement station site (called SHA for "shadow") was difficult due to complex terrain features, as the chosen location was near the top of a mountain that was reached after an off-road trail with several obstacles. The site was chosen due to its location within the maximum eclipse area, avoidance of horizon obstruction due to geographical features and, despite difficulties, the possibility to access it by vehicle. A panoramic image of the location is presented in Figure 4, with a highlight of the station's location. At this site, the solar disc was only covered for around one hour during sunrise and was not significantly obstructed at sunset.



Figure 4. Surroundings for the measurement station at the site of the total eclipse (SHA).

The SHA station had a full tracker station with pyranometers and pyrheliometer, with an RSI station as backup, but due to issues during transportation of equipment, the thermopile pyrheliometer connection station was rendered non-operational, as a result of which this station did not directly measure the direct normal irradiance, which was calculated from the global horizontal and the diffuse horizontal, along with the zenith angle (while being compared to RSI DNI measurements). All data shown in this work for the SHA station corresponds to thermopile instruments.

All data were rescaled to one-second intervals using linear interpolation between the original measurements, so as to ensure a uniform temporal resolution across all data sets to allow for comparison. The data was assessed using basic quality criteria so as to check for data consistency between irradiance components, as well as physical plausibility, in detail. The formulation of the quality control scheme is presented in Table 2, for GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance), and DIF (Diffuse Horizontal Irradiance). In [23–25], several approaches for gap-filling are presented, ranging from linear interpolation to more complex techniques; therefore, given the local character of each measurement site and the high sampling frequency, in the case of any data gaps or decidedly erroneous data, they are corrected using persistency of clearness index and diffuse fraction for irradiance and linear interpolation for the remainder of the variables.

Table 2. Quality control criteria used for data assessment.

Criteria	Description	Pass Criteria	Source
1	Plausibility check GHI	$0 < GHI < \left(100 + 1.5G(\sin\alpha)^{1.2}\right)$	BSRN [26]
2	Plausibility check DIF	$0 < DIF < \left(50 + 0.95G(\sin\alpha)^{1.2}\right)$	BSRN [26]
3	Consistency check	$DIF + DNI \sin \alpha > 50 \& \left \frac{GHI - (DIF + DNI \sin \alpha)}{GHI} \right < 0.08 \ if \ \alpha > 15^{\circ}$ $DIF + DNI \sin \alpha > 50 \& \left \frac{GHI - (DIF + DNI \sin \alpha)}{GHI} \right < 0.15 \ if \ \alpha < 15^{\circ}$	BSRN [26]
4	Consistency check 2	0 < DNI < G	RMIB [27]

3. Solar Eclipse and Irradiance Modeling Framework

3.1. Clear Sky Modeling

To establish a baseline for solar irradiance without the effect of the solar eclipse, a clear sky model is employed to estimate the irradiance under cloudless sky conditions. Due to its accuracy and simplicity, the European Solar Radiation Atlas (ESRA) Clear Sky Model was implemented, as described in [28], and subsequently a correction was introduced for very low turbidities, as presented in [29].

To estimate the Linke turbidity parameter, which encompasses the overall atmospheric attenuation, the procedure developed by [30] was employed, requiring as input the atmospheric water vapor, the aerosol optical depth, and an estimation of atmospheric pressure. The inputs for these models were obtained by processing data from the NASA Earth Observations repository [31] for elevation, water vapor column, and aerosol optical depth at 550nm for the week from 26 June through 3 July, due to the significantly increased spatial coverage, compared to the daily available data. All data possessed a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$. In order to estimate the atmospheric pressure, the barometric equation that can be derived from first principles is used, requiring a location's altitude and temperature as inputs. Data from the Terra/MODIS and Aqua/MODIS instruments were employed and processed using Quantum GIS 3.2.3 with GRASS 7.4.1 software.

Figure 5 presents the workflow for this procedure. This implementation of the model was evaluated for different locations in Chile for the period 2012–2017 in [32], where it was found to have good agreement with ground measurements. In this framework, ambient temperature (T_c) and site elevation above sea level (Z) are used as inputs to calculate the normalized atmospheric pressure (P_{po}), along with gravitational acceleration (g), molar mass of air (mm), and ideal gas constant (R). The uncorrected Linke turbidity (T_{L2}) is then calculated as a function of P_{po} along with the Aerosol Optical Depth at the 550 nm wavelength ($AOD_{@550nm}$) and the Integrated Water Vapor Column (WV). Finally, if applicable, the corrected Linke turbidity is calculated (T_{L2_c}), resulting in the value to be used for each pixel.



Figure 5. Graphical workflow of Linke turbidity estimation methodology.

3.2. Solar Disk Occultation Modeling

So as to assess the impact of the solar eclipse on a wide area, at the regional level, an efficient yet accurate method to model the solar disc occultation dynamics is required. Different models have been proposed in the literature to model the transit, such as [11]. Across this wide area, both total and partial eclipses will occur, for which the model ought to be independent of the type of eclipse and the specific geometric dynamics between the Sun's and Moon's disk as viewed from different locations. From [11], it can be seen that the eclipse occultation dynamics follow a Gaussian profile that is truncated in the case of a total solar eclipse, a fact also observed in [16]. Considering that some models, such as [11], rely on assumptions regarding the motion of the Moon and Sun (i.e., linear trajectories), it is likely that, when implementing such models over wide geographical regions, some differences will start to appear due to the effect of latitude. Therefore, the model used for this study should be as insensitive to this effect as possible or at least discard these kinds of assumptions.

In the light of this, a simple model was developed based on the previous evidence, as well as in the work by [33], where an entire chapter is devoted to describing the mathematical modeling required to determine the existence, duration, and coverage of a solar eclipse at a given location on Earth. The interested reader is referred to this work if more detailed information is required. For the present work, it suffices to define the concepts of eclipse obscuration, magnitude, and time for contact points, the first being the quotient of the

apparent areas of the lunar over the solar disc and the second the quotient of the apparent lunar over the solar disc diameters during the transit. In total, there are up to five instances of interest or contact points, C_1 and C_4 being the times at the first and last contacts of the solar and lunar disc, C_2 and C_3 being the times of start and end of the total eclipse, and finally, T_{MAX} being the time at which the maximum eclipse occurs. Mahooti [34] implemented the "ECLTIMER" routine by [33], which was used in this work, to determine these parameters for a given location and, with this information, fit a Gaussian function to reproduce the behavior. Equation (1) was derived empirically for the modeling, and Figure 6 presents graphically the results of this procedure, comparing the estimated attenuation against the clear sky clearness index, which, during clear skies without occultation, should be close to unity. From 18:30 to 19:30 UTC-0, a small attenuation is observed for the measurements, which corresponded with a transient dust cloud reported by the researchers in the field, which occurred due to a change in wind speed and direction that lifted the dust:



$$O_{b(t)} = M_g e^{\left(-\frac{(t-1_{MAX})}{(T_{MAX} - T_{C1})0.58333}\right)}$$
(1)

Figure 6. Comparison between modelled and observed effect of the eclipse, using the CPO station as an example. Apparent attenuation before eclipse was caused by a dust cloud. Vertical dashed line marks beginning of the eclipse according to astronomical algorithm.

3.3. Overall Atmospheric Attenuation Estimation

To estimate the irradiance that would have occurred under no eclipse conditions, the approach was to discern, from the overall observed attenuation with respect to the clear sky model, which attenuation corresponded to the eclipse and how much corresponded to un-modeled atmospheric attenuation and/or cloud phenomena. To this end, the clear sky clearness indexes were used for GHI and DIF; however, for the sake of simplicity, only the procedure for GHI will be presented in detail as the procedure for DIF is the same. However, under ideal conditions, the total attenuation would be the product of the clear sky clearness index multiplied by the attenuation caused by the eclipse. Nonetheless, due to the presence of different atmospheric phenomena, this simplification would lead to errors in estimating the contribution of each effect. Considering this scenario for the measurements, it is necessary to account for different factors in order to accurately separate how much radiation is lost to the occultation of the solar disk and how much is due to atmospheric phenomena.

First, the overall clear sky clearness indexes were calculated as follows:

$$K_{t_{cs_{(t)}}} = \frac{GHI_{(t)}}{GHI_{cs_{(t)}}}; K_{d_{cs_{(t)}}} = \frac{DIF_{(t)}}{DIF_{cs_{(t)}}}; K_{n_{cs_{(t)}}} = \frac{DNI_{(t)}}{DNI_{cs_{(t)}}}.$$
(2)

where $GHI_{(t)}$, $DIF_{(t)}$, and $DNI_{(t)}$ are, respectively, the global horizontal, diffuse horizontal, and direct normal irradiances at time t, with the suffix "cs" representing their corresponding clear sky irradiances and $K_{t_{cs}(t)}$, $K_{d_{cs}(t)}$, and $K_{n_{cs}(t)}$ being the clear sky, diffuse, and direct normal clearness indexes.

Then, considering the atmospheric transmittance changes as a function of the zenith angle, this behavior was modeled using the clear sky as a reference. Therefore, the overall clearness index was calculated as:

$$K_{t_{(t)}} = \frac{GHI_{cs_{(t)}}}{I_{o_{(t)}}} \,. \tag{3}$$

 I_o represents the extraterrestrial irradiance in a plane parallel to the surface, at the top of the atmosphere. Because the two definitions for the clearness index use a different variable for normalization, it is, therefore, necessary to make an equivalence between both of them. Under completely clear skies, the $K_{t_{cs_{(t)}}}$ will be close to the unity during most of the day, while the K_t will not exhibit this behavior. The scaled clearness index ($K'_{t_{(t)}}$) allows one to account for the losses in irradiance due to the changing profile over time, and thus is calculated as:

$$K_{t_{(t)}}' = \frac{GHI_{cs_{(t)}}}{I_{o_{(t)}}} \cdot \frac{\operatorname{mean}\left(K_{t_{\forall \alpha > 20^{\circ}}}\right)}{\operatorname{mean}\left(K_{t_{cs_{\forall \alpha > 20^{\circ}}}}\right)} .$$
(4)

The criteria of only using values with solar altitudes above 20 degrees allows one to obtain a representative dataset of the day's clearness index while reducing or eliminating the amount of data points affected by the eclipse. Therefore, the attenuation that is expected would be the product of the scaled clearness index by the attenuation caused by the occultation of the solar disk. Then, $K_{t_{loss}}$ would represent the actual attenuation caused by the eclipse:

$$K_{t_{loss}_{(t)}} = K'_{t_{(t)}} \left(1 - O_{b_{(t)}} \right).$$
(5)

Thus, the reconstructed clear sky clearness index time series ($K_{t_{cs_{NOECL}(t)}}$) would be the sum of the original time series plus $K_{t_{loss}(t)}$ (to reinstate the losses due to the occultation of the solar disk), and would then be de-normalized against I_o :

$$K_{t_{cs_{NOECL}(t)}} = \left(K_{t_{(t)}} + K_{t_{loss}(t)}\right) \frac{I_{o_{(t)}}}{GHI_{cs_{(t)}}} \,. \tag{6}$$

Finally, the GHI under no eclipse conditions is:

$$GHI_{NOECL_{(t)}} = K_{t_{cs_{NOECL_{(t)}}}} \times GHI_{cs_{(t)}} .$$
⁽⁷⁾

As stated, the same procedure was performed for the DIF to obtain the DIF under no eclipse conditions ($DIF_{NOECL_{(t)}}$), and the DNI under no eclipse conditions was calculated as:

$$DNI_{NOECL_{(t)}} = \frac{GHI_{NOECL_{(t)}} - DIF_{NOECL_{(t)}}}{\sin \alpha_{(t)}} .$$
(8)

Finally, the difference between the estimated irradiance against the measured irradiance allows one to determine the accuracy of the proposed method, as well as to quantify its uncertainty. To this end, the mean bias error (*MBE*) and normalized root mean squared

error (*NRMSE*) are calculated for GHI and DNI during the period of the eclipse, according to the following equations:

$$MBE = \frac{\sum_{i=1}^{i=n} \left(I^{i}_{estimation} - I^{i}_{measurement} \right)}{n} .$$
⁽⁹⁾

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{i=n} \left(I^{i}_{estimation} - I^{i}_{measurement}\right)^{2}/n}}{\frac{\sum_{i=1}^{i=n} \left(I^{i}_{measurement}\right)}{2}}.$$
 (10)

4. Solar Eclipse Effect Quantification

Because solar power generation is dependent upon the solar resource, especially widespread photovoltaic power that depends instantaneously on changes on solar irradiance, it is of interest to determine the impact that an astronomical event of this magnitude has on the overall power generation within the affected area. The first approach towards this task is to quantify the amount of energy that does not reach the Earth's surface and therefore causes losses for solar generation. To quantify these losses, two definitions of attenuation are employed: the first one refers to the amount of energy lost due to the eclipse (ATT_1) and the second refers to the changes in the apparent transmittance that result in solar radiation attenuation (ATT_2) ; both effects are considered only during the occurrence of the eclipse. ATT_1 allows for an intuitive understanding, from the perspective of energy, of the losses, while ATT_2 allows certain decoupling of the effect of the time at which the eclipse occurs, as the losses in energy are affected by the changes in solar irradiance due to its natural profile. ATT_1 and ATT_2 are defined as:

$$ATT_{1} = 1 - \frac{\int Irradiance_{eclipse}}{\int Irradiance_{no \ eclipse}};$$
(11)

$$ATT_{2} = 1 - \operatorname{mean}\left(\frac{Irradiance_{eclipse}}{Irradiance_{no \ eclipse}}\right)$$
(12)

Additional to the measurement stations, this same method is applied to the Chilean territory. Using the Linke turbidity and elevation rasters, for each pixel, the ESRA clear sky model is applied, the eclipse attenuation as a function of time is estimated, and the attenuated irradiance curves are calculated throughout the day, using a time step of 10 s. In this case, $Irradiance_{eclipse}$ is calculated as the clear sky irradiance multiplied by the eclipse attenuation, while $Irradiance_{no \ eclipse}$ represents the clear sky irradiance without changes. In all cases, it will be considered that the eclipse starts when there is at least 1% attenuation due to the eclipse.

5. Proposed Modeling Methodology Compared to Measured Data

Figure 7 illustrates graphically the procedure described in Section 3.3, applied to the TOC station. From the measured data and clear sky irradiance (Figure 7a), the $K_{t_{cs_{(t)}}}$ and $K_{n_{cs_{(t)}}}$ (Figure 7b,e) are calculated, along with the corresponding overall GHI and DNI attenuation, in which the effect of the eclipse in the apparent atmospheric transmittance are observed. Then, by isolating the effect of the eclipse attenuation (Figure 7c,f) it is possible to extract the affected irradiance and add it back to the original profile to estimate the corrected $K_{t_{cs_{(t)}}}$ and $K_{n_{cs_{(t)}}}$ curves under no eclipse conditions (Figure 7d,g). Finally, clear sky indexes are then converted to their respective irradiances (Figure 7h) and, as observed, the simulated irradiance under eclipse conditions (ECLSIM suffix), calculated from the estimated irradiance under no eclipse conditions (NOECL suffix), has good agreement with the measured irradiance.



Figure 7. Estimation of atmospheric attenuation and reconstruction of irradiance under no eclipse conditions. Vertical dashed lines mark the beginning and end of the eclipse according to astronomical algorithm. (**a**) Measured and clear sky irradiances, (**b**) clear sky clearness index and GHI attenuation, (**c**) eclipse obscuration as a function of time, (**d**) corrected clear sky clearness index and GHI attenuation to discount eclipse effect, (**e**) clear sky beam transmittance and DNI attenuation, (**f**) eclipse obscuration as a function of time, (**g**) corrected clear sky beam transmittance and DNI attenuation to discount eclipse effect, (**h**) estimation of irradiance discounting eclipse effect.

Figure 8 presents the model's performance in more detail in the hours around and during the eclipse for the TOC station, to further complement the results shown in Figure 7. As can be seen, there is good agreement for GHI and DNI in general, although at specific moments close to the maximum eclipse effect, the relative error can rise up to 50% for DNI and 25% for GHI. Nevertheless, while the relative error can be large, this is transitory and mainly due to the extremely low values for GHI and DNI during these instances, coupled with a very low solar elevation at the end of the day. Tables 3 and 4 present the error metrics for the assessment of the entire period of the eclipse.



Figure 8. Detail on estimation error time series for GHI and DNI during eclipse conditions. Vertical dashed lines mark the beginning of the eclipse according to astronomical algorithm.

Table 3. Estimation errors f	for clearness ind	lexes under no ec	lipse conditions	s for the measu	rement stations.
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	K_{tcs}			K_{ncs}		
Station	MBE (-)	RMSE (-)	NRMSE (–)	MBE (–)	RMSE (-)	NRMSE (–)
TMG	-0.003	0.005	0.009	$-3.00 imes10^{-4}$	0.005	0.019
TOC	0.012	0.018	0.036	0.022	0.018	0.079
LIK	-0.003	0.012	0.023	-0.006	0.012	0.033
DDA	-0.017	0.028	0.058	-0.037	0.028	0.097
CPO	-0.014	0.020	0.037	-0.004	0.020	0.032
SHA	-0.019	0.039	0.080	-0.044	0.039	0.114
UCH	0.017	0.024	0.058	0.014	0.024	0.055
PUC	0.026	0.035	0.090	0.024	0.035	0.100

Table 4. Estimation errors for irradiance under no eclipse conditions for the measurement stations.

	GHI			DNI		
Station	MBE (W/m ²)	RMSE (W/m ²)	NRMSE (–)	MBE (W/m ²)	RMSE (W/m ²)	NRMSE (–)
TMG	-0.008	1.347	0.007	-0.004	6.214	0.014
TOC	0.037	3.607	0.021	-0.014	24.308	0.071
LIK	-0.005	2.141	0.012	-4.664	11.166	0.032
DDA	-0.045	7.418	0.045	-0.14	36.757	0.093
CPO	-0.032	5.785	0.033	-0.018	19.904	0.044
SHA	-0.172	9.596	0.058	-0.256	75.466	0.157
UCH	0.193	3.215	0.028	0.046	12.666	0.046
PUC	0.98	4.82	0.043	-0.35	29.753	0.122

The difference between the clear sky and measured irradiances is due to the atmospheric attenuation of solar radiation caused by a light cloud coverage that allows most of the DNI to pass. For CPO and SHA stations, because the prevalent conditions were clear sky, there was an excellent agreement between the estimated clear sky irradiance and the measured irradiance when modeled using the ESRA clear sky model and the estimated Linke turbidity from the previously described satellite estimation procedure. In the remainder of the stations, clear sky irradiance resulted significantly higher than the measured irradiance, which could be attributed to errors due to geographic smoothing caused by the spatial resolution of the satellite data and/or the cloud coverage that, while it does affect irradiance, cannot be considered as part of the atmospheric turbidity according to the Linke turbidity definition. Nevertheless, in all cases, the estimation error was fairly low and a summary of its results is presented in the following tables.

6. Solar Eclipse Field Observations

For the most part, all of the measurement sites experienced considerable variability throughout the day due to fluctuating cloud covers, except for the CPO and SHA stations. Figure 9 presents the irradiance time series for 2 July 2019 on all of the measurement sites. All stations exhibited the same pattern of irradiance decrease as the eclipse progressed, and it slightly increased as it approached completion, albeit with much lower irradiance values due to sunset. As expected, the most profound effect is on DNI; however, both GHI and DIF are also impacted. As the TMG, TOC, and LIK stations were the farthest from maximum obscuration, the corresponding attenuations are lower, as evidenced in Figure 9. Two sets of stations, DDA–CPO and UCL–PUC, were located to the north and south of the SHA station, respectively, with similar levels of obscuration, resulting in similar irradiance values at the point of maximum eclipse, which are much lower than for the TMG, TOC, and LIK stations. Finally, for the SHA station, clear sky conditions were present during the day, for which the only sources of irradiance attenuation in this location were the clear sky atmospheric absorption and scattering, as well as the solar disc occultation during the eclipse.



Figure 9. Irradiance time series for each measurement station for 2 July 2019. Vertical dashed lines mark the beginning and end of the eclipse according to astronomical algorithm.

With respect to the meteorological variables, all stations exhibited a similar pattern regarding temperature and relative humidity, while wind speed and direction were quite different, as shown in Figure 10. As the day progressed and irradiance increases, so does temperature, while relative humidity decreases. However, since the start of the eclipse, an early sunset effect was observed in all stations, as temperature decreased and, correspondingly, relative humidity increased. Even though wind speed and direction behavior was different among the different stations, in all cases but DDA and TMG, wind speed significantly dropped as the eclipse progressed, when compared to pre-eclipse values.



Figure 10. Meteorological variables for 2 July 2019 at the measurement stations: wind speed, ambient temperature, and relative humidity. Ambient temperature is displayed with a scaling factor of \times 3. Dashed vertical lines show the beginning and end of the eclipse according to astronomical algorithm.

The TMG, TOC, and PUC stations recorded the highest increases in relative humidity, from close to 20% pre-eclipse to over 50% post-eclipse, with DDA slightly increasing from 30 to 50%, while the remainder showed no significant changes during the eclipse, standing under 20% for LIK, CPO, and SHA. Regarding temperature, TMG and TOC registered the sharpest eclipse-induced temperature decreases of 7 °C, while for LIK it was 6 °C, DDA and PUC, 5 °C, SHA, 4 °C, and CPO, 2 °C.

Some anomalies were observed during measurement and data analysis on the staffed locations. CPO experienced a sharp temperature drop as a strong wind gust developed, lifting some dust in the location, causing a detectable decrease in DNI and an increase in DIF. After this, temperature presented a slow decline as the eclipse progressed and significantly dropped at sunset, which would explain the lower decrease in temperature when compared to the remainder of stations. Unusual peaks were detected for temperature and relative humidity just after the eclipse, which were caused by the proximity of staff to

the temperature and humidity probe when returning the station to its nominal operation routine. As for the SHA station, a sudden increase in wind speed around 14 h UTC-0 was recorded; however, this value is inaccurate as the responsible wind gust was of such magnitude that it toppled the mast on which the wind sensor was mounted.

Figure 11 presents a detail of the time series for the SHA station during the eclipse, along with the photographic record of the event. Pictures were taken with a Canon EOS Rebel T2i APS-C camera mounted on a two-axis tracker and using a solar filter. The images were processed using PixInsight software to recover and highlight features around the corona during the maximum obscuration shot, which was an HDR composite of several exposures. From the correlation between the time series and the images, a high sensitivity of DNI with the occultation of the solar disk is observed.



Figure 11. Detailed time series for the total eclipse at the SHA station, along with photographic record of the event. Vertical dashed lines mark contact points C1 through C3 according to astronomical algorithm.

One interesting finding was observed when analyzing the SHA station data. This station possessed both thermopile and photodiode instruments, with very different response times: under 5 s for thermopile and under 1 s for photodiode. Even when considering any potential differences due to calibration, compensation, temperature, and cosine response differences, GHI measurements differed with respect to the recorded length of totality for the eclipse.

Totality was calculated using the astronomical algorithm described in Section 3.2 to define the start and end of the eclipse, which were used as a baseline for this analysis, resulting in a value of 2.07 min. When considering the time between the first and last zero values recorded, the thermopile instrument registered a duration of around 8 min, while the photodiode instrument registered 4.5 min. Further, when only consistently zero values are considered to discard influence of noise, the recorded duration was 2.95 min.

This dynamic can be attributed to the different principles of operation for each sensor, but both are related to a shift in the energy balance. For the thermopile sensor, during totality the receiving sensing surface would not be receiving radiation but would instead be emitting in the infrared due to the temperature difference against the space, therefore resulting in decreased and negative values. For the photodiode sensor, this effect is much less pronounced as the readings are not directly dependent upon the energy balance as for a thermopile sensor, resulting in a measured time of eclipse much closer to the theoretical expectation derived from the astronomical model. Figure 12 presents the time series in detail for GHI measurements for both types of sensors, in which a higher dispersion is observed in the photodiode curve due to the high speed of response of the photodiode pyranometer and the lower inherent damping for this type of sensor.



Figure 12. Differences in measurements of the eclipse between thermopile and photodiode sensors. Vertical dashed lines mark contact points C1 through C3 according to astronomical algorithm.

7. Solar Eclipse Effect in the Chilean Territory

Figure 13 shows an estimation of the Linke turbidity coefficient for the Chilean territory. As observed, most of the areas are characterized by low turbidities, except for the Metropolitan region, where Santiago is located, until the La Araucanía region (Latitude 38° S). From Figure 9, it is observed that the CPO and SHA stations presented clear skies during the day and the estimated clear sky radiation has good agreement with the measurements. For the remaining stations, in all cases, the measured radiation was below the clear sky irradiances, which can be caused by a combination of thin clouds that attenuate somewhat the irradiance while still letting through significant amounts of DNI, or estimation error between the estimated turbidity from satellite means and the real local turbidity.

Figure 14 presents a map of the estimated attenuation (ATT_1) for the Chilean territory during the eclipse. Irradiance attenuation in the measuring stations presents differences according to the eclipse obscuration and sky conditions, but has a good agreement overall. Figure 15 shows the relationship between obscuration and irradiance attenuation (ATT_1) obtained by applying the proposed methodology to the Chilean territory and how it compares to the measured data. To evaluate if there were effects due to latitude, data points for locations to the north and south of SHA station were plotted with different colors, as it bears some relation to the Chilean geographic and climatological context: to the north of the eclipse, desert climates are prevalent, while to the south, Mediterranean climates are the most common. The effect of latitude is presented indirectly through the obscuration, and the effect of longitude presents as the "band" in which the estimated values exist, as, depending on the location, the eclipse could occur sooner or later during the daytime, affecting the amount of attenuated irradiance.



Figure 13. Estimated Linke turbidity for the Chilean territory on 2 July 2019.



Figure 14. Maximum obscuration and estimated GHI and DNI attenuations for the Chilean territory during the 2 July 2019 solar eclipse.

The proposed model presents a good fit to estimate GHI attenuation, where each station reported presents minimal differences between expected and measured irradiance. Only the DDA station presents a significant difference with respect to the expected irradiance. On the other hand, the DNI attenuation model has a larger margin of error, when compared to results obtained for GHI. LIK, TMG, and CPO attenuation values coincide with the model. Meanwhile, TOC, DDA, UCL, PUC, and SHA stations show a high variation of the attenuation during the eclipse that can be explained by some atmospheric processes that are not appropriately accounted in the present analysis. The CPO and SHA stations presented overall clear sky conditions; however, there was a good fit in the first case, but this was not so in the latter. The reason for this is not related to atmospheric modeling, but eclipse modeling, as the estimated attenuation was slightly larger than the observed.



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Figure 15. Estimated attenuation as a function of local obscuration, calculated for the Chilean mainland territory. Uncertainty interval considers proposed method error and clear sky and instrumentation uncertainty.

To obtain the attenuation, three components were used: clear sky model, irradiance measurements, and eclipse modeling. Therefore, the obtained results must be put into context with the uncertainty in estimation in these parameters. From a previous work by the authors [35], measurement uncertainty from ISO 9060:2018 Spectrally Flat Class A Instruments (ISO 9060:1990 Secondary Standard, thermopile-based) resulted in $\pm 1.8\%$ for GHI and $\pm 2.7\%$ for DNI, and for ISO 9060:2018 Fast Response Class C Instruments (photodiode-based) it was $\pm 1.9\%$ for GHI and $\pm 3.3\%$ for DNI, which were found to be in accord with the scientific literature. For clear sky modeling, Antonanzas et al. [36] performed an extensive analysis of 70 clear sky models, finding that their typical errors are $\pm 3\%$ for GHI and $\pm 8\%$ for DNI, even in perfectly clear sky conditions. When considering these uncertainties, along with the estimation error of the proposed method subject of this work, the uncertainty interval for the estimation (calculated as the root-square-sum of sources of uncertainty [37]) is presented in Figure 15.

A contrast between the proposed two methods to quantify the attenuation is shown in Table 5. ATT_1 GHI ratios are lower than the values from the ATT_2 method because the sun elevation angle decreases from the start of the eclipse. For this reason, GHI decreases have different weights throughout the eclipse due to its dependence on the solar elevation angle. Conversely, this effect is lower on the DNI analysis, where the results from ATT_1 and ATT_2 are very similar in five of the eight measurement stations because the DNI presents a lower dependence on the solar elevation angle. Finally, both methods show different properties from the eclipse, especially ATT_1 , which assigns a higher weight to significant differences on the expected and measured irradiance, while ATT_2 offers a similar response to the variation on the irradiance, regardless of the magnitude of the measurement. It is expected that ATT_1 definition provides a simple and straightforward method to quantify the energy that is actually lost due to the eclipse, while ATT_2 allows one to decouple the attenuation from the angular dependence observed in the case of GHI.

Station	G	HI	DNI		
Station	ATT_1	ATT_2	ATT_1	ATT ₂	
TMG	0.323	0.362	0.366	0.366	
TOC	0.346	0.403	0.418	0.428	
LIK	0.338	0.396	0.381	0.386	
DDA	0.35	0.437	0.374	0.414	
CPO	0.377	0.449	0.457	0.459	
SHA	0.406	0.491	0.456	0.457	
UCH	0.396	0.501	0.48	0.502	
PUC	0.397	0.516	0.479	0.517	

Table 5. GHI and DNI measured attenuations, comparing the results of the two attenuation definitions employed in this work.

8. Discussion of Results

The testing of quality control (QC) was applied to the measurements of the eight solarimetric stations used in this study, resulting in the activation of several QC flags during the beginning and end of the day, which is a normal situation due to low solar elevation. In the same way, some flags turned on during the solar eclipse in the stations with obscuration greater than 75% because the irradiance level was significantly lower than expected for that solar altitude. Thus, the TMG station did not raise QC flags during the eclipse, while in TOC and LIK stations the QC consistency checks raised flags only in the maximum obscuration percentage, more indicators are activated due to the decrease in irradiance to levels close to or equal to zero. Nevertheless, after assessment and inspection, the data used is consistently deemed as valid.

Regarding the meteorological variables, all of the stations registered a decrease in temperature during the eclipse. Normally the temperature decreased to the end of the day, but as a consequence of eclipse obscuration, its decrease was more abrupt or went ahead in time. In the zone of the total eclipse it is possible to notice the direct effect of the eclipse on temperature, due to the temperature rise once the eclipse finishes. As far as wind speed is concerned, there is no evidence of any specific pattern in magnitude or direction that covers the dynamic of all the stations.

The comparison between modeled irradiance and the measurements in the eight solarimetric stations is consistent in the period pre- and post-eclipse, and during the period of eclipse presented NRMSE lower than 0.06 for GHI and lower than 0.16 for DNI, obtaining lower magnitudes in the error estimators for the stations with lower variability in the irradiance, as a consequence of lower variability in the cloudiness. The value of these metrics allows using the irradiance modeled as a base to quantify the irradiance lost by the eclipse effect.

From Figure 15, the effect of cloud presence at the moment of the eclipse is observable, as stations with a clear sky during the eclipse (DDA, CPO, and SHA) present attenuation values lower than the expected, while stations with cloud presence (SCL, PUC, LIK, TOC, and TMG) show higher values regarding the proposed model. This is due to a combination of effects First, because cloud effects are greater on the DNI than on GHI, any errors in the estimation of DNI should be higher than on GHI, and in either case constitute non-modeled atmospheric attenuations sources that exceeds those of the modeled clear sky. On the other hand, stations with clear skies resulted in lower attenuations than predicted due to the fact that there is an overestimation of the eclipse attenuation in the starting and ending phases, in which the estimated eclipse obscurity is around 5% when it actually is just starting.

In Figure 14, the contour lines for the GHI and DNI attenuation have different slopes when compared to those of maximum obscuration. This can be attributed to the following effects. First, the atmospheric turbidity affects differently the GHI and DNI differently; in the case of the GHI the increase of the turbidity near the coast in comparison with the east (Figure 13) produces a bigger decrease in the GHI attenuation on the west. While a larger decrease on the DNI is observed on the east and second, the eclipse had different durations along the same latitude, which also affects the eclipse dynamics and, therefore, the total attenuation.

Finally, two different methods for characterizing the attenuation were evaluated, as a function of energy loss (ATT_1) and as a function of mean atmospheric transmittance (ATT_2) . It was found that ATT_2 values were more consistent than the ATT_1 values for DNI and, conversely, for GHI. This is caused by the higher dependence of GHI on the changes of the Sun's elevation angle, whereas DNI has a much more stable profile once the solar elevation angle exceeds a certain magnitude. It is thought that ATT_2 provides a decoupled measurement of the attenuation, irrespective of the time of day; however, ATT_1 is a more representative measure of the true impact of the occultation phenomenon, as it causes a measurable loss in the energy that reaches the Earth's surface. More studies need to be performed in this regard on eclipses that occur at different moments of the day, and preferably in clear sky conditions, to confirm this conclusion. When considering the error metrics presented in Tables 3 and 4, it can be concluded that ATT_2 has a slightly greater uncertainty than ATT_1 , as clear sky index NRMSEs are higher than irradiance ones, which relate to ATT_2 and ATT_1 , respectively.

9. Conclusions

In this work, a complete methodology to estimate the effect a solar eclipse has on the three components of solar irradiance over the terrestrial surface, regardless of the locally observed maximum obscuration, has been presented and validated against measured data from eight solarimetric stations throughout Chilean territory. The method requires the geographical coordinates and altitude of a location, as well as an atmospheric modeling that allows one to estimate the irradiance under clear sky conditions. Results showed an overall good agreement between the estimate from satellite measurements and the measured data, with differences being attributed to: (a) uncertainty in the inputs, mainly due to the fact that it is a week average instead of a daily average as well as the intra-pixel differences in respect to the pixel value and; (b) The presence of a cloud layer of sufficient optical thickness to allow for DNI to pass through in significant amounts but with enough attenuation effect to diminish irradiance from clear sky conditions. To better account for atmospheric phenomena, it is suggested that, for future studies, a measurement campaign of at least one week of duration is performed at the measurement site around the days of the eclipse event.

The main differences encountered in the eclipse attenuation modeling occurred at the initial and final stages. Nevertheless, the overall effect in the estimation is deemed to be non-significant for practical purposes, as the combined effects of (a) the short duration of the observed difference when compared to the integration interval and (b) the low magnitude of the difference between estimated and measured obscuration lead to a small overall estimation error. Other references exist in the literature for modeling the obscuration of the solar disk that may offer more accuracy in the modeling, but the obtained results showed excellent agreement with the measured data, both at the local and regional scales, despite using a much simpler mathematical model. Additionally, a simple procedure to decouple irradiance attenuation due to atmospheric phenomena from attenuation due to solar disc occultation was developed and provided excellent results, with MBEs under 1 W/m² for GHI and 5 W/m² for DNI and NRMSEs under 6% and 16% for GHI and DNI, respectively. Likewise, an uncertainty analysis for the total estimation has been performed; therefore, future works aiming to apply the proposed methodology can include this information in their uncertainty modes, to make informed decisions relating to this uncertainty.

Regarding the measurements, the role of high-frequency measurements, as well as fast response equipment, is confirmed as paramount, as the short duration of the phenomena demands instrumentation that is able to resolve details of the physical process to fully register its dynamic characteristics. However, it was found that thermopile sensors can report values equal to or less than zero around the maximum eclipse. It is the authors' hypothesis that this can be attributed to the sudden obscuration that leads to a negative energy balance in the sensor, as it rapidly undergoes a change from a state in which it gains significant amounts of energy due to irradiance to a state in which the infrared emission is greater as the sensor emits radiation into space.

While the proposed method poses scientific interest on its own, its greater relevance comes from its potential application to analyze electric dispatch under solar eclipse CON-DITIONS, allowing system operators to better prepare for such conditions in advance, as the proposed method constitutes a proven framework for evaluation of the effect of a solar eclipse on irradiance over wide geographical contexts and with a high temporal resolution that allows one to model changes in irradiance due to this astronomic phenomenon. Therefore, the proposed method can be applied in the future to study the impact on the dynamic response of solar powered generators, especially photovoltaic plants, due to their proportional and instantaneous dependence on changes in irradiance. With this information, regional solar power production can be estimated, and the economic dispatch problem can be more accurately and economically solved by considering, in advance, the effect of the eclipse on the available primary energy for the grid. This could also benefit solar generators, as it will provide confidence in their ability to supply power during the day of the eclipse, compared with a potential reduction in revenue should the dispatch be overly conservative to avoid upsets due to the comparatively fast ramping caused during the eclipse and curtail their output because of this phenomenon.

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